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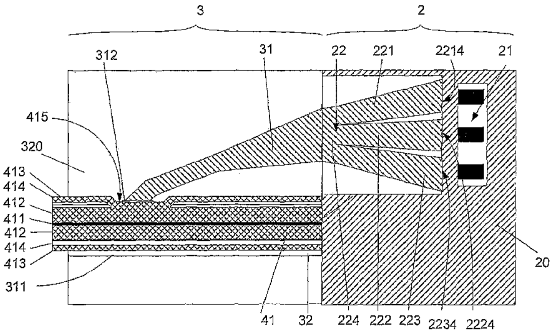
**(54) Title:** A COUPLING PART, AN OPTICAL COUPLING DEVICE, A LIGHT SOURCE PART, AN END COUPLED OPTICAL DEVICE, A LIGHT SOURCE MODULE, AND A SIDE COUPLED OPTICAL DEVICE



**(57) Abstract:** The invention relates to a coupling part (3) comprising at least one essentially planar coupling waveguide (31) formed on a coupling-substrate (30), the coupling-substrate having opposite waveguide- and substrate faces, the coupling waveguide or waveguides each having an output face, the coupling waveguides being adapted to be optically coupled to source waveguide or waveguides for supplying light power to the coupling part. An object of the present invention is to provide a cost-efficient scheme for integrating one or several light sources with optical waveguides with minimum loss of brightness and power. A further object of the invention is to facilitate the coupling of the light from a light source into passive or active application waveguides. A further object of the invention is to facilitate the coupling of the light from a light source module into passive or active application waveguides. The problem is solved in that the coupling part (3) comprises a) at least one elongate groove (32) in the form of a recess in the waveguide face, the groove being adapted to receive an elongated optical application waveguide (41), and b) at least one coupling waveguide (31) and at least one groove (32) are formed on the coupling-substrate (30) relative to each other so that the output face of the coupling waveguide is suitable for being side-coupled to an application waveguide (41) located in said groove. The invention further relates to a light source part and a light source module and to optical devices based on these parts. The invention may e.g. be used in high power fibre lasers or fibre amplifiers.

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# A coupling part, an optical coupling device, a light source part, an end coupled optical device, a light source module, and a side coupled optical device

## TECHNICAL FIELD

This invention relates in general to beam shaping and waveguide coupling of light emitted from multiple high power laser diodes, and more particularly to beam shaping and waveguide coupling arrangements, which maintain a high optical brightness in a low cost and mechanically robust configuration.

The invention specifically relates to a coupling part for coupling light to an application part, the coupling part comprising at least one essentially planar coupling waveguide formed on a coupling-substrate, the coupling-substrate having opposite waveguide- and substrate faces, at least one of the coupling waveguides having an input and an output face, the input face of the coupling waveguide or waveguides being adapted to be optically coupled to source waveguides for supplying light power to the coupling part.

The invention also relates to an optical coupling device comprising a coupling part and an application part.

The invention furthermore relates to a light source part comprising a) a multitude of N laser diodes $LD_i$ with predetermined numerical apertures $NA_{LD,i}$, i=1, 2, ..., N, each individual laser diode having an emitting face with a laser stripe for emitting light power, b) a multitude of M essentially planar optical input source waveguides $WG_j$ with predetermined numerical apertures $NA_{WG,j}$, j=1, 2, ..., M, the waveguides each having an input face with a capture area for capturing light, and the waveguides being formed on a source-substrate, c) each waveguide being adapted to receive light from one or more corresponding laser diodes, and d) an output interface for making light from the laser diodes available.

The invention also relates to an end coupled optical device comprising a light source part and an application part.

The invention furthermore relates to a light source module comprising a light source part and a coupling part.

The invention also relates to a side coupled optical device comprising a light source module and an application part.

The invention may e.g. be useful in applications such as high power fibre lasers or fibre amplifiers.

## BACKGROUND ART

The following account of the prior art relates to one of the areas of application of the present invention, high power fibre lasers.

### High power fibre lasers:

The key to volume applications of fibre lasers is their ability to compete with more-conventional lasers, most notably diode pumped solid state lasers (DPSS). In DPSS systems, thermal management within the laser cavity is a concern, which leads to compromises between beam quality and system efficiency. Because the fibre creates an optical laser cavity that is several meters long with a very large surface area, heat dissipation in a fibre laser cavity is substantially accelerated. This eliminates the beam quality degradation and reduced system efficiency caused by adverse thermal effects.

Further, a double-clad fibre geometry ensures that substantially all pump light is absorbed within the laser cavity, which increases optical-to-optical conversion efficiency by a factor of two over conventional DPSS systems (having a conversion efficiency of e.g. 35-40%) to in excess of 75%.

Fibre lasers are mechanically rugged and robust structures. In a fibre laser, e.g. based on an integrated, single-mode silica fibre, there is no potential for performance degradation from intra-cavity contamination or misalignment. Consequently, a fibre laser system can maintain diffraction-limited beam quality (maximum brightness) independent of variables like system age or environmental changes.

All in all fibre lasers have a lot of very attractive technical features, the main factor limiting the commercial application of fibre lasers is the cost, and in particular the cost of pump power. Coupling the pump light from a semiconductor diode (array) into a small waveguide (10-200 µm in diameter) is with the present technology much more complicated than coupling the pump light into a solid state laser crystal with diameters of 3-12 mm. This results in the cost of pump light for fibre lasers being typically 10 times higher, than the cost of pump light for solid state lasers. Today the practical applications of fibre lasers are therefore significantly limited by the cost of the pump light for these lasers.

Thus to fully exploit the advantages of high power fibre lasers, there is a need for a low cost, high brightness, high power light source module and for a low loss and low cost coupling of such a module to an application waveguide (e.g. an active fibre).

<u>High brightness, high power diode laser sources for use in high power fibre lasers:</u>

The present invention relates to a high power, high brightness, potentially low cost diode laser module and its applications, in particular for pumping high power fibre lasers.

Broad area diode lasers are very attractive as high power, low cost laser sources. Unfortunately, however, traditional waveguide (fibre) coupled modules suffer from a significant loss of brightness following the waveguide coupling. FIG. 1.a. shows brightness versus output power for the light emitted directly from a (1x100 µm width, 0.3x0.1 NA and 4 W output) broad area laser as well as the brightness for two different types of commercially available waveguide (fibre) coupled modules, referred to as 'low brightness' and 'high brightness', respectively. These modules are described further in the following section. It is clear from FIG. 1.a that:

- A brightness reduction of 1-2 orders of magnitude follows the waveguide coupling of broad area lasers based on existing techniques.
- 'The high brightness' coupling schemes do not scale well with the power, i.e. in the 'high brightness' schemes brightness is reduced as power is increased.

Cost effective, high power, high brightness diode laser sources are required for many applications, for example material processing, e.g. medical treatment, marking, welding, etc. FIG. 1.b shows the minimum beam quality (beam parameter product) and power required for different types of material processing. Please note that the beam parameter product, q, used in FIG. 1.b is closely related to the brightness, B, as

$$q = \sqrt{P/(\pi B)}$$

where P is the optical power. FIG. 1.b clearly indicates, that the number of material processing applications for a given laser type increases with power and brightness (decreasing beam parameter product).

FIG. 1.c represents a combination of FIG. 1.a. and FIG. 1.b. and shows the beam parameter product versus output power for the 'low' and 'high' brightness waveguide coupled modules of FIG. 1.a.

It is clear from FIG. 1.c, that a high power diode laser waveguide coupling with improved brightness/beam-parameter-product would enable a number of new applications for this type of laser source.

High brightness is critical to the pumping of solid state lasers and in particular double-clad fibre lasers.

- The maximum output power of these fibre lasers is often limited by non-linear effects, which scale with the length of the active fibre. Consequently, it is desirable to be able to design high power fibre lasers with short lengths of fibre. Short fibre lengths will require an effective absorption of the pump light from the pump core (inner cladding) into the signal core. This absorption increases as the overlap between the core and the inner cladding increases, i.e. the smaller the inner cladding, the more efficient absorption.
- To obtain a given output power, a given pump power must be coupled into the inner-cladding of the fibre. If a low brightness pump source is used, a large inner cladding is required, whereas a small inner cladding (large overlap to the core) can be used, if a high brightness pump source is available.

In the presently available waveguide-coupled high power laser modules, the output from a single high power multimode diode or a diode array is coupled into an optical fibre by individual optical lenses or by arrays of optical lenses. One example of such a system is described in US-6,421,178 where two lens arrays, two angle transforming elements and a Fourier transforming element is used to couple the light from a diode laser array into an optical fibre.

This technology is characterised by a number of issues such as low brightness and high cost (e.g. due to the need for extra optical elements and their alignment relative to waveguides and/or laser diodes).

Low brightness: A significant loss of brightness results from the fibre coupling. A typical diode laser has an output power of 4 W from a 1 x 100 μm stripe with NAs (NA=Numerical Aperture) of 0.1 in one axis and 0.3 in the other axis. This corresponds to a brightness (luminance) of 965 GW/($m^2$sr). In typical single diode fibre coupled devices (2 W, 100 μm, NA = 0.2), the brightness is reduced to 3.35 GW/($m^2$sr), corresponding to a loss of brightness of more than two orders of magnitude.

High brightness coupling schemes are available (cf. e.g. WO-02/50599). Modules like these can provide 5 W in a 25 μm fibre with an NA of 0.6 corresponding to a brightness of 15 GW/($m^2$sr). However, these high brightness coupling schemes do not scale well with power (see e.g. FIG. 1.a, legend "High Brightness").

High cost: The fibre coupling and beam shaping require careful alignment and fixing of a multitude of advanced lenses with respect to the diode lasers. This is a manual, time consuming and expensive process.

For a 'low brightness' module like that described in US-6,421,178, 18 different optical elements has to be aligned of which 6 are specially designed precision manufactured passive optical elements. All these elements have to be aligned with very high accuracy (a few μm) relative to each other to obtain the desired coupling efficiency of the fibre-coupled diode laser module.

For 'high brightness' modules like that described in WO-02/50599, even more optical elements are required, which obviously leads to even more labour intensive and expensive modules.

Pumping of (double) clad optical fibres can essentially be divided into end- and side-pumping. End-pumping is the most simple approach but has major drawbacks with respect to:

- Power scaling; since there are only two ends of a fibre and high power, high brightness sources are not readily available. This tends to limit the maximum pump power available for end pumped fibre lasers to the order of 100 W.
- Reliability. End coupled fibre lasers are pumped by fibre coupled high power diode arrays. Diode arrays tend to have a poorer reliability than single emitters. The reason is the difficulties in heat dissipation from the arrays and the mechanical stress introduced in the bonding of the diode arrays to substrates, which typically have different thermal expansion coefficients.
- Pump coupling requires optical multiplexers, typically consisting of di-croich mirrors and collimating optical lenses. This adds to the complexity of the fibre lasers and will hence increase cost and reduce reliability.

For these reasons side-pumping will in general be the preferred pump coupling scheme and is presently used by the main commercial manufacturers of high power fibre lasers. Various schemes for side-coupling light to optical fibres using a coupling window in the fibres are disclosed in the prior art.

Side-coupling based on multi-mode fibre couplers are described in for example US-6,434,295 and US-5,999,673. In this case traditional (low NA) multimode fibres are tapered and fused to (high NA) double-clad fibre. The drawback of this method is that, the pump signal has to be inserted from a multimode fibre with a significantly lower diameter or NA than the double-clad fibre. This implies a fairly limited power per pump fibre (typically around 2 W). Consequently, many fibre connections and individually packaged diode lasers are required for high power operation, which will add significantly to the cost.

Side-coupling based on grooves in the double-clad fibre is described in for example US-5,854,865. In this case a groove is etched or cut into the multimode region of the double-clad fibre. When pump light is inserted from the other side of the fibre, it can be reflected (total internal reflection) by the groove and be coupled into the multimode part of the double-clad fibre.

US-5,923,694 deals with a pumped fibre laser including turns of optical fibre defining a wound pack, the fibre comprising a core, a cladding around the core and a concentric layer of a porous glass matrix material (e.g. sol-gel) around the cladding. The fibre laser further includes a pump laser (e.g. a semiconductor laser bar) and a wedge device (and possibly additionally a lens element between the pump laser and the wedge) for directing the light from the lasing regions into the side of the optical fibre at a plurality of different turns thereof.

Other examples are found in US-6,317,537 and US-6,490,388.

The prior art solutions comprise complicated beam focusing accessories (e.g. US-5,923,694) and/or complex input coupling means attached to/integrated with the waveguide (e.g. US-6,317,537). All in all, these schemes all require some sort of very delicate active alignment between laser diode and fibre. Further hermetic sealing of the laser diode part is tricky as large areas with complex geometries have to be sealed.

WO-03/038497 deals with an optical device fabricated on a substrate, a tranverse-transfer optical waveguide fabricated on the substrate and a transmission optical waveguide. This invention requires the optical power to be coupled between the two waveguides by either mode-interference coupling or adiabatic optical power transfer. Both of these techniques require accurate control of the coupling length and depth of the two waveguides and hence complex processing of the waveguide interface area.

In summary, the prior art technologies for providing pump light for fibre lasers have the following drawbacks:

- A significant loss of brightness results from the waveguide coupling of high power diode lasers
- Schemes for coupling the light from the diode laser into the application waveguide (e.g. the fibre laser) are cumbersome, expensive and labour intensive because they require active and accurate alignment of a multitude of precision manufactured optical elements

## DEFINITION OF TERMS

The definitions in the present section 'Definition of terms' are intended to be valid (where appropriate) for all embodiments as described in the following sections of the description and as defined in the accompanying claims.

### *Planar optical waveguides*

In the present context, the term 'essentially planar optical waveguides' is taken to mean that the waveguides are obtainable by a planar processing technology such as a silica on silicon or semiconductor technology.

The optical waveguides each comprise a central region (e.g. a core region) comprising a matrix material having a refractive index $n_c$ surrounded by one or more surrounding regions (e.g. one or more cladding regions) each comprising a matrix material having refractive indices, respectively, $n_{s1}$, $n_{s2}$, etc. Micro-structural elements (e.g. extending in a longitudinal direction of a waveguide) having refractive indices different from those of the matrix materials may be dispersed in the matrix materials. The term 'surrounding' is in the present context taken to mean fully or partially enclosing, to include a waveguide where the central region has one or more 'coaxially surrounding regions' (i.e. one neighbouring region that fully encloses the central region and which may itself be fully enclosed by a second neighbouring region) or has several 'neighbouring surrounding regions' each of which has an interface to the central region in question (cf. e.g. FIG. 11.b).

The border between two neighbouring planar waveguides is taken to be midway between the central regions of the two waveguides as defined by the centrelines of the central regions in a direction of light propagation of the waveguides between the input and output ends of the waveguides.

### *Numerical Aperture*

By the term numerical aperture (throughout this application abbreviated as NA) of an optical component is understood a measure of the divergence of a light beam emitted from or captured by the device. NA is defined as the sine of the maximum angle of meridional rays that can enter or leave an optical system or element, multiplied by the refractive index of the medium in which the angle is measured (i.e. by 1 in air). For an optical fibre in which the refractive index decreases from $n_1$ in the central region to $n_2$ in the cladding, an expression of the extent of the fibre's ability to accept, in its bound modes, non-normal incident rays is given by $NA = (n_1^2 - n_2^2)^{1/2}$ (for a step index fibre). NA for a light emitting device may e.g. be measured from the output far-field radiation pattern in a specific beam projection (cf. specification EIA/TIA-455-47). For a laser diode with an emitting face defining an X-Y-plane with a width w in the X-direction and a height h in the Y-direction (cf. e.g. FIG. 8), numerical apertures $NA_x$ and $NA_y$ in the X- and Y-directions, respectively, may relevantly characterize emitting properties of the laser diode (together with physical dimensions and wavelength spectrum). Similarly, $NA_x$ and $NA_y$ values for a planar waveguide may be defined to characterize the ability of the waveguide to capture light from a source (and indicating the solid angle from/to which the waveguide can capture/transmit light).

***Brightness***

In the present context, the term 'brightness' is taken to mean optical intensity per solid angle being measured as the optical power flow per unit area and steradian (Peter W. Milonni and Joseph H. Eberly, "Lasers", John Wiley & Sons, 1989)

***Refractive indices***

The term "the refractive index" of a region or volume represented by a particular cross sectional area of a waveguide is in the present context taken to mean the geometrical refractive index. If the region in question is constituted by one homogeneous material with a specific refractive index, the geometric refractive index is the normal refractive index for a homogeneous material. If the region in question is constituted by several smaller areas each of a homogeneous material, the geometric refractive index is the geometrically weighted average of the normal refractive indices of these smaller areas, i.e. the sum of the products of refractive index $n_i$ and ratio $A_i/A$ of the partial area $A_i$ in question to the area A of the whole region being considered (i.e. $SUM(n_i \cdot (A_i/A))$, $i=1, 2, \ldots, m$, where m is the number of smaller (or partial) areas constituting the region being considered). In some cases the effective refractive index $n_{eff}$ is conveniently used to characterize properties of an optical waveguide. Instead of considering the true waveguide structure with core and cladding the light propagation may be described as a plane wave propagating in a homogeneous medium having a refractive index $n_{eff}$, the so-called effective refractive index. This effective index is rooted in eigenvalue equations originating from Maxwell's equations. The effective refractive index of a bound mode is greater than the cladding refractive index, and lower than the core refractive index. The effective index is furthermore a function of the waveguide core cross-sectional geometry, see e.g. H. Nishihara et al., "Optical Integrated Circuits", McGraw-Hill (1989).

***Other definitions***

The term 'the substrate having essentially opposite waveguide- and substrate faces' is in the present context taken to mean that the *layered structure* comprising the substrate and waveguides, etc., deposited or grown thereon, has, respectively, a face comprising waveguides and an opposite face facing away from the direction of 'growth' (the 'back side' of the substrate) The waveguide- and substrate faces of a light source part and a coupling part are illustrated in FIG. 3.a and referred to with reference numerals 201, 301 (waveguide face) and 200, 300 (substrate face), respectively.

The opposite faces of the light source and coupling parts are essentially parallel to the direction of transmission of the essentially planar waveguides of the parts in question. In other words, the opposing waveguide and substrate faces are essentially perpendicular to a direction of growth of the essentially planar waveguides on the substrate in question. The waveguide face is the outermost face of the light source and coupling parts in a direction of growth or deposition of layers on the substrate of the parts. The outermost face may e.g. comprise the final layer added during processing.

In the present context, the term a 'double-clad optical fibre' is taken to mean a fibre comprising at least two cladding regions with different geometrical refractive indices, e.g. an inner and outer cladding region, the inner and/or outer cladding region e.g. comprising micro-structural features (e.g. voids).

In the present context, the term an 'air-clad' fibre is taken to mean a micro-structured fibre wherein light to be propagated is confined to a part of the fibre within a circumferential distribution of longitudinally extending voids in the cladding of the fibre.

The term 'optically coupled' is in the present context taken to mean that the objects in question are either directly physically coupled (e.g. butt coupled or integrated) or coupled in a way relatively to each other so that light can propagate from one waveguide to the other (e.g. via a free space region, a lens, etc.).

The term 'an application part' is in the present context taken to mean an article comprising an application waveguide, optionally an application waveguide in itself (or possibly mounted on a carrier).

It should be emphasized that the term "comprises/comprising" when used in this specification is taken to specify the presence of stated features, integers, steps or components but does not preclude the presence or addition of one or more other stated features, integers, steps, components or groups thereof.

## DISCLOSURE OF INVENTION

The present invention deals with various aspects of the subject of coupling light from a light source to a waveguide to provide one or more of the following features

- A high power, highly reliable, high brightness waveguide coupled diode laser module.
- A high power, side pumped active waveguide (fibre) laser or amplifier.
- Low assembly and packaging costs of the units mentioned above.

An object of the present invention is to provide a cost-efficient scheme for integrating one or several light sources with optical waveguides with minimum loss of brightness and power. A further object of the invention is to facilitate the coupling of the light from a light source into passive or active application waveguides.

These and other objects of the invention are achieved by the invention as defined in the accompanying claims and as described in the following. Further objects of the invention are achieved by the embodiments defined in the dependent claims and in the detailed description of the invention.

The invention provides in its various embodiments (among other things) one or more of the following features compared to the prior art (for terminology, please refer to FIG. 2 and the corresponding description):

- Minimization of loss of brightness in the coupling between light source(s) and source waveguides on the light source part or module.
- Simple, reliable and cost-efficient assembly and packaging of the light source part or module
- Simple, reliable and cost-efficient coupling of light from the light source part or module (via a coupling part) to an application part comprising one or more waveguides.

A coupling part:

An object of the invention is to enable coupling of light from planar waveguides into active or passive application waveguides of other types (e.g. fibres). This object is achieved by a coupling part as defined in the following.

The present invention provides a coupling part for coupling light into one or more optical application waveguides (for terminology, please refer to FIG. 2 and the corresponding description). A coupling part for coupling light to an application part is provided, the coupling part comprising at least one essentially planar coupling waveguide formed on a coupling-substrate, the coupling-substrate having opposite waveguide- and substrate faces, at least one of the coupling waveguides having an input and an output face, the input face of the coupling waveguide or waveguides being adapted to be optically coupled to one or more source waveguides for supplying light power to the coupling part wherein the coupling part comprises at least one elongate groove in the form of a recess in the waveguide face, the groove being adapted to receive an elongate optical application waveguide, and at least one coupling waveguide and at least one groove are formed on the coupling-substrate relative to each other so that the output face of the coupling waveguide is suitable for being side-coupled to an application waveguide when said application waveguide is located in the groove.

An advantage of the invention is that a relatively simple and reproducible side coupling interface between a planar waveguide and the application waveguide is provided. This has the potential of reducing coupling loss and cost of a system e.g. a laser system. It will for example be possible to define both coupling waveguides and application waveguide grooves in lithographic patch processes in which case <<1 μm alignment tolerances can be achieved and active alignment between the two waveguides can be avoided in the final assembly steps.

In an embodiment of the invention, the groove or grooves in the coupling substrate has/have an U- or V-formed shape in the sense that the walls of a groove has a U- or V-form when viewed in a cross section perpendicular to its longitudinal direction. In an embodiment of the invention, a coupling waveguide has its output face to coincide (i.e. form part of) with said U- or V-formed walls of a corresponding groove so that the output face of the coupling waveguide is positioned for being directly side-coupled to an application waveguide located in the groove. In an embodiment, the wall of the groove around the output face of the coupling waveguide is concave whereby the output face of the coupling waveguide extend from the wall, thereby facilitating the coupling (e.g. fusion or gluing) to an application waveguide (cf. 321 in FIG. 4.a, c) .

In an embodiment of the invention, the groove and the coupling waveguide are adapted so that when an application waveguide is placed in the groove, there is a direct contact between the output face of the coupling waveguide and the side of the application waveguide. In an embodiment of the invention, the shape of a groove is adapted to the shape of the application waveguide to be received by the groove in a cross section perpendicular to the direction of propagation of light in the application waveguide (when positioned in the groove).

The side of the application waveguide is taken to mean a part of the longitudinal surface as opposed to an end face (the latter being viewed in a cross section perpendicular to the longitudinal direction of the application waveguide, e.g. an end facet of a fibre).

In embodiments of the invention, groves are etched or sawed/diced into the coupling substrate to assure that the heights of the application waveguides are adapted to the heights of the corresponding coupling waveguides. Typically, it is desirable that the centre of an application waveguide is in the same plane as the centre of a coupling waveguide (the centre of a coupling waveguide e.g. being taken as the centre of the core region in a direction perpendicular to a direction of growth of the planar coupling waveguide). This may e.g. be achieved by adjusting the depth of the groove to the configuration of the application and coupling waveguides in question.

In an embodiment of the invention, the coupling part comprises a multitude of coupling waveguides, e.g. such as more than 2, such as more than 8, such as more than 24. In an embodiment of the invention, the coupling part comprises a multitude of essentially parallel grooves (e.g. such as more than 2, such as more than 8, such as more than 24) each adapted for receiving a respective application waveguide. In an embodiment of the invention, the coupling part comprises a multitude of coupling waveguides, each being connected to a groove for being optically coupled to an application waveguide mounted in the groove. In an embodiment of the invention, the coupling part comprises a multitude of coupling waveguides, each being connected to the same groove for being optically coupled to an application waveguide mounted in the groove.

In an embodiment of the invention, two or more of the coupling waveguides are merged to form one single output coupling waveguide.

In an embodiment of the invention, the coupling waveguides are coupled into the application waveguides at a side-coupling angle, α. In an embodiment of the invention, a coupling waveguide and a groove (wherein an application waveguide for receiving light from the coupling waveguide may be placed) meet at an angle α. To achieve full coupling between the two waveguides the side-coupling angle α must fulfil the following criteria:

$$\alpha \leq \theta_{C2} - \theta_{C1}$$

where $\theta_{c1}$ and $\theta_{c2}$ are the critical angles internally in the waveguide of the first coupling waveguide and the second application waveguides, respectively. $\theta_{c1}$ and $\theta_{c2}$ relate to the numerical aperture of the two waveguides as

$$NA = n_1 \sin\theta_c = \sqrt{n_1^2 - n_2^2}$$

where $n_1$ and $n_2$ are the refractive indices of the core and the cladding of the respective waveguides.

In a typical implementation, NA of the passive (‘coupling’) waveguide is 0.32 and NA of the (multi-mode) part of the double-clad (‘application’) fibre is 0.60. Assuming a refractive index of the core glass of 1.46, we find that:

$$\theta_{c1} = 12^{o}\, and\, \theta_{c2} = 24^{o} \Rightarrow \alpha \leq 12$$

In an embodiment, the groove comprises a bend adapted to force the application waveguide against the output face of the coupling waveguide.

In an embodiment, said at least one coupling waveguide is a multimode waveguide at least over a part of its length.

An advantage of using multimode source and coupling waveguides is that it relaxes the mechanical tolerances on the alignment of the light source to the respective waveguide input ends and of the coupling of light between the source waveguides and their corresponding coupling waveguides. In an embodiment of the invention, the coupling waveguides have a larger height and/or width dimension than the source waveguides. This eases the coupling of light between corresponding waveguides of the source part and coupling parts.

In an embodiment, said at least one coupling waveguide is a single mode waveguide at least over a part of its length.

In an embodiment, said output face of said at least one coupling waveguide and/or said groove is/are adapted to receive a double-clad application waveguide.

In an embodiment, said output face of said at least one coupling waveguide and/or said groove is/are adapted to receive a double-clad, micro-structured application waveguide, preferably an air-clad optical fibre.

In an embodiment of the invention, the coupling waveguides are glass waveguides on a Si-platform such as a silica-on-silicon planar technology. In an embodiment of the invention, the coupling waveguides are implemented in a high-refractive index technology such as SiON, SiN, etc. In an embodiment of the invention the coupling waveguides are implemented by UV-exposure of a photosensitive material (e.g. Ge doped silica). In an embodiment of the invention, the groove or grooves is/are implemented using photolithographic steps of the technology in question.

An optical coupling device:

An object of the invention is to enable coupling of light from planar waveguides into active or passive application waveguides of other types (e.g. fibres). This object is achieved by a coupling part as defined in the following.

The present invention further provides an optical coupling device comprising a coupling part as described in the section "A coupling part" above (and as defined in the claims) and an application part wherein the application part comprises an application waveguide in the form of an optical fibre located in said groove or grooves of said coupling part and said application waveguide is optically coupled to said output face of said at least one of the coupling waveguides of said coupling part (for terminology, please refer to FIG. 2, specifically FIG. 2.e and the corresponding description).

An advantage of the invention is that a relatively simple and reproducible side coupling interface between a planar waveguide and the application waveguide is provided. This has the potential of reducing coupling loss and cost of a system e.g. a laser system.

In an embodiment, the coupling and/or application waveguide or waveguides comprise(s) - when viewed in a cross section perpendicular to their direction of light propagation – concentric areas of different geometrical and/or effective refractive indices.

In an embodiment, the optical coupling device comprises coupling and/or application waveguides that are multimode waveguides at the wavelength-range in question at least over a part of their lengths.

In an embodiment, an application waveguide comprises a cladding recess extending in the longitudinal direction of said application waveguide and facing said output face of said at least one coupling waveguide.

In an embodiment, said application waveguide – when viewed in a cross section perpendicular to a longitudinal direction of the waveguide - has a D-shape over the longitudinal extent of said cladding recess, the essentially flat part of the D-shape being optically coupled to the output face of the coupling waveguide by means of butt coupling, fusion or an index matching material such as a glue, a gel or an oil.

In an embodiment, the application waveguide is a double-clad fibre.

In an embodiment, at least one of said concentric areas comprise(s) a background matrix material hosting micro-structured features in the form of micro-areas having a refractive index different from the refractive index of the background matrix material.

In an embodiment of the invention, the application waveguide is a double-clad, high NA, air-clad, micro-structured fibre (alternatively termed photonic crystal fibre, holey fibre, etc.). Advantages of air-clad, double-clad, micro-structured fibres are:

- Higher NA, than can be obtained with other double-clad technologies. This allows more efficient coupling of pump power into the fibre.
- Efficient pump absorption.
- Efficient schemes for side-coupling to the source waveguides (collapse of holes).

In an embodiment of the invention, the application waveguide or waveguides comprise air-clad micro-structured fibres and the coupling waveguides are coupled into the application waveguides by heat-collapsing the air-clad holes in the air-clad fibre, cf. international patent application no. PCT/DK03/00180 "Microstructured optical fibre with cladding recess, a method of its production, and apparatus comprising same" (published as WO-03/079077), which is incorporated herein by reference. The heat collapsing can for example be achieved by electro-splicers, filament splicers or laser heating.

In an embodiment, the micro-structured application waveguide has an inner and an outer cladding separated by an air-clad comprising a circumferential distribution of longitudinally extending voids.

In an embodiment, at least a part of said longitudinally extending voids of said air-clad have been removed or collapsed over at least a part of the longitudinal extent of said cladding recess.

In an embodiment, said cladding recess creates a side window allowing coupling of light in and out of said inner cladding of said application fibre.

In an embodiment of the invention, the application fibre comprises active ions in appropriate amounts (e.g. Er and/or Yb or other rare earth ions) and reflecting elements to form a fibre laser.

In an embodiment of the invention, the application fibre comprises active ions (e.g. Er and/or Yb or other rare earth ions) and reflection suppressing elements (e.g. isolators or angled or anti reflectively (AR-) coated end-facets) to form a fibre amplifier.

In an embodiment of the invention, the application fibre comprises a passive fibre for distributing the output of the light source.

In a preferred embodiment of the invention, the application waveguide is a double-clad, air-clad application fibre is adapted to be side pumped from a planar optical coupling waveguide by collapsing the air-clad holes and fusing the application fibre to the coupling waveguide using a low power $CO_2$ laser (e.g. Access laser Lazy5).

A light source part:

The present invention further deals with the subject of propagating light from a number of light sources to an output interface to provide a light source part (i.e. a possible independent functional sub-part of the light source module described in the section "A light source module" below (for terminology, please refer to FIG. 2 and the corresponding description)). Problems include:

- Simple, cost-efficient and reliable assembly and packaging of the light source part
- The propagation, shaping and/or uniting of beams from individual laser diodes or arrays of laser diodes to a predetermined target object area (e.g. the end face of an optical waveguide).
- The minimization of loss of light power in the laser diode output to waveguide input coupling.

- The minimization of loss of brightness in the coupling between the laser diode output and the waveguide output
- The management of power dissipation of a multitude of laser diodes in the face of the desire to achieve a high brightness output from the module.

A further object of the present invention is to provide a relatively simple, yet flexible scheme for implementing a light source module for providing one or more light beams with predetermined shape.

A light source part according to the invention may comprise

a) a multiptude of N laser diodes $LD_i$ with predetermined numerical apertures $NA_{LD,i}$, i=1, 2, ..., N, each individual laser diode having an emitting face with a laser stripe for emitting light power,

b) a multitude of M essentially planar optical input source waveguides $WG_j$ with predetermined numerical apertures $NA_{WG,j}$, j=1, 2, ..., M, the waveguides each having an input face with a capture area for capturing light, and the waveguides being formed on a source-substrate ($M \leq N$),

c) each waveguide being adapted to receive light from one or more corresponding laser diodes,

d) an output interface for making light from the laser diodes available, and optionally

e) a beam shaping part (e.g. providing tapering or pitch conversion) where the source waveguides shape the properties of the incoming light from the laser diodes to make them match beam requirements at the output interface.

The input source waveguides and their corresponding laser diode or diodes have matching numerical apertures and physical dimensions of their capture area and laser stripe, and the laser diodes are mounted or formed on the source-substrate with the emitting faces relative to the input faces of the waveguides to minimize the loss of power between the emitting face of the individual laser diodes and the input face of the individual waveguides.

An advantage of the invention is that the coupling of light from the light source to the source waveguides can be fully automated and done passively (e.g. by a flip-chip bonder using machine vision). A further advantage is that a light source part is provided having standardized coupling of light from laser diodes to planar waveguides which may be combined with easily customizable planar waveguides to form a particular output beam pattern.

By the term a 'multitude of lasers' is in the present context understood one or more such as two or more laser diodes, either individual diodes each formed or placed on their own diode substrate or all diodes formed on a single diode substrate or a mixture thereof (e.g. a combination of several diode bars each comprising a number of laser diodes formed on a common substrate, possibly mixed with individual diodes).

In an embodiment of the invention, the light source part comprises only one laser diode.

The term 'a laser stripe for emitting light power' is taken to mean the area of the laser diode from which laser light is emitted. It may take any form such as quadratic or rectangular and is typically elongated with a relatively high aspect ratio (e.g. 100/1, i.e. 100 μm wide, 1 μm high). In the latter case, the numerical aperture is typically smaller along a direction parallel to the longer axis of the stripe, e.g. termed the x-axis than in a direction perpendicular to the longer axis of the stripe, termed the y-axis, where z is the intended direction of light transmission (cf. FIG. 8.a).

The term the 'capture area' of a waveguide is taken to mean the area on an input face of a waveguide defining the cross sectional area of the waveguide in which light is confined (i.e. where no leakage of light occurs, i.e. wherein light is guided by total internal reflection or by photonic band-gap effects). In an embodiment of the invention, the capture area is taken as the cross sectional area of the core region.

In the present context, the term 'matching numerical apertures and physical dimensions of their capture area and laser stripe' is taken to mean that numerical apertures and physical dimensions of the corresponding waveguides and laser diodes (i.e. those laser diodes from which the waveguide in question is adapted to receive light, i.e. which are positioned relative to each other to enable coupling of light between laser diode and waveguide) facilitate a low loss coupling between laser diode or diodes and corresponding waveguide.

In the present context, the term 'the laser diodes are mounted on the waveguide substrate with the emitting faces relative to the input faces of the waveguides to minimize the loss of brightness between the emitting face of the individual laser diodes and the input face of the individual waveguides' is taken to mean

1) that the laser diode or diodes and their corresponding waveguide are aligned relative to each other in a plane parallel to a reference plane defined by the input face of the waveguide so as to align the laser stripe or stripes to the capture area of the corresponding waveguide, and

2) that the physical distance in a direction perpendicular to the reference plane between the emitting face of the laser diode or diodes and the input face of the corresponding waveguide is adapted to minimize the loss of power between the emitting face of the individual laser diodes and the input face of the individual waveguides.

In an embodiment of the invention, the light source part has an output face for coupling light out of the waveguides.

In an embodiment of the invention, the width and height of the source waveguides are 'significantly' larger than the width and height of the light emitting area of the light source. By large is here understood dimensions comparable to the accuracy of the equipment used to align the light source to the source waveguide. In an embodiment of the invention, the equipment used to align the light source to the source waveguide is a flip-chip bonder with alignment accuracies in the range of 1-10 μm. Compared to traditional solutions, where the width and height of the source waveguides are 'comparable' to the width and height of the light emitting area of the light source, the relative dimensions of this embodiment implies that alignment tolerances are relaxed and coupling efficiency is improved. This has the advantages that:

- Low cost assembly equipment (e.g. standard 5 μm accuracy flip-chip bonders) can be used for assembly rather than expensive high accuracy optobonders with alignment tolerances below 1 μm.
- Special high accuracy passive alignment steps (as for example described in US 6,459,158 and US 5,499,312) can be avoided. This leads to a reduction in processing costs of the source waveguides.
- Special laser designs (see for example the spot size converter lasers of US 6,192,170) can be avoided; this leads to reduced laser processing costs.

- In the proposed embodiment, coupling loss can be low, such as well below 0.5 dB for alignment tolerances of +/- 2 μm (for example for a 1x100 μm laser coupled into a 4x110 μm waveguide). As a comparison, prior art using standard lasers has coupling losses of the order 7 dB for alignment accuracies of the order of 1 μm and coupling losses using spot size converter lasers of the order of 4 dB for alignment accuracies of the order of 2 μm (cf. e.g. Kitagawa et al, IEICE Trans. Electron., Vol. E85-C, No. 4, April 2002).

In an embodiment of the invention, the output end of a waveguide is shaped to focus the light (e.g. by etching the waveguide end to form a lens). An alternative way of shaping the output of the light from a particular waveguide is to form the waveguide as a graded index waveguide (wherein the central region has a refractive index that gradually decreases as the distance from the centre of the waveguide increases). In another embodiment of the invention, two or more of the waveguides are adapted to direct the light towards a common focal point located external to the waveguides.

In an embodiment of the invention, the light source part comprises one or more high power diode lasers having an output power lager than 1 W, e.g. in the form of broad area lasers, such as lasers having a stripe width larger than 50 μm. In an embodiment of the invention, the high power lasers are semiconductor lasers. In an embodiment of the invention, one or more of the diode lasers are multimode lasers.

Typical high power laser wavelengths are in the range of 600 to 1600 nm. Laser diodes may e.g. be fabricated in GaAs technology for wavelengths in the 800 – 1300 nm-range and in InP-technology for wavelengths in the 1100-1600 nm –range.

The typical cross-sectional area of a high power diode laser is 1 x 100 μm (i.e. having a laser stripe of height of 1 μm and width 100 μm). Typically, these lasers have NA of 0.1 in the slow axis (along the width of the laser stripe, typically the largest dimension) and NA of 0.3 in the fast axis height (along the height of the laser stripe, typically the smallest dimension). Typical output power in the range of 2 – 6 W may be achieved for high power diode lasers.

In an embodiment of the invention, the light source comprises one or several diode laser bars, where a multitude of diode lasers are mounted on the same substrate. The advantage of using diode laser bars is that many individual laser sources can be handled in one process step which significantly reduces handling cost. Typical diode laser bars contain 20 individual diodes and have a length of 10 mm.

In an embodiment of the invention, the light source comprises one or several individual diodes on individual substrates. The advantage of using individual diodes compared to the use of laser bars, is that individual laser diodes in general have a longer lifetime because:

- Individual diodes can be cooled more effectively (larger heat spreading) than laser bars.
- Thermally induced stress between the mounting substrate and the laser diode substrate will be less critical for small structures (single emitters) than for large structures (laser bars).

In an embodiment of the invention, laser diodes with relatively low NA's are used.

- This could for example be lasers with a NA of less than 0.3, such as less than 0.2, such as e.g. of 0.15 in both the height and the width direction. The advantage of using such lasers is that improved coupling efficiency will be achieved compared to using high NA lasers (for example with a NA of 0.3 in the height direction).
- This could for example be lasers with a NA in the width direction of less than 0.15, such as less than 0.1, such as e.g. of 0.05. The advantage of using such lasers is that tapering to narrow waveguide widths is possible thereby allowing many lasers to be combined before they are launched into a high NA application waveguide with a specific cross section

In an embodiment of the invention, the laser diodes are identical (i.e. have essentially identical numerical apertures and characteristic physical dimensions). Alternatively, individual diodes may have different characteristic properties.

In an embodiment of the invention, the source waveguides are glass waveguides on a Si-platform such as a silica-on-silicon planar technology. In an embodiment of the invention, the source waveguides are implemented in a high-refractive index technology such as SiON, SiN, etc. In an embodiment of the invention the source and/or coupling waveguides are implemented by UV-exposure of a photosensitive material (e.g. Ge doped silica).

In an embodiment of the invention, the width and height of the source waveguides are larger than the width and height of the light emitting area of the light source. In an embodiment of the invention, the widths of the source waveguides are 10% larger than the width of the light emitting area (the laser stripe) of their corresponding light source, such as 20% larger, such as 50% larger. In an embodiment of the invention, the heights of the source waveguides are 50% larger than the height of the light emitting area of their corresponding light source, such as 100% larger, such as 200% larger, such as 500% larger. An advantage of using large source waveguides is that it relaxes the mechanical tolerances on the alignment of the light source to the respective waveguide input ends.

In an embodiment of the invention, the light source part comprises a multitude of planar waveguides, such as 5 or more, such as 10 or more.

In an embodiment of the invention, the waveguides of the light source part have an input end and an output end. In an embodiment of the invention, the waveguides have the same pitch (centre-to-centre-distance between the central regions of neighbouring waveguides) at the input and output ends. In an embodiment of the invention, the waveguides are parallel (i.e. the centrelines of the central regions of the waveguides are parallel).

In an embodiment of the invention, the total distance (defined relative to their centrelines) between the two outermost waveguides (i.e. the two waveguides that are the farthest apart on the substrate) is larger at the input end than at the output end, e.g. corresponding to an even decrease in pitch between neighbouring waveguides from input to output. This has the advantage of enabling a relatively large distance between individual laser diodes, while maintaining a relatively small distance between waveguide outputs, which facilitates the management of power dissipation from the laser diodes (i.e. making possible a reduction in thermal load leading to an improved reliability and life time).

In an embodiment of the invention, the total distance between the two outermost waveguides is larger at the output end than at the input end, e.g. corresponding to an even increase in pitch between neighbouring waveguides from input to output. This may e.g. be relevant when the light source comprises diode arrays having a relatively small distance between neighbouring laser diodes.

In an embodiment of the invention, the numerical aperture of the waveguides is identical at the input and output ends. In an embodiment of the invention the widths of the waveguides are decreased (tapered) from the input to the output ends, which allows the light to be confined into a smaller area. If for example the light from a 100 μm wide broad-area diode laser with an NA of 0.1 in that direction is coupled into a 120 μm wide passive waveguide with an NA of 0.3, the light coupled in will in general only take up one third of the available mode-space. Consequently, it will in many cases be possible to taper the waveguide width from e.g. 120 to e.g. 40 μm with minimum loss of power.

In an embodiment of the invention, the source waveguides are used to shape the properties of the beams emitted from the output interface of the light source part. In a preferred embodiment of the invention, the widths of the source waveguides are tapered from the input to the output in order to couple the light out of the waveguides with the smallest possible width. In order to achieve this tapering without loss of power, the numerical aperture of the light source in the width (x) direction must be smaller than the numerical aperture of the source waveguide in the width (x) direction (cf. e.g. FIGs. 8, 14), i.e.:

$$NA_{WG,x} > NA_{LD,x},$$

In the ideal case, it is possible to taper the width of the source waveguide down with a factor, which corresponds to the ratio between $NA_{WG,x}$ and $NA_{LD,x,}$. This corresponds to a beam shaping without loss of brightness. In practice it will often be convenient to allow some loss of brightness, i.e. to have:

$$w_i \bullet NA_{LD,x} \leq w_o \bullet NA_{WG,x}$$

Where $w_i$ is the width of the source waveguide at the input and $w_o$ is the width of the source waveguide at the output.

In an embodiment, the ratio of the widths of a source waveguide at the input (i.e. at the light source end) and output (i.e. at the interface to the coupling part) $w_{i,x}/w_{o,x}$ in the x-direction (cf. FIGs. 8, 14) is larger than 1, such as larger than 1.5, such as larger than 2, such as larger than 3, such as larger than 5, such as larger than 10. If two or more source waveguides are merged to one waveguide at the output interface, the width $w_{i,x}$ is taken to be the sum of the individual source waveguide widths at the input.

In an embodiment, the ratio of the widths of a source waveguide at the input and output $w_{i,x}/w_{o,x}$ is substantially equal to the ratio of the numerical apertures of the source waveguide at the input $NA_{WG,x}$ and of the light source $NA_{LD,x}$, in the x-direction (cf. FIG. 8). In an embodiment, $w_{i,x}/w_{o,x} \leq NA_{WG,x}/NA_{LD,x}$, such as $\leq 0.9$ times $NA_{WG,x}/NA_{LD,x}$, such as $\leq 0.7$ times $NA_{WG,x}/NA_{LD,x}$, such as $\leq 0.5$ times $NA_{WG,x}/NA_{LD,x}$. This has the advantage of compromising the tapering length and the tapering loss to provide waveguide lengths of practically advantageous dimensions.

In an embodiment, the tapering of a waveguide is linear (i.e. the width decreases linearly from input to output), e.g. piecewise linear. In an embodiment, the tapering of a waveguide follows a polynomial function (i.e. the curve limiting the extent of the core in a longitudinal direction of the waveguide from input to output may be described by a polynomial function). In an embodiment, the tapering of a waveguide follows an exponential function, e.g.:

$$w\ (z) = w_i + (w_o - w_i)\frac{e^{\frac{z-z_i}{L}} - 1}{e-1},$$

where w(z) is the width of the tapered waveguide at coordinate z along the longitudinal direction of the waveguide, $z_i$ being the z-coordinate at the input face of the waveguide and L the length of the tapering in the longitudinal direction ($L=z_o-z_i$, $z_o$ being the z-coordinate at the output face of the waveguide). In an embodiment, the tapering is terminated before the output face of the waveguide in which case $w_o$ and $z_o$ should be substituted by the corresponding values where the tapering ends.

In an embodiment of the invention, the NA of the source waveguide will match the NA of an application waveguide, e.g. a high NA double-clad fibre, which typically will be 0.6 for a photonic crystal fibre. In a typical configuration light will be launched into a 95 µm wide, 0.6 NA source waveguide from a broad area diode laser having an NA of 0.12 and a stripe width of 90 µm. In this case, the source waveguide can ideally be tapered down to a width of 95 µm * 0.12/0.6 = 19 µm at the output interface.

An advantage of this scheme is that the light from several lasers can be combined and launched into the application waveguide. In the case described above where the application waveguide is an end-coupled 0.6 NA fibre, up to 12 lasers having a 0.12 NA can ideally be launched into such a fibre provided that it has a (pump) core width of minimum 228 μm.

In another embodiment of the invention, one or more of the waveguides are adapted so that the numerical aperture of the waveguide is larger at the output end than at the input end of the waveguide, e.g. by tapering the refractive index difference between the waveguide and the cladding (cf. FIG. 11.c and the corresponding description). Thereby a shaping of the light beam leading to a concentration of the light power is achieved. The tapering of the refractive index difference may e.g. be achieved by UV-exposure (in case of waveguides implemented in a technology in which the refractive index is sensitive to UV-exposure, e.g. Ge-doped silica).

In an embodiment of the invention, the height of a waveguide is increased from the input end of the waveguide to the output end. This may be achieved by grey-scale etching of the waveguides. An embodiment in which the width is decreased and the height is increased from input to output has the advantage of being able to shape a beam transmitted by the waveguide from an initially rectangular shape to a more square shape at the output.

In an embodiment of the invention, at least one of the source waveguides are multi-layer waveguides. Hence, waveguides at different heights (i.e. a dimension perpendicular to the direction of growth of the waveguides) can be combined in the same 'plane' at the output. The advantages of this are that:

- More power can be inserted into an application waveguide at a single coupling point.
- More simple focussing optics can be used to focus the output of the source waveguide into a single spot (e.g. the end of a fibre).
- A large flexibility in the beam shaping is possible.

In an embodiment of the invention comprising a laser diode with an emitting face defining an X-Y-plane (cf. FIG. 8) with a width $w_{LD}$ in the X-direction and a height $h_{LD}$ in the Y-direction and numerical apertures $NA_{LD,x}$ and $NA_{LD,y}$, and a waveguide having a capture area with a width $w_{WG}$ in the X-direction and a height $h_{WG}$ in the Y-direction and numerical apertures $NA_{WG,x}$ and $NA_{WG,y}$, the numerical apertures $NA_{WG,x,p}$ and $NA_{WG,y,p}$ of waveguide p ($WG_p$) are substantially equal to or larger than, respectively, the numerical apertures $NA_{LD,x,p}$ and $NA_{LD,y,p}$ of its corresponding laser diode ($LD_p$), and the characteristic dimensions of the capture area $w_{WG,p}$ and $h_{WG,p}$ of the waveguide $WG_p$ are substantially equal to or larger than the characteristic dimensions of the laser stripe $w_{LD,p}$ and $h_{LD,p}$, respectively, of the corresponding laser diode $LD_p$. In an embodiment of the invention $NA_{WG,x,p} \geq NA_{LD,x,p}$, $NA_{WG,y,p} \geq NA_{LD,y,p}$ and $w_{WG,p} \geq w_{LD,p}$, $h_{WG,p} \geq h_{LD,p}$ for all waveguides and laser diodes p=1, 2, ...., N of the module. In an embodiment of the invention, the shortest distance $d_{LD\text{-}WG}$ between the emitting face of a laser diode and the input face of its corresponding waveguide (i.e. in the z-direction perpendicular to the x-y-plane defined by the emitting face of the laser diode as discussed above) is adapted to the height $h_{WG}$ and width $w_{WG}$ of the capture area of the waveguide and the numerical aperture $NA_{LD}$ of the laser diode to fulfil the relations

$$h_{WG} \geq 2\bullet d_{LD\text{-}WG}\bullet(NA_{LD,y}/[1-(NA_{LD,y})^2]^{0,5}) = 2\bullet d_{LD\text{-}WG}\bullet tg\Theta_{LD,y}$$

$$w_{WG} \geq 2\bullet d_{LD\text{-}WG}\bullet(NA_{LD,x}/[1-(NA_{LD,x})^2]^{0,5}) = 2\bullet d_{LD\text{-}WG}\bullet tg\Theta_{LD,x}$$

where $NA_{LD,y} = \sin\Theta_{LD,y}$ and $NA_{LD,x} = \sin\Theta_{LD,x}$.

An advantage of this scheme is a relaxed coupling accuracy requirement between source laser and source waveguide input.

In an embodiment of the invention, the alignment of laser diode and waveguide in a direction of growth of the substrate of the waveguides on which the laser diodes are mounted is controlled by adapting the level of the substrate at the location of the laser diodes to allow the laser stripe of a particular laser diode to be positioned at a predetermined desired level relative to the capture area (e.g. a core region or a cladding region) of the corresponding waveguide. This level may advantageously be implemented with a precision corresponding to the precision of the process in question used for the formation of waveguides on a substrate (e.g. any semiconductor process, a silicon on insulator, silicon-oxy-nitride or a silica on silicon process). In an embodiment of the invention, the centre lines of the laser diodes and the corresponding source waveguides are at the same level.

In an embodiment of the invention, alignment of the laser diodes on the source waveguide substrate relative to the waveguides in a plane parallel to a direction of growth of the substrate is performed by means of alignment marks on the source waveguide substrate (or on layers applied to the substrate) and laser diode chips made with the high precision available in the processing in question. In an embodiment of the invention, the mounting of the laser diodes on the source waveguide substrate is performed by means of machine vision on the basis of alignment marks (e.g. such alignment marks made during processing).

In an embodiment of the invention, the light sources (diode lasers) are flip-chip bonded directly onto the source waveguide substrate. An advantage of this configuration is that flip-chip bonding is a well established, high throughput, low-cost assembly technology.

For typical high power diode lasers coupled into a high index (NA = 0,32) planar waveguide with a cross section of 4 x 110 µm, the coupling efficiency will be above 90% for laser to waveguide distances of:

- $\Delta x = \pm 3\ \mu m$
- $\Delta y = \pm 1.5\ \mu m$
- $\Delta z = \pm 1.5\ \mu m$

Where x, y and z refer to orthogonal directions defined in FIG. 8.

The planar nature of the light source part provides a large freedom in shaping the beam or beams out of the part to match a particular target object, since the waveguide(s) of the light source part may be varied in number, configuration (merging/no merging, tapering/no tapering, etc.), pitch, width and height.

In an embodiment of the invention, each input waveguide has an output face, i.e. each waveguide is discrete (no interleaving of waveguides) so that a module has M inputs (coupled to laser diodes) and M outputs (for coupling light to one or more target objects, e.g. M optical waveguides or M different inputs to the same waveguide).

In an embodiment of the invention, the M input waveguides are coupled to Q output waveguides. The number of output waveguides Q may be larger or smaller than the number of input waveguides M.

In an embodiment of the invention, two or more input waveguides are merged to one output waveguide. This has the advantage of concentrating the light power. Further, it may be used to introduce system redundancy (i.e. to improve system reliability), by providing more laser diodes (optionally on/off-controllable) than needed for providing the specified amount of output light power. In an embodiment of the invention, all input waveguides are merged into one output waveguide. This embodiment has the ability to provide low cost waveguide coupled diode laser modules with potential brightness values about one order of magnitude larger than for modules based on prior art, see FIG. 1.a. For a 4 W 1x100 µm laser diode with NA of 0.1 and 0.3 in the two axes being coupled with 90% efficiency into a 4x110 µm waveguide with NA of 0.32 in both directions, the brightness at the output of the source waveguide will be reduced by a factor of only 17 compared to the brightness of the light emitted from the diode. This is to be compared with the brightness reductions of 65 times for 'high brightness' fibre coupled modules and 250 times for 'low brightness' fibre coupled modules.

Furthermore, this embodiment has the advantage that a high brightness can be maintained independently of the total output power. Furthermore, this embodiment has the advantage that high power waveguide coupled diode laser modules can be based on several individual laser diodes or several diode arrays with only a few diodes per array. It is well known that the reliability of individual laser diodes is better than the reliability of diode arrays and that the reliability of diode arrays with a few diodes is better than the reliability of diode arrays with many laser diodes.

In an embodiment of the invention, the width of an output waveguide is substantially equal to the sum of the widths of the input waveguides from which it is merged.

In an embodiment of the invention, a 1:1 correspondence exists between the number of and relative positions of the laser diodes and waveguides, i.e. there is an equal number of laser diodes and waveguides on the module (N=M), in other words each waveguide has one corresponding laser diode and a waveguide and its corresponding laser diode are positioned relative to each other to minimize coupling loss. Alternatively, each waveguide (or some of them) may have several laser diodes (e.g. a bar of laser diodes) that are arranged to emit into the capture area of the waveguide in question.

In an embodiment of the invention, an M to 1 to M branching unit is implemented on the source substrate between the input of the source waveguides coupled to the laser diodes and the output of the source waveguides for being coupled to a coupling part or to an application part. This has the advantage of providing a redundant component that is tolerant to failure in one or more of the laser diodes.

In an embodiment of the invention, one or more of the source waveguides comprise active ions (e.g. Er and/or Yb). In an embodiment of the invention, a single mode planar waveguide is formed on the source substrate and side coupled into and integrated with a source waveguide over a part of the length of the single mode waveguide, the source waveguide being a multimode waveguide comprising active ions, thereby forming a waveguide amplifier.

In an embodiment of the invention, the laser diodes are hermetically sealed to avoid contamination and improve lifetime. A major advantage of the present invention is that the hermitical sealing can be placed just over the (small) laser diodes, rather than - as it is the case with most existing technologies - over the entire module. The cost of hermetic sealing will be significantly reduced with the reduction of the volume to be sealed. This can be done by placing a hermetically sealable cover with current feed-throughs over a single or a number of laser diodes.

In an embodiment of the invention, the output end of the waveguides is optically connected to a connector for facilitating connection of the light source part to one waveguide (e.g. a fibre) or to an array of waveguides (e.g. planar waveguides, e.g. a coupling part, or fibres).

## An end coupled optical device:

The present invention further provides an end coupled optical device comprising a light source part as described in the section “A light source part” above (and as defined in the corresponding claims) and an application part wherein the application part comprises an optical application waveguide comprising an end face optically coupled to the light source part (for terminology, please refer to FIG. 2, specifically FIGs. 2.c and 2.f and the corresponding description).

In an embodiment of the invention, the application waveguide comprises a passive waveguide for distributing the output of the light source. In an embodiment of the invention, the output of the light source part is focused onto the end of a fibre.

In an embodiment of the invention, the application waveguide is a multimode waveguide, such as a multimode optical fibre.

In an embodiment of the invention, the application waveguide comprises an active waveguide for amplifying the output of the light source. In an embodiment of the invention, the application waveguide is formed on the source substrate as a continuation of an output waveguide of the light source part. This has the advantage that coupling losses are eliminated from the light source part to the application part.

In an embodiment, the application waveguide is an optical fibre, positioned in a groove formed in a substrate of the application part. In an embodiment, the substrate of the application part on which the application fibre is positioned is identical to the substrate of the light source part. This has the advantage of facilitating alignment of the end facet of the application fibre to the output facet or facets of the source waveguides, because the groove may be made in the same process flow providing tolerances similar to those of the source waveguide(s).

In an embodiment of the invention, the application waveguide comprises active ions (e.g. Er and/or Yb) to form an amplifier or additionally reflecting elements to form a planar waveguide laser on the source substrate or alternatively on a separate substrate.

In an embodiment of the invention, the output of the light source part is coupled into the end of a fibre comprising active ions (e.g. Er and/or Yb) and reflecting elements to form a fibre laser or amplifier.

In an embodiment of the invention, the output of the light source part is coupled into the end facet of a double-clad fibre. Double-clad optical fibres are e.g. described in “Rare-Earth-Doped Fibre Lasers and Amplifiers”, 2nd edition, ed. by Michel J.F. Digonnet, Marcel Dekker, Inc., New York, Basel, 2001, cf. specifically p. 121. In an embodiment, the double-clad fibre comprises a core, an inner and an outer cladding. In an embodiment, the double-clad fibre has a multimode core and an inner cladding forming a multimode core for light propagated in the inner cladding. In an embodiment, the double-clad fibre has a single mode core and an inner cladding forming a multimode core for light propagated in the inner cladding. In an embodiment, the light propagated in the inner cladding is pump light coupled into the inner cladding at end facet of the double-clad application fibre from the light source part. In an embodiment, the pump light is used for pumping an actively doped part of a single mode core spatially delimited by reflecting elements (e.g. Bragg gratings) and forming a fibre laser.

In an embodiment, the double-clad fibre is a photonic crystal fibre, such as a high NA photonic crystal fibre. This has the advantage of allowing a larger amount of light to be coupled into the optical fibre (e.g. by means of more pump laser diodes). Fabrication and use of such fibres are e.g. described in US-5,907,652 and WO-03/19257. High-NA photonic crystal fibres are discussed in a book by Bjarklev, Broeng, and Bjarklev in "Photonic crystal fibres", Kluwer Academic Press, 2003, chapter 7.4, p. 245-246. The Book is referred to in the following as [Bjarklev et al.-2003].

In a preferred embodiment of the invention, the output of the light source part is coupled into the end facet of an actively doped double-clad photonic crystal high NA fibre. This has the advantage of utilizing a larger part of the 'NA-space', thus enabling a larger amount of power to be coupled into the fibre in a single coupling point. Applications of high-NA photonic crystal fibres are discussed in [Bjarklev et al.-2003], chapter 7.5, p. 247-249.

In an embodiment of the invention, light is coupled from the light source part to the application part via a free space region. In an embodiment, the end facet of a source waveguide is optically coupled to the end facet of the application waveguide by means of an index matching material, such as epoxy or a soft glass. This has the advantage of minimizing optical loss at the free space interfaces. In an embodiment, an optical component is inserted between the end facet of a source waveguide and the end facet of the application waveguide.

A light source module:

An object of the present invention is to provide a cost-efficient scheme for integrating one or several light sources with optical waveguides with minimum loss of brightness and power. A further object of the invention is to facilitate the coupling of the light from a light source into passive or active application waveguides (for terminology, please refer to FIG. 2 and the corresponding description).

An object of the invention is achieved by a light source module comprising a light source part and a coupling part as described in the section "A coupling part" above (and as defined in the corresponding claims), the light source part comprising a multitude of essentially planar optical source waveguides formed on a source-substrate, the source-substrate having essentially opposite waveguide- and substrate faces, the source waveguides each having an input face adapted to be coupled to a light source formed or mounted on the source-substrate, the source waveguides being adapted to be optically coupled to the coupling waveguide or waveguides of said coupling part.

An advantage of the invention is that the alignment between light source and application waveguide is facilitated and that the interface is simplified by avoiding lenses or prisms, thereby reducing coupling loss and assembly cost. More specifically the coupling of light from the light source to the source and coupling waveguide can be done fully automatically and passively (e.g. by a flip-chip bonder using machine vision) and the alignment between the application waveguide and the source waveguide can be done fully passively by lithographic processes defining the source waveguides and the application waveguide grooves, respectively.

In an embodiment of the invention, the light source part and the coupling part are formed on the same substrate, e.g. a silicon substrate. In other words, the source substrate is integral with the coupling substrate. This has the advantage of making the fabrication simpler and avoids alignment and connectorization problems and associated losses. In an embodiment of the invention, the source waveguides continue uninterrupted into corresponding coupling waveguide or waveguides to form continuous waveguides from the input faces of the source waveguides (coupled to laser diodes) to the output faces of the coupling waveguide or waveguides (side coupled to respective application waveguides in grooves in the substrate).

In an embodiment of the invention, the source waveguides merge to one output waveguide which is continued uninterrupted on the coupling substrate and formed to join a groove in the coupling substrate and adapted for being side coupled to an application waveguide received by the groove.

In an embodiment of the invention the source and coupling parts are two separate parts. This has the advantage of providing the possibility of making a standard light source part and a coupling part that is customized to a particular application, the interface between the light source and coupling parts being standardized. Thus the functions of the light source module are distributed on a high-volume part (light source part) and a customized lower volume part (coupling part). In an embodiment of the invention, the waveguides of the source and coupling parts are aligned to each other to form a direct physical interface between corresponding waveguides to enable a low loss optical coupling between them. In an embodiment of the invention, the outputs of waveguides of the source part and the inputs of the waveguides of the coupling parts are adapted to conform to a standardized interface (e.g. in the form of an optical connector and/or an intermediate waveguide).

In an embodiment of the invention, the source waveguides are multimode waveguides (at the wavelength-range in question). In an embodiment of the invention, the coupling waveguides are multimode waveguides. An advantage of using multimode source and coupling waveguides is that it relaxes the mechanical tolerances on the alignment of the light source to the respective waveguide input ends and of the coupling of light between the source waveguides and their corresponding coupling waveguides. In an embodiment of the invention, the coupling waveguides have a larger height and/or width dimension than the source waveguides. This eases the coupling of light between corresponding waveguides of the source part and coupling parts.

In an embodiment, the light source part comprises a light source formed or mounted on the source-substrate. In an embodiment, said light source comprises at least one laser diode.

In further embodiments the light source part is as described in the section "A light source part" above (and as defined in the claims related to a light source part) whereby corresponding advantages are provided.

## A side coupled optical device:

An object of the present invention is to provide a cost-efficient scheme for integrating one or several light sources with optical waveguides with minimum loss of brightness and power. A further object of the invention is to facilitate the coupling of the light from a light source into passive or active application waveguides.

An object of the invention is achieved by a side coupled optical device comprising a light source module as defined in the section "A light source module" above (and as defined in the corresponding claims) (the light source module comprising a light source part and a coupling part either formed on one common substrate or on different substrates) and an application part optically cooperating with the light source module wherein the application part comprises an application waveguide in the form of an optical fibre located in a groove or grooves in the coupling part of the light source module and the application waveguide is optically side coupled to at least one of the coupling waveguides of the coupling part (for terminology, please refer to FIG. 2, specifically FIGs. 2.a and 2.d and the corresponding description).

An advantage of a side coupled optical device according to the invention is that it is relatively easy to manufacture and has the potential of providing a low cost, low loss coupling of light into the application waveguide or waveguides because the alignment of light source to application waveguide or waveguides is concentrated to the alignment of light sources to planar waveguides in the light source module and to alignment of the application waveguide in a groove of the coupling part. The former may be achieved by proper dimensioning of the laser diodes and the input waveguides and in practice precisely implemented using processing alignment features and automated bonding equipment. The latter may be achieved by proper adaptation of the groove to the application waveguide.

In an embodiment of the invention, the application waveguide or waveguides comprise(s) - when viewed in a cross section perpendicular to their direction of light propagation – concentric areas of different geometrical and/or effective refractive index. In an embodiment of the invention, at least one of said concentric areas comprise(s) a background matrix material hosting micro-structured features in the form of micro-areas having a refractive index different from the refractive index of the background matrix material.

In an embodiment of the invention, the source, coupling and application waveguides are multimode waveguides at the wavelength-range in question.

In an embodiment, an application waveguide comprises a cladding recess extending in the longitudinal direction of said application waveguide and facing said output face of said at least one coupling waveguide.

In an embodiment, said application waveguide – when viewed in a cross section perpendicular to a longitudinal direction of the waveguide - has a D-shape over the longitudinal extent of said cladding recess, the essentially flat part of the D-shape being optically coupled to the output face of the coupling waveguide by means of butt coupling, fusion or an index matching material such as a glue, a gel or an oil.

In an embodiment of the invention, the application part comprises waveguides in the form of double-clad optical fibres.

In an embodiment of the invention, the application waveguide is a double-clad, high NA, air-clad, micro-structured fibre (alternatively termed photonic crystal fibre, holey fibre, etc.). Advantages of air-clad, double-clad, micro-structured fibres are:

- Higher NA, than can be obtained with other double-clad technologies. This allows more efficient coupling of pump power into the fibre.
- Efficient pump absorption.
- Efficient schemes for side-coupling to the source waveguides (collapse of holes).

In an embodiment of the invention, the application waveguide or waveguides comprise air-clad micro-structured fibres and the coupling waveguides are coupled into the application waveguides by heat-collapsing the air-clad holes in the air-clad fibre, cf. international patent application no. PCT/DK03/00180 “Microstructured optical fibre with cladding recess, a method of its production, and apparatus comprising same” (published as WO-03/079077), which is incorporated herein by reference. The heat collapsing can for example be achieved by electro-splicers, filament splicers or laser heating.

In an embodiment, the micro-structured application waveguide has an inner and an outer cladding separated by an air-clad comprising a circumferential distribution of longitudinally extending voids.

In an embodiment, at least a part of said longitudinally extending voids of said air-clad have been removed or collapsed over at least a part of the longitudinal extent of said cladding recess.

In an embodiment, said cladding recess creates a side window allowing coupling of light in and out of said inner cladding of said application fibre.

In an embodiment of the invention, the application fibre comprises active ions in appropriate amounts (e.g. Er and/or Yb or other rare earth ions) and reflecting elements to form a fibre laser.

In an embodiment of the invention, the application fibre comprises active ions (e.g. Er and/or Yb or other rare earth ions) and reflection suppressing elements (e.g. isolators or angled or anti reflectively (AR-) coated end-facets) to form a fibre amplifier.

In an embodiment of the invention, the application fibre comprises a passive fibre for distributing the output of the light source.

In an embodiment of the invention, the application fibre is a multimode fibre.

In an embodiment of the invention, the application part comprises ONE application fibre that is arranged to be side-pumped by the coupling waveguides of the light source module. This has the advantage that a large amount of light power may be coupled into one and the same fibre e.g. to pump a high power fibre laser. In an embodiment of the invention, the application fibre is coiled onto a carrier drum. In an embodiment of the invention, light from a different coupling waveguide is coupled into the application fibre for each turn of the fibre on the drum.

In a preferred embodiment of the invention, a double-clad, air-clad application fibre is adapted to be side pumped from a planar optical coupling waveguide by collapsing the air-clad holes and fusing the application fibre to the coupling waveguide using a low power $CO_2$ laser (e.g. Access laser Lazy5).

BRIEF DESCRIPTION OF DRAWINGS

The invention will be explained more fully below in connection with a preferred embodiment and with reference to the drawings in which:

FIG. 1 shows brightness vs. power for various laser types (FIG. 1.a), beam parameter product vs. power required for different types of material processing (FIG. 1.b) and beam parameter product vs. power required for different types of material processing together with beam parameter product vs. power for the ‘low’ and ‘high’ brightness waveguide coupled modules of FIG. 1.a. (FIG. 1.c),

FIG. 2 shows the various functional parts of the present invention and their cooperation to illustrate the terminology used in the application, FIG. 2.a illustrating a light source module coupled to an application part, FIG. 2.b illustrating a light source part coupled to an application part, FIG. 2.c illustrating an embodiment of FIG. 2.b in the form of a fibre laser where a light source part is used as the pump (forming an end coupled optical device), FIG. 2.d illustrating an embodiment of a side coupled optical device, FIG. 2.e illustrating an embodiment of an optical coupling device and FIG. 2.f an embodiment of an end coupled optical device according to the invention,

FIG. 3 shows an optical side coupled device comprising a light source part, a coupling part and an application part according to the invention, FIG. 3.a being a side view of the device, FIG. 3.b being a bottom view of the light source part and the coupling part as separate parts, and FIG. 3.c as integrated parts,

FIG. 4 shows a coupling part comprising a coupling waveguide side coupled to a micro-structured application waveguide positioned in a groove of the coupling part, FIG. 4.a being a view (along AA on FIG. 4.b) of the fibre in a cross section not comprising the coupling waveguide, FIG. 4.b being a top view (along BB on FIGs.

4.a and 4.c), FIG. 4.c a view (along CC on FIG. 4.b) of the fibre in a cross section comprising the coupling waveguide where the application waveguide comprises a cladding recess, FIG. 4.d an embodiment where the groove has a bend to force the application waveguide against the end face of the coupling waveguide, and FIG. 4.e being a top view of a light source module comprising the coupling part of FIG. 4.b and a light source part as illustrated in FIG. 12.a,

FIG. 5 shows details of the splicing of a micro-structured application waveguide positioned in a groove of a coupling part to a coupling waveguide of the coupling part, FIG. 5.a and FIG. 5.b showing a situation before and after the splicing, respectively,

FIG. 6 shows a sketch of the coupling angles of interest for side coupling a coupling waveguide to an application waveguide,

FIG. 7 shows a light source part according to the invention comprising laser diodes mounted on a source substrate for coupling light into planar waveguides formed on the source substrate; in FIG. 7.a the laser diodes take the form of a laser diode array and in FIG. 7.b individual laser diodes,

FIG. 8 shows details of the coupling of light from a laser diode to a planar waveguide, FIG. 8.a being a perspective view and FIG. 8.b a side view,

FIG. 9 shows a light source part and a coupling part adapted for being optically connected via an optical connector, FIG. 9.a with source waveguides of equal width and FIG. 9.b with tapered source waveguides,

FIG. 10 shows different views of a light source part according to the invention, FIG. 10.a being a top view including a lid for enclosing the laser diodes and FIG. 10.b being a side view of the part comprising the laser diodes being hermetically sealed,

FIG. 11 shows a light source part comprising tapered waveguides which decrease in width and where the pitch is decreased from input end to output end (FIG. 11.a) and a way of implementing the tapering, FIG. 11.b illustrating the schematic structure of the waveguide and FIG. 11.c the variation in refractive indices,

FIG. 12 shows a light source part according to the invention where the inputs merge to one output, FIG. 12.a illustrating the light source part in isolation and FIG. 12.b illustrating the use of a light source part in combination with an application part to form an end coupled optical device,

FIG. 13 shows an application of a light source module to form a fibre laser, and

FIG. 14 shows a light source part according to the invention where the source waveguides are tapered and merge to one output.

The figures are schematic and simplified for clarity, and they just show details which are essential to the understanding of the invention, while other details are left out. Throughout, the same reference numerals are used for identical or corresponding parts.

## MODE(S) FOR CARRYING OUT THE INVENTION

FIG. 1.a shows brightness vs. power for various commercially available waveguide coupled semiconductor Broad Area Laser (BAL) types. The term ‘low brightness’ refers to commercially available low cost fibre coupled BALs such as they are available from for example the company Jenoptik AG (Jena, Germany). The term ‘high brightness’ refers to commercially available BALs, where advanced coupling schemes like those of WO-02/50599 are used to provide high brightness fibre coupled laser modules. It is noted that for these lasers, there is a clear tendency that brightness is reduced as the power is increased. The point denoted ‘Broad Area Laser’ refers to the brightness of a typical single broad area diode laser with an output power of 5 W, a height of 1 μm, a width of 100 μm and NA of 0.11 and 0.3 in the width and height directions, respectively.

FIG. 1.b shows beam parameter product vs. power required for different types of material processing. For a given material processing application it is necessary to have a given maximum beam parameter product and minimum power level. As an example, marking requires a maximum beam parameter product around 1 mm-mrad and a minimum power level around 20 W.

FIG. 1.c shows a combination of FIG. 1.a and FIG. 1.b, where brightness has been converted into beam parameter product by using the equation $q = \sqrt{P/(\pi B)}$. This figure basically shows the material processing applications which are possible with different kinds of waveguide coupled broad area lasers. For 'low brightness' fibre coupled diode lasers it is seen that there are very few material processing applications possible. Polymer welding is the only real candidate according to FIG. 1.c. For 'high brightness' diode laser modules, the material processing applications are still quite limited, but certain areas of printing and soldering can now be addressed. FIG. 1.c. implies that further improvements in the brightness/beam products of waveguide coupled high power diode lasers could significantly increase the number of material processing applications of such lasers.

FIG. 2 shows the various functional parts of the present invention and their cooperation to introduce and illustrate the terminology used in the application.

FIG. 2.a shows a first optical component 5 comprising a light source module 1 optically coupled 140 to an application part 4. The light source module 1 comprises a light source part 2 optically coupled 230 to a coupling part 3. The light source part 2 comprises a light source 21 optically coupled 220 to a multitude of planar optical source waveguides 22 formed on a source substrate 20, the light source 21 being formed or mounted on the source substrate 20. The coupling part 3 comprises at least one optical coupling waveguide 31 formed on a coupling-substrate 30 and waveguide receiving means 32 adapted for receiving an application waveguide 41 from the application part 4. The application part 4 comprises an application waveguide 41 adapted for being coupled to a coupling waveguide 31 of the coupling part via waveguide receiving means 32 and may further comprise supporting means 42 for supporting the application waveguide or waveguides 41.

FIG. 2.b shows a second optical component 6 comprising a light source part 2 optically coupled 240 to an application part 4. The light source part 2 comprises a light source 21 optically coupled 220 to a multitude of planar optical source waveguides 22 formed on a source substrate 20, the light source 21 being formed or mounted on the source substrate 20. The application part 4 comprises an application waveguide 41 adapted for being coupled to one or more source waveguides 22 of the light source part 2 and may further comprise supporting means 42 for supporting the application waveguide or waveguides 41.

FIG. 2.c illustrates an embodiment of FIG. 2.b in the form of a fibre laser 6 wherein light from a light source part 2 comprising a light source 21 and light guiding means 22 (both supported by a substrate 20) is end coupled 240 to and used for pumping an application waveguide 41 in the form of an actively doped fibre (e.g. e.g. a silica fibre doped with Er and/or Yb) provided with reflecting elements 42 (e.g. UV-written Bragg gratings) separated by a length of doped fibre 415.

FIG. 2.d shows an embodiment of a side coupled optical device 5 according to the invention, in the form of a light source part 2 optically coupled to a coupling part 3 together constituting a light source module 1 optically coupled to an application part 4 wherein application waveguides 41 are located in grooves of the coupling part 3 and optically side coupled to waveguides on the coupling substrate (cf. also description of FIG. 3). The source waveguides of the light source part 2 are shown schematically to be of constant width from input to output. In a preferred embodiment, however, the source waveguides are tapered to decrease in width from input to output (i.e. in a direction towards the coupling part 3 of FIG. 2.d).

FIG. 2.e shows an embodiment of an optical coupling device 7 according to the invention, in the form of a coupling part 3 optically coupled to an application part 4 wherein application waveguides 41 are located in grooves of the coupling part 3 and optically side coupled to waveguides on the coupling substrate.

FIG. 2.f shows an embodiment of an end coupled optical device 6 according to the invention, in the form of a light source part 2 wherein the tapered source waveguides 22 formed on a substrate 20 are merged to one common output waveguide (cf. description of FIG. 12) which is optically end coupled to an application part 4 comprising a double-clad optical fibre 41. The double clad fibre may comprise a core 416 and inner and outer cladding regions 415, 414, respectively. The application fibre 41 is aligned to the output source waveguide and the width 225 of the source output waveguide is adapted to the diameter 413 of the inner cladding region of the application fibre 41 and to the mutual distance 226 between the opposing end facets of the source output waveguide and the application fibre, respectively, to ensure a maximum transfer of light to the inner cladding of the application fibre (see also – correspondingly - the description of FIG. 8). In a preferred embodiment of the invention, the source waveguides are multimode waveguides. In another preferred

embodiment, the application waveguide is a multimode waveguide. In yet another preferred embodiment, the application waveguide is a double clad waveguide, wherein the inner cladding region is a multimode waveguide for the light from the source waveguide(s) of the light source part. In yet another preferred embodiment, the double-clad application waveguide is an air-clad, micro-structured fibre (cf. also FIG. 12.b).

FIG. 3 shows an optical side coupled device 5 comprising a light source module 1 (the light source module 1 comprising a light source part 2 and a coupling part 3) and an application part 4 according to the invention.

FIG. 3.a illustrates a side view of the component, indicating that the light source 2 and coupling 3 parts have their waveguide faces facing the application part 4. The application part comprises a carrier drum 42 on which an application fibre 41 is coiled. The fibre is e.g. spooled onto a spool with a (possibly varying) diameter matched to the particular application of the fibre.

FIG. 3.b is a bottom view (i.e. showing the waveguide faces) of the light source part 2 and the coupling part 3 (mounted with application fibres 41 in the grooves 32 of the coupling part). The light source part 2 comprises an array of laser diodes 21 mounted on a common diode substrate and mounted on the source substrate 20. The laser diodes are aligned with and coupled to a corresponding number of planar optical waveguides 22. The coupling part 3 comprises a corresponding number of planar optical waveguides 31 formed on a coupling substrate 30, each of the waveguides joining a different of a corresponding number of parallel grooves 32 formed in the coupling substrate to receive an application waveguide 41. The coupling waveguides join the groove at an angle α relative to a longitudinal axis of the groove. The angle α between the application fibre 41 and the coupling waveguide 31 is defined by the numerical aperture of the two. In a typical situation, an air-clad fibre would have an NA of 0.6 and the planar waveguide an NA of 0.32. In this case the maximum angle (allowing in principle 100% coupling) would be approximately 12°. By this arrangement light is coupled to the same fibre at a number of instances along the fibre determined by a turn of the fibre on the carrier drum 42.

The fibre is de-coated over a length corresponding at least to the length of the side-coupling region (e.g. by hot sulphur-acid or laser de-coating). This is preferably done as an array process, where several parts of the application fibre are de-coated simultaneously. Possibly the fibre is de-coated over a length shorter than the length of the corresponding groove of the coupling chip to allow for coated external fibre interfaces.

The fibre (array) is placed in the groove(s) of the coupling part. Optionally, a top is placed over the coupling chip to press the fibres into the grooves of the coupling part. Alternatively, the fibres can be glued onto the bottom of the grooves.

FIG. 3.c shows an embodiment of a light source module 1 wherein the light source part 2 and the coupling part 3 are formed on the same carrier substrate 20.

The source waveguides of the light source part 2 of FIGs. 3.b and 3.c are shown schematically to be of constant width from input to output. In a preferred embodiment, however, the source waveguides are tapered to decrease in width from input to output (i.e. in a direction towards the coupling part 3).

In an embodiment of the invention using micro-structured application fibres, as described in more detail below with reference to FIGs. 4 and 5, the fibre holes are collapsed in the part of the fibre facing the coupling waveguides and the fibres are fused to the waveguide, e.g. by laser welding (e.g. $CO_2$, cf. below).

The fibre grooves are e.g. sealed with glue.

A large number of grooves (e.g. more than 10, such as more than 20, such as more than 50) may be made in a coupling substrate. Likewise, several light source modules may be mounted along the periphery of the carrier drum. Further, several carrier drums may be arranged ‘in series’ so that a practically unlimited number of coupling points may be provided for a single application waveguide.

In FIGs. 3.a and 3.b, the light source part 2 and the coupling part 3 are shown to be separate units. This may be an advantage from a handling point of view. They may, however, just as well be formed on one common substrate so that the waveguides of the light source part continue on the coupling part without any intermediate stages (cf. FIG. 3.c).

In a preferred embodiment of the invention (as indicated in FIG. 3), the laser to waveguide-coupling and the waveguide to fibre coupling are performed on two individual waveguide 'chips'. These chips can then be connected using for example standard optical array connectors (e.g. AMP LIGHTRAY MPX), cf. also FIG. 9.

One chip (the coupling part) can be optimised with respect to the waveguide to fibre coupling efficiency and these chips will typically vary depending on the fibre type, but will have a standardised pump coupling interface: The other chip (the light source part) can have a standardised pump output coupling interface (corresponding to a standardized input on a multitude of different coupling parts) but can be varied to accommodate different pump laser chips. Furthermore, optical signal processing (e.g. pump mixing could be performed on this module).

The 'light source chip' can have waveguide dimensions smaller than those of the 'coupling chip'. Dimensions of the light source waveguides could for example be 3 x 110 μm (height x width) and dimensions of the waveguides of the coupling chip be 6 x 120 μm. This would allow good coupling efficiency using standard single mode fibre array connectors.

The application fibre 41 can be positioned relative to the coupling waveguide 31 by etching or wafer sawing a groove 32 in the 'coupling chip'.

The application waveguide may be an on optical fibre of various kinds, typically a double-clad fibre. An important advantage of double-clad fibres is that side-coupling from the coupling waveguide can be performed exclusively into the inner-cladding without disturbing the main signal propagating in the fibre core. Another advantage of double-clad fibres is their high numerical aperture of the inner cladding which - according to the equations for $\alpha$ and $\theta_{c1}$ and $\theta_{c2}$ above - allows side-coupling at relatively large angles $\alpha$ from coupling waveguides having relatively high numerical apertures. In a preferred embodiment, the application waveguide is double-clad, air-clad, micro-structured fibre where the light from the coupling waveguide is coupled into the inner-clad/pumping region of the fibre and is used to pump the fibre core which is co-doped with active ions such as Pr, Tm, Nd, Yb, Er or a combination of these. This preferred embodiment is exemplified in FIGs. 4 and 5 and discussed below together with possible methods of joining the coupling waveguide and the application waveguide in the groove to ensure a low coupling loss.

FIG. 4 shows a coupling part comprising a coupling waveguide 31 side coupled to a micro-structured application waveguide 41 positioned in a groove 32 of the coupling part, FIG. 4.a being a view (along AA on FIG. 4.b) of the fibre in a cross section not comprising the coupling waveguide, FIG. 4.b being a top view (through cladding layer 320 along BB on FIGs. 4.a and 4.c), FIG. 4.c a view (along CC on FIG. 4.b) of the fibre in a cross section comprising the coupling waveguide where the application waveguide comprises a cladding recess 415, FIG. 4.d an embodiment where the groove has a bend 325 to force the application waveguide against the end face 311 of the coupling waveguide 31, and FIG. 4.e being a top view of a light source module comprising the coupling part 3 of FIG. 4.b and a light source part 2 as illustrated in FIG. 12.a (cf. the corresponding discussion regarding the features of the light source part). In FIG. 4.e, the light source part 2 and the coupling part are illustrated as separate parts formed on separate substrates 20, 30, but they might as well be one integrated part formed on the same substrate (as exemplified on FIG. 3.c). The source waveguides 221, 222, 223 are merged to one source waveguide 224 matching the width (and height) of the coupling waveguide 31 at the output interface to the coupling part (cf. 2225 on FIG. 12). Further, the source and coupling waveguides are tapered in a direction from the light source (here laser diodes) towards the application part (here in the form of a side coupled application waveguide 41, e.g. a double-clad, air-clad fibre). Optionally the tapering of the coupling waveguide 31 may be omitted. Preferably, the width of the coupling waveguide at the interface to the light source part is equal to (or larger than) the width of the source waveguide at the interface. See the following discussion for the meaning of the features of the coupling part 3 of FIG. 4.e. The application waveguide 41 may optionally continue in a groove in the substrate 20 of the light source part 2.

The application waveguide, 41, (typically a micro-structured fibre) is placed in a groove 32 of the substrate 30 supporting the coupling waveguide 31.

The application waveguide groove 32 formed in the coupling waveguide substrate 30 can be manufactured by different techniques. Regardless of the processing technique, it is important that the sidewalls of the groove 321 are ‘steep’ (preferably essentially perpendicular to the substrate plane) to assure that the coupling waveguide at the application waveguide interface 311, 415 is in good thermal and mechanical contact with its substrate 30. Otherwise the coupling waveguide may be destroyed (e.g. melt) when the coupling waveguide is fixed to the application waveguide (for example by a $CO_2$ laser fusion).

One well-established technology for making the groove is chemical etching for example by $CF_6$ in combination with $O_2$. By correct adjustment of these two components, it is possible to etch several 100 μm into the Si-substrate of the coupling part and achieve sufficiently steep sidewalls. For the person skilled in the art, other chemical combinations can also be pursued such as other Fluoride and/or Chloride based compounds. Alternatively, the grooves can be etched by wet-chemical etching using for example KOH.

An alternative to etching the grooves will by to 'dice' the grooves using for example a wafer saw having a blade of a thickness corresponding to the desired width of the groove.

Etching will in general be the preferred technology for forming the grooves. One reason is that etching gives a great flexibility in the design of the grooves (they can bend, change width etc.). Another reason is that etching can be performed on wafer level in high throughput processes providing low processing cost in high volume.

A method of side coupling a waveguide to a micro-structured fibre comprising a cladding recess over a length of the fibre around the coupling is disclosed in international patent application no. PCT/DK03/00180, from which the following description is adapted.

The micro-structured application fibre comprises an inner cladding 412, and an outer cladding 413, 414 around the inner cladding. The outer cladding comprises a first outer cladding region having elongated features 414 extending along the fibre axis. The outer cladding region optionally comprises a further second outer cladding region, e.g. in a solid form. The elongated features in the outer cladding allow guiding in the inner cladding 412 either by modified total internal reflection or by the photonic band gap effect. A coating, usually made of a polymer, surrounds the outer cladding to protect the fibre mechanically. This coating is typically stripped in the vicinity of the cladding recess and therefore omitted in the figures. In the cladding pumped configuration an embedded core 411 may be present within the inner cladding 412. In this case the inner cladding 412 operates as a region wherein pumping light can be coupled to. If it is desired, the cladding recess can be designed to provide optical access to other parts of the cladding, e.g. the inner cladding, the outer cladding, or both.

The present invention covers preferred embodiments, wherein the cladding recess 415 creates a side window allowing coupling in or out of the inner cladding from the side of the fibre.

The cladding recess 415 is made by removing the outer cladding 413, 414 to give direct access to the inner cladding 412. This method is applicable to fibres wherein the elongated features 414 of the micro-structured outer cladding 413, 414 are made of, or constituted by, a gas, or of a solid material. The removal of the outer cladding can be carried out by several techniques. Polishing is a well-established technique. The section of the fibre to be processed is placed on a polishing jig pressing the sample on a moving plate containing an abrasive powder, such as alumina, diamond, or zirconium powder. The powder grain size and the pressure applied by the jig give fine control on the thickness removed. Etching is an alternative to polishing. Etching can be carried out by dipping the side of the fibre in an acidic solution. A solution containing hydrofluoric acid is particularly effective when dealing with silica fibres. The etching process can also rely on a gas, rather than a solution. Here the segment of the micro-structured fibre wherein the recess is to be formed is introduced into a chamber containing the etching gas, typically containing chlorine or fluorine. The etching rate is controlled by the concentration of the gas and by the temperature in the chamber. In the plasma etching technique, a well-established technique within the microelectronics industry and known to be effective to remove silica, the power of the plasma gives fine control on the etching rate. An example of polished or etched fibre side-coupled to an application waveguide is shown in figure 4.c. In this case the polished fibre is placed in the application waveguide groove and is connected to the coupling waveguide by an index matching material 312 which can be either a glue, a gel or an oil. Yet another technique consists in evaporating the outer cladding on a portion of the fibre by exposing it to a localized heat source, such as a focused laser beam, a resistive filament, or an electrical arc. To accelerate the evaporation it may be preferred to place the sample in a vacuum chamber while heating. A laser is a well-suited heat source because of its ability to concentrate power in space and time. The vast majority of materials used to produce optical fibres, and in particular silica, strongly absorb radiations at a wavelength of around 10 μm. A $CO_2$ laser beam may be a versatile heat source to produce a recess by evaporation. A preferred method is to orient the focussed beam tangentially to the fibre and translate the fibre along its axis over the length desired for the recess. Similarly we can leave the fibre still and translate the beam across its length. This is conveniently achieved using a moving mirror. A filament made of a high melting point metal with a large electrical resistivity, such as tungsten, is also a suitable heat source. The shape of the filament (e.g. straight or Ω shaped), the position of the fibre respective to the filament, and the current thought the filament determine the temperature gradient in the fibre and therefore the profile of the evaporated surface.

When the microstructures 414 of the outer cladding 413, 414 consist of elongated features made of, or constituted by, either vacuum or gas, such as air, another method may be applicable. The recess may be made by collapsing the hollow features 414 of the micro-structured outer cladding 413, 414 on the inner cladding 412, as illustrated in FIG. 4.b. The guiding in the inner cladding is disrupted due to the collapse of a section of the guiding hollow features, and the inner cladding is optically accessible from the collapsed solid outer cladding forming the recess. Laser or other heat sources, as described above, may also be used to collapse the holes/voids.

With both methods, i.e. removal or collapse of outer cladding, the recess can extend along a part of the circumference of the fibre as shown in FIG. 4.b, or all around the fibre. The recess is intended to provide optical interaction with the outside over a short extend. Typically it will extend over a few hundred micrometers to a few millimetres. If the interaction is required to be over a very short length, the recess can be made as short as a few tens of micrometers long. On the other hand, if for example several apparatus need to be affixed to the recess, it can be made to extend over a few centimetres. A recess may be made by collapsing voids (air filled holes) of the outer cladding all along the circumference of the fibre. For this, a commercially available fibre splicer – trademark Vytran FFS 2000 – has been used. The fibre was placed in the centre of the Ω-shaped resistive filament. During heating, the filament was surrounded with Ar gas and was moved along the axis of the fibre. The extent of the travel determined the length of the recess, which in this example was 180 μm. To primarily melt the outer parts of the fibre, a short, intense heat treatment was chosen. In this example, the heating power was 30 W and the duration was less than a second. The fibre was made of synthetic silica. It was 200 μm in diameter with a single circular layer of air holes forming the micro-structured outer cladding. Both the micro-structured outer cladding and the solid outer cladding were 14 μm thick, combining into a 28 μm thick outer cladding. The inner cladding was 142 μm in diameter. The outer cladding comprised 38 holes, separated by approximately 0.95 μm thick bridge. The bridge width, b, is defined as the smallest distance between to voids in a cross-section of the outer cladding region (cf. FIG. 4.a).

For a good coupling between the coupling and the application waveguide it is preferable that these two waveguides are in close physical contact at the interface 311, 415. This can be achieved be applying an external mechanical pressure to the application waveguide towards the coupling waveguide when the two waveguides are fixed to each other. In a preferred embodiment, the waveguide groove 32 has a small bend 325 (as shown in FIG. 4.d) around the coupling waveguide interface 311, 415, this bend assures that the 'stiffness' of the application waveguide/fibre 41 will press the fibre towards the coupling waveguide end face 311.

The coupling waveguide interfaces the application waveguide at an angle, α. For that purpose, the coupling waveguide will typically have to bend towards the etched groove. The bend radii should be as small as possible to allow for a compact chip but on the other hand sufficiently large to provide negligible bend-loss in the coupling waveguide. For typical waveguides with a width of 120 μm and a difference in index of refraction of 2 %, a bend radius of 40 mm is preferred.

FIG. 5 shows details of the splicing of a micro-structured application waveguide positioned in a groove of a coupling part to a coupling waveguide of the coupling part, FIG. 5.a and FIG. 5.b showing a situation before and after the splicing, respectively.

Initially, the application fibre 41 is de-coated over a length similar to or longer than the coupling region (typically about 500 μm). The coating is not shown in the figures. If the application fibre cladding recess (415 in FIG. 4) is made independently of the splicing process, the de-coating is done before the fibre is placed in the application groove. The fibre is placed in the groove and by forming a bend (cf. 325 in FIG. 4.d) in the groove or by applying external pressure (e.g. by inserting a wedge formed body (e.g. consisting of or comprising glue) between the application waveguide and the wall of the groove opposite the window of contact between the coupling waveguide and the application fibre) the fibre is pressed towards the coupling waveguide interface region.

An optical connection between the coupling waveguide 31 and the side of the application fibre 41 can be established by 'splicing' the two together by applying an external heat-source to the vicinity of the interface 311, 415. Such a heat-source 8 could for example be a $CO_2$-laser (cf. 8 in FIG. 5.a). The splicing could be established with a low power $CO_2$ laser (<10 W) with the output beam focused to a spot size of approximately 50 μm and focussing the light very close to the interface 311, 415 between the coupling waveguide 31 and the application fibre 41. Exposure time will typically be of the order of 1-10 s and the beam can either be scanned over the length of the interface region (typically 500 μm) or the beam can be expanded elliptically to match the length of the interface region.

For many micro-structured fibres, the cladding recess generation and the waveguide coupling fusion can be combined into one process step. By applying heat to the micro-structured fibre, the cladding air-holes 414 can be made to collapse in the same process, where the fibre 41 is fused to the waveguide 31.

In many cases it will be important to have a good thermal contact between the application fibre 41 and the coupling waveguide substrate 30. If such a thermal contact is not made, the heat applied to the interface region 311, 415 will spread across the entire cross section of the fibre 41 and might therefore collapse more than the intended air-holes 414 in the micro-structured fibre. Collapse of cladding air-holes outside the coupling area 415 is in general undesired as this will introduce an additional loss onto any signal propagating in the inner cladding 412 of the fibre. Furthermore, micro-structured fibres can also have air-holes in the innner clading 412 and in the core 411. If these holes collapse, an additional loss will by introduced to the signal propagating in the core.

One method of establishing a good thermal contact is to apply a thermally conducting glue (not shown) at the bottom of the application waveguide groove 32 around the coupling waveguide interface 311.

FIG. 6 shows a sketch of the coupling angles of interest for side coupling a coupling waveguide 31 to an application waveguide 41. To achieve full coupling between the two waveguides the side-coupling angle α between the longitudinal axis of the coupling and application waveguides must fulfil the following criterion: $\alpha \le \theta_{C2} - \theta_{C1}$, where $\theta_{c1}$ and $\theta_{c2}$ are the critical angles internally in the waveguide of the coupling and application waveguides, respectively.

FIG. 7 shows a light source part 2 comprising laser diodes 211 mounted on a source substrate 20 for coupling light into planar waveguides 22 formed on the source substrate 20.

In FIG. 7.a an array 21 of laser diodes 211 mounted on a common substrate 210 is mounted on the source substrate 20, whereas in FIG. 7.b individual laser diodes 211, 212 - each mounted on their own substrate 2110, 2120 - are mounted on the source substrate 20. In fig. 7.b a semiconductor laser 211 is mounted on the substrate 20 of the source waveguides 221, 222.

The precise positioning on the source substrate 20 of the individual laser diodes 211, 212 or the array of laser diodes 21 relative to the waveguides 221, 222 is performed by means of alignment marks 24, 219, 2112 on the upper cladding layer 23 and laser diode substrate 210 or substrates 2110, 2120, respectively.

The semiconductor laser 211 will typically be a high power broad area laser formed on a GaAs substrate and have an active area of 1 x 100 mm (cf. e.g. 2111 and $h_{LD}$ x $w_{LD}$ on FIGs. 8.a and 8.b).

To obtain good coupling efficiency it is in general preferred to have the dimensions of the source waveguides 221 exceeding those of the laser active area. Typical source waveguides will have cross sectional dimensions of 4 x 110 μm (cf. 2211 and $h_{WG}$ x $w_{WG}$ on FIGs. 8.a and 8.b).

In the waveguide plane (x- and z-directions) the laser chip 211 can be aligned to its corresponding waveguide 221 by matching alignment marks 2112 on the laser diode substrate 2110 to similar alignment marks 24 on the upper cladding layer 23 of the source waveguides. Alternatively, alignment in the waveguide plane can be performed by passive structures etched into the source waveguide chip and/or substrate.

Alignment in the 'height' (y-direction) of the laser diode 211 with respect to the waveguide 221 is determined by the height of the material to which the laser diode is mounted. To achieve good coupling between the laser and the waveguide, it is important that the centre line of a laser diode is aligned quite accurately to the centre line of its corresponding source waveguide (cf. 2214 on FIG. 8.b). This will in general require that the laser die 211 is lifted relative to the source waveguide substrate 20.

A simple way to mount the laser diode is the so-called die-bonding, where the laser die is bonded directly onto the Si-substrate of the source waveguide. To obtain a correct alignment between the diode and the waveguides, the level of the source waveguide substrate supporting the waveguides is reduced relative to the level of the source waveguide substrate supporting the laser. This can be done be chemical etching in the source waveguide substrate prior to the deposition of the source waveguides.

Alternatively, the laser can be placed on special plateaus etched into the source waveguide glass, the level of these plateaus assuring a correct alignment between the laser and the source waveguides. Electrical connection can then be established with solder bumps (typically 80/20% AuSn) deposited at the source waveguide substrate.

In a preferred embodiment of the invention, the laser diode 211 or array of laser diodes 21 is flip-chip bonded (P-side down) to the source-substrate 20 using standard, commercially available, high precision flip-chip bonders (e.g. Karl Süss FC150 or Finetech Fineplacer-96 "Lambda").

'Flip-chip' describes the method of electrically connecting the die to a carrier in the form of a package or a substrate. The interconnection between the die and carrier in flip chip packaging is made through a conductive "bump" that is placed directly on the die surface. The bumped die is then "flipped over" and placed face down, with the bumps connecting to the carrier directly.

The source waveguide substrate will - through the bonding connection - provide the heat sink necessary to cool the laser diode. An additional heat sink may be connected to the backside of the source substrate. This can be done by metallising the source waveguide substrate on the back and soldering the light source part or module to a (e.g. copper-tungsten) heat sink.

The source waveguides 221, 222 of the light source part 2 are in FIGs. 7.a and 7.b shown schematically to be of constant width from input to output (i.e. in a direction away from laser diodes 21). In a preferred embodiment, however, the source waveguides are tapered to decrease in width from input to output.

FIG. 8 shows details of the coupling of light from a laser diode 211 to a planar waveguide 221, FIG. 8.a being a perspective view and FIG. 8.b a side view. FIG. 8.b shows a cross section in the intended direction of light transmission (z) indicating the characteristic dimensions and angles of the laser diode 211 and the waveguide 221. The laser diode is mounted relative to the waveguide in the y-direction so that laser diode and waveguide share a common centreline 2214. The centreline is positioned at the centre of the core 2211 midway between lower 2212 and upper 2213 cladding layers of the waveguide 221.

The laser diode 211 has an active area 2111 with a width $W_{LD}$ and a heigth $h_{LD}$. The laser is placed at the distance $d_{LD\text{-}WG}$ from an adjacent waveguide facet 2211. The laser has (FWHM) emission angles of $\Theta_{LD,x}$ and $\Theta_{LD,y}$ in the width (x) and height (y) directions respectively. The waveguide 221 has a width of $w_{WG}$ and height $h_{WG}$ and has absorption angles of $\Theta_{WG,x}$ and $\Theta_{WG,y}$ in the width and height directions, respectively.

A good coupling can be obtained, when, the waveguide parameters are ‘comparable to or larger’ than the laser parameters and when the laser 211 is placed sufficiently close to the waveguide 221. For example more than 90% coupling efficiency can be obained with:

$w_{LD} = 100\ \mu m < 110\ \mu m = w_{WG}$

$h_{LD} = 1\ \mu m < 4\ \mu m = h_{WG}$

$\Theta_{LD,x} = 18^\circ < 19^\circ = \Theta_{WG,x}$

$\Theta_{LD,y} = 11^\circ < 19^\circ = \Theta_{WGy}$

$d_{LD\text{-}WG} \leq 4\ \mu m$

In FIGs. 9. and 9.b the source part 2 is optically coupled to the coupling part 3 (or alternatively an application part) through an optical interface 231, for example an optical connector 232, 233. The coupling is performed from one planar waveguide to the other. To obtain low coupling loss and good tolerances in the coupling it may be advantageous to couple from waveguides 22 on the light source part to slightly larger waveguides 31 on the coupling (or application part) part. This could for example be to couple from source waveguides with cross sections of 4 x 110 μm to coupling waveguides with cross sections of 8 x 120 μm. In FIG. 9, only a section of the coupling part 3 is shown. The section comprising grooves into which application waveguides 31' are side couples (cf. FIG. 3.b) is not shown.

The laser diodes 21 on the source part 2 are covered by a shield 215 which will provide a mechanical protection and which may also be used to encapsulate the laser diodes hermetically in a well defined atmosphere. This atmosphere is typically an inert gas like $N_2$ or He, which in some cases may include well defined concentrations of $O_2$, to avoid catastrophically optical damage caused by carbon deposition at the front facet of the laser.

The waveguide substrate may also support other optical functionalities than the basic optical waveguiding from source laser to application waveguide. This can for example be to provide a mixing of the light from several waveguides into a number of other waveguides as indicated by the component 33 of FIG. 9. This mixing has the advantage that the input to any particular application waveguide will not depend entirely on the output of a single laser diode and thereby making the system less vulnerable to the failure of individual laser diodes. The function of component 33 may optionally include a pitch conversion between incoming 31 and outgoing 31' waveguides.

Other functions which can be provided on the waveguide substrates would be tapping and monitoring of the signals from the light source(s). A waveguide branch could be included to all or some of the waveguides and the power coupled into these branches could be fed to photodiodes (typically in the form of a diode array) which could be mounted onto the waveguide substrate by the same methods used for the laser diodes. In this way the performance of the laser diodes could be monitored constantly and allow quick diagnosis in case of failure or preventive maintenance for application critical systems.

Furthermore, the waveguide substrate may be used to support functions which relate to the signal processing of the application waveguide. If for example, the light source is semiconductor pumps which are coupled into the inner cladding of a double-clad fibre with an actively doped single mode core, then the waveguide substrate may also be used for signal processing relating to the signal propagating in the single mode core of the double-clad fibre.

One example would be to use planar waveguide technologies in relation to fibre laser feedback and power combinations as shown and discussed in connection with FIG. 13.

In FIG. 9.a the width of the source waveguides 22 is uniform from input to output, whereas in FIG. 9.b the source waveguides are tapered to decrease in width from input to output. This has the advantage of facilitating the transfer of optical energy from the laser diodes to the source waveguides thereby relaxing alignment requirements, etc. It further has the advantage of concentrating the light in a smaller cross-sectional area, thereby allowing more power to be coupled into a high NA application waveguide of a given cross-section.

FIG. 10 shows different views of a light source part 2 according to the invention, FIG. 10.a being a top view including a lid 215 for enclosing the laser diodes and FIG. 10.b being a side view of the part comprising the laser diodes being hermetically sealed.

The lid 215 is placed over the lasers 211. The lid includes electrical feedthroughs 216, 217 (ground and signal, respectively) which are electrically connected by wire bonds 218 to the top and the bottom of the laser diodes. The electrical feedthroughs 216, 217 can then be connected to a laser current source to provide the necessary current to the lasers. The lid 215 can be fixed to the top-cladding 214 of the light source part by metallising the lid and the relevant part of the source part and soldering 219 the lid and the source part together.

The laser diodes 211 in FIG. 10 may be an array of diodes (FIG. 7.a), individual diodes (FIG. 7.b) or a combination thereof.

The 'height' (y-direction, cf. FIG. 8) of the laser diode 211 with respect to the waveguide 221 may be determined by the height of the substrate to which the laser diode is mounted. The height of the laser diode stripe (2111 in FIG. 8.a) with respect to the waveguide core (2211 in FIG. 8.a) can be determined with a large degree of freedom by etching a laser-mount plateau 201 on the waveguide substrate. This allows the laser chip to be mounted directly on the Si-substrate (without intermediate glass) leading to very effective heat dissipation from the laser to the substrate.

The source waveguides 22 of the light source part 2 of FIG. 10.a are shown schematically to be of constant width from input to output. In a preferred embodiment, however, the source waveguides are tapered to decrease in width from input to output (i.e. in a direction away from the laser diodes 211 (i.e. the electrical feedthroughs 217 of FIG. 10.a).

Example of manufacturing a light source part:

A method of manufacturing a light source part may comprise the following steps using silicon-based technology as an example:

1) A Si-wafer is metallized on the back.

2) A Si plateau is etched to lift the laser into the correct height relative to the core of the waveguide (typical height may be 15 μm).

3) The Si-wafer is oxidised to form the lower cladding of the waveguides. Using e.g. a 12 μm APOX layer, this leads to glass formation 4 μm down into the Si-substrate and additional APOX grown 8 μm above the Si surface (before oxidisation). This can be done in an oven with Oxygen flow.

4) Using photolithographic processes, broad waveguides are defined. These can be based on a relatively thick, high index core deposited layer (e.g. 6 μm SiON with $\Delta n$ of 2.5%, grown by plasma enhanced chemical vapour deposition (PECVD)). The width of the waveguides (x-direction on FIG. 8) will depend on the width of the adjacent laser diode chip. For a typical laser width of 100 μm, a typical waveguide width would be 110 μm.

5) An upper cladding is deposited (e.g. 12 μm by PECVD).

6) Using photolithographic processes, the glass deposited above the laser plateau is etched away.

7) To get a high quality waveguide facet, the glass outside the laser platform may optionally (but typically) also be etched away (to a level below the laser plateau) in an area 5-15 μm between the laser plateau and the waveguide.

8) Using photolithographic processes, metal is applied to the laser plateau for bonding the laser diode(s) to the Si-substrate. This metallization could for example be Platin-Gold. Additional metallization is also applied to areas which will serve as (wire)bonding pads and optionally also for areas which can be used to solder a laser protective cover to the waveguide substrate.

9) The laser diode(s) is/are bonded to the substrate and electrical connections are made by wire-bonding the laser to the bonding pads.

10) Finally the hybridised laser may optionally (but typically) be hermetically sealed by a lid (e.g. an electrically insulating lid) to enhance reliability and life time of the part.

Similar processing steps (specifically steps 1-5) may be used to implement waveguides on a coupling part. The formation of a groove or grooves is discussed above in connection with FIG. 4.

The techniques of photolithography and etching are described in further detail in S.M. Sze, “VLSI Technology”, second edition McGraw-Hill Book Company, (1988). The photolithography is described in chapter 4, whereas the etching techniques are described in chapter 5, which are incorporated herein by reference.

PECVD also known as Plasma CVD, PCVD and Low Pressure Chemical Vapour Deposition LPCVD) are described in further detail in Hiroshi Nishihara, Masamitsu Haruna and Toshiaki Suhara “Optical integrated circuits”, McGraw-Hill Book Company, (1989), cf. e.g. p. 141, which is incorporated herein by reference.

Various relevant aspects of the silica-on-silicon technology is e.g. discussed in M. Kawachi, ”Silica waveguide on silicon an their application to integrated-optic components”, Opt. Quant. Electr. 22 (1990) 391-416, which is incorporated herein by reference.

Example of optically coupling an application waveguide to a coupling part:

A method of optically coupling an application waveguide to a coupling part, the method comprising the steps of

a) providing a double clad optical fibre such as a micro-structured optical fibre, such as an air clad optical fibre;

b) decoating the optical fibre over a part of its length, preferably at least corresponding to the width of the output output face of the coupling waveguide in the groove of the coupling part;

c) optionally forming a cladding recess over at least a part of the decoated length of the fibre, optionally to collapse air holes in the fibre over at least a part of its peripheral extent, which part is to be facing the output face of the coupling waveguide when mounted in the groove;

d) mounting the fibre in the groove, arranging that the decoated part of the fibre is facing the output face of the coupling waveguide;

e) providing an optical coupling between the fibre and the output face of the coupling waveguide by

e1) butt coupling, preferably by including a bend in the groove forcing the application fibre to contact the output face of the coupling waveguide, or by

e2) applying an external heat source – preferably a $CO_2$ laser source - to fuse the fibre to the coupling waveguide, or by

e3) gluing the application fibre to the output face of the coupling waveguide.

In a preferred embodiment, the application waveguide is an air clad fibre. In a preferred embodiment, the recess and the fusion of the application fibre to the output face of the coupling waveguide is made in a single step, thereby omitting the optional intermediate step c).

FIG. 11 shows a light source part comprising tapered waveguides which decrease in width and where the pitch is decreased from input end to output end (FIG. 11.a) and a way of implementing the tapering, FIG. 11.b illustrating the schematic structure of the waveguide and FIG. 11.c the variation in refractive indices.

In FIG. 11.a the widths of the waveguides 221, 223, 224 decrease from the input end 2214 close to the laser diodes 21 to the output end 2215. Further, the pitch 2217, 2216 between adjacent waveguides decreases from the input end to the output end, respectively. This embodiment provides high brightness output, where the brightness at the output is higher than it would have been if the waveguides had not been tapered. Furthermore, this embodiment provides a concentration of the light, which can be used to increase the power coupled into an application waveguide (or a coupling waveguide) interface of a given width.

This embodiment can be implemented for example by utilising either of the two methods described below. In one case it is utilised that the laser NA (emission angle, $NA_{LD,out}$) in the waveguide plane is lower than the waveguide NA (acceptance angle, $NA_{WG,in}$) in the waveguide plane. Consequently, the mode space of the waveguide is not filled by the laser modes, but by tapering the waveguides, the width of the waveguides can be reduced while the mode space of the waveguides is being filled. In one case, the NAs of the waveguides are made to vary over the lengths of the waveguide. At the waveguide input, the waveguide NA in the waveguide plane will match the laser NA in the waveguide plane. The widths of the waveguides are then decreased along the length of the waveguides while the NA in the waveguide plane is increased accordingly (to $NA_{WG,out}$ at the output). One way to implement such waveguides is to use a photosensitive top-cladding. By exposing the area just outside the waveguides to UV-light it is possible to increase the refractive index of the top cladding with a value, which depends on the exposed UV-light, cf. FIG. 11.b and 11.c. In this way, the NA of the waveguide will be reduced in areas exposed to UV-light.

FIG. 11 shows a light source part comprising tapered waveguides which decrease in width and where the pitch is decreased from input end to output end (FIG. 11.a) and a way of implementing the tapering, FIG. 11.b illustrating the schematic structure of the waveguide and FIG. 11.c the variation in refractive indices.

FIG. 14 is identical to as in FIG. 11.a except that the numerical aperture $NA_{WG}$ of a source waveguide in FIG. 14 is identical at input and output). The widths of the waveguides 221, 223, 224 decrease from the input end 2214 ($w_i$) close to the laser diodes 21 to the output end 2215 ($w_o$). Further, the pitch 2217, 2216 between adjacent waveguides decreases from the input end to the output end, respectively. The pitch conversion provides a high brightness output. The source waveguide tapering enables a large amount of light to be fed into a high-NA application waveguide (cf. 41 in FIG. 12.b). Furthermore, this embodiment provides a concentration of the light, which can be used to increase the power coupled into an application waveguide (or a coupling waveguide) interface of a given width. Preferably, $w_i/w_o \sim NA_{WG}/NA_{LD,out}$, e.g. around 3-10. It may be of interest, though - for practical reasons - to make a compromise between ideal tapering and the length of waveguide over which the tapering is performed. In a specific case where $NA_{WG}/NA_{LD,out} \sim 5$, e.g., a taper with a slightly smaller width ratio, e.g. 3-4, is implemented to get a reasonable length over which the tapering is performed with a view to losses.

FIG. 12.a shows an embodiment of a light source part according to the invention, where the input waveguides 221, 222, 223 having facets 2214, 2224, 2234 receiving light from an array 21 of laser diodes merge to one waveguide 224 providing light from all laser diodes in one output facet 2225. The width of the output waveguide 224 at the output facet 2225 is essentially equal to the sum of the widths of the input waveguides at the input facets 2214, 2224, 2234.

FIG. 12.b shows an end coupled optical device 6 according to the invention. The device comprises a light source part 2 as exemplified by FIG. 12.a (but with tapered source waveguides) and an application part 4, exemplified by a double-clad fibre 41, here an air-clad, micro-structured fibre. An end facet 412 of the air-clad fibre 41, the fibre comprising a ring of longitudinally extending air holes 411 (here the air-cladding), is optically end coupled to the output face 2225 of the source waveguide 224 of the light source part 2. The source waveguides are tapered so that the width of the output waveguide 224 at the output facet 2225 is smaller than the sum of the widths of the input waveguides at the input facets 2214, 2224, 2234.

The cross sectional dimensions of the inner cladding of the application waveguide (i.e. the region within the ring of air holes 411), here the diameter 413, and the distance 226 between end facets 412, 2225 of the application waveguide 41 and source waveguide 224, respectively, are adapted to minimize the loss of brightness between the emitting face 2225 of the source waveguide and the input facet 412 of the application fibre. The width (and height, cf. FIG. 8) of the source waveguide (cf. 225 on FIG. 2.f) and the distance 226 between the emitting and receiving facets are adapted to ensure that the cross-sectional dimensions of the emitted mode field are appropriate for the extent and form of the inner cladding of the double-clad fibre to minimize the loss of brightness at this interface. In other words, the maximum cross sectional dimension 413 of the inner cladding at the end facet 412 should preferably be larger than the maximum cross sectional dimension of the core part of the output facet 2225 of the source waveguide, and increasingly larger with increasing distance 226 between the facets (i.e. the outer boundary of the core of the end facet 2225 of the source waveguide should preferably be encircled by the outer boundary of the inner cladding region wherein the light from the light source part is to be propagated.

In an embodiment, an optical component is inserted between the end facets 412, 2225. Optionally, the end facets 412, 2225 may be separated by a free space region. Optionally, the end facets 412, 2225 may be joined by an index matching material, e.g. an epoxy or a glass.

The light source part in FIG. 12.b may take other forms than the one illustrated, e.g. the form of FIG. 11.a comprising a multitude of output source waveguide facets (optionally of different widths and/or heights) or any other form within the scope of the invention.

In an embodiment, the form of the inner cladding of the application fibre to which light from the light source part is coupled has a form that resembles the form of the output face or faces of the source waveguide(s), e.g. an elliptical form.

FIG. 13 shows a fibre laser application of the invention, where the planar waveguide platform of the light source module (comprising light source and coupling parts) is used not just for fibre laser pumping but also for further signal processing. The fibre laser consists of a number of fibre amplifiers 101 to 104. These consists of actively doped double-clad fibres 411 to 414, pumped through coupling parts 301 to 304, which are connected to light source parts 201 to 204. The fibre amplifiers 101 to 104 are forced to lase at different and well-defined wavelength by providing wavelength selective feedback to the ends of the fibres. This wavelength selective feedback is provided by two planar arrayed waveguide couplers (AWGs) 431, 432 with reflections 433, 434 at the outputs. In FIG. 13, these two reflections are provided by a loop mirror 433 given an almost 100% reflection and the open output facet of the AWG 434 given a 4% reflection.

The light from a given fibre will at the AWGs experience a wavelength filtering from the input towards the reflection and then another wavelength filtering from the reflection and back towards the fibre. This wavelength filtering will effectively assure that each fibre will lase at wavelengths determined by the AWGs and that each fibre will lase at different wavelengths. Furthermore the AWGs can be used to provide a low loss combination of the output of the different fibres in order to make very high power lasers. Assuming for example that 40 fibre lasers each having an output power of 100 W are combined in an AWG with 1.5 dB loss, the total output (at the AWG output facet 434) of the fibre laser will be 2.8 kW.

The reflection and wavelength filtering unit 430 of FIG. 13 can be physically implemented on of the existing light source or coupling parts or it can be realised as a separate unit.

This configuration is just one example of how the planar waveguide platform can be used for other purposes than just pump to application waveguide coupling. Another obvious application would be to include tap couplers and flip-chip mounted photodiodes on the light source and coupling parts to provide continuous monitoring of the operation of the different laser diodes and coupling schemes.

Some preferred embodiments have been shown in the foregoing, but it should be stressed that the invention is not limited to these, but may be embodied in other ways within the subject-matter defined in the following claims.

## CLAIMS

1. A coupling part for coupling light to an application part, the coupling part comprising at least one essentially planar coupling waveguide formed on a coupling-substrate, the coupling-substrate having opposite waveguide- and substrate faces, at least one of the coupling waveguides having an input face and an output face, the input face of the coupling waveguide or waveguides being adapted to be optically coupled to source waveguides for supplying light power to the coupling part wherein the coupling part comprises at least one elongate groove in the form of a recess in the waveguide face, the groove being adapted to receive an elongate optical application waveguide, and said at least one coupling waveguide and said at least one groove are formed on the coupling-substrate relative to each other so that said output face of said coupling waveguide is suitable for being side-coupled to said application waveguide located in said groove.

2. A coupling part as claimed in claim 1 wherein the groove and the coupling waveguide are adapted so that when an application waveguide is placed in the groove, there is a direct contact between the output face of the coupling waveguide and a side of the application waveguide.

3. A coupling part as claimed in claim 1 or 2 wherein the coupling part comprises a multitude of essentially parallel grooves each adapted for receiving a respective application waveguide.

4. A coupling part as claimed in any of claims 1 to 3 wherein coupling waveguides are coupled into respective application waveguides at a side-coupling angle, $\alpha$ by arranging that a coupling waveguide and a corresponding groove for receiving an application waveguide meet at an angle $\alpha$, and the side-coupling angle $\alpha$ fulfils the following criterion $\alpha \leq \theta_{C2} - \theta_{C1}$ where $\theta_{c1}$ and $\theta_{c2}$ are the critical angles internally in the waveguide of the coupling and the application waveguides, respectively.

5. A coupling part as claimed in any of claims 1 to 4 wherein the groove comprises a bend adapted to force the application waveguide against the output face of the coupling waveguide.

6. A coupling part as claimed in any of claims 1 to 5 wherein said at least one coupling waveguide is a multimode waveguide at least over a part of its length.

7. A coupling part as claimed in any of claims 1 to 6 wherein said at least one coupling waveguide is a single mode waveguide at least over a part of its length.

8. A coupling part as claimed in any of claims 1 to 7 wherein said output face of said at least one coupling waveguide and/or said groove is/are adapted to receive a double-clad application waveguide.

9. A coupling part as claimed in any of claims 1 to 8 wherein said output face of said at least one coupling waveguide and/or said groove is/are adapted to receive a double-clad, micro-structured application waveguide, preferably an air-clad optical fibre.

10. An optical coupling device comprising a coupling part as claimed in any of claims 1-9 and an application part wherein the application part comprises an application waveguide in the form of an optical fibre located in said groove or grooves of said coupling part and said application waveguide is optically coupled to said output face of said at least one of the coupling waveguides of said coupling part.

11. An optical coupling device as claimed in claim 10 wherein the coupling and/or application waveguide or waveguides comprise(s) - when viewed in a cross section perpendicular to their direction of light propagation – concentric areas of different geometrical and/or effective refractive indices.

12. An optical coupling device as claimed in claim 10 or 11 comprising coupling and application waveguides that are multimode waveguides at the wavelength-range in question at least over a part of their lengths.

13. An optical coupling device as claimed in any of claims 10 to 12 wherein an application waveguide comprises a cladding recess extending in the longitudinal direction of said application waveguide and facing said output face of said at least one coupling waveguide.

14. An optical coupling device as claimed in claim 13 wherein said application waveguide – when viewed in a cross section perpendicular to a longitudinal direction of the waveguide - has a D-shape over the longitudinal extent of said cladding recess, the essentially flat part of the D-shape being optically coupled to the output face of the coupling waveguide by means of butt coupling, fusion or an index matching material such as a glue, a gel or an oil.

15. An optical coupling device as claimed in any of claims 10 to 14 wherein the application waveguide is a double-clad fibre.

16. An optical coupling device as claimed in any of claims 11 to 15 wherein at least one of said concentric areas comprise(s) a background matrix material hosting micro-structured features in the form of micro-areas having a refractive index different from the refractive index of the background matrix material.

17. An optical coupling device as claimed in claim 16 wherein the micro-structured application waveguide has an inner and an outer cladding separated by an air-clad comprising a circumferential distribution of longitudinally extending voids.

18. An optical coupling device as claimed in claim 17 wherein at least a part of said longitudinally extending voids of said air-clad have been removed or collapsed over at least a part of the longitudinal extent of said cladding recess.

19. An optical coupling device as claimed in claim 18 wherein said cladding recess creates a side window allowing coupling of light in and out of said inner cladding of said application fibre.

20. A light source part comprising

a) a multitude of N laser diodes $LD_i$ with predetermined numerical apertures $NA_{LD,i}$, i=1, 2, ..., N, each individual laser diode having an emitting face with a laser stripe for emitting light power,

b) a multitude of M essentially planar optical input source waveguides $WG_j$ with predetermined numerical apertures $NA_{WG,j}$, j=1, 2, ..., M, the waveguides each having an input face with a capture area for capturing light, and the waveguides being formed on a source-substrate,

c) each waveguide being adapted to receive light from one or more corresponding laser diodes, and

d) an output interface for making light from the laser diodes available

wherein

said input source waveguides and their corresponding laser diode or diodes have matching numerical apertures and physical dimensions of their capture area and laser stripe, and the laser diodes are mounted or formed on the source-substrate with the emitting faces relative to the input faces of the waveguides to minimize the loss of brightness between the emitting face of the individual laser diodes and the input face of the individual waveguides.

21. A light source part as claimed in claim 20 wherein a one to one correspondence exists between the number of and relative positions of the laser diodes and waveguides.

22. A light source part as claimed in claim 20 or 21 wherein the source substrate or layers deposited or grown thereon comprises alignment marks for alignment of the laser diodes on the source-substrate relative to the source waveguides.

23. A light source part as claimed in claim 22 wherein alignment marks are formed during processing of the substrate or layers deposited or grown thereon.

24. A light source part as claimed in any of claims 20 to 23 comprising a mount for alignment of a particular laser diode and a corresponding source waveguide in a growth direction of the source substrate, the level of the mount on which the laser diodes are mounted being controlled by adapting the level of the substrate and/or layers deposited or grown thereon to allow the laser stripe of a particular laser diode to be positioned at a predetermined desired level relative to the capture area of the corresponding waveguide.

25. A light source part as claimed in any of claims 20 to 24 wherein the laser diodes are adapted to be flip-chip bonded directly onto the source substrate and/or to layers deposited or grown thereon.

26. A light source part as claimed in any of claims 20 to 25 wherein at least one or all of said waveguides are adapted for propagating more than one electromagnetic mode.

27. A light source part as claimed in any of claims 20 to 26 wherein said waveguides are fabricated in a silica-on-silicon planar technology.

28. A light source part as claimed in any of claims 20 to 27 wherein said laser diodes are fabricated in a GaAs or InP technology.

29. A light source part as claimed in any of claims 20 to 28 wherein said multitude of laser diodes are hermetically sealed by arranging a hermetically sealable cover with current feed-throughs over each laser diode or over a multitude of laser diodes.

30. A light source part as claimed in any of claims 20 to 29 wherein at least one of said laser diodes is a high power laser diode, such as a semiconductor laser diode emitting a light power larger than 2 W or a broad area laser, such as a semiconductor laser diode having a stripe width larger than 50 μm.

31. A light source part as claimed in any of claims 20 to 30 wherein at least one of said laser diodes is a multimode laser diode.

32. A light source part as claimed in any of claims 20 to 31 wherein some of said laser diodes are constituted by one or more diode laser bars,. where a multitude of diode lasers are mounted on the same substrate.

33. A light source part as claimed in any of claims 20 to 32 wherein at least one of said laser diodes is constituted by an individual diode formed on an individual substrate.

34. A light source part as claimed in any of claims 20 to 33 wherein said laser diodes have a relatively low numerical aperture, NA, such as NA less than 0.2 in both the height and the width direction of the laser diode.

35. A light source part as claimed in any of claims 20 to 34 wherein the laser diodes are identical in the sense of having essentially identical numerical apertures and characteristic physical dimensions.

36. A light source part as claimed in any of claims 20 to 35 wherein the source waveguides have the same pitch at the input and output ends.

37. A light source part as claimed in any of claims 20 to 35 wherein the total distance between the two outermost source waveguides is larger at the input end than at the output end.

38. A light source part as claimed in any of claims 20 to 35 wherein the total distance between the two outermost waveguides is larger at the output end than at the input end.

39. A light source part as claimed in any of claims 20 to 38 wherein the numerical aperture of the waveguides is identical at the input and output ends.

40. A light source part as claimed in any of claims 20 to 38 wherein one or more of the source waveguides are adapted so that the numerical aperture of the waveguide is larger at the output end than at the input end of the waveguide.

41. A light source part as claimed in any of claims 20 to 40 wherein the width of the waveguides is decreased from the input to the output.

42. A light source part as claimed in any of claims 20 to 41 wherein the ratio of the widths of a source waveguide at the input and output $w_{i,x}/w_{o,x}$ in the x-direction is larger than 1, such as larger than 1.5, such as larger than 2, such as larger than 3, such as larger than 5, such as larger than 10.

43. A light source part as claimed in any of claims 20 to 41 wherein the ratio of the widths of the source waveguides at the input and output $w_{i,x}/w_{o,x}$ is less than or equal to the ratio of the numerical apertures of the source waveguide at the input $NA_{WG,x}$ and of the light source $NA_{LD,x}$, in the x-direction, such as $\leq 0.9$ times $NA_{WG,x}/NA_{LD,x}$, such as $\leq 0.7$ times $NA_{WG,x}/NA_{LD,x}$, such as $\leq 0.5$ times $NA_{WG,x}/NA_{LD,x}$.

44. A light source part as claimed in any of claims 20 to 43 wherein the tapering is linear, piecewise linear, follows a polynomial function or follows an exponential function.

45. A light source part as claimed in any of claims 20 to 44 wherein the height of a source waveguide is increased from the input end of the waveguide to the output end.

46. A light source part as claimed in any of claims 20 to 45 wherein at least one of the source waveguides are multi-layer waveguides.

47. A light source part as claimed in any of claims 20 to 46 wherein the shortest distance $d_{LD\text{-}WG}$ between the emitting face of a laser diode and the input face of its corresponding source waveguide is adapted to the height $h_{WG}$ and width $w_{WG}$ of the capture area of the waveguide and the numerical aperture $NA_{LD}$ of the laser diode to fulfil the relations
$h_{WG} \geq 2 \bullet d_{LD\text{-}WG} \bullet (NA_{LD,y}/[1-(NA_{LD,y})^2]^{0,5}) = 2 \bullet d_{LD\text{-}WG} \bullet tg\Theta_{LD,y}$
$w_{WG} \geq 2 \bullet d_{LD\text{-}WG} \bullet (NA_{LD,x}/[1-(NA_{LD,x})^2]^{0,5}) = 2 \bullet d_{LD\text{-}WG} \bullet tg\Theta_{LD,x}$
where $NA_{LD,y} = \sin\Theta_{LD,y}$ and $NA_{LD,x} = \sin\Theta_{LD,x}$ are the numerical apertures in air of a laser diode in the height and width directions, respectively.

48. A light source part as claimed in any of claims 20 to 47 wherein two input source waveguides are merged to one output source waveguide.

49. A light source part as claimed in any of claims 20 to 48 wherein all input source waveguides are merged to one output source waveguide.

50. A light source part as claimed in any of claims 20 to 47 wherein each input source waveguide has an output face so that a module has M inputs coupled to laser diodes and M outputs for coupling light to one or more target objects, such as an application part.

51. A light source part as claimed in any of claims 20 to 47 wherein the M input waveguides are coupled to Q output waveguides where Q is different from M.

52. A light source part as claimed in any of claims 20 to 41 wherein the output face of a source waveguide is shaped to focus the light.

53. A light source part as claimed in any of claims 20 to 52 wherein a source waveguide is adapted to have a graded refractive index wherein the central region of

the waveguide has a refractive index that gradually decreases as the distance from the centre of the waveguide increases.

54. A light source part as claimed in any of claims 20 to 53 wherein two or more of the output source waveguides are adapted to direct the light towards a common focal point located external to the waveguides of the light source part.

55. An end coupled optical device comprising a light source part as claimed in any of claims 20 to 54 and an application part wherein the application part comprises an optical application waveguide comprising an end face optically coupled to said light source part.

56. An end coupled optical device as claimed in claim 55 wherein the application part comprises a passive waveguide for distributing the output of the light source.

57. An end coupled optical device as claimed in claim 55 or 56 wherein the application part comprises an active waveguide for amplifying the output of the light source.

58. An end coupled optical device as claimed in any of claims 55 to 57 wherein the application part comprises a waveguide comprising active ions, such as Er and/or Yb, and reflecting elements to form a waveguide laser.

59. An end coupled optical device as claimed in any of claims 55 to 58 wherein the application waveguide is a multimode waveguide.

60. An end coupled optical device as claimed in any of claims 55 to 59 wherein the application waveguide is formed on the source substrate as a continuation of an output source waveguide of the light source part.

61. An end coupled optical device as claimed in any of claims 55 to 59 wherein the application waveguide is an optical fibre, positioned in a groove formed in a substrate of the application part.

62. An end coupled optical device as claimed in claim 61 wherein the substrate of the application part on which the application fibre is positioned is identical to the substrate of the light source part.

63. An end coupled optical device as claimed in claim 61 or 62 wherein the output of the light source part is coupled into the end facet of a double-clad fibre comprising a core, an inner and an outer cladding.

64. An end coupled optical device as claimed in claim 63 wherein the double-clad fibre has a single mode core and an inner cladding forming a multimode core for light propagated in the inner cladding.

65. An end coupled optical device as claimed in claim 63 or 64 wherein the double-clad fibre is a photonic crystal fibre, such as a high NA photonic crystal fibre.

66. A light source module comprising a light source part and a coupling part according to any one of claims 1 to 9, the light source part comprising a multitude of essentially planar optical source waveguides formed on a source-substrate, the source-substrate having essentially opposite waveguide- and substrate faces, the source waveguides each having an input face adapted to be coupled to a light source formed or mounted on the source-substrate, the source waveguides being adapted to be optically coupled to the coupling waveguide or waveguides of said coupling part.

67. A light source module as claimed in claim 66 wherein the source and coupling parts are two separate parts.

68. A light source module as claimed in claim 67 wherein the waveguides of the source and coupling parts are aligned to each other to form a direct physical interface between corresponding waveguides to enable a low loss coupling between them.

69. A light source module as claimed in claim 67 or 68 wherein the waveguides of the source and coupling parts are coupled to each other via optical connectors and/or intermediate waveguides.

70. A light source module as claimed in claim 66 wherein the light source part and the coupling part are formed on the same substrate.

71. A light source module as claimed in claim 70 wherein the source waveguides continue uninterrupted into corresponding coupling waveguides to form continuous waveguides from the input faces of the source waveguides to the output face or faces of the coupling waveguide or waveguides.

72. A light source module as claimed in any of claims 66 to 71 wherein the light source part comprises a light source formed or mounted on the source-substrate.

73. A light source module as claimed in claim 72 wherein said light source comprises at least one laser diode.

74. A light source module as claimed in any preceding claim comprising a light source part as claimed in any of claims 20 to 54.

75. A side coupled optical device comprising a light source module as claimed in any of claims 66 to 74 and an application part wherein the application part comprises an application waveguide in the form of an optical fibre located in a groove or grooves in the coupling part of said light source module and said application waveguide is optically coupled to at least one of the coupling waveguides of said coupling part.

76. A side coupled optical device as claimed in claim 75 wherein the source, coupling and/or application waveguide or waveguides comprise(s) - when viewed in a cross section perpendicular to their direction of light propagation – concentric areas of different geometrical and/or effective refractive indices.

77. A side coupled optical device as claimed in claim 75 or 76 comprising source, coupling and application waveguides that are multimode waveguides at the wavelength-range in question.

78. A side coupled optical device as claimed in any of claims 75 to 77 wherein an application waveguide comprises a cladding recess extending in the longitudinal

direction of said application waveguide and facing said output face of said at least one coupling waveguide.

79. A side coupled optical device as claimed in claim 78 wherein said application waveguide – when viewed in a cross section perpendicular to a longitudinal direction of the waveguide - has a D-shape over the longitudinal extent of said cladding recess, the essentially flat part of the D-shape being optically coupled to the output face of the coupling waveguide by means of butt coupling, fusion or an index matching material such as a glue, a gel or an oil.

80. A side coupled optical device as claimed in any of claims 75 to 79 wherein the application waveguide is a double-clad fibre.

81. A side coupled optical device as claimed in any of claims 76 to 80 wherein at least one of said concentric areas comprise(s) a background matrix material hosting micro-structured features in the form of micro-areas having a refractive index different from the refractive index of the background matrix material.

82. A side coupled optical device as claimed in claim 81 wherein the micro-structured application waveguide has an inner and an outer cladding separated by an air-clad comprising a circumferential distribution of longitudinally extending voids.

83. A side coupled optical device as claimed in claim 82 wherein at least a part of said longitudinally extending voids of said air-clad have been removed or collapsed over at least a part of the longitudinal extent of said cladding recess.

84. A side coupled optical device as claimed in claim 83 wherein said cladding recess creates a side window allowing coupling of light in and out of said inner cladding of said application fibre.

85. A side coupled optical device as claimed in any of claims 75 to 84 wherein the application part comprises one application fibre that is arranged to be side-pumped by the source and coupling waveguides at several distinct locations along its length.

86. A side coupled optical device as claimed in claims 85 wherein said application fibre is coiled onto a carrier cylinder.

87. A side coupled optical device as claimed in any of claims 75 to 86 wherein said application fibre comprises active ions and reflecting elements to form a fibre laser.

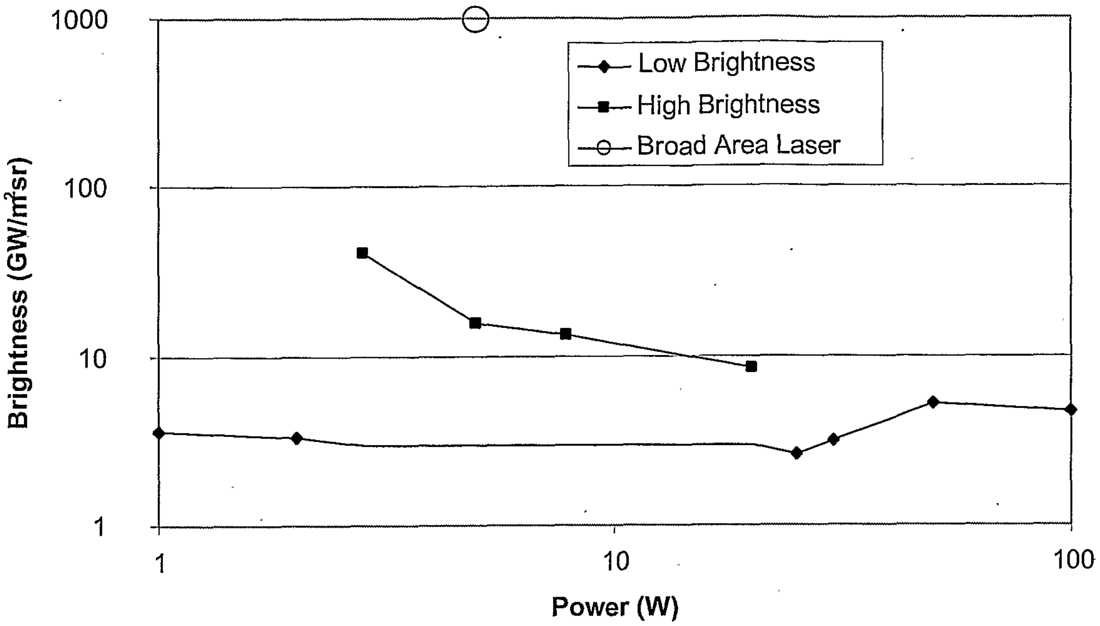

1000
100
10
1
Brightness (GW/m²sr)
Low Brightness
High Brightness
Broad Area Laser
1
10
100
Power (W)

Fig. 1.a

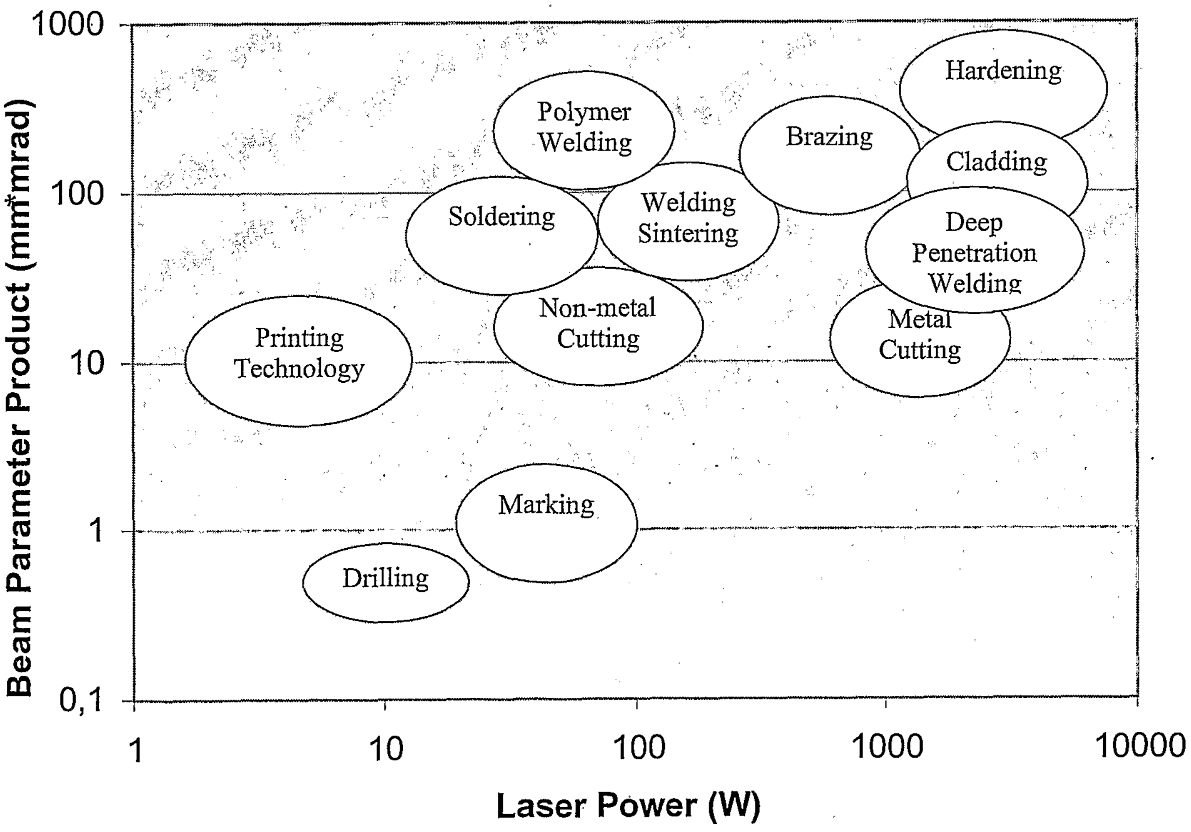

1000
100
10
1
0,1
Beam Parameter Product (mm*mrad)
Hardening
Polymer Welding
Brazing
Cladding
Soldering
Welding Sintering
Deep Penetration Welding
Non-metal Cutting
Metal Cutting
Printing Technology
Marking
Drilling
1
10
100
1000
10000
Laser Power (W)

Fig. 1.b

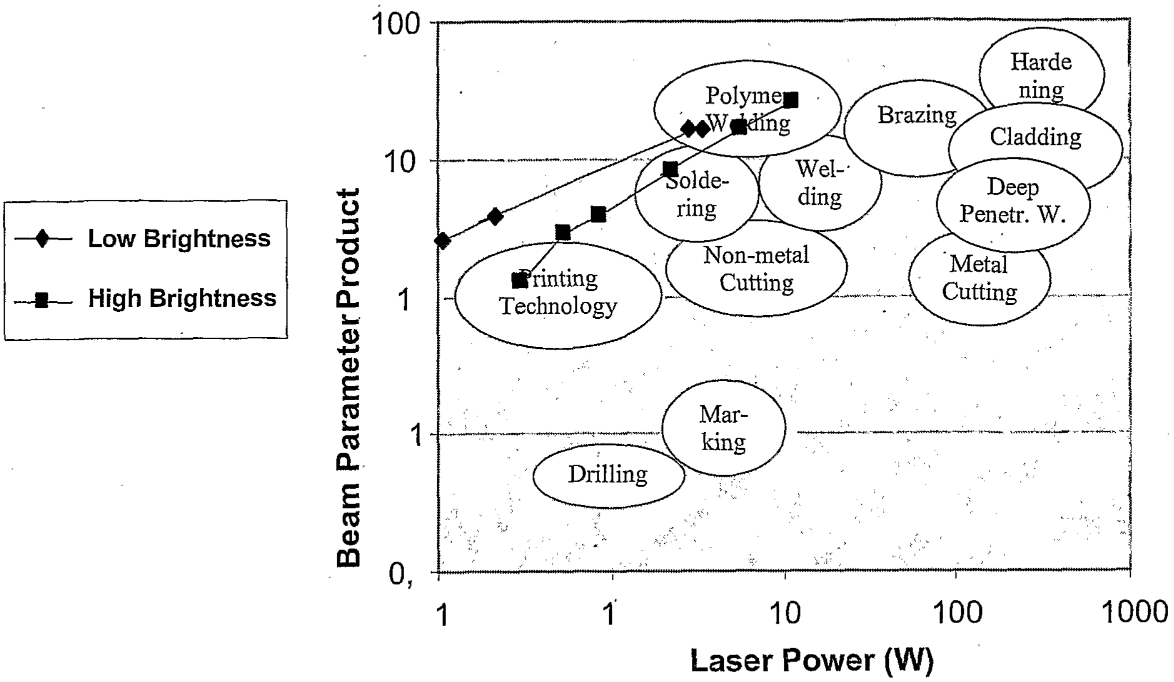

Low Brightness
High Brightness
100
10
1
1
0,
Beam Parameter Product
1
1
10
100
1000
Laser Power (W)
Polymer Welding
Brazing
Harde ning
Cladding
Deep Penetr. W.
Solde- ring
Wel- ding
Non-metal Cutting
Metal Cutting
Printing Technology
Mar- king
Drilling

Fig. 1.c

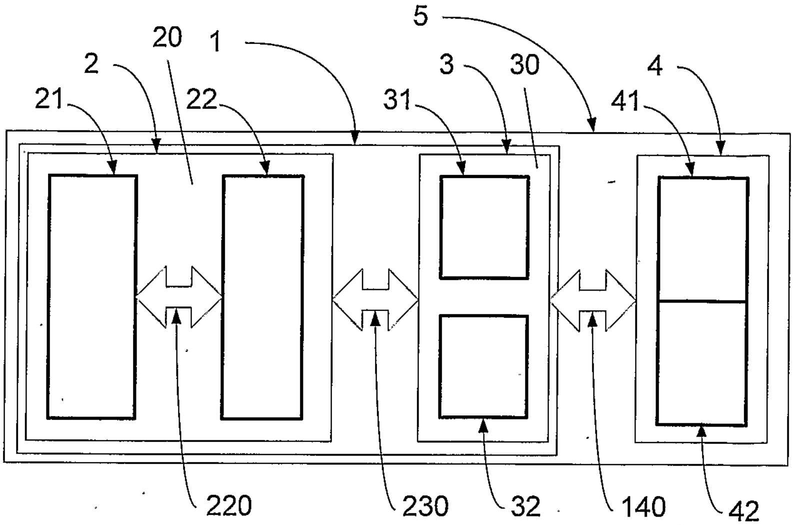


Fig. 2.a

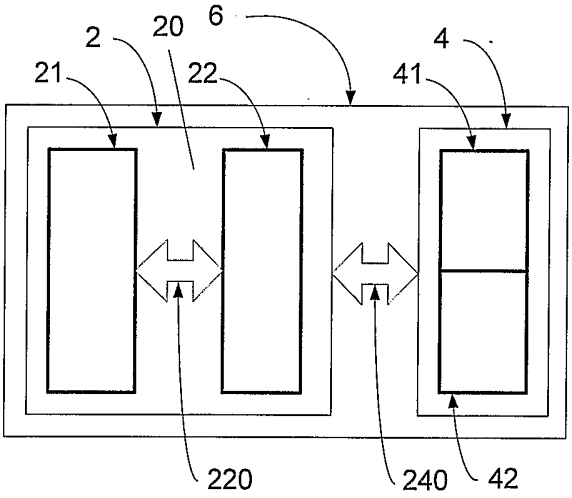


Fig. 2.b

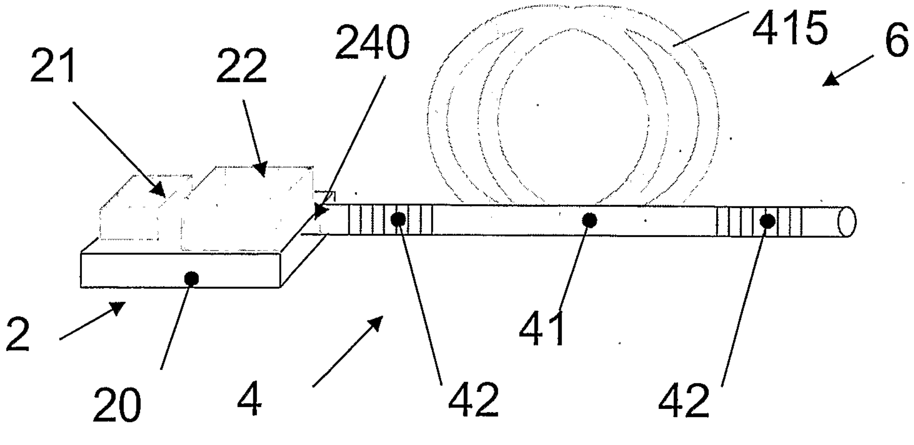


Fig. 2.c

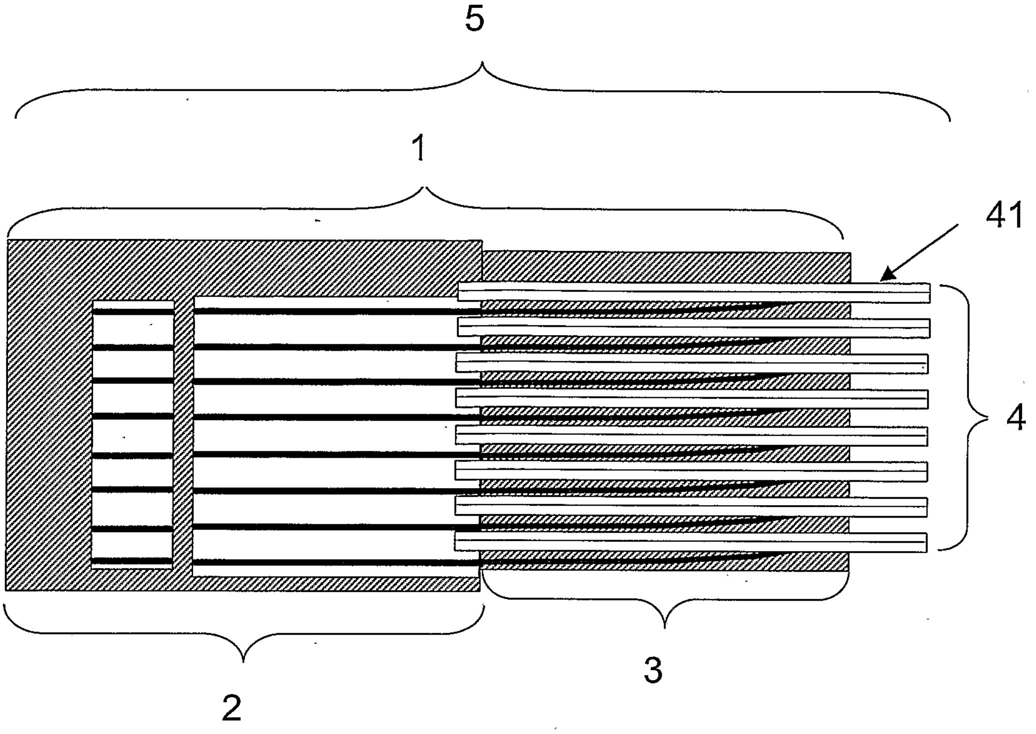


Fig. 2.d

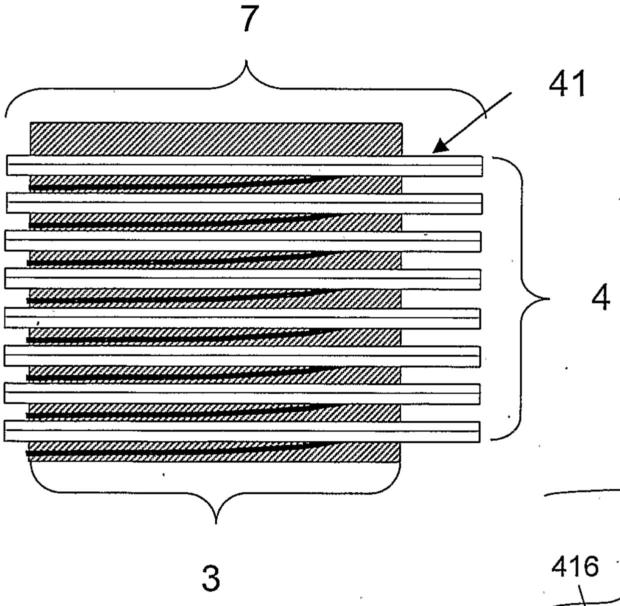


Fig. 2.e

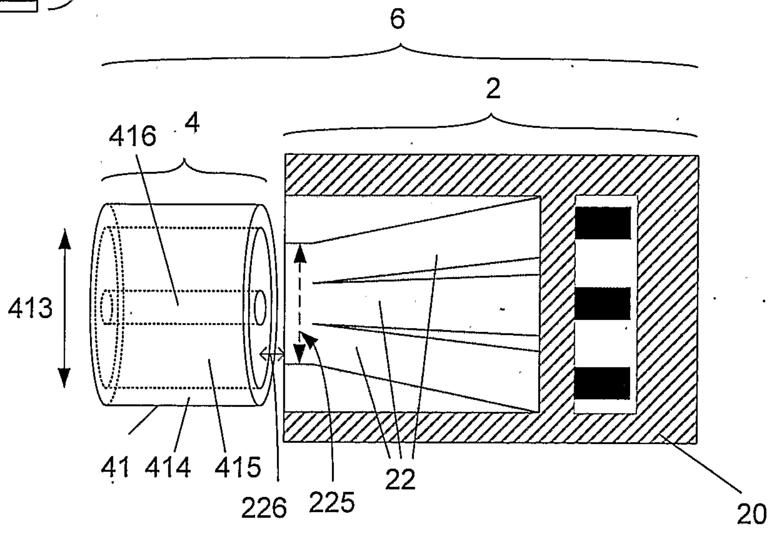


Fig. 2.f

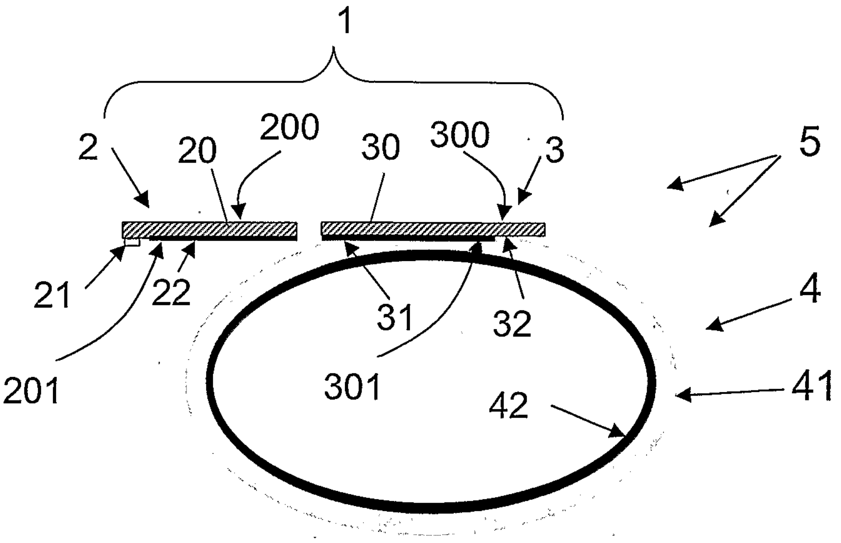


Fig. 3.a

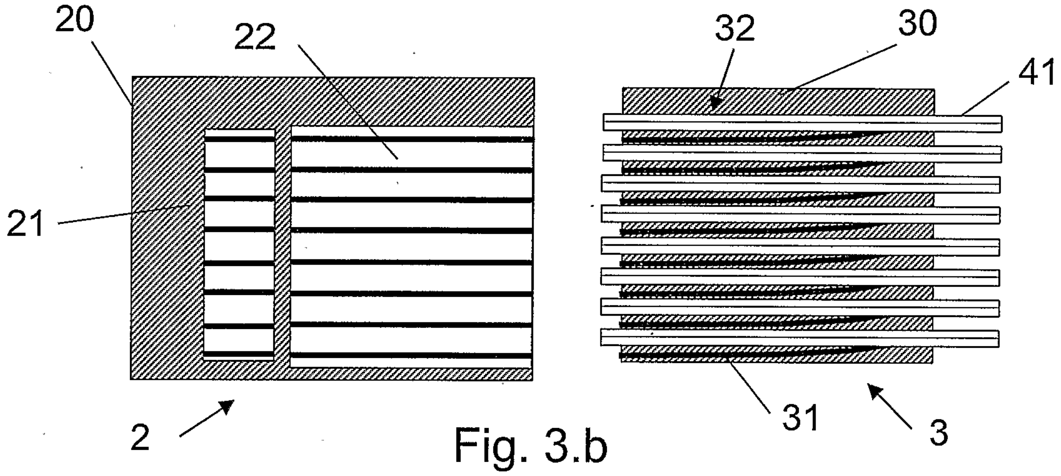


Fig. 3.b

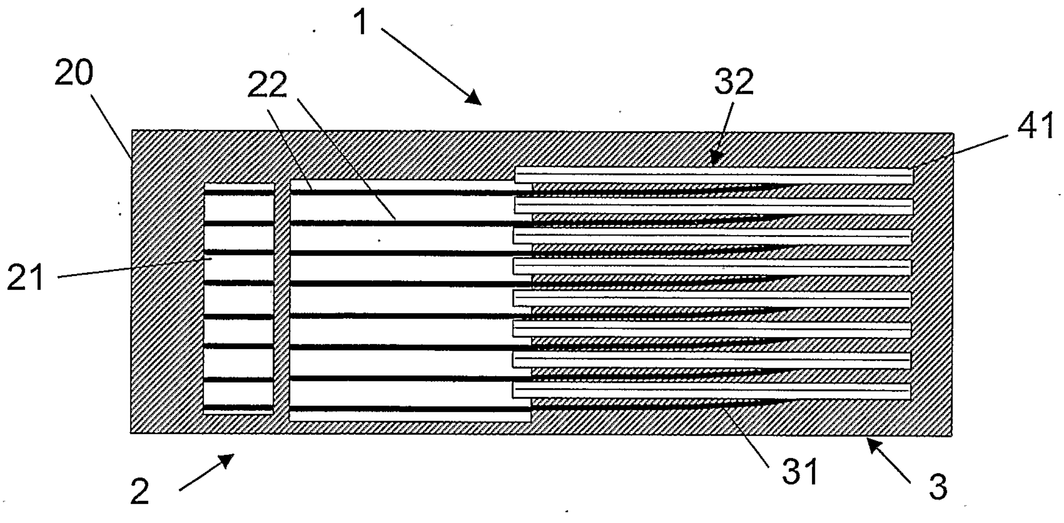


Fig. 3.c

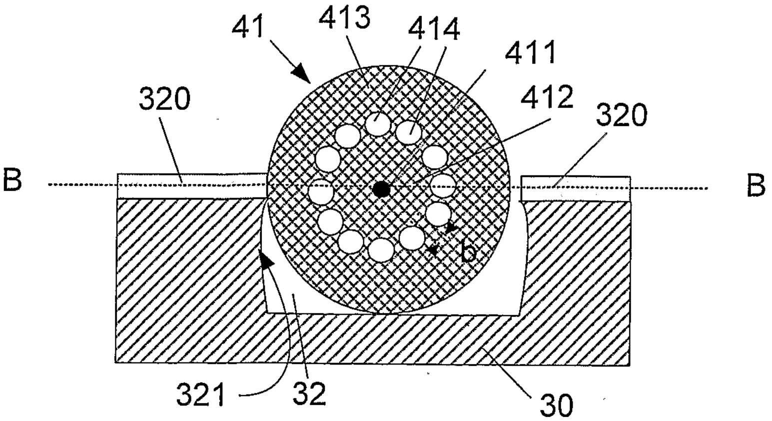


Fig. 4.a

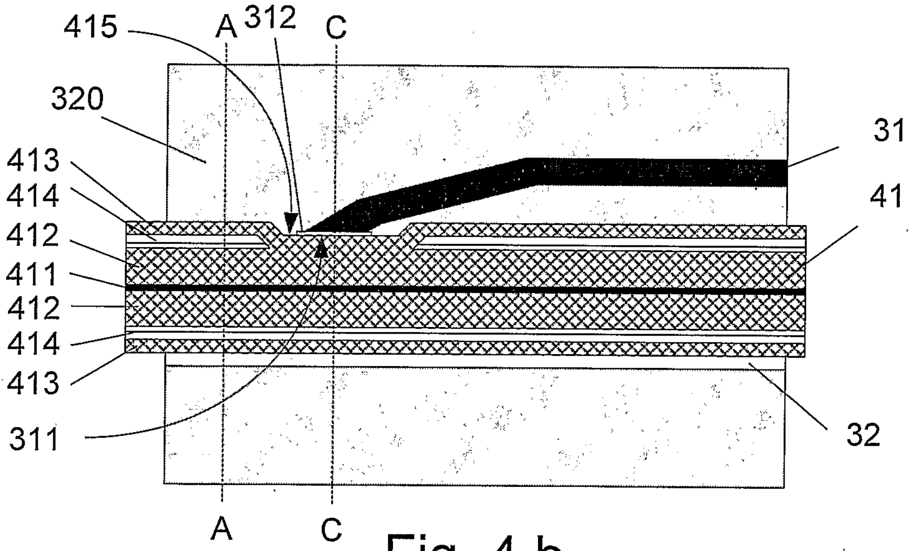


Fig. 4.b

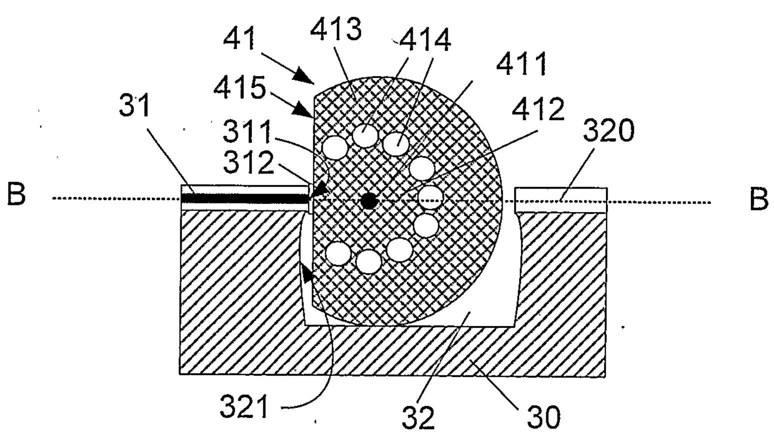


Fig. 4.c

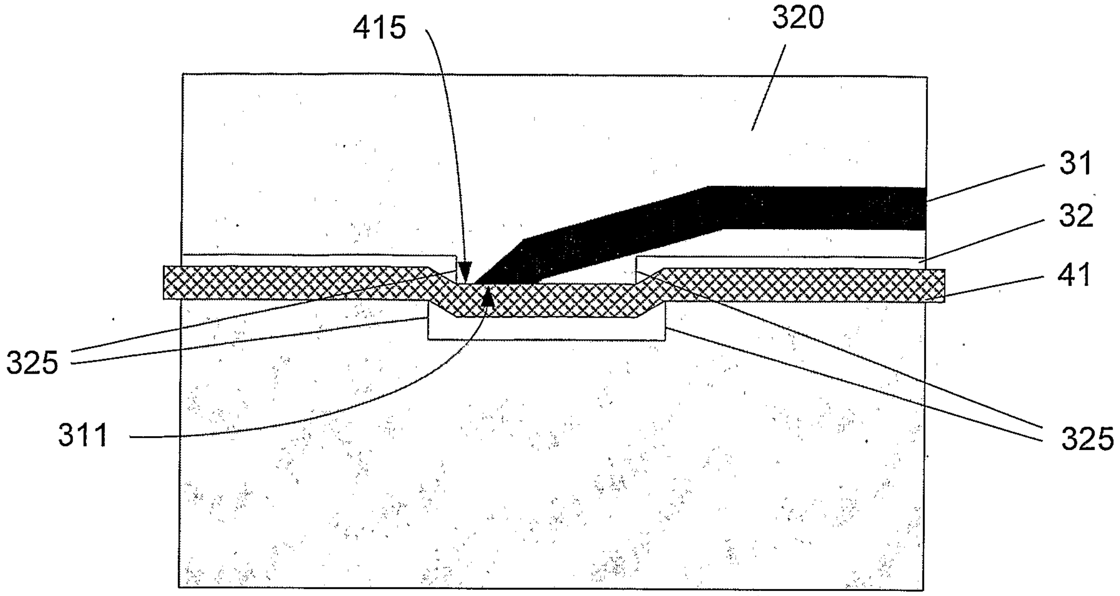
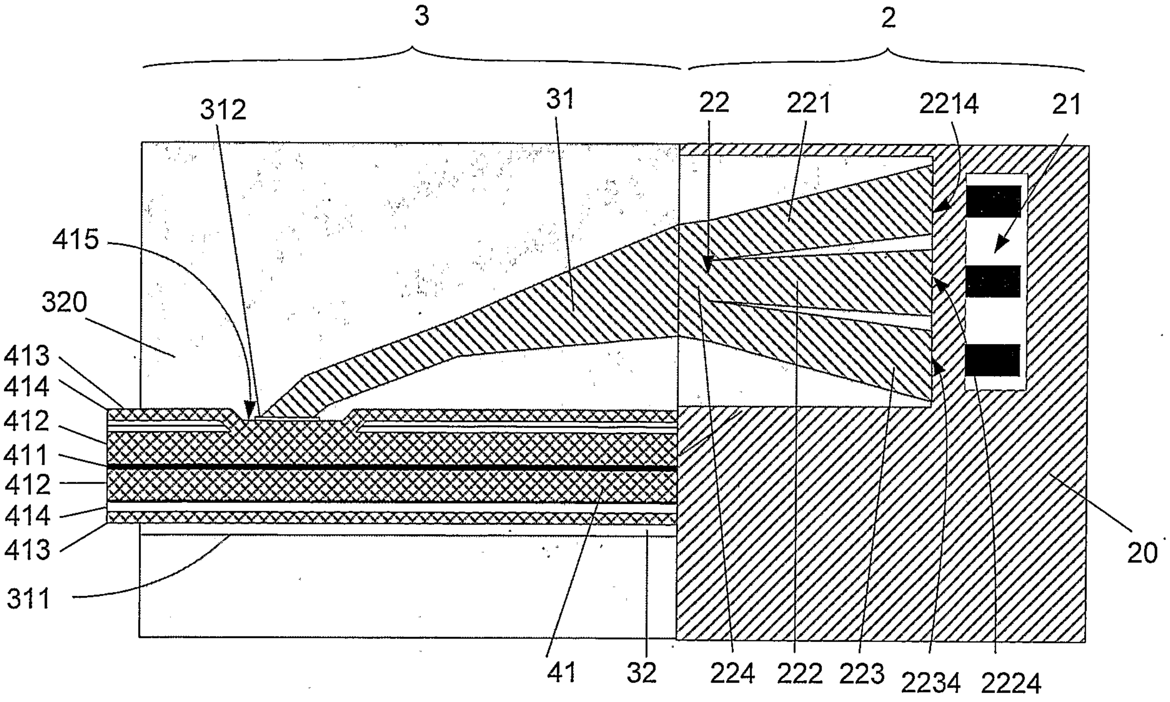

415
320
31
32
41
325
311
325

Fig. 4.d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2214
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32
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222
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2234
2224

Fig. 4.e

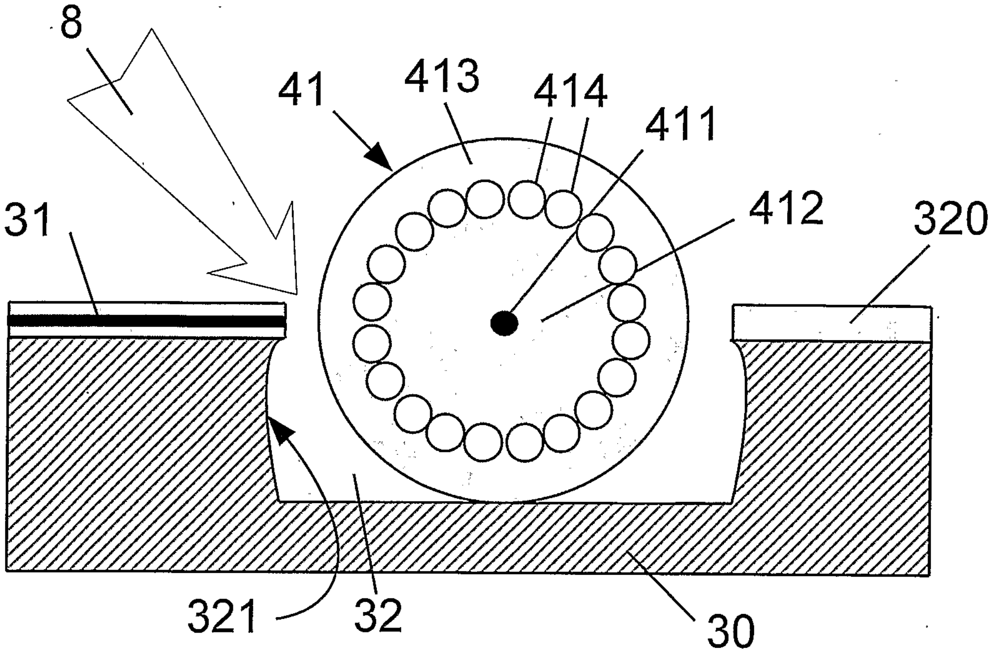
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Fig. 5.a

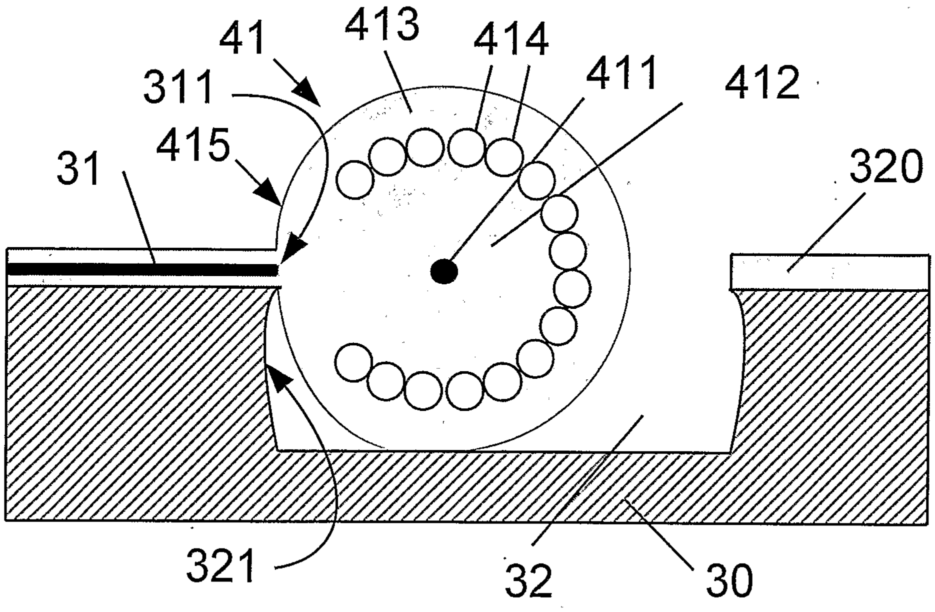
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Fig. 5.b

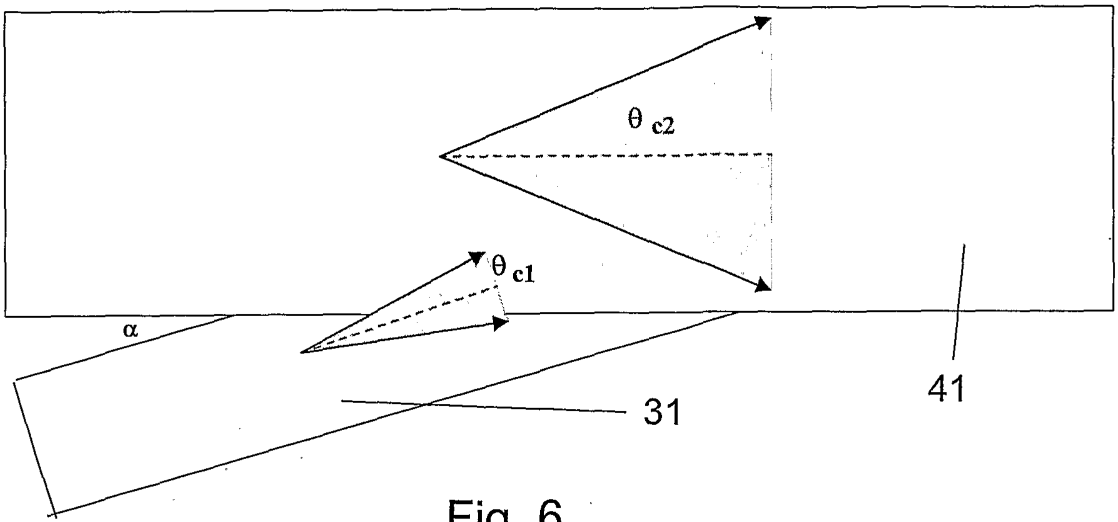


Fig. 6

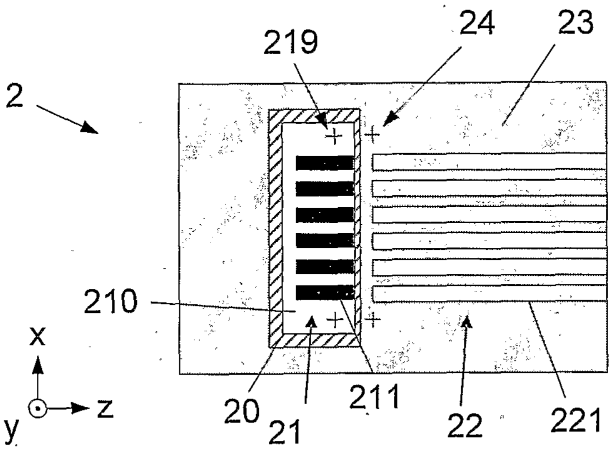


Fig. 7.a

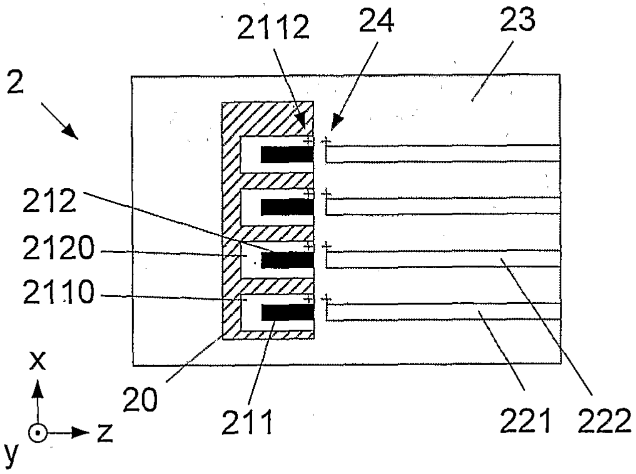


Fig. 7.b

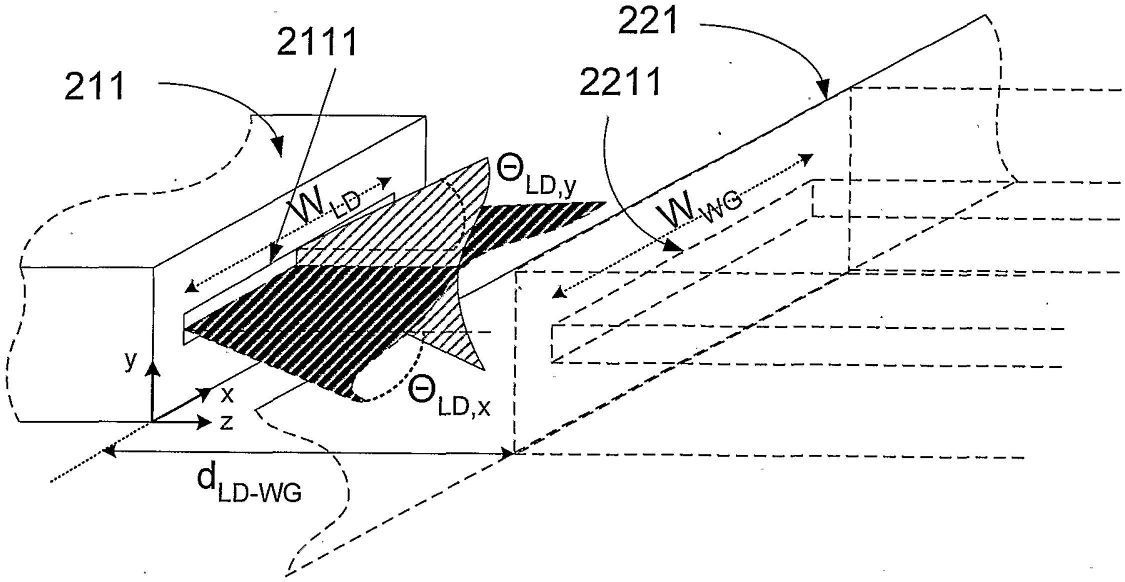

211
2111
221
2211
$W_{LD}$
$\Theta_{LD,y}$
$W_{WG}$
y
x
z
$\Theta_{LD,x}$
$d_{LD-WG}$

Fig. 8.a

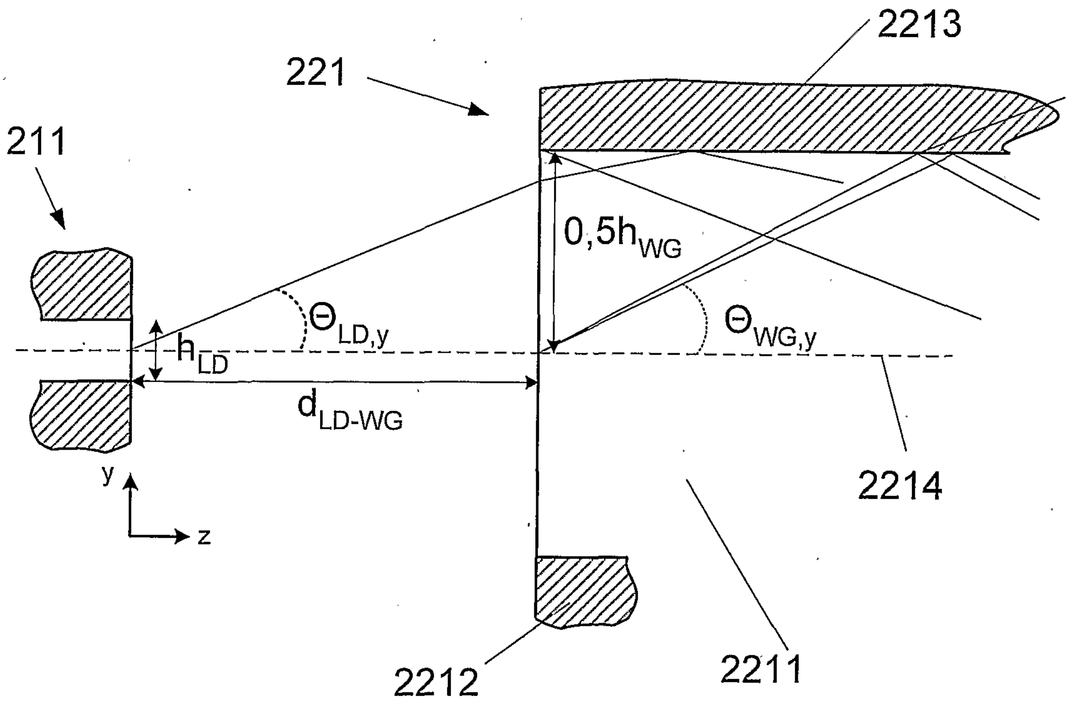

2213
221
211
$0,5h_{WG}$
$\Theta_{LD,y}$
$\Theta_{WG,y}$
$h_{LD}$
$d_{LD-WG}$
2214
y
z
2212
2211

Fig. 8.b

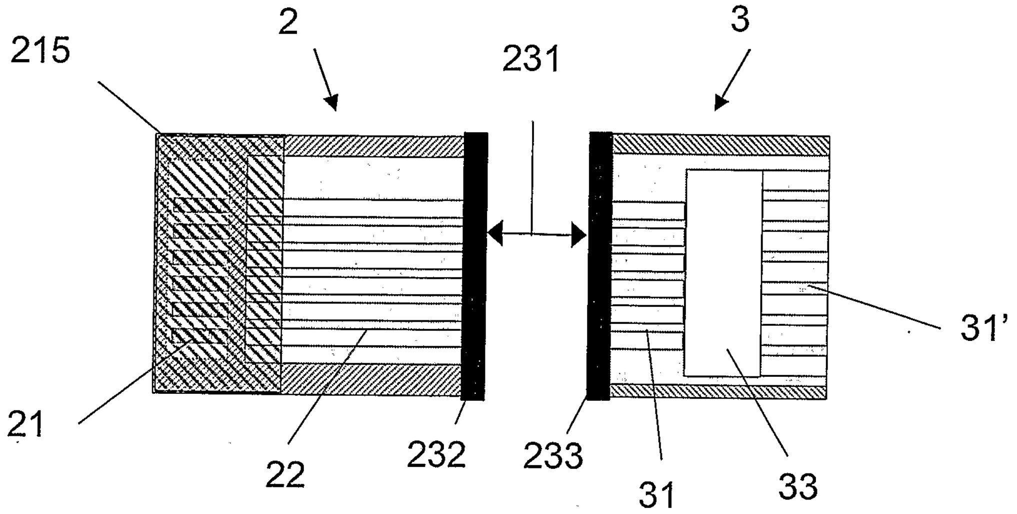


Fig. 9.a

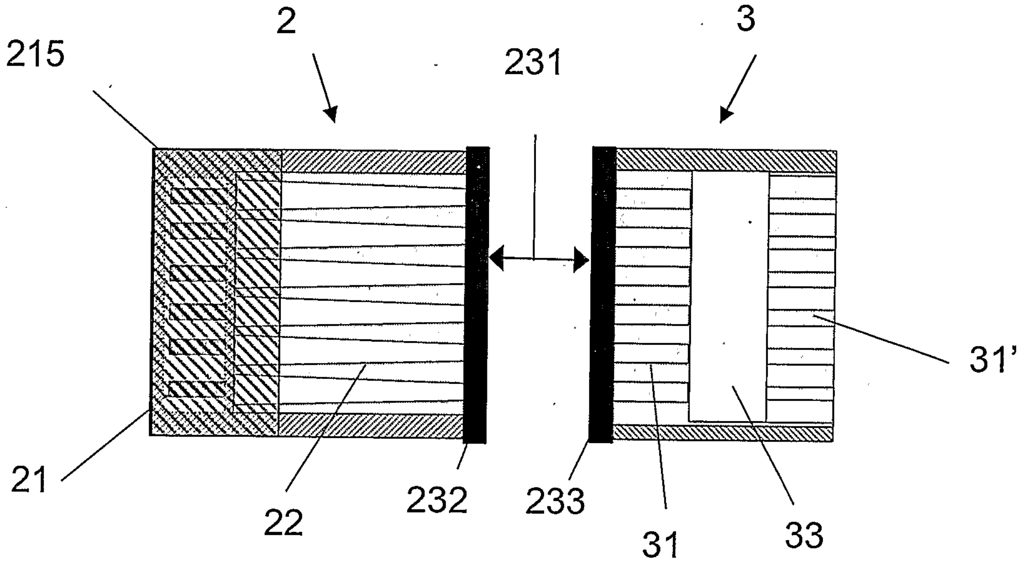


Fig. 9.b

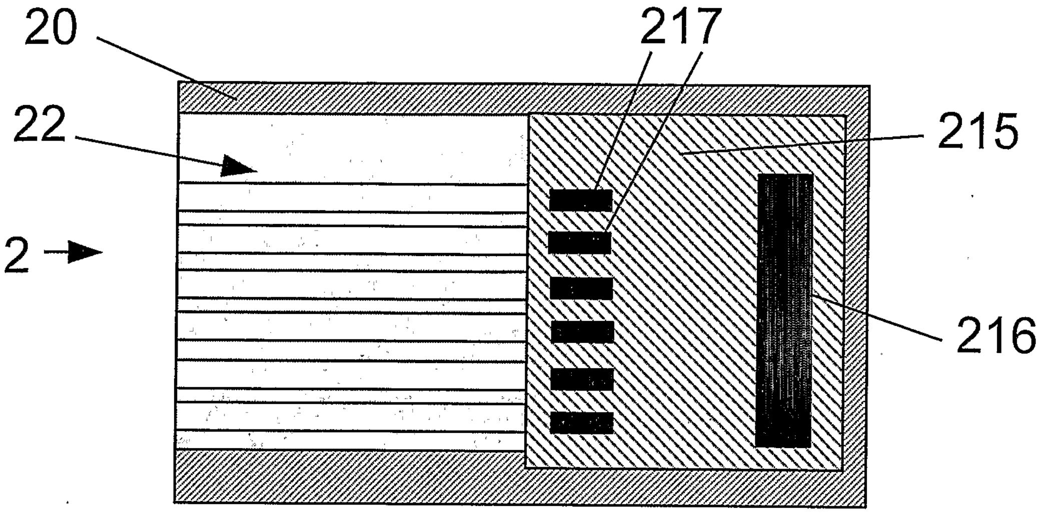


Fig. 10.a

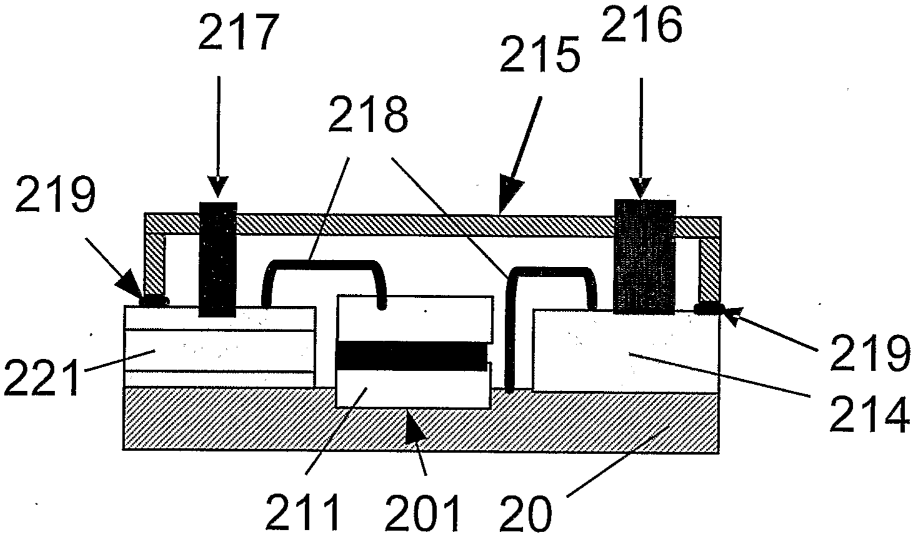


Fig. 10.b

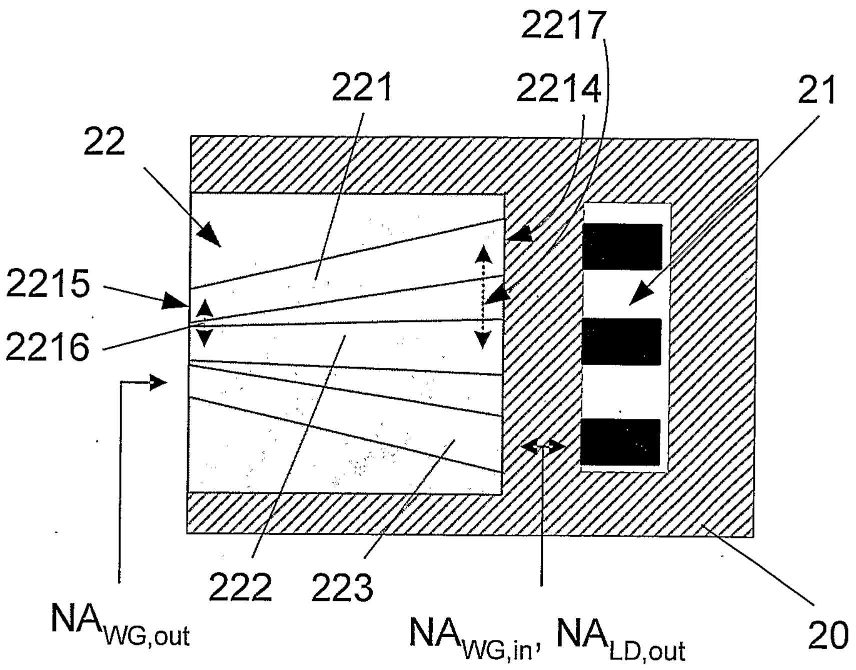


Fig. 11.a

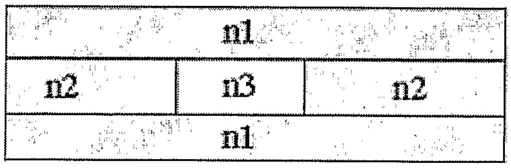


Fig. 11.b

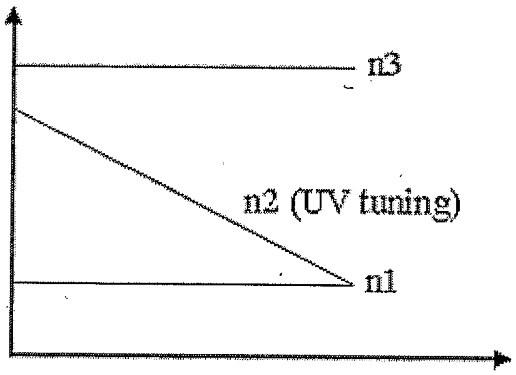


Fig. 11.c

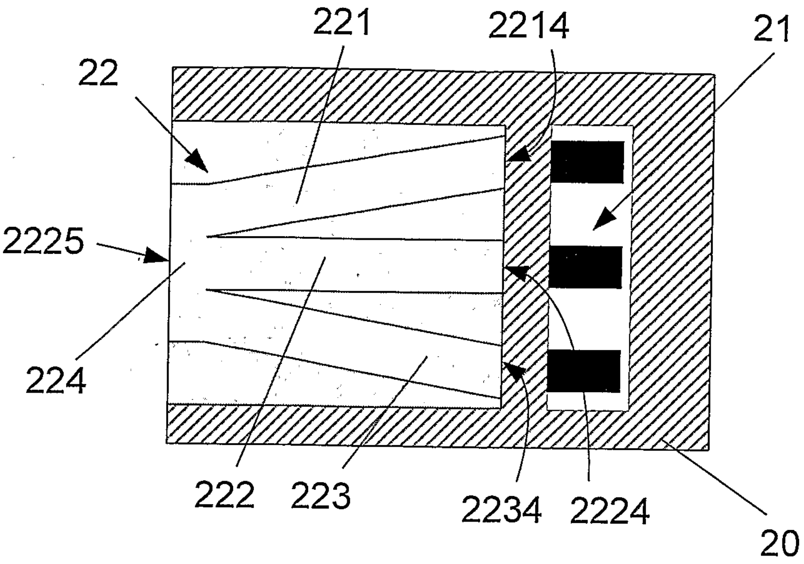


Fig. 12.a

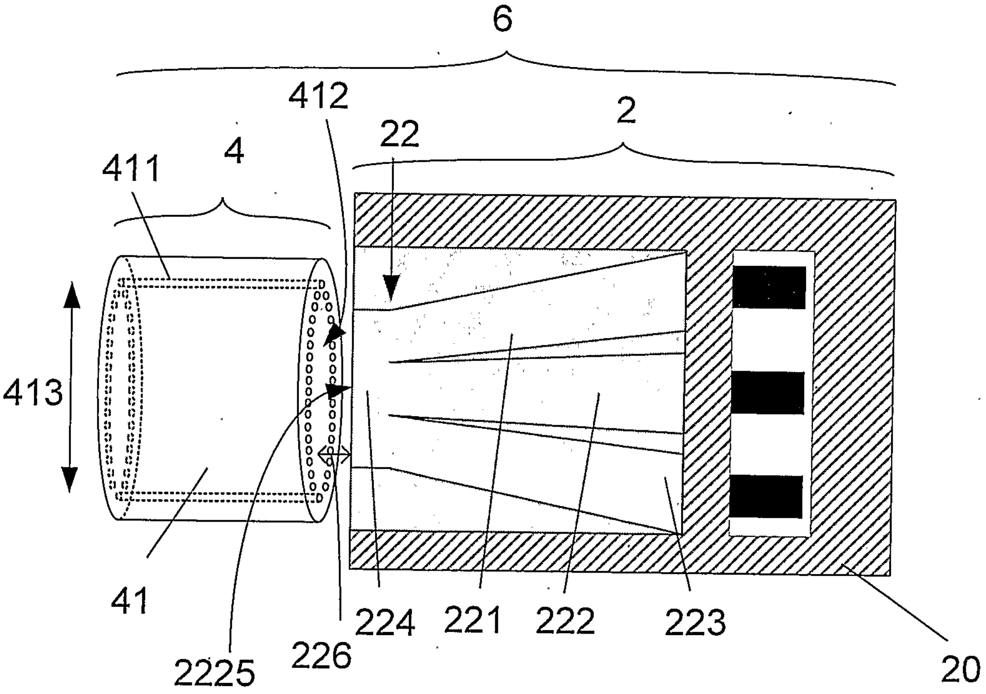
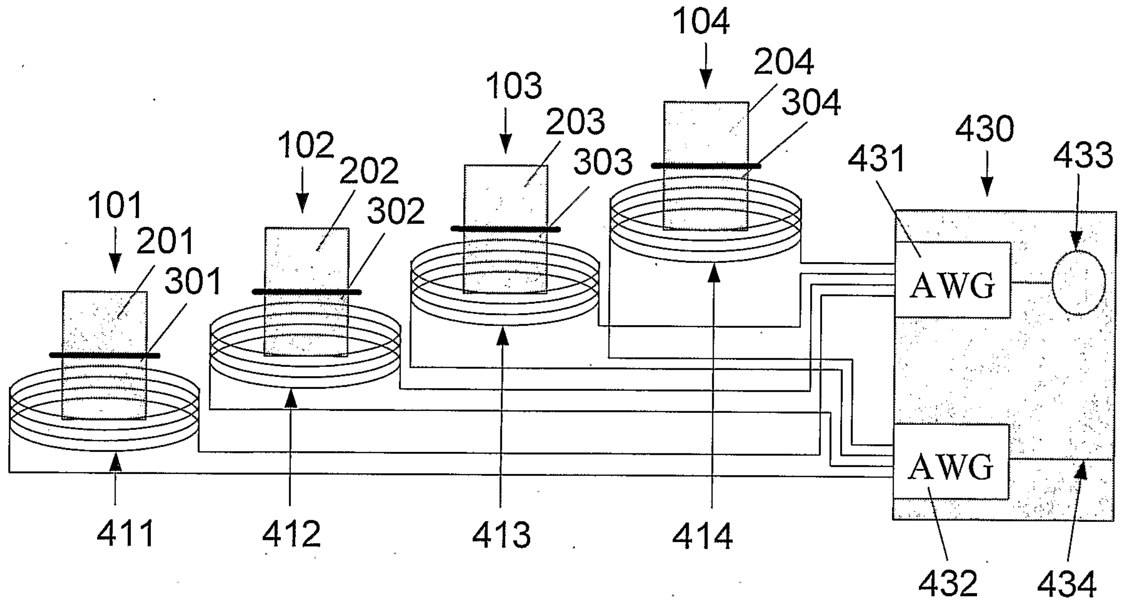


Fig. 12.b


104
204
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202
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431
101
201
301
AWG
AWG
411
412
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414
432
434

Fig. 13

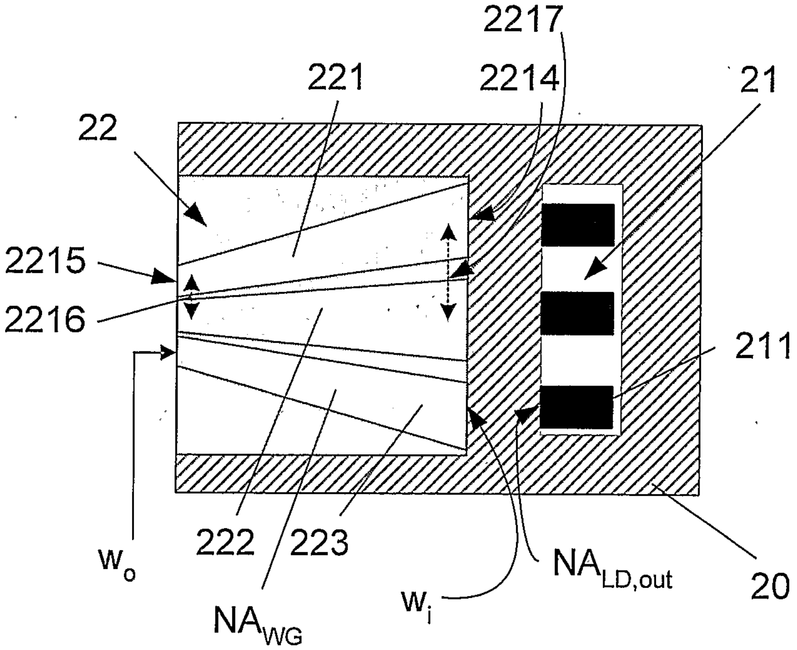
2217
221
2214
21
22
2215
2216
211
222
223
$w_o$
$NA_{WG}$
$w_i$
$NA_{LD,out}$
20

Fig. 14