

(19) World Intellectual Property
Organization
International Bureau



(43) International Publication Date
23 December 2004 (23.12.2004)

PCT

(10) International Publication Number
WO 2004/111694 A1

(51) International Patent Classification⁷: **G02B 6/12**, 6/30

(21) International Application Number:

PCT/IT2003/000368

(22) International Filing Date: 13 June 2003 (13.06.2003)

(25) Filing Language: English

(26) Publication Language: English

(71) Applicants (for all designated States except US):
PIRELLI & C. S.P.A. [IT/IT]; Via Gaetano Negri, 10,
I-20123 Milano (IT). **MASSACHUSETTS INSTITUTE
OF TECHNOLOGY** [US/US]; 77 Massachusetts Av-
enue, Cambridge, MA 02139 (US).

(72) Inventor; and

(75) Inventor/Applicant (for US only): **GORNI, Giacomo**
[IT/IT]; c/o Pirelli Labs S.p.A., 222, Viale Sarca, I-20126
Milano (IT).

(74) Agents: **BATTIPEDE, Francesco** et al.; Pirelli S.p.A.,
222, Viale Sarca, I-20126 Milano (IT).

(81) Designated States (national): AE, AG, AL, AM, AT, AU,
AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU,
CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH,
GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC,
LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW,
MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE,
SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ,
VC, VN, YU, ZA, ZM, ZW.

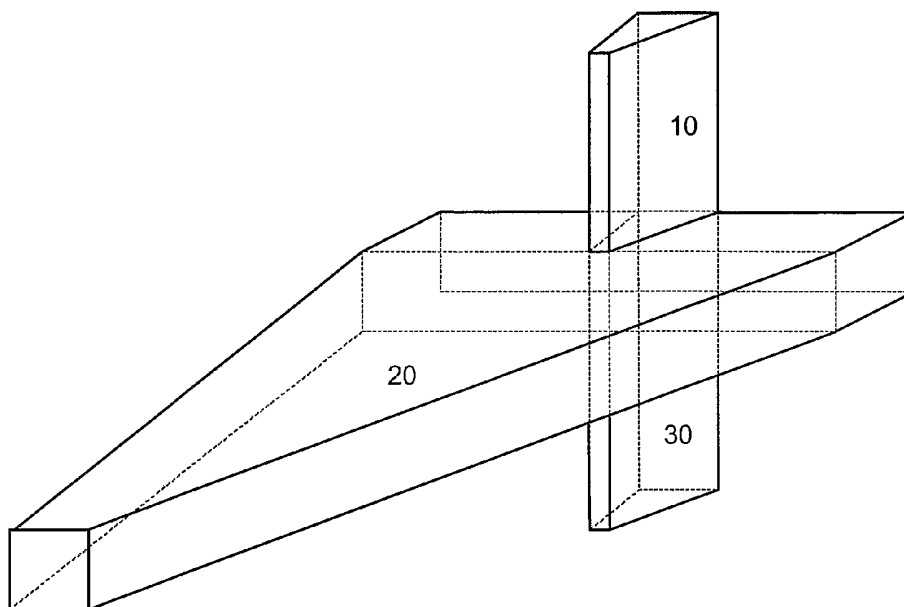
(84) Designated States (regional): ARIPO patent (GH, GM,
KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW),
Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),
European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE,
ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO,
SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM,
GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report

For two-letter codes and other abbreviations, refer to the "Guid-
ance Notes on Codes and Abbreviations" appearing at the begin-
ning of each regular issue of the PCT Gazette.

(54) Title: TAPERED MODE TRANSFORMER



(57) Abstract: A tapered mode transformer is formed from multiple horizontal tapers, without vertical tapering. The top and bottom layers surrounding a central layer have the same shape, providing symmetry that is well suited to mode transformation. The layers can be any type of horizontal taper. The central layer is much longer than the top and bottom layers. The input port of the central layer is for coupling to a fiber optic waveguide, and so the input port has a generally symmetric shape. In some embodiments, the input port has an asymmetric shape, as dictated by the incoming mode. The length of the central layer is sufficiently long to allow adiabatic transformation of the vertical mode. The device waveguide can be any shape, such as rectangular or cross-shaped, that is, having vertical and horizontal arms.

WO 2004/111694 A1

TAPERED MODE TRANSFORMER

BACKGROUND OF THE INVENTION

The present invention relates to coupling opto/optoelectronic devices to electronic devices, and more particularly, is directed to a coupling device that acts as a mode
5 transformer between a large mode optical fiber waveguide and a small mode on-chip waveguide.

The mode of an optical wave is the power distribution of its guided field. A single mode optical fiber has a circular mode with a core of about 5-10 μm diameter. An on-chip device waveguide for a high density circuit is typically rectangular with small cross-sectional
10 dimensions, ranging from about 6 μm to about 100 nm, depending on how high is the index contrast between the core and the cladding material. For single mode waveguides, an index contrast $\Delta n = 2$ corresponds to a width of 300 nm, while an index contrast $\Delta n = 0.004$ corresponds to a width of 8 μm . The rectangular cross section results in an elliptical mode. Thus, there is mode field mismatch between the optical fiber and the device, resulting in
15 decreased power transfer therebetween.

Various techniques exist for transforming the optical modes between the fiber and the device. One popular technique is a tapered mode transformer located on the device, sometimes referred to as a taper. The taper's input port is coupled to the optical fiber waveguide, and its output port couples with the device waveguide. The taper itself is long
20 relative to the cross-sectional dimensions of its ports to enable adiabatic (gradual) mode transformation.

Numerous configurations have been proposed for tapers. Moerman et al., "A Review on Fabrication Technologies for the Monolithic Integration of Tapers with III-V Semiconductor Devices," *IEEE J. Selected Topics in Quantum Electronics*, vol. 3, no. 6,
25 December 1997, pp 1308-1320, presents an overview of taper designs. In a lateral or

CONFIRMATION COPY

horizontal taper, the width of the guiding layer is changed along the device. In a vertical taper, the thickness of the guiding layer is changed along the device. In a combined taper, both the horizontal and vertical dimensions are changed. Moerman notes that many designs incorporate two waveguides. Horizontal tapers are easy to construct using standard
5 photolithography followed by wet or dry etching; sharp taper tips are defined by electron beam writing. Vertical tapers are difficult to construct; many complicated techniques have been proposed for constructing vertical tapers.

To improve mode transformation efficiency, most recent designs have involved vertical tapering of some form. However, these are difficult to manufacture.

10 Schwander et al., "Simple and Low-Loss Fibre-to-Chip Coupling by Integrated Field Matching Waveguide in InP", *Electronics Letters*, vol. 29, no. 4, 18 February 1993, pp 326-328, discloses a nested taper structure in InGaAsP/InP, using only horizontally tapered waveguides, that transforms the fundamental mode of an integrated waveguide to the mode profile of a single mode fiber. The incoming field has to be converted by two nested
15 waveguide tapers into the fundamental mode of a rib waveguide. Because most of the field conversion takes place at the inner waveguide tip, this region has to be designed very carefully.

Consequently, there is room for an improved taper that is easy to manufacture.

SUMMARY OF THE INVENTION

20 In accordance with an aspect of this invention, there is provided a tapered mode transformer for coupling an optical fiber waveguide with a device waveguide, comprising a horizontally tapered top layer, a horizontally tapered central layer, and a horizontally tapered bottom layer, wherein the length of the central layer is substantially longer than the length of the top and bottom layers.

The central layer generally has a first long portion devoid of top and bottom layers, and a second short portion where the width of the central layer is substantially fixed, and the top and bottom layer are introduced.

Applicant found that, by introducing top and bottom layers above and below the second portion of the central layer, but not above and below the first portion of the central layer, the incoming optical wave, i.e. the mode of the lightwave being guided at the input of the first portion of the central layer, can be substantially adiabatically transformed along the first portion of the central layer so that it corresponds, at the transition between the first and second portion, to the fundamental mode of second short portion of the central layer. This can limit the perturbation due to the effect of the top and bottom layers at the transition between the first and second portion of the central layer.

In some aspects, each of the top layer, central layer and bottom layer is devoid of vertical tapering, and the top and bottom layers have substantially the same shape. The nose width of the top and bottom layers is substantially less than the nose width of the central layer. Portions of the sides of the central layer follow an exponential curve.

When the device waveguide is cross-shaped with vertical and horizontal arms, the width of the back edge of the top and bottom layers is substantially equal to the height of the horizontal arms of the device waveguide.

When the device waveguide is rectangular, the width of the back edge of the top and bottom layers is substantially equal to the width of the device waveguide.

In accordance with another aspect of this invention, there is provided an optical arrangement including a device waveguide having a cross-shaped configuration with horizontal and vertical arms and a tapered mode transformer for coupling an optical fiber waveguide with the device waveguide. The tapered mode transformer has a tapered top layer for coupling to the top vertical arm of the device waveguide, a tapered central layer for

coupling to the horizontal arms of the device waveguide, and a tapered bottom layer for coupling to the bottom vertical arms of the device waveguide.

In some aspects, each of the layers is tapered horizontally and is devoid of vertical tapering. The length of the central layer is substantially longer than the length of the top and
5 bottom layers. The central layer consists of a first portion having a length that allows adiabatic transformation of an incoming optical wave, and a second portion having a length substantially equal to the length of the top and bottom layers. The top and bottom layers have substantially the same shape. The nose width of the central layer is approximately equal to the height of the central layer. The nose width of the top and bottom layers is substantially
10 less than the nose width of the central layer.

In accordance with still another aspect of this invention, there is provided an optical arrangement including a device waveguide having a rectangular configuration and a tapered mode transformer for coupling an optical fiber waveguide with the device waveguide. The tapered mode transformer comprises a tapered top layer, a tapered central layer, and a tapered
15 bottom layer. The length of the central layer is substantially longer than the length of the top and bottom layers.

In accordance with a further aspect of this invention, there is provided a method of constructing a tapered mode transformer for coupling an optical fiber waveguide with a device waveguide. First, a bottom layer is deposited using a deposition process, masking,
20 and etched to produce a bottom horizontal taper. Second, a central layer is deposited using a deposition process, masking, and etched to produce a central horizontal taper. Third, a top layer is deposited using a deposition process, masking, and etched to produce a top horizontal taper. The length of the central layer is substantially longer than the length of the top and bottom layers.

It is not intended that the invention be summarized here in its entirety. Rather, further features, aspects and advantages of the invention are set forth in or are apparent from the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

5 Figs. 1A and 1B are diagrams showing a side view cross-sections of layers of tapers according to the present invention;

Figs. 2A-2F are diagrams showing top down views of tapers according to the present invention;

10 Figs. 3A, 3B and 3E are three-dimensional diagrams showing the tapers of Figs. 2A, 2B and 2E, respectively;

Fig. 4 is a graph showing how the size of the nose in the embodiment of Fig. 2B was chosen;

Fig. 5 is a graph showing misalignment tolerances for an optical fiber coupling to the embodiment of Fig. 2B;

15 Fig. 6A is a graph showing mode transformation efficiency versus taper length for the long portion of the central taper of the embodiment of Fig. 2B when the nose width of the top and bottom tapers is 50 nm;

20 Fig. 6B is a graph showing mode transformation efficiency versus taper length for the long portion of the central taper of the embodiment of Fig. 2B when the nose width of the top and bottom tapers is 100 nm;

Fig. 6C is a graph showing mode transformation efficiency versus taper length for the long portion of the central taper of the embodiment of Fig. 2A when the nose width of the top and bottom tapers is 100 nm;

25 Fig. 7 is a graph showing, for various wavelengths, the coupling efficiency of the embodiment of Fig. 2B for the TE and TM modes;

Figs. 8A, 9A and 10A respectively show cross sections of the mode transformer of Fig. 2B at the nose of the central taper, just before the nose of the top and bottom tapers and at the back edge of the mode transformer;

Figs. 8M, 9M and 10M respectively show the TM mode at the cross-sections of Figs.

5 8A, 9A and 10A;

Figs. 8E, 9E and 10E respectively show the TE mode at the cross-sections of Figs. 8A, 9A and 10A;

Figs. 11A and 11B respectively show the side and bottom view of the TE mode propagating along the length of the central taper of the mode transformer of Fig. 2B; and

10 Figs. 12A and 12B are graphs showing mode transformation efficiency versus taper length for the long portion of the central taper of the embodiments of Fig. 2E and 2F, respectively, when the nose width of the top and bottom tapers is 100 nm.

DETAILED DESCRIPTION

A tapered mode transformer according to the present invention is formed from
15 multiple horizontal tapers, without vertical tapering. Accordingly, the taper is easy to manufacture. In some embodiments, top and bottom layers surrounding a central layer have the same shape, providing symmetry that is well suited to mode transformation.

Although an even number of layers can be used, an odd number is preferred for symmetry. Generally, as layers are more remote from the central layer, the length of the
20 layer decreases. For ease of fabrication, a smaller number of layers is better. The embodiments discussed herein are assumed to have three layers, for illustrative purposes and not for limiting purposes. Also, corresponding layers offset above and below the central layer are assumed to be symmetric, but this is not required. The layers can be any type of horizontal taper.

Generally, the central layer is much longer than the top and bottom layers. The input port of the central layer is for coupling to a fiber optic waveguide, and so the input port has a generally symmetric shape for polarization independence between the incoming transverse electric (TE) and transverse magnetic (TM) modes. In some embodiments, the input port has
5 an asymmetric shape, as dictated by the incoming mode.

The central layer generally has a first long portion devoid of top and bottom layers, and a second short portion where the width of the central layer is substantially fixed, and the top and bottom layer are introduced.

The top and bottom layers are introduced above and below the central layer after the
10 incoming optical wave, i.e. the mode of the lightwave being guided, has been substantially adiabatically transformed into the fundamental mode of second short portion of the central layer.

It is preferred that at least 70% of the mode be adiabatically transformed prior to introduction of the top and bottom layers, but more preferably at least 90% of the mode
15 should be transformed. The length of the central layer is sufficiently long to allow the substantially adiabatic transformation of the mode to occur.

The top and bottom taper layers serve to vertically guide the modes of the incoming optical wave without requiring complicated vertical taper manufacturing processes. The incoming port of the top and bottom tapers should be relatively narrow, to minimize abrupt
20 field perturbations. The length of the top and bottom tapers can be very short. The output port of the top and bottom tapers is for coupling to the device waveguide.

A cladding, or a plurality of cladding layers, is further provided around the tapered layers to provide light confinement.

The device waveguide can be any shape, such as rectangular or cross-shaped (with
25 vertical and horizontal arms). As described in co-pending U.S. patent application serial no.

60/422,413, filed October 30, 2002, the disclosure of which is hereby incorporated by reference, a cross-shaped device port is useful to split the vertical and horizontal polarization modes of the incoming optical wave. As used herein, rectangular includes substantially square.

5 Fig. 1A shows a side view cross-section of layers of a three-layer tapered mode transformer according to the present invention. Top taper 10 and bottom taper 30 are seen to have the same length. Central taper 20 is much longer than top taper 10 and bottom taper 30. The heights of the tapers are shown as being similar, but this is not required. In many embodiments, top taper 10 and bottom taper 30 have the same height, while central taper 20
10 has a different height.

Fig. 1B shows a side view cross-section of layers of a five-layer tapered mode transformer according to the present invention.

Figs. 2A-2F show top down views of six embodiments of a three-layer tapered mode transformer. Figs. 3A, 3B and 3E are three-dimensional diagrams for the first, second and
15 fifth embodiments. The top and bottom tapers in each of these embodiments are similar, and for brevity, only the top taper is discussed. The first through fourth embodiments are for coupling a circular optical fiber waveguide to a cross-shaped device waveguide. The fifth and sixth embodiments are for coupling a circular optical fiber waveguide to a rectangular device waveguide.

20 In the embodiment of Fig. 2A, central taper 20 has nose 20a and sides 20b along long portion 20L, and sides 20c and back edge 20d along short portion 20S. Top taper 10 has nose 10a, sides 10b and back edge 10c.

Nose 20a of central taper 20 serves as an input port to receive an optical wave from an optical fiber waveguide. The width w_2 of nose 20a is approximately equal to the height h_2 of
25 central taper 20 to minimize polarization dependent coupling. Long portion 20L extends

from nose 20a to where the width of taper 20 becomes constant; long portion 20L is basically triangular. Long portion 20L provides strong horizontal confinement of the modes of the incoming wave. Long portion 20L allows adiabatic transformation of an incoming optical wave. The length t_2 of the long portion of central taper 20 is much longer than the length L_1 of short portion 20S, such as ten times as long. Short portion 20S has a constant width and is basically rectangular. Vertical perturbation of the incoming wave occurs over the length L_1 of short portion 20S; in fact, the guided mode is mostly perturbed by the index step corresponding to the start of top taper 10 and bottom taper 30, but coupling to radiative modes and scattering losses are minimized due to the strong horizontal confinement provided at the wide end of long portion 20L. The total length L_2 of taper 20 is $(L_1 + t_2)$.

The width e_2 of back edge 20d is approximately equal to the width of the horizontal arms of a cross-shaped device waveguide (not shown).

Nose 10a of top taper 10 causes an abrupt vertical discontinuity in the waveguide, resulting in perturbation of the guided modes of central taper 20. Accordingly, the width w_1 of nose 20a is relatively narrow, preferably as small as can practically be manufactured.

The width e_1 of back edge 10c is approximately equal to the width of the vertical cross arm of the device waveguide. In some embodiments, the width of the vertical and horizontal arms of the cross-shaped device waveguide are approximately equal, so $e_1 \approx h_2$.

The tapered mode transformer of Fig. 2A is constructed by first, depositing a bottom layer using a deposition process, masking the bottom layer, and etching the masked bottom layer to produce a bottom horizontal taper; second, depositing a central layer using a deposition process, masking the central layer, and etching the masked central layer to produce a central horizontal taper; third, depositing a top layer using a deposition process, masking the top layer, and etching the masked top layer to produce a top horizontal taper. The masking steps can be effected for example by a photolithographic technique or,

preferably, by electron beam lithography, the latter allowing a better definition to be achieved, e.g., equal to or better than 50 nm. The construction does not involve vertical tapering of any of the layers.

The embodiment of Fig. 2B is similar to that of Fig. 2A, except sides 21b of central taper 21 have an exponential shape, to improve the adiabaticity of mode transformation. Sides 11a of top taper 11 also have an exponential shape, although they could be straight as depicted in Fig. 2A.

Fig. 4 is a simulation graph of butt-coupling power transmission efficiency relative to the width w2 of nose 21a of central taper 21 after butt-coupling the fiber to the input section of the embodiment shown in Fig. 2B. The solid line illustrates the TM mode while the dashed line illustrates the TE mode. The ordinate (vertical axis) of Fig. 4 shows power transmission, while the abscissa (horizontal axis) shows the width in nm of the nose of the central taper. Fig. 4 assumes the following:

index n_{clad_fiber} of the fiber cladding (not shown) = 1.445

index n_{core_fiber} of the fiber core (not shown) = 1.4493

fiber core diameter d (not shown) = 9 microns

heights h1 = h2 = h3 of tapers 11, 21, 31 (not shown) = 250 nm

width w1 of noses 11a, 31a of tapers 11, 31 = 50 nm

width e1 of back edges 11c, 31c of tapers 11, 31 = 250 nm

width w2 of nose 21a of central taper 21 = 200 nm

width e2 of back edge 21d of central taper 21 = 750 nm

length t2 of long portion of central taper 21 = 500 μ m

length L1 of short portion of central taper 21 = 50 μ m

index n_{clad} of cladding (not shown) surrounding tapers 11, 21, 31 = 1.445

index n_{core} of tapers 11, 21, 31 = 2.2

Fig. 4 shows that selecting a width w_2 for nose 21a of 200 nm provides a tolerance of ± 20 nm for staying on the maximum part of the TE and TM curves. The butt-coupling efficiency at nose 21a is seen to be about 96% or -0.17 dB. Moreover, the Polarization Dependent Loss (PDL) is minimum for a width w_2 of around 200 nm, and remains low with w_2 in a range of at least ± 20 nm around the minimum.

Fig. 5 is a simulation graph showing misalignment tolerances for an optical fiber coupling to the tapered mode transformer of Fig. 2B, assuming parameters as set forth above. The solid line illustrates the TE mode while the dashed line illustrates the TM mode. The ordinate (vertical axis) of Fig. 5 shows butt-coupling power transmission efficiency, while the abscissa (horizontal axis) shows the offset between the fiber and the tapered mode transformer in microns. Fig. 5 shows that nose 21a has good tolerance to a misalignment between the optical fiber and the taper axis. Additional loss of about 0.88 dB can be expected for a $2 \mu\text{m}$ offset.

Fig. 6A is a simulation graph showing mode transformation efficiency (or conversion efficiency) versus taper length for the long portion of central taper 21 when the nose width of top taper 11 and bottom taper 31 is 50 nm. The solid line illustrates the TE mode while the dashed line illustrates the TM mode. The dash-dot lines indicate radiative modes. The ordinate (vertical axis) of Fig. 6A shows power transmission, while the abscissa (horizontal axis) shows the length in μm of the long section of the central taper. If the length t_2 is under $500 \mu\text{m}$, the guided mode is strongly perturbed by the index step corresponding to the start of top taper 11 and bottom taper 31, resulting in coupling to the radiative modes instead of the guided mode, which is particularly damaging for the vertically polarized TM mode. If the length t_2 is at least $500 \mu\text{m}$, this damaging behavior does not occur.

Fig. 6B is similar to Fig. 6A, except the nose width of top taper 11 and bottom taper 31 is 100 nm.

Fig. 6C is similar to Fig. 6B, except is for the embodiment of Fig. 2A.

Fig. 7 is a graph showing, over a wavelength range of 100 nm, the coupling efficiency of tapered mode transformer of Fig. 2B. The ordinate (vertical axis) of Fig. 7 shows power transmission, while the abscissa (horizontal axis) shows the wavelength in nm of the incoming light wave. The solid line illustrates the TE mode, while the dashed line illustrates the TM mode. The device is seen to be almost independent of the wavelength. The very flat bandwidth response is a consequence of the geometrical and non-interferometric behavior of the coupling device.

Figs. 8A, 9A and 10A respectively show cross sections of the mode transformer of Fig. 2B at the nose of the central taper, just before the nose of the top and bottom tapers and at the back edge of the mode transformer. Figs. 8M, 9M and 10M respectively show the TM mode at the cross-sections of Figs. 8A, 9A and 10A. Figs. 8E, 9E and 10E respectively show the TE mode at the cross-sections of Figs. 8A, 9A and 10A. The ordinates (vertical axes) of Figs. 8M, 9M, 10M, 8E, 9E and 10E show the width in microns, while the abscissas (horizontal axes) show the height in microns. The length of each axis in Figs. 8M and 8E is 10 microns. The length of each axis in Figs. 9M, 9E, 10M and 10E is 2.5 microns. The TE and TM modes are shown as equal power level lines according a dB scale. At nose 21a, the TE and TM modes are very similar with large spots and quasi-circular shapes. At just before nose 11a, the TE guided mode is smaller, more elliptical and more confined than the TM guided mode. At the cross-shaped back edge of the tapered mode transformer of Fig. 2B, the TE and TM modes are again similar. The mode transformer of Fig. 2B is seen to guide the TM and TE modes along its entire length. The TE mode is more sensitive to horizontal variations in the structure of the mode transformer, while the TM mode is more sensitive to vertical variations in the structure of the mode transformer.

Figs. 11A and 11B respectively show the side and bottom view of the TE mode propagating along the length of the central taper of the mode transformer of Fig. 2B. The ordinates (vertical axes) of Fig. 11A and 11B respectively show the height and width of the tapered mode transformer, while the abscissas (horizontal axes) show the length of the device. In each of Figs. 11A and 11B, the length of the ordinate is about 10 microns and the length of the abscissa is about 500 microns.

Tables 1 and 2 compare tapered mode transformer performance for the embodiment of Fig. 2B when the width w_1 of noses 11a, 31a is 50 nm and 100 nm. A larger nose width w_1 gives stronger perturbation of the vertical TM mode, resulting in slightly higher losses.

Table 3 indicates tapered mode transformer performance for the embodiment of Fig. 2B when the width w_1 of noses 11a, 31a is 250 nm. A nose as large as the back edge, i.e., no tapering for the top and bottom layer 11, 31 results in higher losses, particularly for vertical TM mode, and in a higher Polarization Dependent Loss.

TABLE 1

$w_1 = 50$ nm	Butt-coupling loss	Conversion efficiency	Total/facet
T_{TE}	-0.20 dB	-0.01 dB	-0.21 dB
T_{TM}	-0.17 dB	-0.11 dB	-0.28 dB
Polarization Dependent Loss (PDL)	+0.03 dB	-0.10 dB	-0.07 dB

TABLE 2

w1 = 100 nm	Butt-coupling loss	Conversion efficiency	Total/facet
T _{TE}	-0.20 dB	-0.01 dB	-0.21 dB
T _{TM}	-0.17 dB	-0.40 dB	-0.57 dB
Polarization Dependent Loss (PDL)	+0.03 dB	-0.39 dB	-0.36 dB

5

TABLE 3

w1 = 250 nm	Butt-coupling loss	Conversion efficiency	Total/facet
T _{TE}	-0.20 dB	-0.06 dB	-0.26 dB
T _{TM}	-0.17 dB	-0.89 dB	-1.06 dB
Polarization Dependent Loss (PDL)	+0.03 dB	-0.83 dB	-0.80 dB

The embodiment of Fig. 2C is also similar to that of Fig. 2A, except that top taper 12 has a long portion with sides 12d and a short portion with sides 12e, similar to central taper

10 22.

In the embodiment of Fig. 2D, top taper 13 is similar to top taper 10. However, nose 23a of central taper 23 is wider than back edge 23d of central taper 23. Sides 23b of central taper 23 have an exponential shape. In other embodiments, sides 23b have a linear or other advantageous shape.

15

The embodiment of Fig. 2E is similar to that of Fig. 2A, except that back edge 14c of top taper 14 has the same width as back edge 24d of central taper 24. This configuration is useful when the device waveguide (not shown) is rectangular, such as when the sum of the

heights of the top, central and bottom tapers is approximately equal to the width of the back edges of the tapers, minimizing polarization effects.

Fig. 12A is a simulation graph showing mode transformation efficiency versus taper length for the long portion of the central taper of the embodiments of Fig. 2E when the nose
5 width of the top and bottom tapers is 100 nm.

The embodiment of Fig. 2F is similar to that of Fig. 2E, except that the sides of taper layers 15, 25, 35 (not shown) follow an exponential curve.

Fig. 12B is similar to Fig. 12A, except is for the embodiment of Fig. 2F.

Although illustrative embodiments of the present invention, and various
10 modifications thereof, have been described in detail herein with reference to the accompanying drawings, it is to be understood that the invention is not limited to these precise embodiments and the described modifications, and that various changes and further modifications may be effected therein by one skilled in the art without departing from the scope or spirit of the invention as defined in the appended claims.

What is claimed is:

1. A tapered mode transformer for coupling an optical fiber waveguide with a device waveguide, comprising:

a horizontally tapered top layer,

a horizontally tapered central layer, and

a horizontally tapered bottom layer,

wherein the length of the central layer is substantially longer than the length of the top and bottom layers.

2. The tapered mode transformer of claim 1, wherein each of the top layer, central layer and bottom layer is devoid of vertical tapering.

3. The tapered mode transformer of claim 1, wherein the length of the central layer is sufficient to allow substantially adiabatic transformation of an incoming wave to occur.

4. The tapered mode transformer of claim 3, wherein the central layer consists of a first portion and a second portion having a length substantially equal to the length of the top and bottom layers, the first portion having a length that allows substantially adiabatic transformation of an incoming optical wave into a fundamental mode of the second portion of the central layer.

5. The tapered mode transformer of claim 1, wherein the top and bottom layers have substantially the same shape.

6. The tapered mode transformer of claim 1, wherein the nose width of the central layer is approximately equal to the height of the central layer.

7. The tapered mode transformer of claim 1, wherein the nose width of the top and bottom layers is substantially less than the nose width of the central layer.

8. The tapered mode transformer of claim 1, wherein the device waveguide is cross-

shaped with vertical and horizontal arms, and the width of the back edge of the top and bottom layers is substantially equal to the height of the horizontal arms of the device waveguide.

9. The tapered mode transformer of claim 1, wherein the device waveguide is rectangular, and the width of the back edge of the top and bottom layers is substantially equal to the width of the device waveguide.

10. The tapered mode transformer of claim 1, wherein the tapering of the central layer is linear.

11. The tapered mode transformer of claim 1, wherein at least portions of the sides of the central layer follow an exponential curve.

12. An optical arrangement including a device waveguide having a cross-shaped configuration with horizontal and vertical arms and a tapered mode transformer for coupling an optical fiber waveguide with the device waveguide, the tapered mode transformer comprising:

a tapered top layer for coupling to the top vertical arm of the device waveguide,
a tapered central layer for coupling to the horizontal arms of the device waveguide, and
a tapered bottom layer for coupling to the bottom vertical arms of the device waveguide.

13. The tapered mode transformer of claim 12, wherein each of the layers is tapered horizontally and is devoid of vertical tapering.

14. The tapered mode transformer of claim 12, wherein the length of the central layer is substantially longer than the length of the top and bottom layers.

15. The tapered mode transformer of claim 14, wherein the central layer consists of a first portion and a second portion having a length substantially equal to the length of the top and bottom layers, the first portion having a length that allows substantially adiabatic transformation of an incoming optical wave into a fundamental mode of the second portion of the central layer.

16. The tapered mode transformer of claim 12, wherein the top and bottom layers have substantially the same shape.

17. The tapered mode transformer of claim 12, wherein the nose width of the central layer is approximately equal to the height of the central layer.

18. The tapered mode transformer of claim 12, wherein the nose width of the top and bottom layers is substantially less than the nose width of the central layer.

19. The tapered mode transformer of claim 12, wherein the tapering of the central layer is linear.

20. The tapered mode transformer of claim 12, wherein at least portions of the sides of the central layer follow an exponential curve.

21. An optical arrangement including a device waveguide having a rectangular configuration and a tapered mode transformer for coupling an optical fiber waveguide with the device waveguide, the tapered mode transformer comprising:

a tapered top layer,

a tapered central layer, and

a tapered bottom layer,

wherein the length of the central layer is substantially longer than the length of the top and bottom layers.

22. A method of constructing a tapered mode transformer for coupling an optical fiber waveguide with a device waveguide, comprising:

first, depositing a bottom layer using a deposition process,

masking the bottom layer,

etching the masked bottom layer to produce a bottom horizontal taper,

second, depositing a central layer using a deposition process,
masking the central layer,
etching the masked central layer to produce a central horizontal taper,
third, depositing a top layer using a deposition process,
masking the top layer, and
etching the masked top layer to produce a top horizontal taper,
wherein the length of the central layer is substantially longer than the length of the top and
bottom layers.

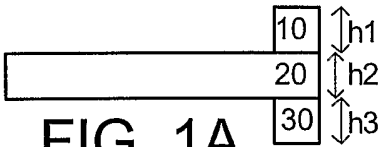


FIG. 1A

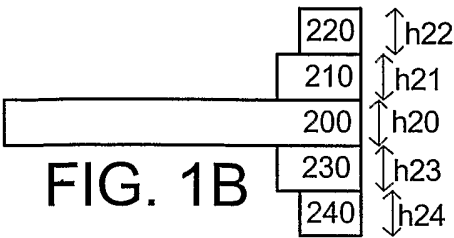


FIG. 1B

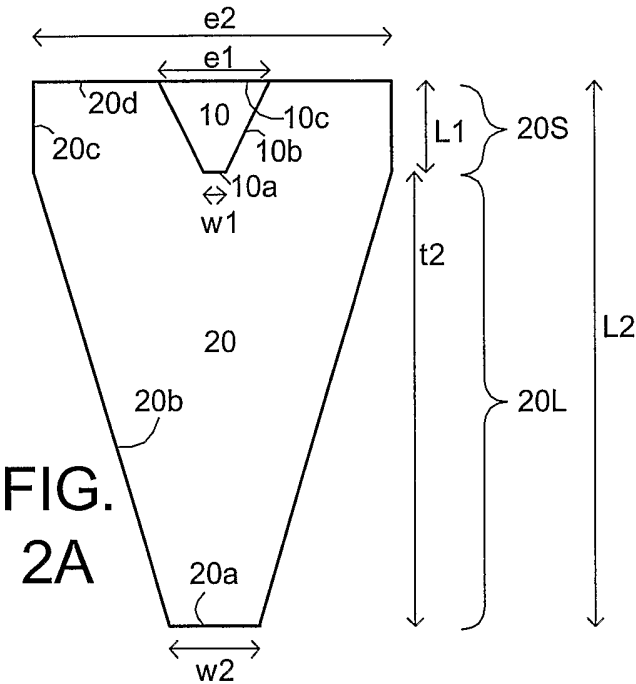


FIG. 2A

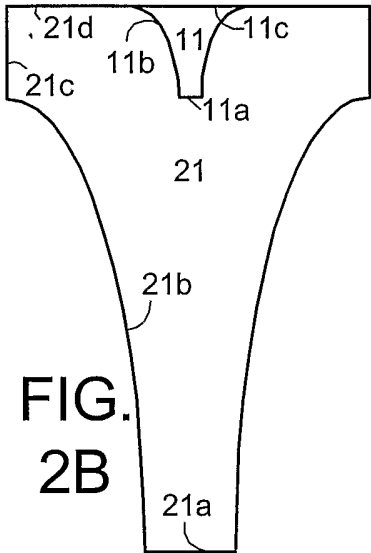


FIG. 2B

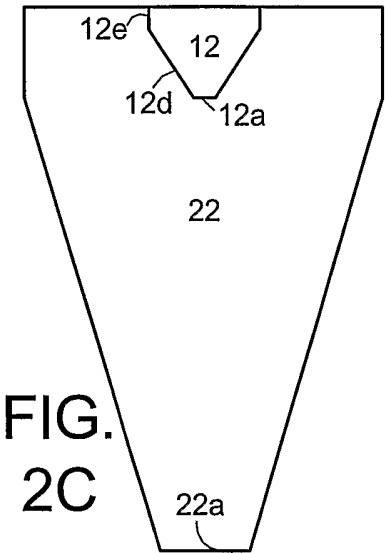


FIG. 2C

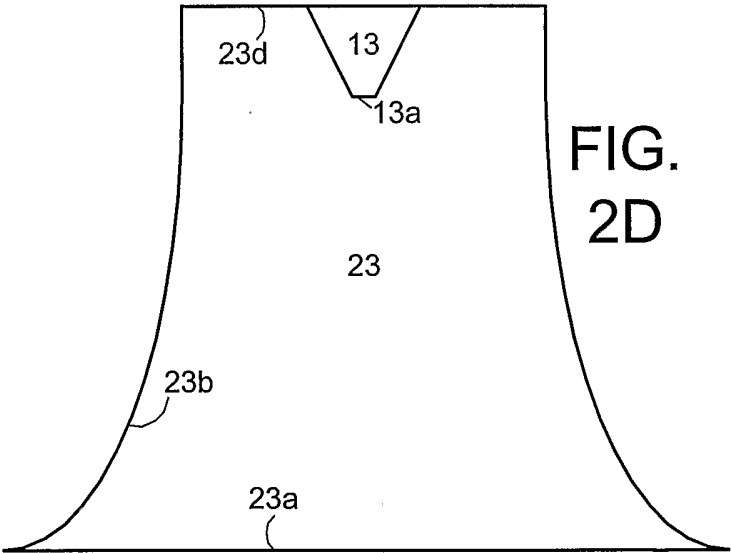


FIG. 2D

FIG. 3A

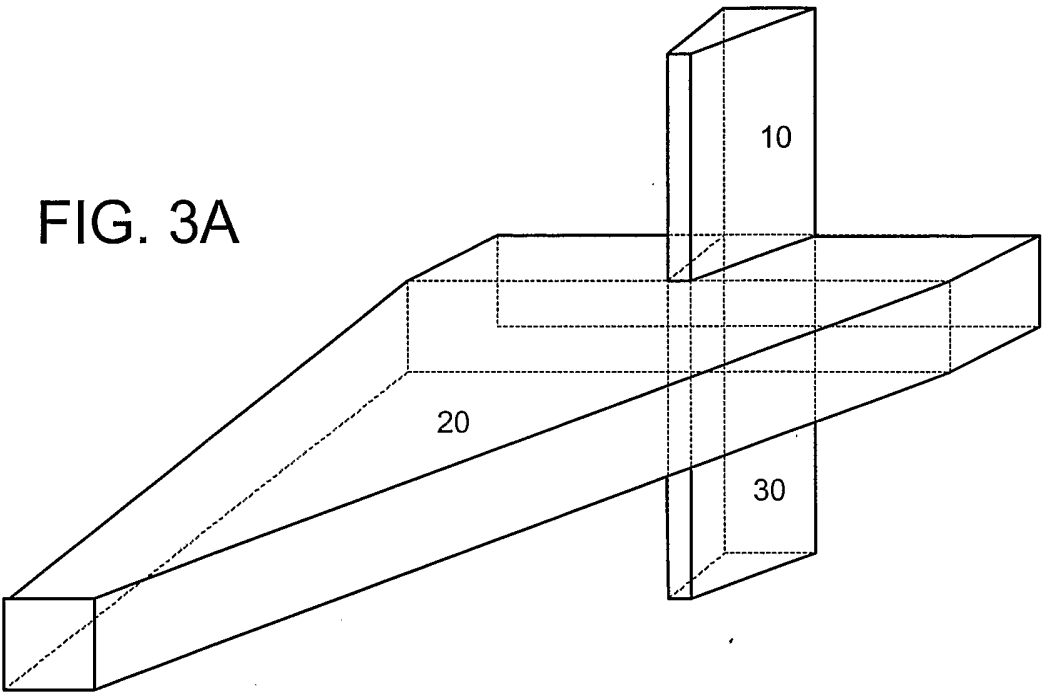
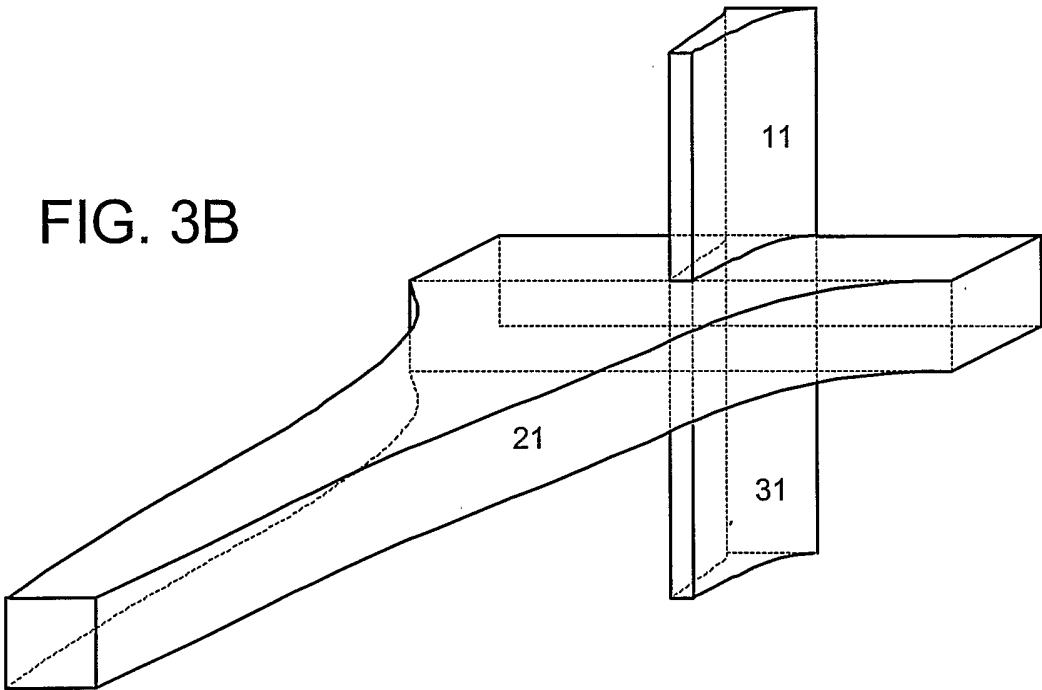


FIG. 3B



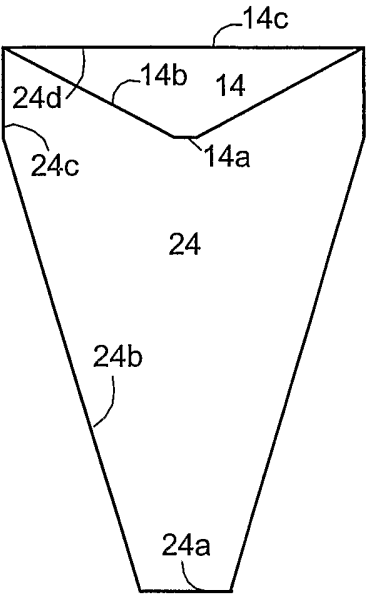


FIG. 2E

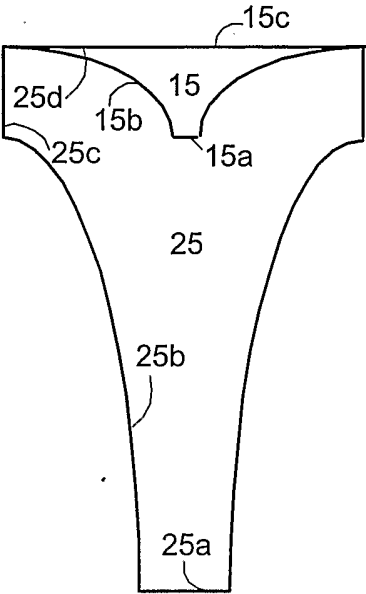


FIG. 2F

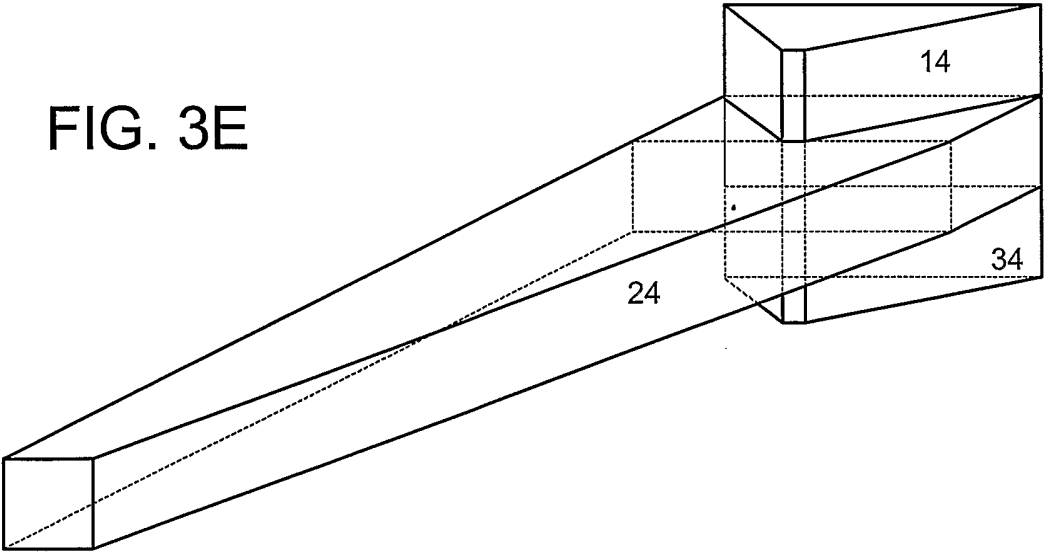


FIG. 3E

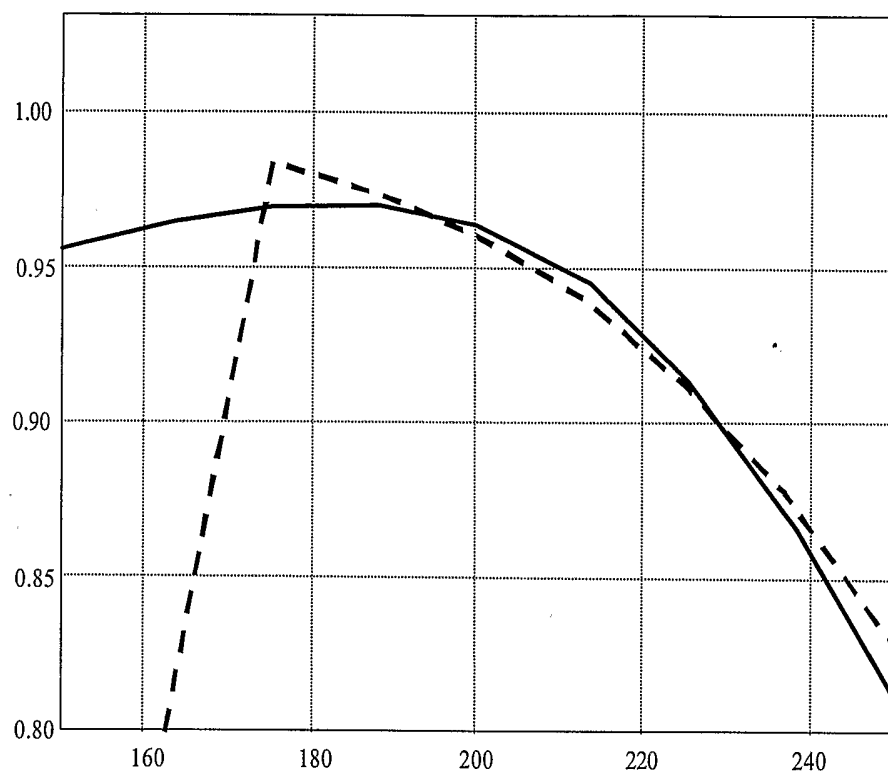


FIG. 4

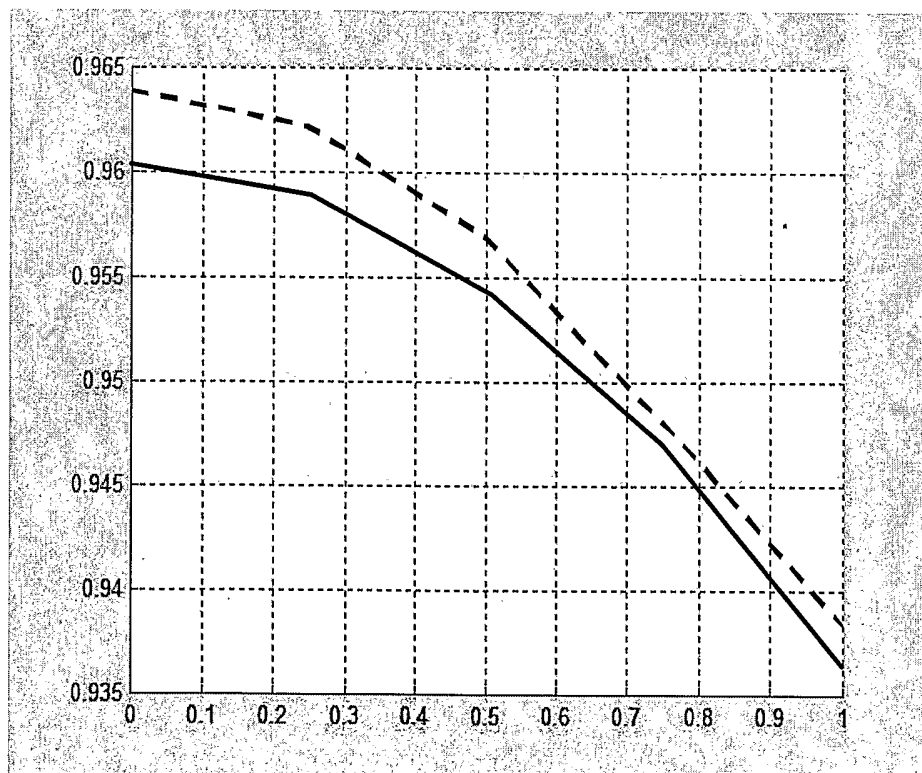
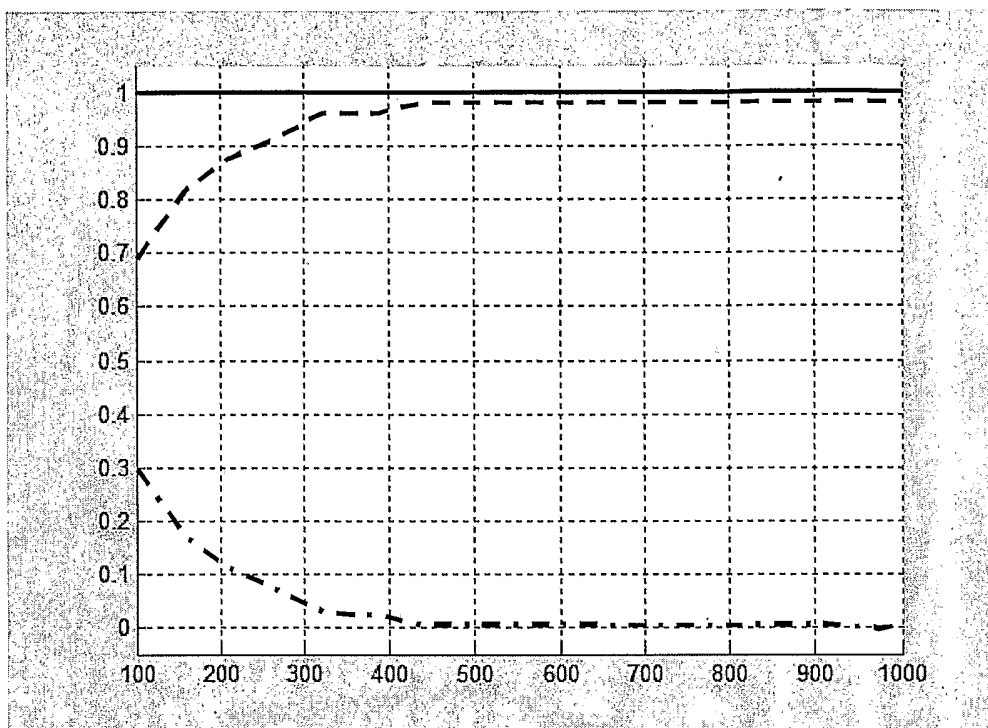
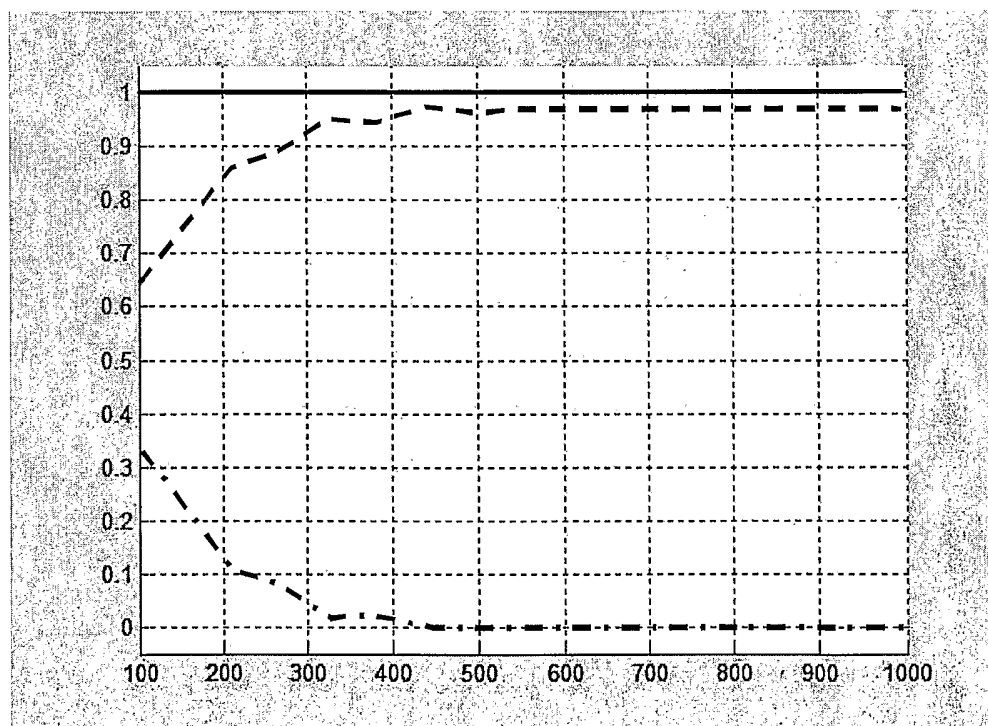


FIG. 5

FIG.
6AFIG.
6B

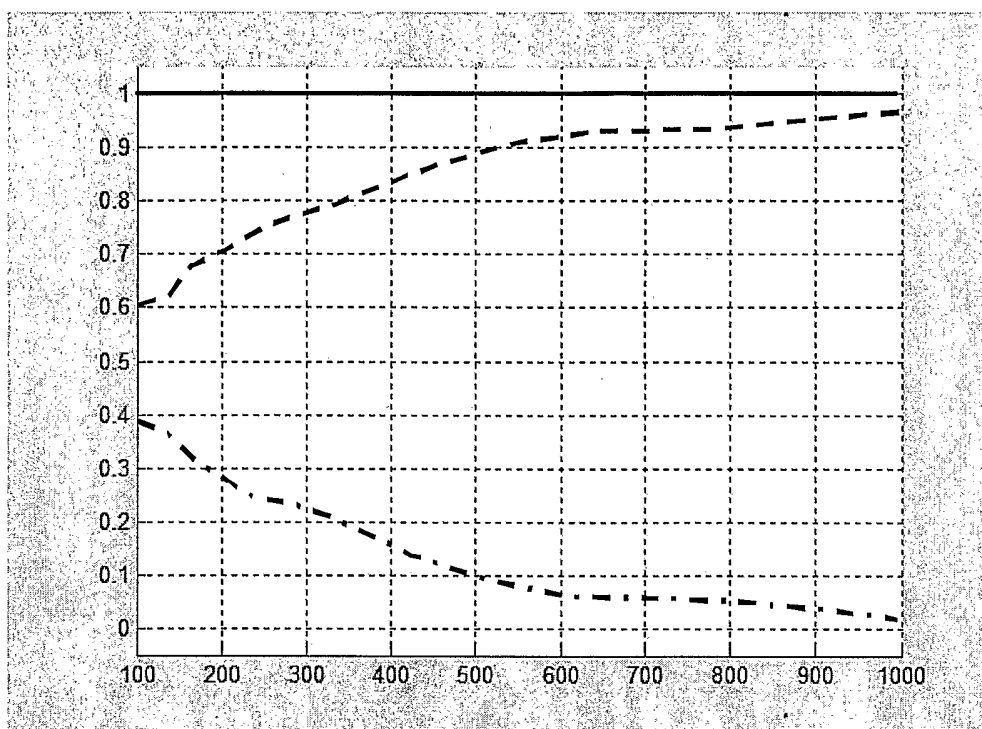
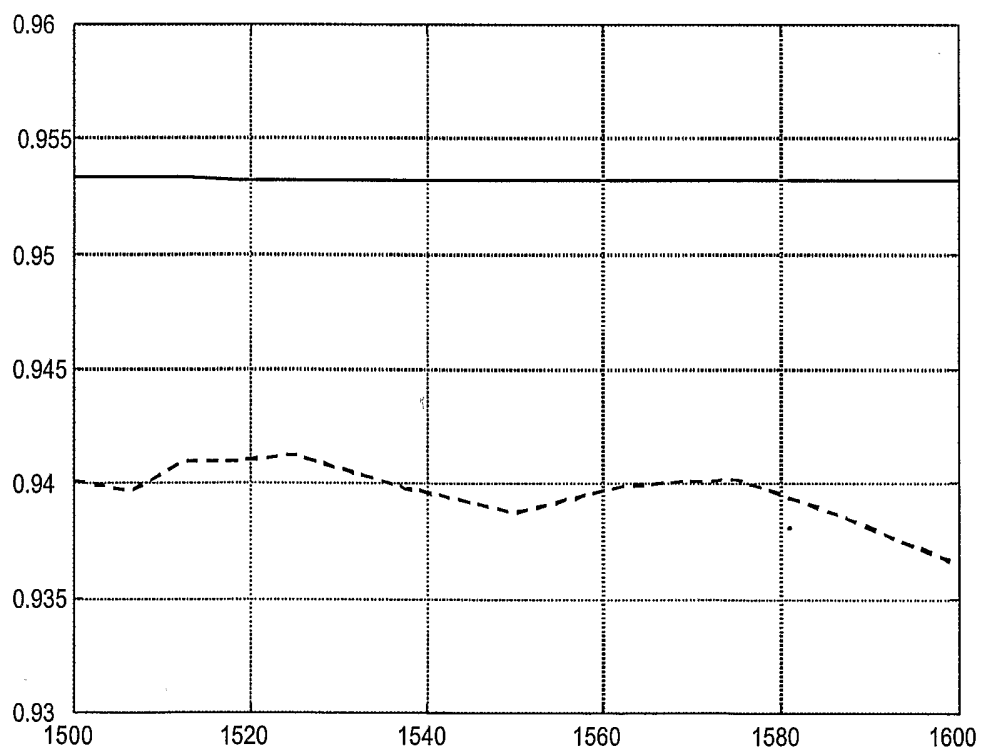
FIG.
6C

FIG. 7

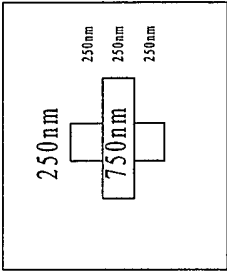


FIG. 10A

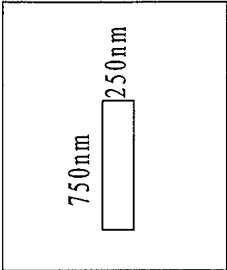


FIG. 9A

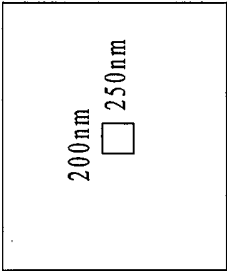


FIG. 8A

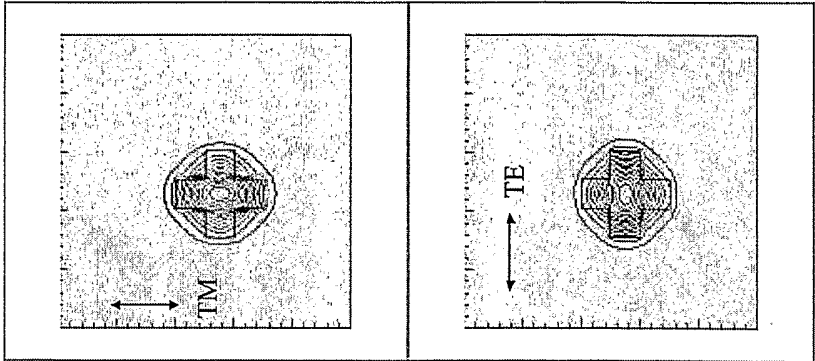


FIG. 10M

FIG. 10E

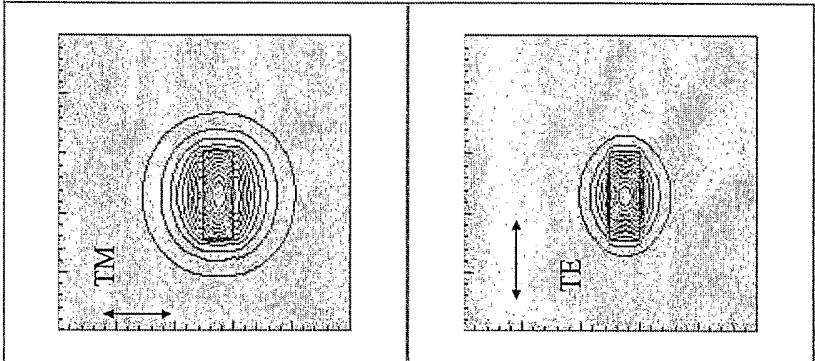


FIG. 9M

FIG. 9E

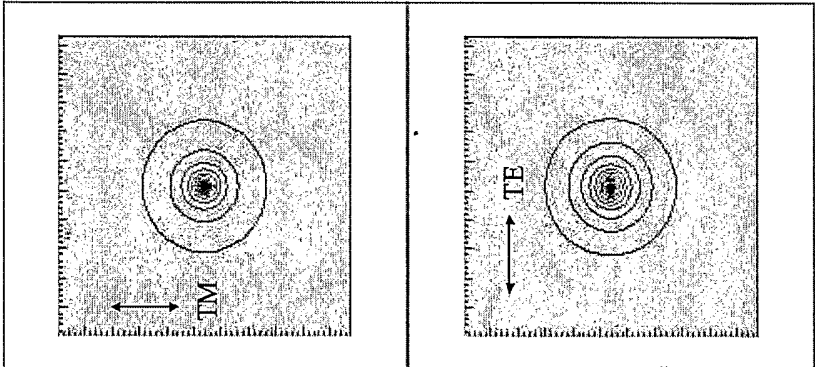


FIG. 8M

FIG. 8E

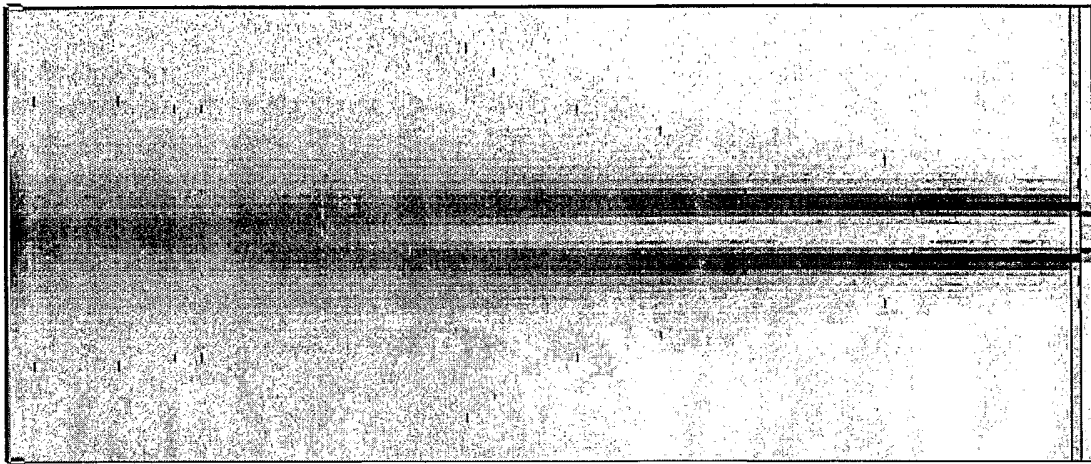


FIG. 11A

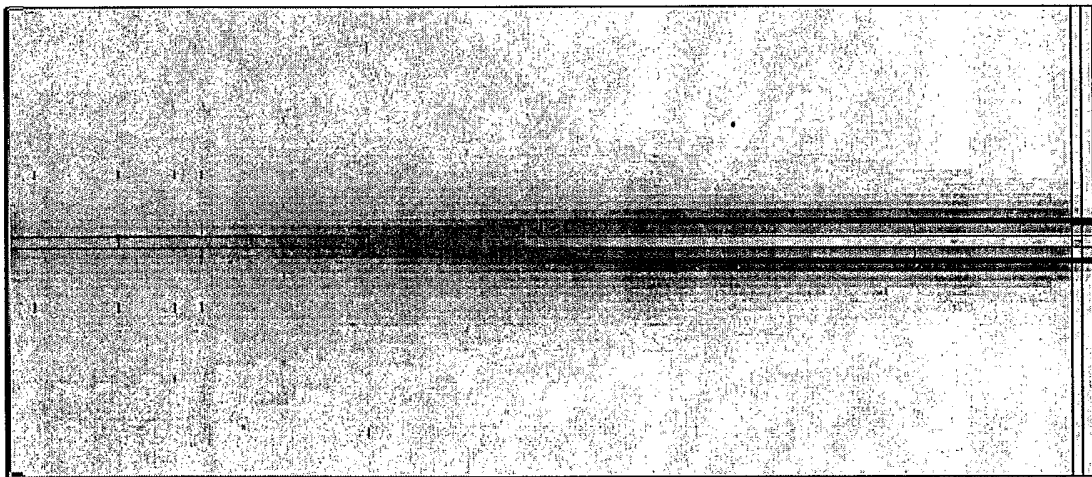
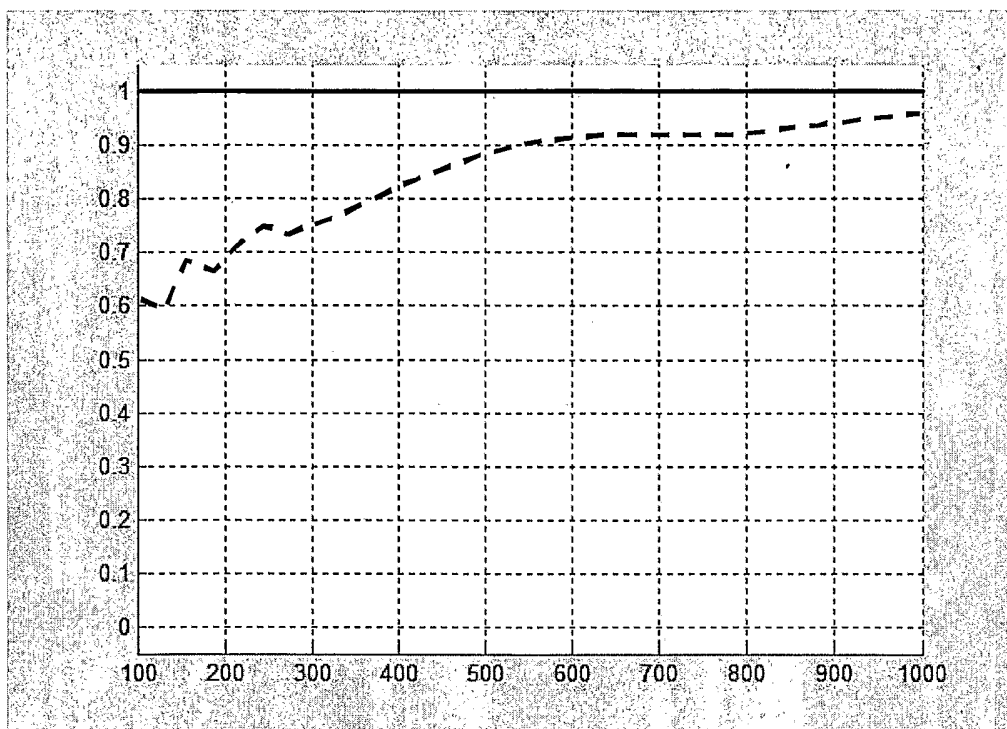
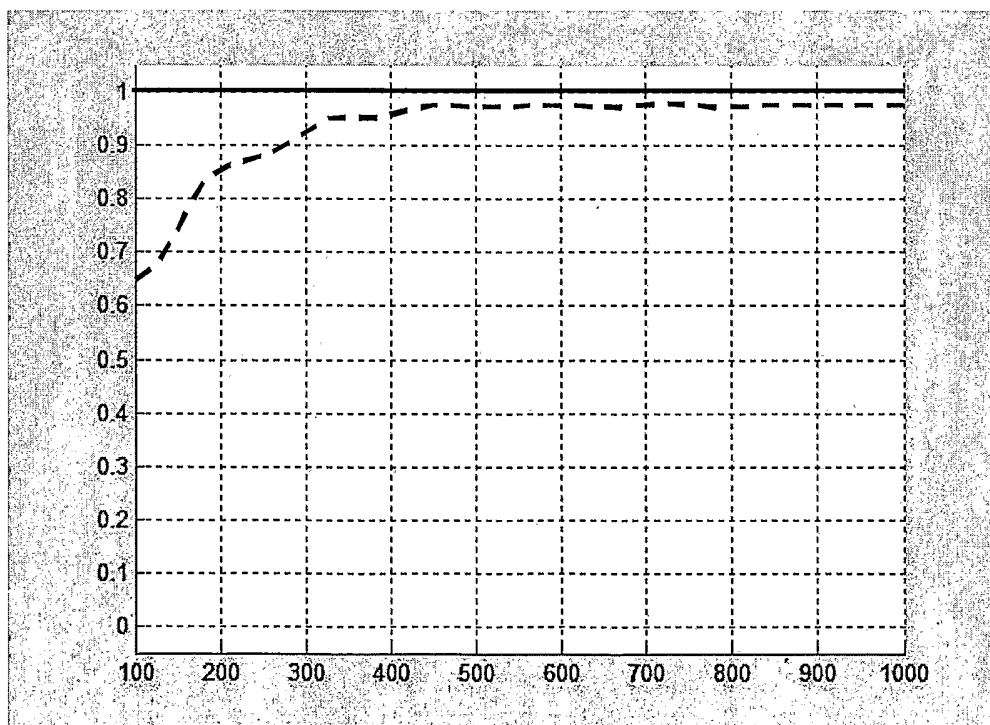


FIG. 11B

FIG.
12AFIG.
12B

INTERNATIONAL SEARCH REPORT

International Application No

PCT/IT 03/00368

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/12 G02B6/30

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SCHWANDER T ET AL: "SIMPLE AND LOW-LOSS FIBRE-TO-CHIP COUPLING BY INTEGRATED FIELD-MATCHING WAVEGUIDE IN INP" ELECTRONICS LETTERS, IEE STEVENAGE, GB, vol. 29, no. 4, 18 February 1993 (1993-02-18), pages 326-328, XP000346051 ISSN: 0013-5194	1-6, 9, 10, 21, 22
Y	page 326 -page 327; figures 1,2 ---	11
A	--- -/--	8, 12-19

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- *&* document member of the same patent family

Date of the actual completion of the international search

10 October 2003

Date of mailing of the international search report

21/10/2003

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

Beutter, M

INTERNATIONAL SEARCH REPORT

International Application No.

PCT/IT 03/00368

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	GIAMPAOLO BENDELLI ET AL: "GAIN SATURATION AND PROPAGATION CHARACTERISTICS OF INDEX-GUIDED TAPERED-WAVEGUIDE TRAVELING-WAVE SEMICONDUCTOR LASER AMPLIFIERS (TTW-SLA'S)" IEEE JOURNAL OF QUANTUM ELECTRONICS, IEEE INC. NEW YORK, US, vol. 28, no. 2, 1 February 1992 (1992-02-01), pages 447-458, XP000249557 ISSN: 0018-9197 page 452; figures 7,9 ----	11
A	MOERMAN I ET AL: "A review on fabrication technologies for the monolithic integration of tapers with III-V semiconductor devices" IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, IEEE SERVICE CENTER, US, vol. 3, no. 6, December 1997 (1997-12), pages 1308-1320, XP002146284 ISSN: 1077-260X figure 2 ----	1-22
A	US 6 108 478 A (MORRIS ROBIN JEREMY RICHARD ET AL) 22 August 2000 (2000-08-22) the whole document -----	1-22

INTERNATIONAL SEARCH REPORT

International Application No

PCT/IT 03/00368

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 6108478	A	22-08-2000	GB 2317023 A	11-03-1998
			AU 5998298 A	26-08-1998
			CN 1246928 T	08-03-2000
			DE 69802948 D1	24-01-2002
			DE 69802948 T2	12-09-2002
			EP 1015922 A1	05-07-2000
			WO 9835250 A1	13-08-1998
			JP 2001510589 T	31-07-2001