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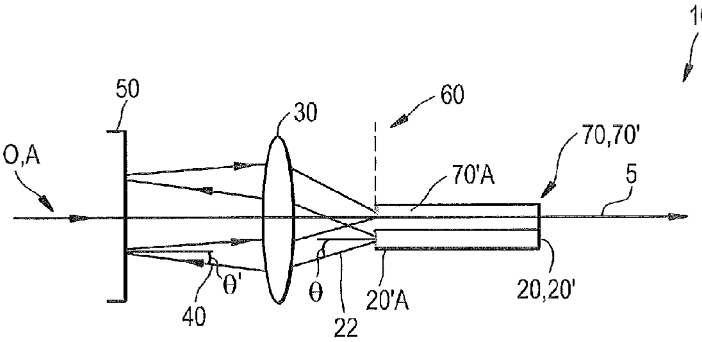
(54) **Title**: FREQUENCY DOUBLED LASER WITH FOLDED OPTICAL PATH

FIG. 1B



(57) **Abstract**: A folded laser system comprising: a coherent light source (20); a reflector (50); a lens I component (30) situated between the light source and the reflector; and a non-linear optical crystal (70), wherein the light source and the non-linear optical crystal are separated by a distance d>50 μm The lens component is positioned to provide a collimated beam when intercepting light from the light source, such that the collimated beam is at an angle to the optical axis of the lens, the reflector is situated to intercept the collimated beam and to reflect the collimated beam to the non-linear optical crystal through the lens; and the lens component is structured to provide an image on the non-linear optical crystal.

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FREQUENCY DOUBLED LASER WITH FOLDED OPTICAL PATH

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 61/371,386 filed on August 6, 2010 the content of which is relied upon and incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] The present invention relates generally to folded laser systems and more particularly folded laser systems with nonlinear optical wavelength conversion, such as frequency doubled green lasers.

Technical Background

[0003] Generation of green laser light can be achieved by non-linear frequency doubling of infrared light. Typically, as illustrated in **Figure 1A**, a light beam 2 from an infrared diode laser (3) is directed into a non-linear optical crystal 4, such as periodically-poled lithium niobate (PPLN) where it is converted into green light 5.

[0004] The practical challenges in the fabrication of this type of a laser arise from a number of issues. First, because of the small optical waveguides used to confine the light in both the diode laser and the nonlinear optical crystal, alignment tolerances for the components (lens, the nonlinear crystal and the diode laser) are on the order of a few tenths of microns. This presents a challenge both for initial assembly of the laser and for maintaining alignment over the laser's lifetime. Second, the output power from the nonlinear optical crystal is sensitive to fluctuations of temperature and to shifts in the infrared optical wavelength provided by the laser. Temperature gradients across the nonlinear optical crystal may cause a reduction in output power of the green laser (i.e., in the output power exiting the nonlinear optical crystal).

SUMMARY OF THE INVENTION

[0005] One aspect of the invention is a folded laser system having an optical axis, the laser system comprising: (I) a coherent light source; (II) a reflector; (III) a lens component situated between the light source and the reflector; and (IV) a non-linear optical crystal, wherein the light source and the non-linear optical crystal are separated by a distance $d > 50\mu m$. The lens component is positioned to provide a collimated beam when intercepting light from the light source, such that the collimated beam is at an angle Θ' to the optical axis and is structured to provide an image of the coherent light source on the non-linear optical crystal. The reflector is situated to intercept the collimated beam and to reflect the collimated beam to the non-linear optical crystal through the lens.

[0006] Preferably, the coherent light source and the non-linear optical crystal are separated by an air gap.

[0007] According to some embodiments the laser system is a green laser, the light source is an infra red (IR) diode laser, and the receiver is a non linear optical crystal, for example SHG (second harmonic generator) for converting IR light to the green light.

[0008] Some advantages provided by the exemplary green laser embodiments of laser system of the present invention are relatively loose alignment tolerances for the optical components; low sensitivity to both heat produced by the diode laser; and maximized green conversion efficiency due to improved coupling between the diode laser and the nonlinear optical crystal. Other advantages provided by the exemplary embodiments of the present invention are minimized temperature gradients across the nonlinear optical crystal, and minimized impact of optical feedback from undesirable reflections and/or backscatter off the nonlinear optical crystal that reach the diode laser.

[0009] Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

[0010] It is to be understood that both the foregoing general description and the following detailed description present embodiments of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the invention, and together with the description serve to explain the principles and operations of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Figure 1A illustrates a prior art laser system;

[0012] Figure 1B schematically illustrates schematically a folded laser system according to one embodiment of the present invention;

[0013] Figure 1C schematically illustrates schematically a folded laser system according to another embodiment of the present invention;

[0014] Figure 2 is a folded cavity green laser system according to one embodiment of the present invention;

[0015] Figure 3 is a thermal model that illustrates heat conduction between the diode laser and the nonlinear crystal of Fig. 2;

[0016] Figure 4 shows change in the optical coupling efficiency between a diode waveguide and a crystal waveguide as a function of waveguide to waveguide spacing d;

[0017] Figure 5A illustrates a cross-sectional side view of an exemplary non-linear crystal;

[0018] Figure 5B illustrates a cross-sectional end view of the exemplary non-linear crystal of Fig. 5A;

[0019] Figure 6 is a is a cross-sectional view of a folded cavity green laser system according to yet another embodiment of the present invention;

[0020] Figure 7 illustrates coupling efficiency vs. waveguide spacing d of two different laser system configurations;

[0021] Figures 8A and 8B illustrate a nonlinear optical crystal mounted over a diode laser in yet another embodiment of the present invention;

[0022] Figure 9 is a plot of coupling efficiency achievable by commercially available lens components which can be utilized in some embodiments of the present invention;

[0023] Figures 10A, 10B and 10C illustrate schematically three exemplary embodiments folded cavity green laser system;

[0024] Figure 11A is a cross-sectional view of a lens component, a crystal waveguide, and a tilted diode laser waveguide according to one embodiment of the present invention;

[0025] Figure 11B illustrates optical coupling (%) as a function of decenter for several embodiments of the present invention;

[0026] Figure 12 is a plot of an optical path length vs. back working distance (BWD) for two exemplary lens components;

[0027] Figure 13 is a plot of coupling efficiency vs. BWD;

[0028] Figure 14 is a is a cross-sectional view of a lens component according to yet another embodiment of the present invention;

[0029] Figure 15 illustrates coupling performance vs. waveguide spacing d of the lens component according to one embodiment of the present invention and two commercially available lens components;

[0030] Figure 16 is a is a cross-sectional view of a lens component according to another embodiment of the present invention;

[0031] Figure 17 is a is a cross-sectional view of a lens component according to yet another embodiment of the present invention;

[0032] Figure18 illustrates the evolution of aberrations (wave front error) as a function of the tilt of an exemplary lens component**;**

[0033] Figure 19 illustrates the evolution of aberrations (wave front error) as a function of the tilt of an exemplary lens component; and

[0034] Figure 20 is a plot of coupling efficiency as a function of the tilt of two exemplary lens components.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0035] Reference will now be made in detail to the present preferred embodiment(s) of the invention, examples of which are illustrated in the accompanying drawings. Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts. One or more exemplary embodiments of the laser system of the present invention is shown in **Figures 1B, 1C** and **2**, and is designated generally throughout by the reference numeral **10**.

[0036] The folded laser system **10** in this exemplary embodiment is a frequency doubled green laser that has a folded cavity configuration. In the laser system **10** light is emitted from a coherent light source **20** in the form of the divergent light beam **22**, and is captured and collimated by a single lens component **30**. The lens component **30** preferably operates in a telecentric or nearly telecentric condition. It is preferable that coherent light source **20** be small ($<1cm^3$), of relatively high power (>10mW) and is modulated at high rates (about 10MHz or higher). In this embodiment coherent light source **20** is an infrared (IR) semiconductor laser (IR diode laser **20′**). The diode laser **20′** includes a diode waveguide **20′A.** The IR light emanates as the divergent light beam **22** from the output facet **21** of the diode waveguide **20′A.** The facet **21**of the laser diode's waveguide may be formed perpendicular to the waveguide's axis, or it may be cleaved at an angle to the waveguide's axis as shown in **Figure 1C** The output facet **21**of the diode waveguide may be formed perpendicular to the waveguide's axis, or it may be cleaved at an angle to the waveguide's axis as shown in **Figure 1C**. The divergent light beam **22** is characterized by the emission half angle Θ at $1/e^2$, for example 20° in one direction and 7° in the other (perpendicular) direction. The emission half angle Θ is measured relative to the average emission angle (beam centroid) provided by the coherent light source. The collimated (IR) beam **40** propagates towards reflector **50** at an angle Θ′ and is then reflected from the reflector **50** back toward lens component **30**. Preferably, according to some embodiments, 0.05 Rad≤ Θ′≤0.2 Rad, and more preferably 0.09 Rad≤ Θ′≤0.17 Rad. The reflector **50** may be, for example, a planar mirror. The reflected beam propagates through the lens component **30** towards the image plane **60**, where it is focused on the input facet of crystal waveguide **70′A** (the waveguide portion) of a non-linear optical crystal **70′**. That is, the lens component **30** provides an image of the output facet of the diode waveguide **20′A** on the input facet of the crystal waveguide **70′A** of the non-linear optical crystal **70′**. As stated above, the lens component **30** preferably operates in a telecentric or nearly telecentric condition. That is, the lens **30** is constructed and is situated such that the entrance and exit pupils of the optical system are located at infinity and/or the of the beam angles incident on the input facet of the crystal waveguide **70′A** (the waveguide portion) of a non-linear optical crystal **70′** are within ±4° and preferably within ±2° (e.g., ±1°) of one another. To maximize light coupling into the crystal, if the crystal waveguide's input facet is formed perpendicular to the non-linear optical crystal waveguide's axis (within ±0.5°), it is preferable that the centroid of the beam incident on the input facet of the crystal waveguide **70′A** should be perpendicular to the non-linear optical crystal's waveguide's axis (within ±1 °, more preferably within ±0.5°).

[0037] The non-linear optical crystal **70′**may be, for example, a second harmonic generator (SHG) such as a periodically poled lithium niobate (PPLN) crystal. Other non-linear optical crystals may also be utilized. In this embodiment the non-linear optical crystal **70′** receives the IR light provided to it by the lens component **30** and converts it to a green light **5**.

[0038] Preferably, the lens component **30** has a short focal length (preferably less than 5 mm, and more preferably less than 3 mm, and even more preferably less than 2 mm), and low astigmatism, in order to achieve excellent optical coupling between the coherent light source **20** and the crystal waveguide **70′A** of the non-linear optical crystal **70′**, while minimizing both

(i) defocusing caused by changes of temperature, and (ii) the overall size of the laser system **10**.

[0039] The reflector **50** may be a conventional (fixed) planar mirror, or may be a mirror with actuation of its tip/tilt angle, such as a micro-electrical mechanical system (MEMS) mirror. The coupling of light between the diode waveguide **20′A** and the crystal waveguide **70′A** may be adjusted in two primary ways. First, the position of the lens component **30** may be moved in x, y, or z (focus) axis. Second, the mirror **50** may be tilted. Because the mirror is located in the collimated space for the infrared beam, angular adjustments will cause position (x, y) movements of the reflected and focused beam at the input facet of the crystal. The non linear optical crystal (e.g., PPLN crystal converts a substantial fraction of the infrared light into green light, which is emitted from the output facet of the crystal waveguide **70′A** (Fig 1B). Thus, adjustments in either of the position of the lens component **30**, or of the angle of the reflector **50** can be utilized to move the focused spot at the input facet of the crystal waveguide **70′A** of the non-linear optical crystal **70′**.

[0040] In this example, both the light source **20** and the receiver (non-linear optical crystal **70′**) are decentered with respect to the optical axis OA (optical axis of the lens component **30**) and are situated symmetrically or approximately symmetrically (departure from symmetry is within ±100 μm, preferably within ±50 μm) with respect to the optical axis. More specifically, in order to minimize aberrations of the light beam at the input facet of the crystal waveguide **70′A** of the nonlinear optical crystal **70′,** the output facet of the diode waveguide **20′A** of the infrared diode **20′** and the input facet of the crystal waveguide **70′A** of the nonlinear optical crystal **70′** are separated by a small air gap and by a small distance **d** compared to the focal length f of the lens **30** (i.e., **d<<f**). Preferably, the focal length f of the lens **30** is 1 to 5 mm (1mm≤ **f** ≤ 5 mm), for example, 1mm, 1.2mm, 1.25mm, 1.3 mm, 1.4mm, 1.5 mm, 1.7 mm, 2 mm or 2.5 mm. Preferably the separation d between the light source **20** and the non-linear optical crystal **70′** is 30 μm ≤ **d** ≤ 1500 μm, more preferably 50 μm ≤ **d** ≤ 750 μm, more preferably 100 μm ≤ **d** ≤ 600 μm, even more preferably 150 μm ≤ **d** ≤ 500 μm and most preferably 300 μm ≤ **d** ≤ 500 μm. For example, the distance d may be 75 μm, 100 μm, 125 μm, 150 μm, 200 μm, 250 μm, 300 μm, 400 μm, or 450 μm. Preferably, the air gap distance AG is 75 μm to 500 μm, for example 100 μm to 500 μm or 200 μm to 400 μm, or 250 μm to 350 μm. Thus, in this embodiment, the light source **20** (diode laser **20′**) and the receiver **70** (non-linear optical crystal optical crystal **70′**) are decentered along the Y axis, with respect to

the optical axis, by a distance d′≈d/2, for example by a distance d′= d/2±100μm. Preferably the decenter distance d′ equals d/2 or is within 50μm of d/2 (i.e., d′= d/2 ± 50μm).

[0041] The folded laser system configuration described herein (for example, see **Figures 1B, 1C, 2, 6, 8A and 8B**) has the advantage of reducing the overall length of the laser cavity (and hence reduces package size of the laser), because the optical path is folded upon itself. The folded laser configuration also advantageously minimizes the effect of non-symmetric optical aberrations produced by the lens component **30,** because the same lens component **30** is used twice – once to collimate the beam and once to refocus the light on the input facet of the crystal waveguide **70′A** of the nonlinear optical crystal **70′**. Given stable and accurate attachment techniques, the laser system **10** may be completely passive (i.e., it may include no moving components). (Such design is illustrated schematically in **Figure 1B**). Alternatively, as described above, the laser system **10** may easily utilize an adjustable reflector such as a MEMS mirror **50A** to actively align the focused beam on the PPLN input facet in two lateral directions.

[0042] Practical realization of folded configurations creates a number of challenges. First, because the folded laser system configuration utilizes a light source (diode laser **20**) and a receiver (non linear crystal 70) that are decentered with respect to the optical axis of the lens component **30**, off axis optical aberrations are present and can be difficult to control. The optical aberrations must be kept small in order to achieve high coupling from the diode laser **20′** into the non-linear optical crystal **70′**. One advantage of the green laser embodiment **10** of the present invention is that off axis aberrations are kept small, even if the lens component **30** is misaligned. Second, close proximity of the diode laser **20′** to the non-linear optical crystal **70′** may also cause heat to be transferred from the diode laser **20′** to the non-linear optical crystal **70′**. Thermal gradients in the non-linear optical crystal degrade conversion efficiency from the infrared light into the green light. One advantage of the green laser embodiments of the present invention is that thermal transfer from the diode laser to the crystal is minimized because the diode waveguide **20′A** of the diode laser **20′** and the crystal waveguide **70′A** of the non-linear optical crystal **70′**are separated by an air gap **AG**. Third, at least some exemplary embodiments of the laser system **10** do not require actuators to control the focus of the optical beam by moving either the reflector **50** or the lens component **30**. These embodiments the laser systems **10** do not defocus (or have a minimal defocus) and do not significantly change lateral positioning of optical components as a function of temperature (otherwise optical coupling between the input facet of the crystal waveguide **70′A** and the diode waveguide **20′A** will be compromised, and the optical output power may be lost). Finally, the laser system **10** of can also advantageously control or minimize the impact of optical feedback. For example, in the green laser embodiments described herein reflections from the front facet of the crystal waveguide **70′A** of the non-linear optical crystal **70′** do not induce undesirable mode hopping behavior from the infrared laser diode **20′**.

[0043] **Figure 2** illustrates schematically mounted optical components that are assembled into one embodiment of a green laser system **10**. The non-linear optical crystal **70′** (PPLN crystal) is placed above the diode laser **20′**, with a small air gap **AG** separating the ends of the two waveguides **70′A**, and **20′A**. The existence and size of this air gap **AG** is important for a several reasons, described below.

[0044] First, one or more wire bonds **23** attach to various sections of the diode laser **20′**, in order to provide current and voltage control signals to the diode laser. These wire bonds form loops **23′** that have a certain minimum bend radius and thus extend by finite height above the diode laser **20′**. A minimum wire bond loop height may be, for example, 75 μm -200 μm or 100 μm -150 μm, defining the minimum possible vertical separation between the diode waveguide **20′A** of the infrared diode laser **20′** and the input facet of the crystal waveguide **70′A** of the nonlinear optical crystal **70′**.

[0045] Second, the air gap AG thermally insulates the non-linear optical crystal **70′** from the diode laser **20′**, which acts as a heat source when operating. Air acts as a good thermal insulator, in particular compared to metals or many other solid materials, preventing heat from the diode laser **20′** from reaching the non-linear optical crystal **70′**. It is preferable to keep heat from reaching the non-linear optical crystal **70′** because the heat can create thermal gradients in the non-linear optical crystal **70′**, thus negatively affecting the nonlinear conversion efficiency of the crystal waveguide **70′A**. More specifically, a thermal gradient in the non-linear optical crystal **70′** can be detrimental, because the temperature affects the refractive index of the crystal waveguide **70′A** within the non-linear optical crystal **70′**. In general, the wavelength dependence of the green output is a sin(x)/x function (with the exact shape depending on the uniformity of the crystal waveguide **70′A**), and thermal gradients distort this function. (Please note that the symbol x represents the deviations in the IR wavelength λ from the optimal wavelength.)

[0046] **Figure 3** is a thermal model that illustrates how heat from the diode laser is conducted in a laser system configuration similar to that shown in **Figure 2**. More specifically, **Figure 3** illustrates a fine element thermal model of the diode laser **20′** and the cantilevered non-linear optical crystal **70′** separated by the air gap **AG**. Although the diode laser **20′** acts as a source of heat, the air gap thermally insulates it from the shown in **Figure 3**. The diode laser is supported by a metal package base. As shown in this figure almost all of the heat generated by the diode is conducted into the metal package base. That is, while the exact thermal conditions will depend on the materials and specific design, this model illustrates that heat is conducted away efficiently by any metal contact, and does not pass from the diode laser **20′** to the non-linear optical crystal **70′**, because of the relatively high thermal impedance of the air gap. Experimental data also demonstrated that, due to the presence of the air gap **AG**, the conversion efficiency of the non-linear optical crystal **70′** was not degraded by thermal effects.

[0047] Third, the distance d between the two wavegudes **70′A, 20′A** should be kept as small as is practically possible, because a large distance requires that either the output facet of diode waveguide **20′A**, or the input facet of the crystal waveguide **70′A** of the non-linear optical crystal **70′**, or both, be substantially decentered (Y axis) with respect to the optical axis (Z axis). Generally the optical axis of the lens component **30** is situated midway between the two waveguides **70′A, 20′A**. This provides both optical coupling of light between the two waveguides **70′A, 20′A**, and also allows an active mirror **50** (if an active mirror is utilized) to be at the center of its actuation range, so that mirror tilt can be used to compensate for small motions of the waveguides. (These motions may be produced, for example, by temperature and humidity changes.) The further either one of the two waveguides is located off the optical axis of the lens, the more optical aberrations will be introduced into the focused spot at the input facet of the crystal waveguide **70′A** of the non-linear optical crystal **70′**. These aberrations include astigmatism, coma, and spherical aberration. **Figure 4** is an illustrative example of how the coupling efficiency between the two waveguides **20′A, 70′A** is reduced as the distance d (vertical distance, along the Y axis) between them is increased. As distance d increases, optical aberrations distort the beam, and coupled power between waveguides **20′A, 70′A** becomes smaller. Because a lens component with a longer focal length will produce an image with less optical aberrations, when the image and the object are displaced by the same distance d’, one way of minimizing these aberrations is to use a lens component with a long focal length. However, we seek to keep the laser package size to a minimum, which dictates that we should use a lens component with the shortest focal length possible. For example the lens component **30** may have a focal length f of about 1 mm to 2mm, or 1.2-1.7 mm (e.g., f=1.25 mm, f=1.3 mm, f=1.4 mm, f=1.37 mm, or f=1.5 mm). That is, it is preferable that the lens component **30** has the short focal length, and provides minimum amount of aberrations at the input facet of the crystal waveguide **70′A,** and that the laser system **10** has a high coupling efficiency determined the optimal center-to-center separation d between the two waveguides **20′A** and **70′A**. (Please note that in **Figure 4** the peak coupling at d= 110 μm rather at zero (no separation) is due to the angled emission of the diode laser **20**.)

[0048] We have determined that preferred waveguide separation distance d is larger than 50 μm, but smaller than 1500 μm and preferably smaller than 700 μm. For example, distances d of 150 μm to 450 μm work well when the focal length of the length component **30** is about 1.5 mm. (A lens component **30** with a slightly larger or smaller focal length f will work well when distance d is somewhat larger 450 μm, or somewhat smaller than 150 μm, respectively). The minimum distance d is determined first by the ability to fit wire bond loops **23′** between the diode laser **20′** and non-linear optical crystal **70′**. In addition, the crystal waveguide **70′A** may not be located at the outermost edge of the non-linear optical crystal **70′**, because typical non-linear optical crystal **70′** has a “cap” layer **70′B** that can be a few microns to hundreds of microns thick. An exemplary cap layer **70′B** and the top layer **70′C** with the crystal waveguide **70′A** therebetween are illustrated schematically in **Figures 5A** and **5B**. Therefore, the minimum possible separation between the two waveguides is set by the thickness of the cap layer **70′B** (if present) plus the minimum distance needed to accommodate the wire bonds **23**. For example, if 150 μm height is needed for wire bond loops **23′**, and if the non-linear optical crystal **70′** has a 200 μm thick cap layer **70′B**, then the minimum possible waveguide separation distance d (center to center) is 350 μm (200 μm + 150 μm=350 μm). The maximum waveguide distance d is determined primarily by the optical aberrations of the lens component **30**, because the optical coupling between the two waveguides **20′A** and **70′A** will decrease as distance d increases.

[0049] Alternatively, the non-linear optical crystal **70′** need not be located above the diode laser **20′**. Instead, the non-linear optical crystal **70′** can be located to the side of the diode laser **20′**. Such a “side- by- side” configuration is shown schematically in **Figure 6**. This configuration has the advantage of allowing a large amount of vertical space for the laser wire bonds **23**. However, it generally requires a wider separation between the two waveguides, because the diode laser's structure has some inherent width (about 300 μm), and in addition, the crystal waveguide **70′A** may not be located at the edge of the non-linear optical crystal **70′**. When utilizing **Figure 6** configuration, in order to prevent thermal crosstalk, separation should be made between the diode laser and the non-linear crystal to provide for an air gap **AG** between them. This "side-by- side" configuration is very similar to that shown in **Figure 2**, except that in this embodiment the locations of diode laser **20′** and the non-linear optical crystal **70′** are rotated by 90 degrees so the separation is a horizontal one (X axis), rather than vertical. The small air gap AG is used to ensure thermal isolation between the diode laser **20′** and the non-linear optical crystal **70′**. The exemplary green laser system **10** shown in **Figure 6** also has the advantage of making the system work along the low numerical aperture or horizontal direction of the diode laser (i.e., the beam **22** has less divergence along the x-axis than along the y axis), such that the coma aberration will degrade the optical coupling more slowly than along the vertical axis. This is illustrated in **Figure 7**. More specifically, **Figure 7** illustrates coupling efficiency vs. waveguide spacing d of two different laser system configurations. In one configuration the non-linear optical crystal **70′** is placed over the laser **20′**(along the Y axis) as shown in **Figure 2** and in another configuration the non-linear optical crystal **70′** is placed adjacent to the laser **20′** (along the X axis) as shown in the "side-by-side" configuration of **Figure 6**. The line with circles corresponds to the "side-by- side" configuration, the line with rectangles corresponds to the cantilevered configuration. Because the numerical aperture of the diode laser beam **22** is smaller (less divergent) in horizontal direction, the side-by-side configuration of **Figure 6** results in higher coupling efficiency at large separation distances d than the cantilevered configuration of **Figure 2**. Therefore, side-by-side mounting will allow a larger spacing d between the two waveguides, while achieving the same coupling efficiency. Preferably the separation d between the light source **20** and the non-linear optical crystal **70′** in a "side by side" configuration is 30 μm ≤ **d** ≤ 1500 μm, more preferably 50 μm ≤ **d** ≤ 750 μm, even more preferably 50 μm ≤ **d** ≤ 500 μm and most preferably 350 μm ≤ **d** ≤ 500 μm. For example, the air gap may be characterized by a distance d of 50 μm, 75μm, 100 μm, 125 μm, 150 μm, 200 μm, 250 μm, 300 μm, 400 μm, or 450 μm.

[0050] Furthermore, it may be advantageous to mount the non linear crystal **70′** from its top surface, i.e. the surface that is furthest away from the waveguide and that corresponds to the top layer **70′C** of the non-linear optical crystal **70′**. This is depicted in **Figures 8A** and

8B. The advantage of this top mounting technique is that non-linear optical crystals **70′** of various cap thicknesses (the distance between the crystal waveguide and the bottom surface of the non-linear crystal) may be used interchangeably in the same laser system. Such interchangeability is advantageous because it allows the use of non-linear optical crystal **70′** from different sources (vendors), which may have different manufacturing techniques and hence different cap thicknesses. As long as the distance d between the top of non-linear optical crystal **70′** and the diode laser **20′** is unchanged, the separation between diode waveguide **20′A** of the diode laser **20′** and the crystal waveguide **70′A** of the non-linear optical crystal **70′** will remain constant. This type of top mounting technique may also be applied to the side-by-side mounting configuration shown in **Figure 6,** with the crystal mounting surface being the one furthest away from the diode laser.

[0051] The laser system **10** shown in **Figures 1B, 2, 6, 8A and 8B** is designed such that the optical path length OPL between the light source **20** (the output facet of diode waveguide **20′A**) and receiver **70** (input facet of crystal waveguide **70′A** of the SHG crystal) has the same optical path length as the diode laser's cavity. ($OPL=D_i \times N_i$, where Di is a distance between surfaces of different components, and N_i is the index of refraction of between these surfaces.) That is, the laser system **10** of **Figures 1B, 2, 6, 8A and 8B** is designed to work in a coupled cavity condition, such that the cavity formed between the output facet of the diode waveguide **20′A** of the diode laser **20′** and the input facet of the crystal waveguide **70′A** of the non-linear optical crystal **70′** has the same optical path length as that of the diode laser's internal cavity. Thus, for example, if the optical path length through the diode waveguide **20′A** of the diode laser **20′** is 9.5 mm, than the optical path length through the laser system **10** (from the light source to the receiver) should be 9.5 mm. Thus, preferably, if the light source **20** is a diode laser, than the optical path length (OPL) from the light source **20** to the lens component **30**, through the lens component **30**, and to the reflector **50** is ½ of the OPL through diode waveguide **20′A**. The advantage of this configuration is to minimize laser wavelength instability created by the parasitic reflections from the input facet of crystal waveguide **70′A** of the nonlinear crystal **70′**.

[0052] The lens component **30** preferably is used to both collimate or to nearly collimate the IR light provided by the diode laser **20′**, and to refocus the light into the crystal waveguide of non-linear optical crystal **70′**. That is, preferably, the distance z1 from the principal plane of the lens component **30** to the output facet of laser diode is about one effective focal length (i.e., EFL≤ z1 ≤1.1EFL and even more preferably EFL≤ z1 ≤1.05EFL, where EFL is preferably ≤2 mm, and more preferably ≤1.5 mm). The lens component **30** is situated to provide magnification M of approximately 1:1. Preferably, the lens component is situated to image the output facet of the diode waveguide **20′A** on the input facet of the crystal waveguide **70′A** at a magnification M and $0.9 \leq |M| \leq 1.1$. More preferably $0.95 \leq |M| \leq 1.05$. Preferably, the lens component **30** has numerical aperture NA between about 0.35 and about 0.6, and a focal length f of 1 mm to 3 mm, a front working distance FWD of 0.3 mm to 3 mm and a back working distance BWD of 0.5 mm to 3 mm. The FWD is a distance along the optical axis from the light source **20** to the front surface S1 of the lens component **30** (i.e., the lens surface facing the light source). The BWD is the distance from the rear surface S2 of the lens component **30** to the reflector **50**. Preferably, the reflector **50** is located in the back focal plane of the lens component **30** which allows optimal optical coupling to be achieved when the direction of the average emission angle (beam centroid) of the light source **20** is parallel to the average beam angle on the receiver **70** (i.e., it is parallel to the centroid of the converging light cone intercepted by the input facet of the non-linear optical crystal **70′)**.

[0053] Preferably, if the light source **20** provides a diverging beam with a maximum half angle Θ, and the reflector **50** is located in the back focal plane of the lens component **30**, or very close to the back focal plane. Preferably, when a decentered light source is located in a focal plane of the lens component, and up to 750 μm off axis, the lens component **30** is structured to provide a collimated or nearly collimated beam such that the beam (beam angle centriod) is at an angle Θ' (with respect to the normal to the reflector surface) such that: 0.05 RAD ≤Θ′ is ≤ 0.2RAD. If the crystal waveguide's input facet is formed perpendicular to the non-linear optical crystal's waveguide's axis (within ±0.5°), then preferably the centroid of the beam incident on the input facet of the crystal waveguide **70′A** is perpendicular to the non-linear optical crystal's waveguide's axis (within ±0.5°, more preferably within ±0.01° of the optical axis of the waveguide **70′A.**).

[0054] The exemplary lens component **30** is structured to provide on the receiver an image of the light source, the image characterized by (i) astigmatism of more than 0.05 waves RMS, and less than 0.1 waves RMS, when the lens component's optical axis is not misaligned with respect to the laser system's axis (midline between the (facets) of two waveguides), or with respect to the average emission angle (beam centroid) of the light source; and (ii) astigmatism of less than 0.05 for tilt angles of 2 to 6 degrees, when the lens component is tilted by of 2 to 6 degrees with respect to the average emission angle of the light source. Thus, advantageously, even if the lens component **30** is misaligned (e.g., slightly tilted or decentered) during assembly of the laser system **10**, the RMS wave front error on the receiver **70** is ≤0.1λ, where λ is the central wavelength provided by the light source **20**.

[0055] It is noted that the astigmatism may be created by: (i) wedge in the lens component, or (ii) decentration of one of the surfaces of the lens component relative to another, or (iii) by one of the surfaces being tilted relative to another.

[0056] The lens component **30** of the embodiments described herein is preferably optimized to allow a relatively wide air gap **AG** between diode waveguide **20′A** and the crystal waveguide **70′A,** with minimal coupling penalty. That is, the lens component **30** retains a high coupling efficiency even though the output facet of the diode waveguide **20′A** and the input facet of the crystal waveguide **70′A** are separated by a relatively large distance d. Because the optical path is folded, and only a single lens component **30** is utilized, the object (output facet of the diode waveguide **20′A**) and image (located at the input facet of the crystal waveguide **70′A**) are situated off the lens component's optical axis. As discussed above, the lens component **30** is preferably designed to have low astigmatism (e.g., between 0.01λ and 0.1λ, where is λ the wavelength provided by the diode laser **20′**) in order to provide minimal distortion of the beam spot at the image plane for the off axis positioned waveguides **20′A, 70′A**. A comparison of the coupling efficiency achievable with various commercially available lens components is shown in **Figure 9.** A first exemplary lens component has lower astigmatism than the second exemplary component, resulting in a greater tolerance to waveguide separation. Coupling curves for the first lens component were also calculated for two different lens-to-mirror distances (BWD) of 2 mm and 2.3mm).

[0057] In addition, a short focal length lens component **30** is preferable in order to minimize laser system's length. (The distance between the mirror **50** and the two waveguides **70′A** and **20′A** is approximately two focal lengths). Furthermore, a short focal length lens component **30** will have less defocus as a function of temperature than a longer focal length lens component. To a first approximation, the change in the lens focal length f caused by temperature induced changes in refractive index of the lens component **30** is approximated by

$$\frac{df}{dT} \approx -\frac{dn}{dT} \cdot \frac{f}{n-1}$$

where *f* is the focal length, n is the nominal refractive index of the lens material, and dn/dT is the change in refractive index with temperature. Thus, shorter focal length lens components will provide less movement in the focal position (smaller df/dT). Therefore, it is preferable that the focal length f be less than 5 mm, more preferably 1 mm ≤ f ≤3 mm, and most preferably 1 mm≤ f ≤2 mm. Lastly, it is preferable to select the lens material that has low dn/dT values.

[0058] While the approximate spacing between the lens component **30** and mirror **50** (i.e., the back working distance BWD) is about one focal length, the exact choice of BWD is influenced by several other considerations. (See **Figure 10A**, for example.) First consideration is the launch angle of the laser beam (average emission angle of the beam **22**, or the angle of beam angle centroid) from the diode laser **20′**. If the diode waveguide **20′A** has a cleave that is not perpendicular to the axis of the diode's waveguide, then the emitted light can easily be launched a few degrees upward or downward away from the z-axis. This means that the optimal BWD will be slightly different than one focal length, which enables the reflected beam enter the input facet of the diode waveguide **20′A** at an optimum angle (e.g., normal to the input facet of crystal waveguide **70′A)**. This is illustrated, for Example in **Figure 10B.** However, this departure from the symmetry in the optical system results in tightening of the alignment tolerances for the placement of the two waveguides **70′A**, **20′A**, and in tightening of the positioning tolerances of the lens component **30**. If the launch angle of the laser beam **22** was instead parallel to the optical axis, then the laser system would retain symmetry and would be telecentric (**Figure 10B)**, resulting in looser tolerances for the positioning of the of the two waveguides **70′A**, **20′A**. Hence it is advantageous to physically mount the diode laser **20′** such that the emitted IR beam **22** is parallel to the lens optical axis of the lens component **30**. This can be done by mounting the diode laser **20′** at an angle as is shown in **Figure 11A**. This design simultaneously increases the amount of coupled light by ensuring the proper angle of incidence onto the input facet of crystal waveguide **70′A**, and widens the alignment tolerances of the optical system by making it telecentric.

[0059] Alternatively, as shown in **Figure 10C,** if the diode waveguide **20′A** has an output facet **21** that is cleaved at the non-normal angle to the waveguide axis, and if the diode waveguide **20′A** is mounted so that its axis is parallel to the optical axis, then the emitted light will launched a few degrees upward or downward away from the z-axis. In this embodiment it is about 3.3° downward relative to the z-axis. If, in this embodiment, the back focal plane of the lens component **30** is spaced by a distance 1.2F from the mirror **50, 50A**, then the input light will enter input facet of the crystal waveguide **70′A** of the non-linear optical crystal **70′** (e.g., SHG) nearly normal to its input facet (at an angle less than 1° relative to the z-axis). Preferably, the distance z2 from the principal plane of the lens component **30** to the input facet of optical crystal **70′** is between about one EFL and 1.25 EFL (i.e., EFL≤ z2 ≤1.25EFL and even more preferably EFL≤ z1 ≤1.2EFL, where EFL is preferably ≤2mm, and more preferably ≤1.5mm). For example, if the lens component **30** has an EFL of 1.37 mm, the distance z2 is about 1.65 mm or smaller (e.g., 1.55 mm-1.6 mm). If, the diode waveguide **20′A** has a facet cleave angle that is not perpendicular to the axis of the diode's waveguide, for example such that the emitted light is launched 3.3 degrees downward with respect to the z-axis, and when the lens component **30** has an EFL of 1.37 mm, and the distance z2 is about 1.57 mm (i.e., making the distance between the lens component **30** and the non-linear optical crystal **70′** 200 μm greater than EFL), then the incidence angle of the laser beam on the input facet of the non-linear optical crystal **70′** is 0.97°. It is noted that increasing the distance between the lens component **30** and the non-linear optical crystal **70′** by a small distance, (e.g., 100-300μm, and in this embodiment by 200 μm) helps create larger range of position tolerances on the placements of both the non-linear optical crystal **70′** and the laser diode with respect to the lens component. Preferably, the angle of the centroid of the incident beam on the input facet of the non-linear optical crystal is less than 1° (more preferably less than 0.5 °, and even more preferably less than 0.01 °) when the exit angle of the centroid of the beam provided by the coherent light source is between 1° and 5°, relative to the optical axis of the laser system.

[0060] The advantage of a telecentric optical system is that it allows for wide placement tolerances of the optical components, namely the positions of the laser diode and non-linear optical crystal relative to the topical axis of the lens. This happens because in such a system no matter where the optical components are placed, the angle of the light beam is preserved between the object and the image. In a non-telecentric system, motion of a component off axis induces a angle change to the light beam. This angle change will make reduce the coupling of light into the SHG waveguide.

[0061] **Figure 11B** shows an example for the wide placement tolerance along the x-dimension for a telecentric folded laser system. The x-axis here is defined as being perpendicular to the optical axis of the diode laser (LD), and also perpendicular to the line connecting both the diode laser's emission point and the non-linear optical crystal's laser light entrance point. In Figure **11B**, the solid line with filled circles indicates that a maximum coupling may be maintained even for placement errors exceeding 200 microns. However, if the LD has a downward emission angle, as was described previously, a coupling penalty is induced because the telecentric optics preserve this angle when the beam strikes the input facet of the crystal waveguide **70′A** of the non-linear optical crystal **70′** such as SHG. This induces the approximately 2.5% coupling penalty, although the system remains very insensitive to the exact position of the components. In order to recover the optical coupling, one may increase the lens component to mirror distance by about 300 microns. This will cause a change in ray angle that converts the 3.3° emission angle of the LD into an approximately 0 deg angle of incidence upon the SHG. The result is shown as the dashed line with open circles in **Figure 11B**. However, this also breaks the telecentricity of the system, and at placement errors of 100μm a noticeable optical coupling penalty is observed.

[0062] A solution to this problem is to build the system slightly non- telecentric, enough to correct most of the angle induced coupling penalty, but not enough to collapse the tolerances of the system. Results of such a design is shown as the dashed curve with open boxes in **Figure 11B**. This system is built with the lens to mirror distance increased by 200 microns compared to a telecentric design. This approach corrects the angled 3.3deg emission of the diode so that the angle of incidence at the SHG is about 0.97°. This configuration produces almost no optical coupling penalty for a perfectly aligned system, but also creates a wider set of placement tolerances, with the penalty for 100 μm or 150 μm of offset being about one-half of that of the system that has a lens to mirror distance set to perfectly correct the 3.3deg emission.

[0063] In order to confirm that such a "slightly off telecentric" system has a significant impact on the manufacturability of lasers, a set of Monte-Carlo optical simulations were performed. These simulations varied not only the positions of the LD and SHG, but also placement angles, tilt and position of the mirror and lens, etc. All parameters were chosen from distributions made to represent known high-volume automated manufacturing capabilities. The systems simulated assumed that the LD emission was angled downward at 3.3deg, due to the facet cleave angle and lack of mechanical compensation. If a perfectly telecentric optical system was used, then the mean coupling was 92.3%, with a two-standard deviation level coupling at >89.7%. If a system was used with the lens to mirror distance increased by 300 microns to perfectly correct the 3.3deg emission angle of the LD, then the average coupling was 94.5%, with a two-standard deviation level coupling at >93.0%. If the “slightly off telecentric” system was used – with the lens to mirror distance only increased by 200 microns compared to telecentric – then the average coupling was 94.7%, with a two-standard deviation level coupling at >93.7%. These results indicate that the distance between the lens component and the reflector should be preferably adjusted to compensate for the angled LD emission, since a few % improvement in coupling will occur. But that a system that does not perfectly compensate the angle, and is instead slightly closer to a telecentric lens to mirror distance, is actually more preferable, due to the wider placement tolerances on its components.

[0064] The second consideration in selecting the BWD is setting the optical path length of the cavity formed between the output facet of the diode laser and the input facet of the crystal waveguide **70′A** equal to that of the diode waveguide itself. The mode spacing of the cavity formed by back reflections from the crystal itself. The efficiency of the nonlinear conversion process is a sensitive function of IR laser wavelength (with the band width Δλ being on the order of 0.2 nm). This makes the green output power of the laser system sensitive to small wavelength changes in the IR light provided by the diode laser **20′**. Because diode lasers are extremely sensitive to even minute amounts of feedback, the input facet of the crystal waveguide **70′A** is anti-reflection coated and angle cleaved to minimize reflections and hence feedback into the diode laser **20′**. Even so, there can still be enough reflection and back scatter to influence the mode selection of the diode laser **20′**. If this feedback changes as a function of time, through thermal changes of the cavities formed by any of the optical components of laser system **10**, or other environmental change, then the diode laser **20′**can experience mode hoping, and output power (green light out put power) of the laser system will fluctuate. One way of minimizing the impact of these changes is to ensure that the external cavity (formed by the input facet of the crystal waveguide **70′A** and output facet of diode waveguide **20′A)** is approximately the same free spectral range as that of the diode laser itself. The mode spacing, or the spectral range of the an optical cavity is determined by the following equation:

$$\Delta\lambda_{FSR} = \frac{\lambda^2}{2nL}$$

where, λ is the laser wavelength (e.g. the IR wavelength of the diode laser) and L is the optical cavity length (e.g., of the diode waveguide), and n is the index of refraction inside the cavity (e.g., inside the diode laser cavity formed by the diode laser **20′**). For example, the mode spacing of a 3 mm long InGaAs infrared diode laser **20′** is approximately 0.06 nm. This means that in this example the required OPL between input facet of the crystal waveguide **70′A** and out put facet of diode waveguide **20′** can be achieved by using a lens component **30** with focal length f of about 1.5 mm.

[0065] **Figure 12** illustrates the optical path length between the diode waveguide **20′A** and the waveguide crystal **70′A** as a function of BWD (lens to mirror spacing), for two different exemplary lens components. The desired optical path length is 9.36mm, which matches the cavity mode spacing of the diode laser **20′**. **Figure 13** illustrates the coupling efficiency as a function of BWD for the same two exemplary lens components. As is shown in **Figure 13**, only small adjustments (hundreds of microns or less) of the BWD away from the optimal coupling distance of are needed to create the optimal optical path length.

Examples

[0066] The invention will be further clarified by the following examples.

EXAMPLE 1

[0067] **Figure 14** illustrates the lens component **30** shown in **Figure 11**. In this exemplary embodiment the lens component **30** of **Figures 2** and **3** is optimized to provide RMS (root mean square) wave front error (WFE) of less than 0.1λ for a ±200 μm field at the 1060 nm wavelength, over a numerical aperture NA of 0.4, and to have a combination of the focal length and thickness such that the optical path length between the light source and the receiver is 9.36 mm.

[0068] The radii of curvature (r_1, r_2), thickness Th (vertex to vertex), and aspheric coefficients of the lens component **30** are selected to advantageously:

1. minimize coma and astigmatism, (the 2 worst aberrations for system performance);
2. obtain a large field of view: low field aberration combined to a large aperture (e.g., NA=0.4), such that the laser system has good coupling efficiency for separation of

400 μm (d=350 μm, ±25 μm) between the waveguide portion of diode laser **20′** and the waveguide portion of non-linear optical crystal **70′**; and

3. provide proper combination of focal length and thickness to allow the laser system **10** to work in coupled cavity condition, such that the cavity formed between the output facet of the diode laser **20′** and the input facet of the non-linear optical crystal **70′** (e.g., second harmonic generating (SHG) crystal) has the same optical path length as that of the diode laser cavity.

[0069] As described above, the lens component **30** has a front surface S1 and a rear surface S2. Preferably, the front surface S1 is convex and aspheric with a radius of curvature r_1. Preferably, the rear surface is convex and aspheric with a radius of curvature r_2 such that $|r_1| > |r_2|$.

[0070] The lens component **30** of **Figure 14** has the following characteristics: (I) it allows the laser system to be in a coupled cavity condition (OPL between the diode laser and the non linear optical crystal equals that of the diode laser within +/-0.05 mm): OPL= (0.9 mm + 1.744 mm x1.5 + 1.18 mm) x 2 = 9.39 mm; and (II) has the following parameters: (i) FWD = 0.90 mm; (ii) thickness T (vertex to vertex) of 1.74 mm; (iii) focal length: f = 1.76 mm; (iv) glass index of refraction N at 1060 nm is 1.5; (v) effective diameter of the front surface S1 is 1.4 mm; (v) effective diameter of the rear surface S2 is 2 mm; (vi) NA = 0.61; (vii) outer diameter of the lens component is 2.5 mm to 3 mm.

[0071] The surface sag of the surfaces s1 and s2 is given by the following equation:

$$z = \frac{c \times r^2}{1 + \sqrt{1 - (1+k)c^2 \times r^2}} + \alpha 1 \times r^2 + \alpha 2 \times r^4 + \alpha 3 \times r^6 + \alpha 4 \times r^8 + \ldots$$

where c is the radius of curvature, r is the radial distance from the lens component's center and k = conic coefficient.

[0072] The surface parameters of the lens component **30** of **Figure 14** are given in Table 1 below.

Table 1

Parameters	S1	S2
radius	1.716884	-1.193855
k	-7.316630	-0.795432
α1	0	0
α2	0	0
α3	0	$4.107084.10^{-3}$
α4	0	$1.121478.10^{-3}$

[0073] **Figure 15** illustrates the performance of the lens component **30** suitable for use in laser systems **10**, and also the performance of two exemplary commercial aspherical lenses typically used for coupling applications. As described above, the output facet of the waveguide of the infrared diode **20′** and the front facet of the waveguide of the nonlinear optical crystal **70′** are separated by a small distance d. **Figure 15** illustrates that the lens component **30** has a higher coupling efficiency than two commercially available aspherical coupling lenses with similar focal lengths. For example, the lens component **30** maintains about 90% of the maximum coupling efficiency or higher when output facet of the waveguide of the infrared diode **20′** and the front facet of the waveguide of the nonlinear optical crystal **70′** are separated by the distance d of up to 450 μm (0.45 mm), while the other two lenses maintained 90% of the maximum coupling efficiency for d values of only 350 μm and 215 μm respectively. Similarly, lens component **30** maintains coupling efficiency of about 80% of the maximum coupling efficiency or higher when output facet of the waveguide of the infrared diode **20′** and the front facet of the waveguide of the nonlinear optical crystal **70′** are separated by the distance d of about 560 μm, while the other two lenses maintained 80% of the maximum coupling efficiency for d values of only about 360 μm and 270 μm respectively.

EXAMPLE 2

[0074] **Figure 16** illustrates another exemplary lens component **30** suitable for use in the laser systems **10**. The lens component **30** of **Figure 16** has the following characteristics:

(I) it allows the laser system to be in a coupled cavity condition (OPL between the diode laser and the non linear laser system equals that of the diode laser within +/-0.05 mm;

(II) and has the following parameters: (i) FWD = 0.568 mm; (ii) thickness Th (vertex to vertex) of 1.82 mm; (iii) focal length: f = 1.4 mm; (iv) glass index of refraction N at 1060 nm is 1.784; (v) NA = 0.4.

[0075] The surface parameters of the lens component **30** of **Figure 16** are given in Table 2 below.

Table 2

wave length	1060
Lens Thickness	1.821
Refractive Index at 1060nm	1.783918
Focal length	1.400
FWD	0.568
Diameter on MEMS (NA=0.4)	1130.500

	R1(Laser side)	R2(Collimated side)
R	2.09063E+00	-1.36564E+00
C	0.47832	-0.73226
K	-15.82514	-0.90661
A4	0.00000E+00	0.00000E+00
A6	0.00000E+00	-2.82400E-03
A8	0.00000E+00	2.45183E-03

EXAMPLE 3

[0076] **Figure 17** illustrates the lens component **30** suitable for use in the laser systems **10**. The lens component **30** of **Figures 2** and **3** has the following characteristics:

(I) it allows the laser system to be in a coupled cavity condition (OPL between the diode laser and the non linear laser system equals that of the diode laser within +/-0.05 mm;

(II) and has the following parameters: (i) FWD = 1.01 mm; (ii) thickness Th (vertex to vertex) of 1.578 mm; (iii) focal length: f = 1.789 mm; (iv) glass index of refraction N at 1060 nm is 1.5; (v) NA = 0.4.

[0077] The surface parameters of the lens component **30** of **Figure 17** are given in Table 3 below.

Table 3

Aspherical Parameters

Sag

Sag = C h ^2 / (1+((1-(1+K)×C^2×h^2))^0.5) +A4h^4+A6h^6+ · · · +A16h^16

h; radius

wave length	1060
Lens Thickness	1.578
Refractive Index at 1060nm	1.502905
Focal length	1.789
FWD	1.014
Diameter on MEMS (NA=0.4)	1.455

	R1(Laser side)	R2(Collimated side)
R	1.88440E+00	-1.22554E+00
C	0.53067	-0.81596
K	-8.60874	-0.80335
A4	0.00000E+00	0.00000E+00
A6	0.00000E+00	2.72444E-03
A8	0.00000E+00	6.31269E-04

Lens Component optimization

[0078] A conventional way to optimize lens systems consists in putting all the optical elements in their nominal position and let the optical design software find a local minimum for a given optimization function. Also, in order to make the positioning tolerances of the optical components as large as possible, the usual optimization method consists of minimizing the aberrations in the intermediate spaces (i.e. between the optical components). That is, during typical optimization the lens designer tries to verify that, after each optical surface that provides optical power, the wave front is as close as possible to a perfect (spherical or plane) wave front. This is usually done by including some constraints over the Seidel coefficients (aberrations) in the intermediate spaces (i.e., in spaces between different surfaces and between optical elements) into the optimization function.

[0079] By applying this method to the folded configuration, we obtained excellent results with diode laser to PPLN crystal distances d of up to 0.5 mm. Unfortunately, all the designs that we obtained using this type of optimization had very tight manufacturing and assembly positioning tolerances, the most critical being probably the tilt of the lens component, which was limited to about 1 degree or less.

[0080] The impact of the slight tilt on either the lens component **30** or the mirror **50** is mostly to introduce some coma and astigmatism, both of which contribute to a coupling degradation (less efficient coupling between the diode laser and the non linear optical crystal).

[0081] **Figure 18** illustrates the evolution of the wave front error as a function of the tilt of one exemplary lens component **30**). In this calculation, the distance d between the diode laser and the PPLN crystal is kept constant (0.35mm) and the focus is adjusted for each value of the lens tilt. As the tilt increases, both the amplitudes of coma and astigmatism (which are the predominant aberrations) increase. The consequence is that the wave front error is very small when there is not lens tilted, but it rapidly degrades as the tilt increases.

[0082] In order to relax the tolerances, we tried another optimization method. The lens component that resulted from that optimization is very similar to the previous one in term of shape and aspherization. However, tolerance analysis indicates that tolerance on lens tilt, mirror angle, are relaxed by factor of 5. In order to understand where that relaxation is coming from, we calculated again the variation of the aberrations as a function of the tilt of the lens. As can be seen on **Figure 19,** the astigmatism curve is not at a minimum when the tilt is at zero and actually decreases as the tilt of the lens increases. This basically means that, when all the components are at their nominal position without tilt, the design presents some residual astigmatism that compensates the one that appears when the tilt of the lens increases.

[0083] The consequence is that the total aberrations remain relatively flat over a wide range of angular tilt of the lens. In other words, the nominal design can accommodate a much larger range of positioning tolerances.

[0084] **Figure 20** illustrates the coupling efficiency calculated for both designs versus the tilt of the lens and the tilt of the mirror respectively. As can be seen, tolerances are dramatically improved without any significant impact on the coupling when the components are at their nominal position.

[0085] This analysis shows that positioning tolerances can be dramatically improved by introducing some residual astigmatism into the design. That astigmatism compensates the one that is generated by the components misalignments which makes the system much more forgiving to positioning tolerances.

[0086] It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. A folded laser system having an optical axis, said laser system comprising:

(I) a coherent light source;

(II) a reflector; and

(III) a lens component situated between the light source and the reflector;

(IV) a non-linear optical crystal, wherein the light source and the non-linear optical crystal are situated substantially symmetrically with respect to the optical axis, and are separated by a distance d>50μm and an air gap;

wherein: (a) the lens component is positioned to provide a collimated beam when intercepting light from the light source, such that the collimated beam is at an angle Θ′ to the optical axis, (b) the reflector is situated to intercept the collimated beam and to reflect the collimated beam to the non-linear optical crystal through the lens; and; and (c) the lens component is structured to provide an image of the coherent light source on the non-linear optical crystal.

2. The laser system according to claim 1, wherein (i) the coherent light source is a diode laser, and the non-linear optical crystal and the diode laser are tilted with respect to one another; and/or (ii) the light from said light source traverses the lens component twice before it reaches said receiver.

3. The laser system according to claim 1, wherein the non-linear crystal is cantilevered over the diode.

4. The laser system according to claim 1, wherein: (i) the coherent light source is a diode laser and the non linear crystal is held using the face of the crystal that is furthest away from the diode laser; and/or (ii) said laser system is characterised by astigmatism of more than 0.05 waves RMS, and less than 0.1 waves RMS.

5. The laser system according to claim 1, wherein d <500 μm.

6. The laser system according to claim 1, wherein: (i) the reflector is located in the focal plane of the lens component, such that the direction of the average emission angle of the

light source is parallel to the average beam angle on the receiver; and/or (ii) said lens component is situated to image at a magnification M and $0.9 \leq |M| \leq 1.1$.

7. The laser system of claim 1, wherein: (i) said light source is a diode laser, and the OPD from the receiver to the diode laser essentially equals OPD inside the diode laser; and/or (ii) the optical path distance OPD is less than 10 mm.

8. The laser system according to claim 1-7, said lens component is a bi-aspheric singlet with a numerical aperture NA of 0.35 to 0.6; and focal length f, wherein1 mm $\leq f \leq$ 3 mm.

9. The laser system according to claim 1-7, wherein the front working distance FWD of the lens component is 0.3 mm to 3 mm and the back working distance BWD of the lens component is 1.5 mm to 3 mm.

10. The laser system of claim 1, wherein

(a) the lens component is positioned to provide a collimated beam when intercepting light from the light source; and

(b) the reflector is situated to intercept the collimated beam and to reflect the collimated beam to the non-linear optical crystal through the lens; and such that the collimated beam is at an angle Θ' to the optical axis wherein angle Θ' is: 0.05 RAD $\leq \Theta$ is $\leq$ 0.2RAD, when the light source is located in a focal plane of said lens, and is decentered from the optical axis of the lens component by a distance d' $\leq$750 μm.

11. The laser system according to claim 10, wherein said angle Θ' is: 0.09 RAD $\leq \Theta'$ is $\leq$ 0.17 RAD.

12. The laser system according to claim 1 or 10, said lens component having

(a) a front surface and a rear surface, the front surface is convex and aspheric with a radius of curvature r_1, the rear surface is convex and aspheric with a radius of curvature r_2 such that $|r_1| > |r_2|$;

(b) NA of 0.35 to 0.5; and

(c) focal length of 1 mm to 3 mm.

13. The laser system according to claim 1, wherein: (i) the reflector is located in the image focal plane of the lens component, such that the direction of the average emission angle of the light source is parallel to the average beam angle on the receiver; and/or (ii) the diode laser is mounted at angle that compensates for the cleave angle of the diode, such that centroid of the emitted beam from the laser diode is parallel to that of the lens component's optical axis.

14. The laser system according to claim 1 or 10, wherein the spacing **z** between the reflector and the principal plane of the lens component is between $EFL \leq z \leq 1.2EFL$.

15. The laser system according to claim 14, wherein the angle of the centroid of the incident beam on the input facet of the non-linear optical crystal is less than 1^{o} when the exit angle of the centroid of the beam provided by the coherent light source is between 1^{o} and 5^{o}, relative to the optical axis of the laser system.

FIG. 1A

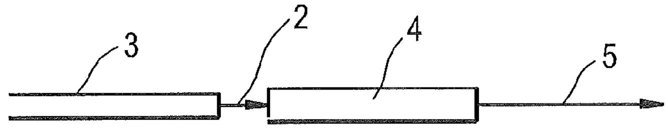
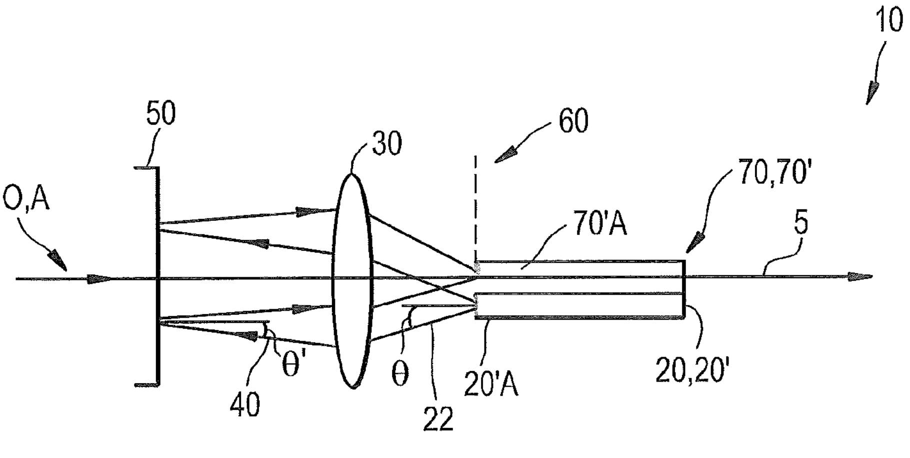


FIG. 1B



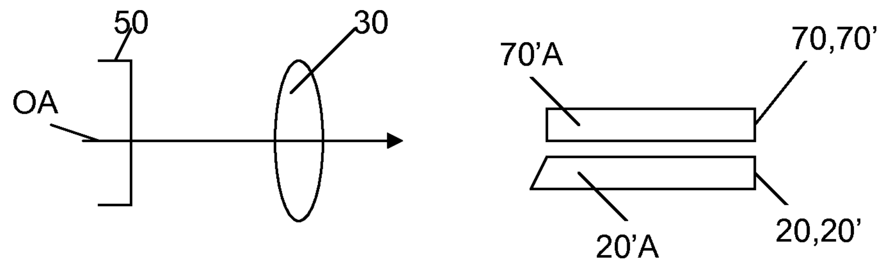


Fig. 1C

FIG. 2

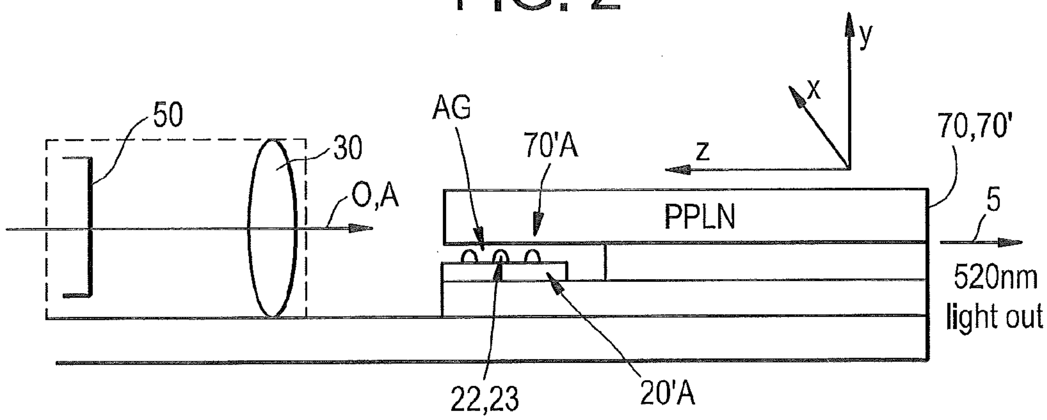

50
30
O,A
AG
70'A
y
x
z
70,70'
PPLN
5
520nm
light out
22,23
20'A

FIG. 3

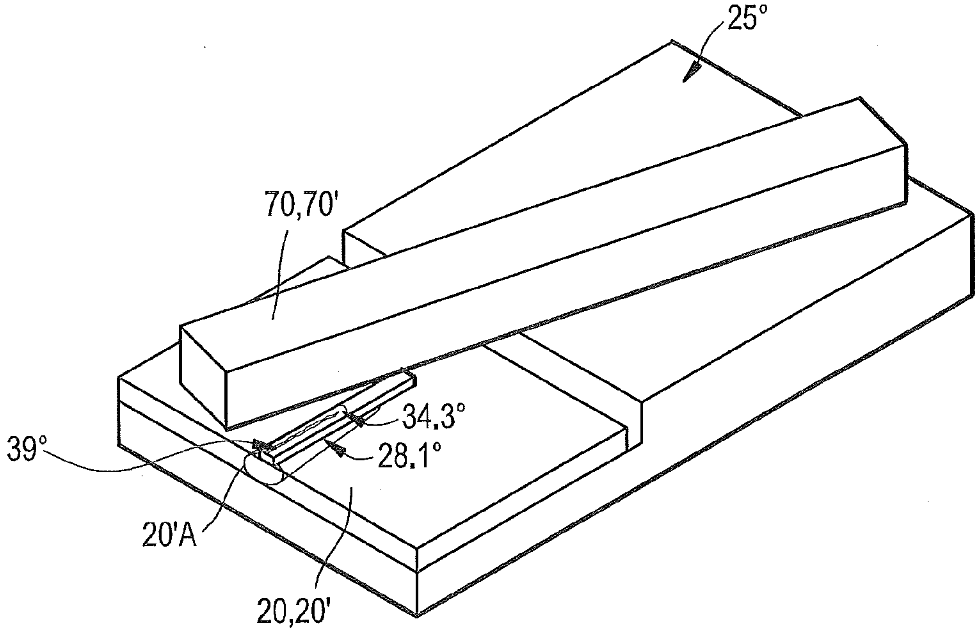

25°
70,70'
34.3°
39°
28.1°
20'A
20,20'

FIG. 4

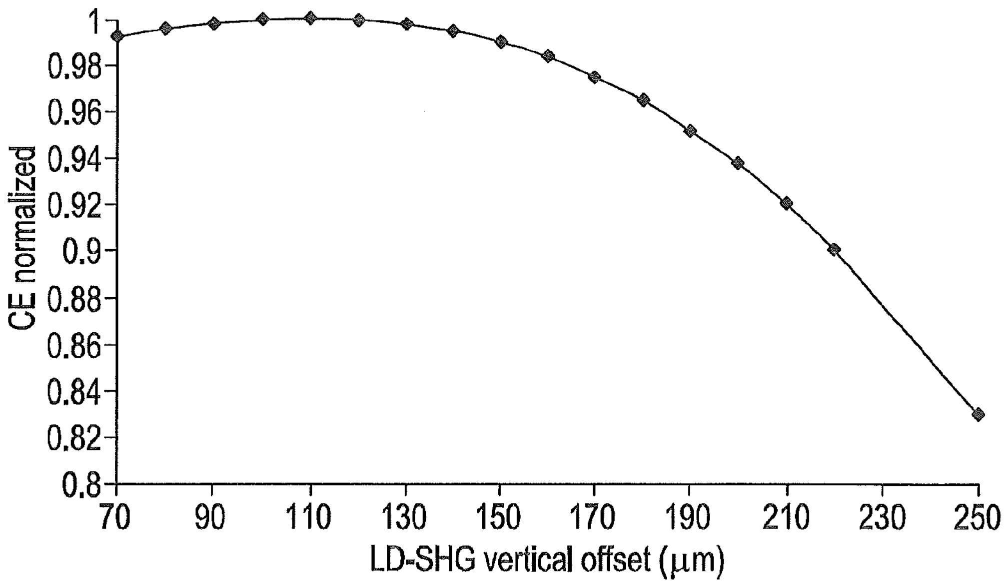


FIG. 5A

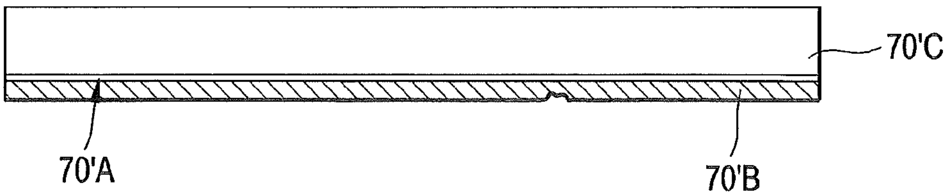


FIG. 5B

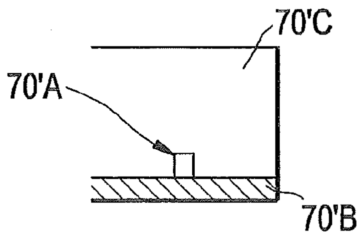


FIG. 6

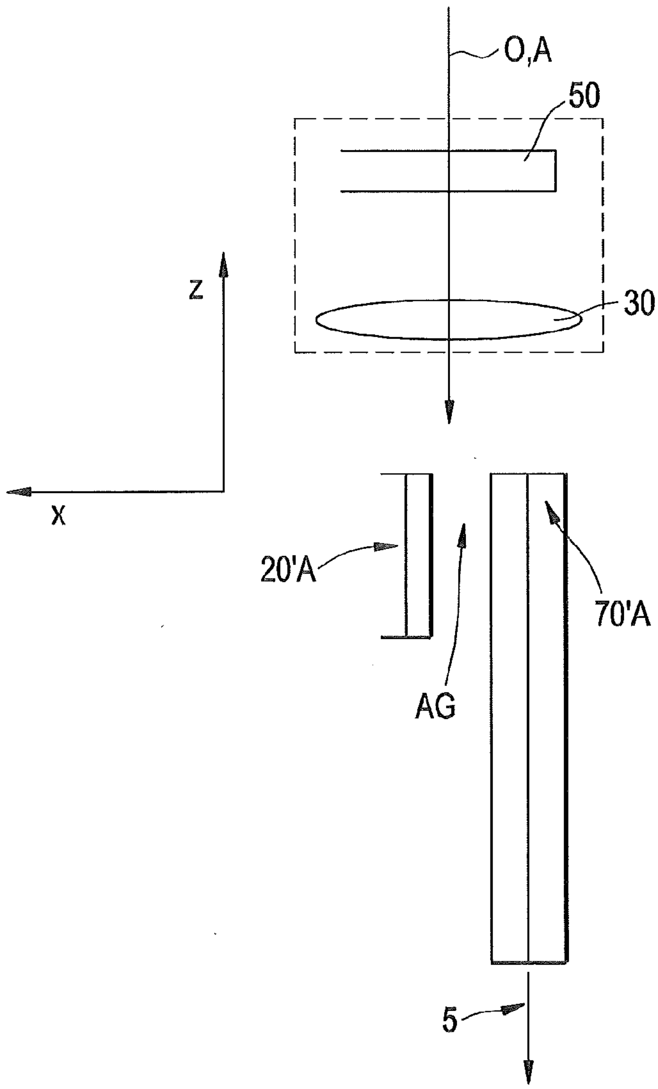


FIG. 7

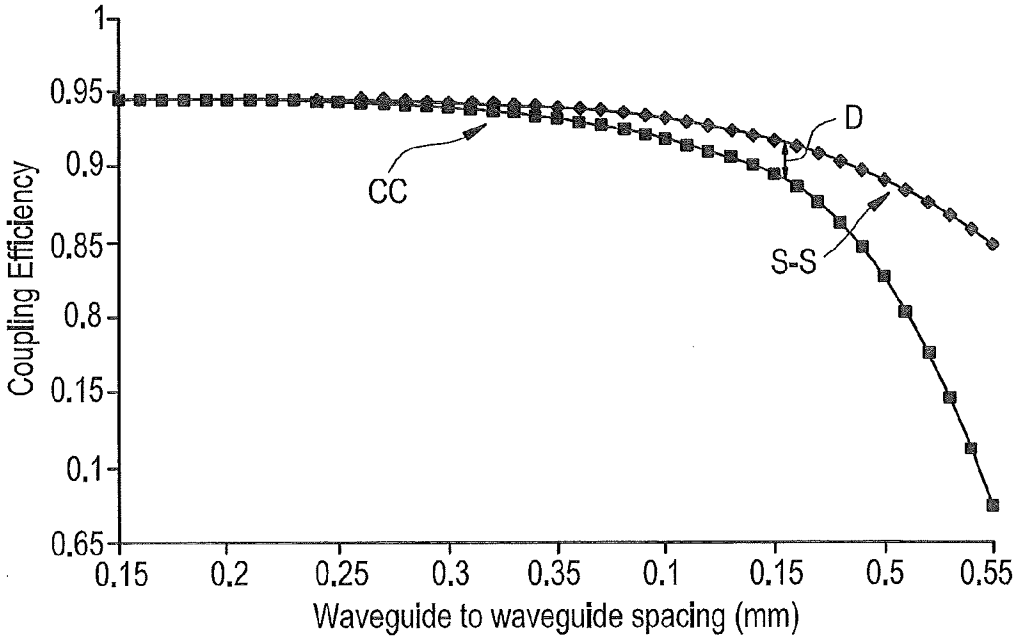

1
0.95
0.9
0.85
0.8
0.15
0.1
0.65
Coupling Efficiency
D
CC
S-S
0.15
0.2
0.25
0.3
0.35
0.1
0.15
0.5
0.55
Waveguide to waveguide spacing (mm)

FIG. 8A

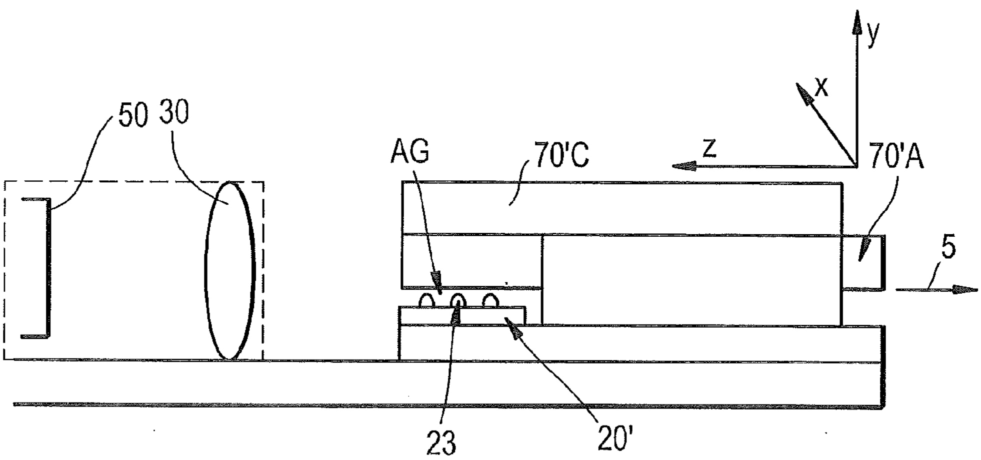


FIG. 8B

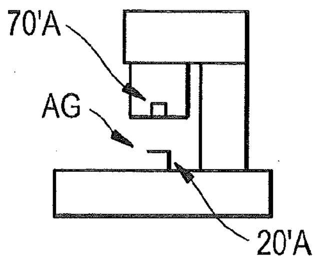


FIG. 9

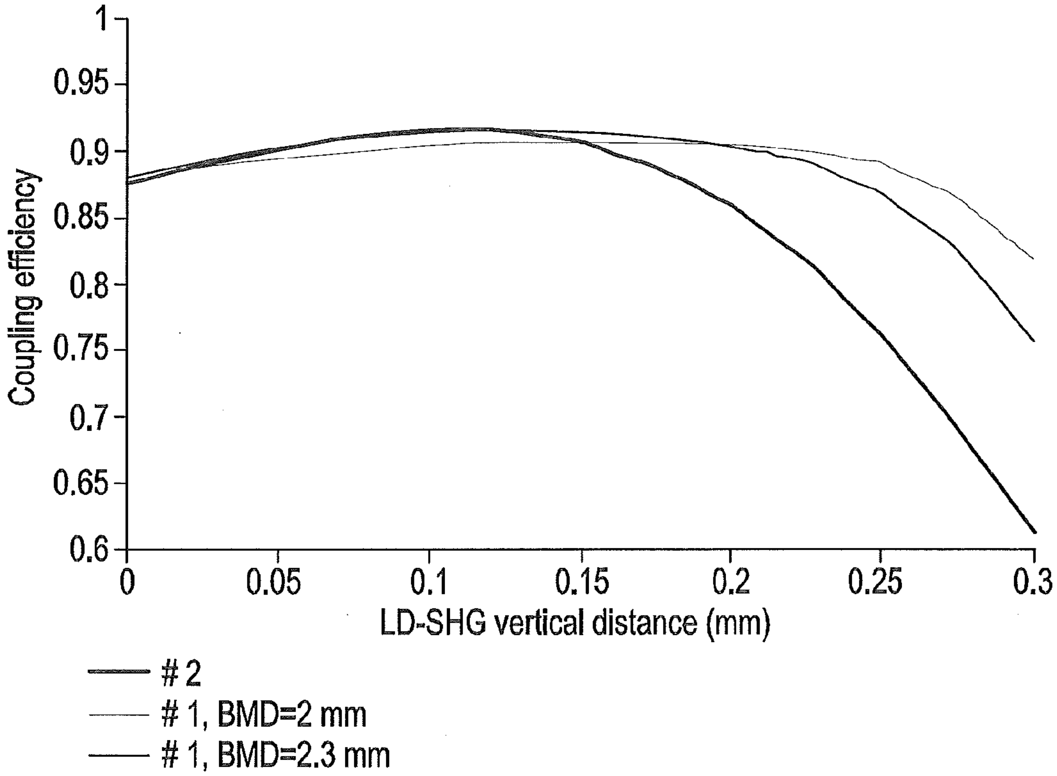


FIG. 10A

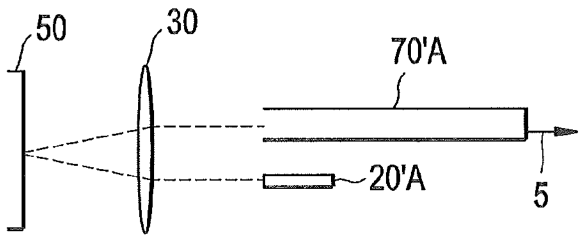
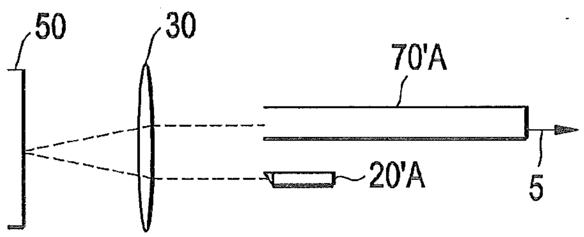


FIG. 10B



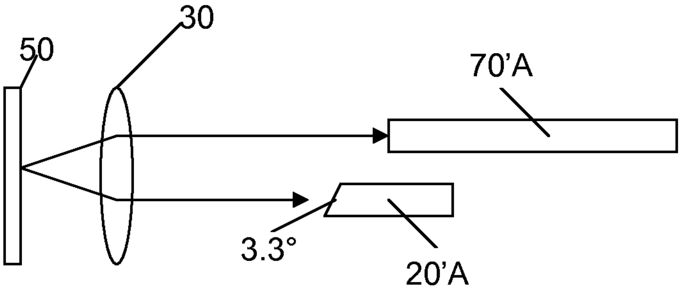


Fig. 10C

Fig 11A

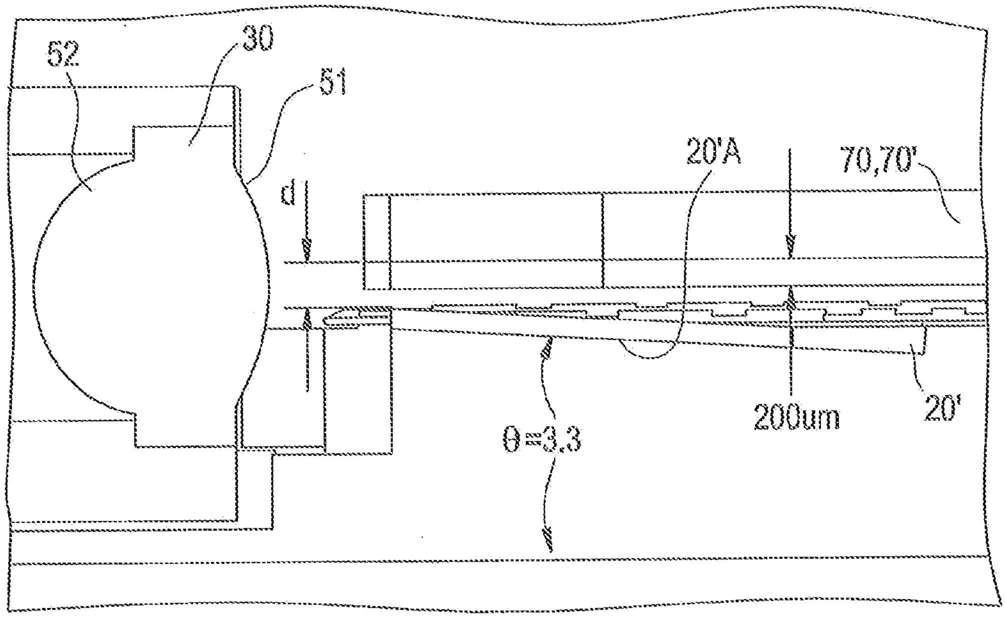


Fig 11B

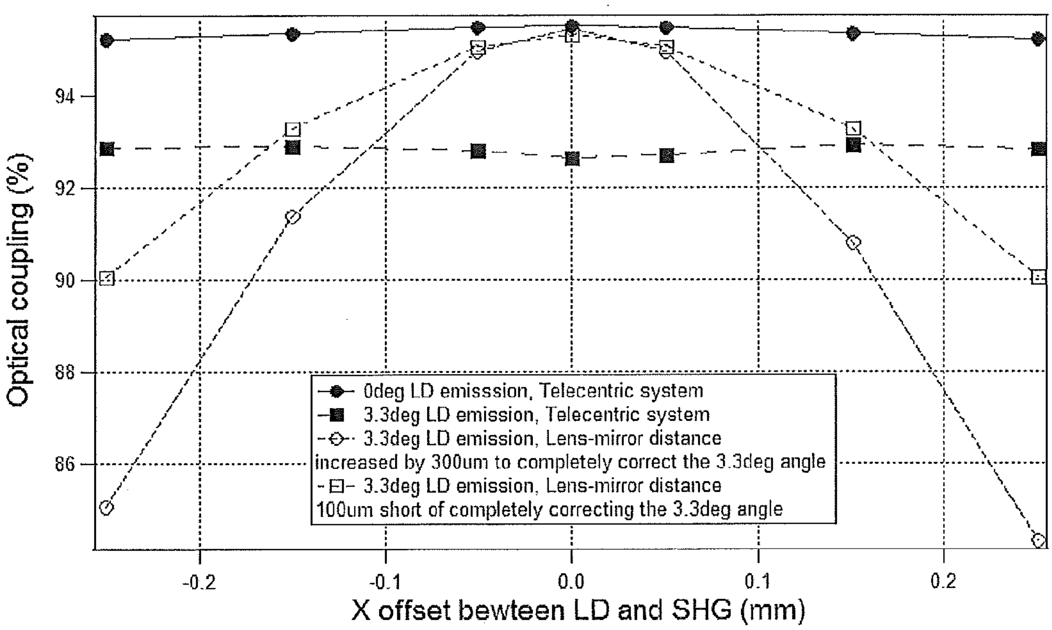

94
92
90
88
86
Optical coupling (%)
-0.2
-0.1
0.0
0.1
0.2
X offset bewteen LD and SHG (mm)
0deg LD emisssion, Telecentric system
3.3deg LD emission, Telecentric system
3.3deg LD emission, Lens-mirror distance
increased by 300um to completely correct the 3.3deg angle
3.3deg LD emission, Lens-mirror distance
100um short of completely correcting the 3.3deg angle

FIG. 12

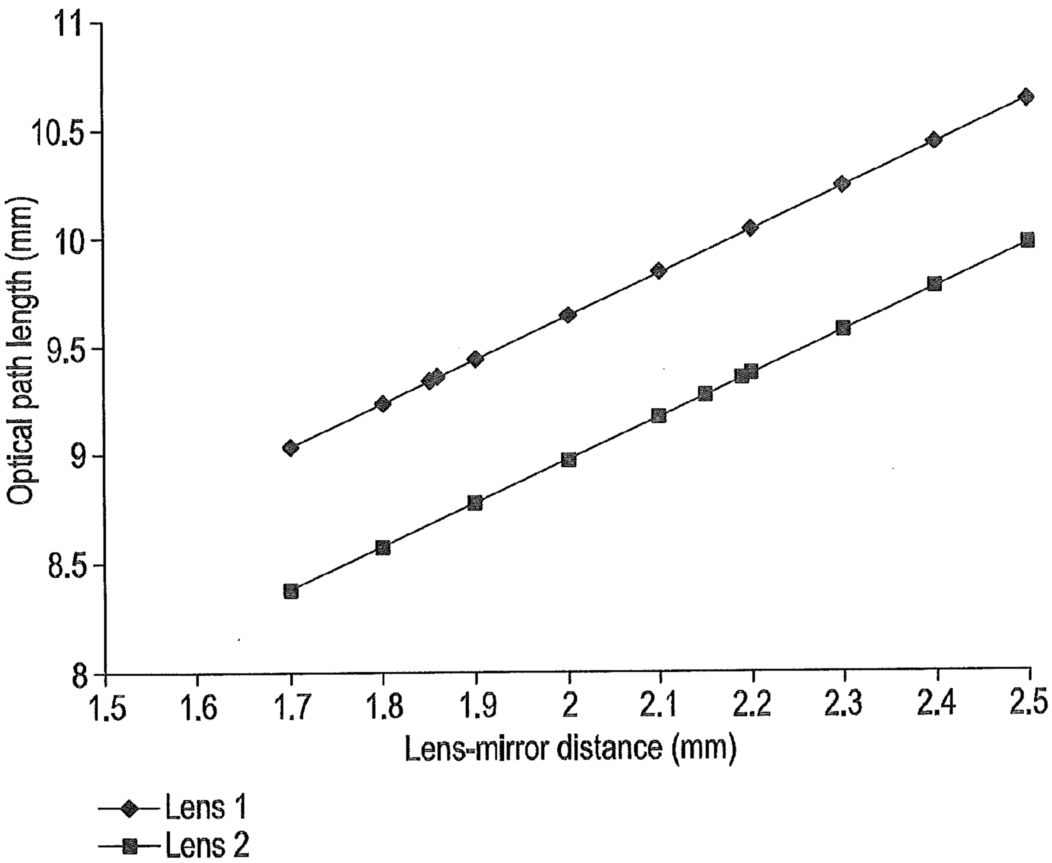
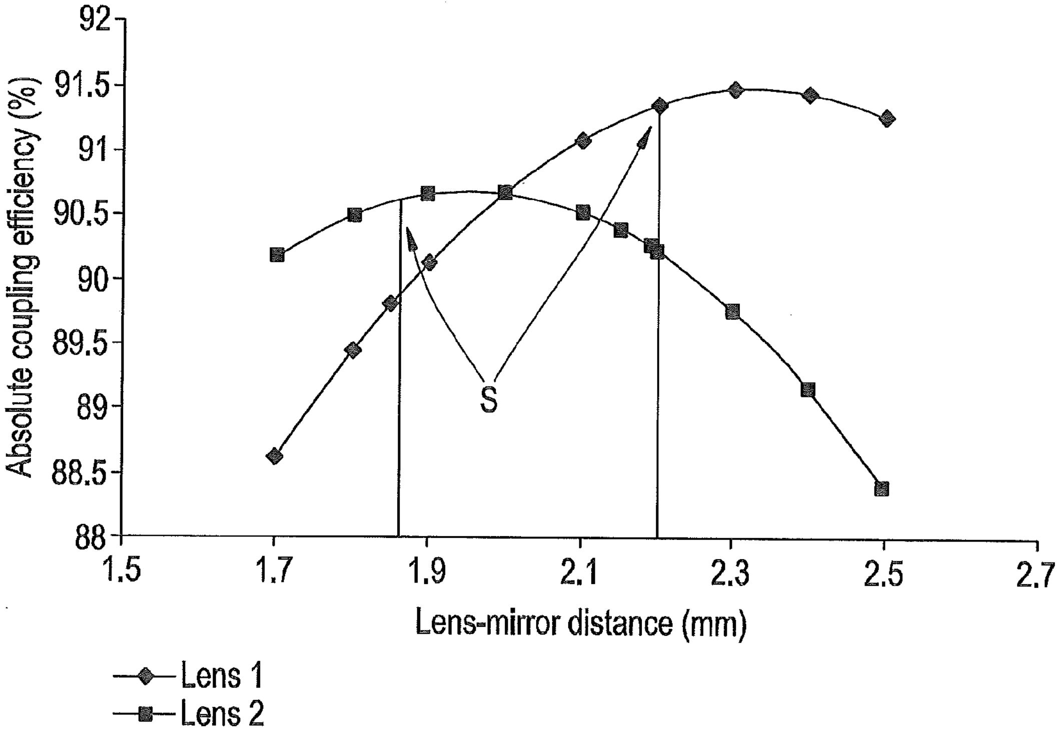

11
10.5
10
9.5
9
8.5
8
Optical path length (mm)
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
2.5
Lens-mirror distance (mm)
Lens 1
Lens 2

FIG. 13



Absolute coupling efficiency (%)
92
91.5
91
90.5
90
89.5
89
88.5
88
1.5
1.7
1.9
2.1
2.3
2.5
2.7
Lens-mirror distance (mm)
S
Lens 1
Lens 2

FIG. 14

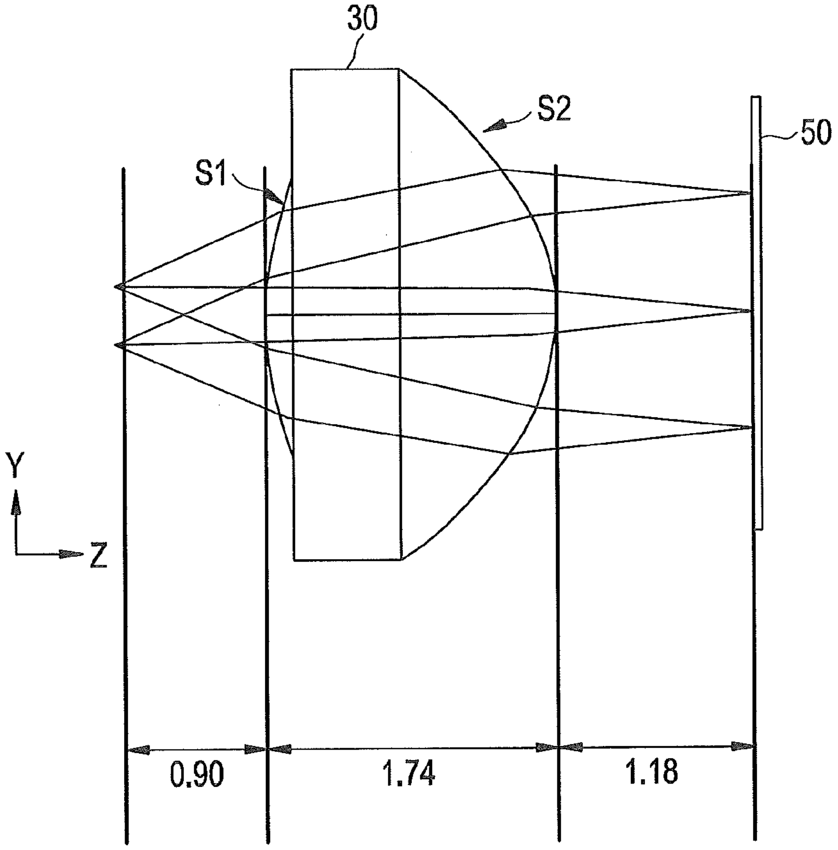


FIG. 15

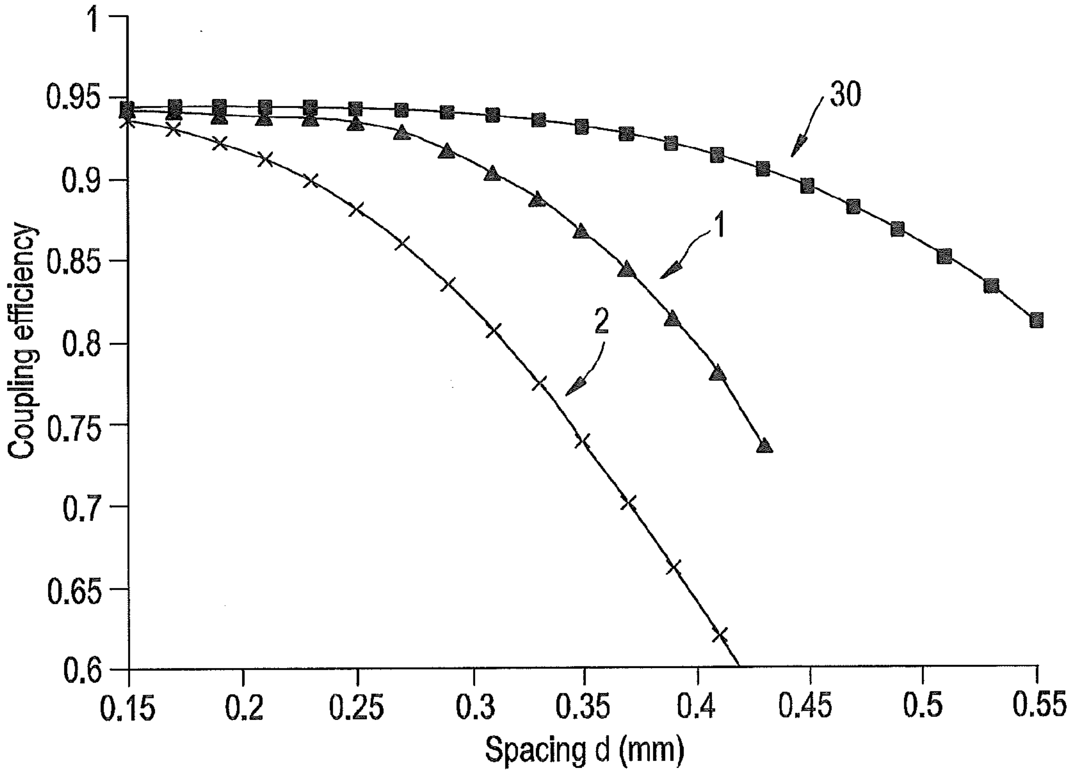

1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Coupling efficiency
30
1
2
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
Spacing d (mm)

FIG. 16

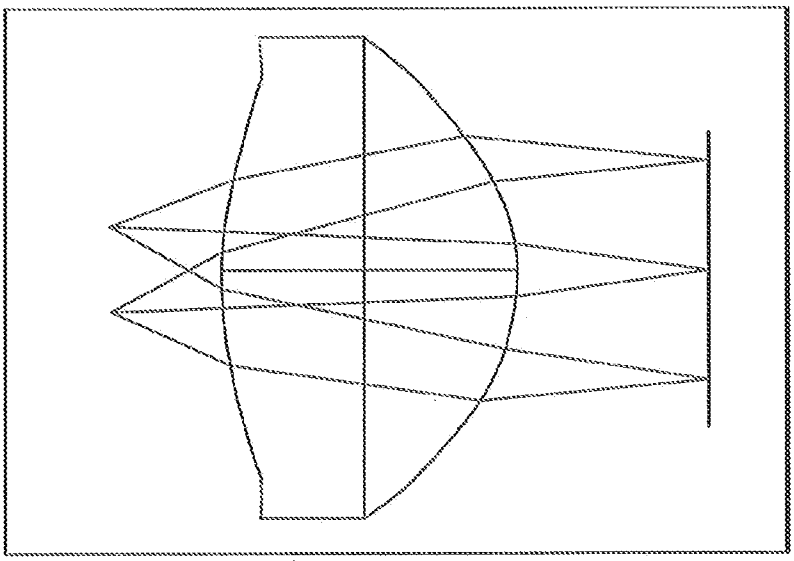


FIG. 17

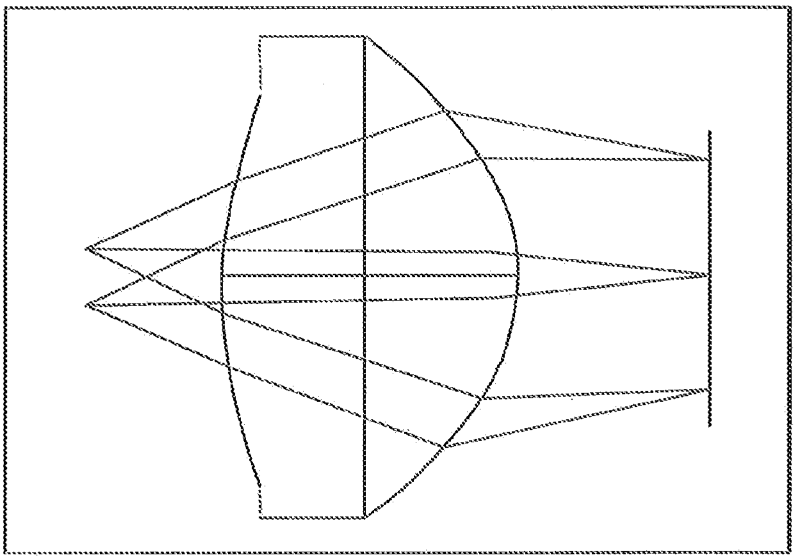


FIG. 18

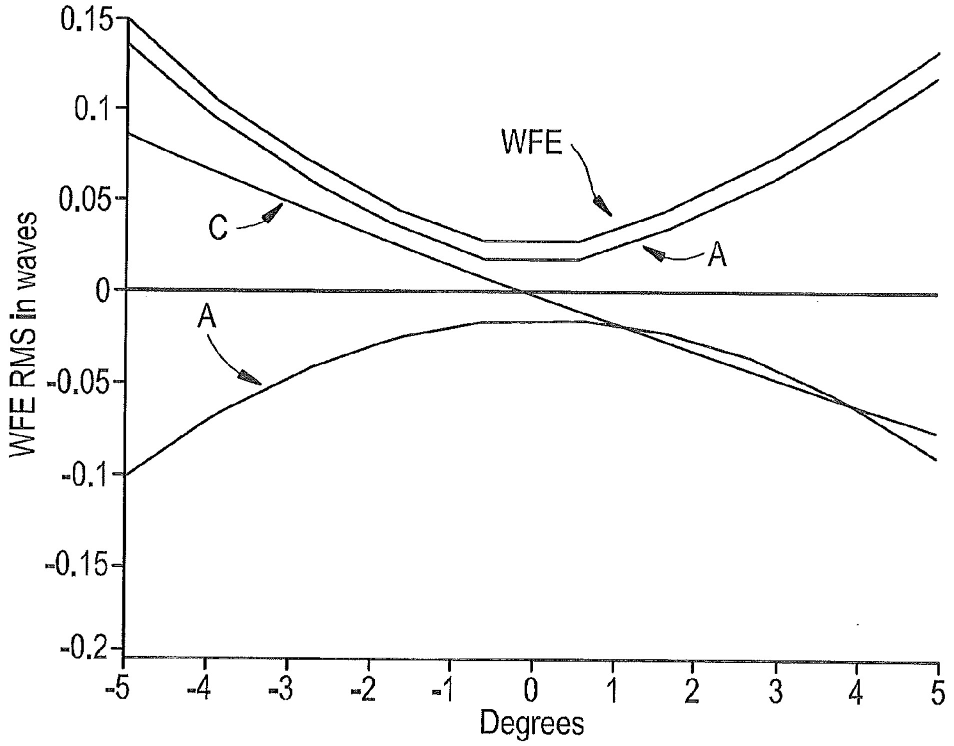

0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
WFE RMS in waves
-5
-4
-3
-2
-1
0
1
2
3
4
5
Degrees
WFE
C
A
A

FIG. 19

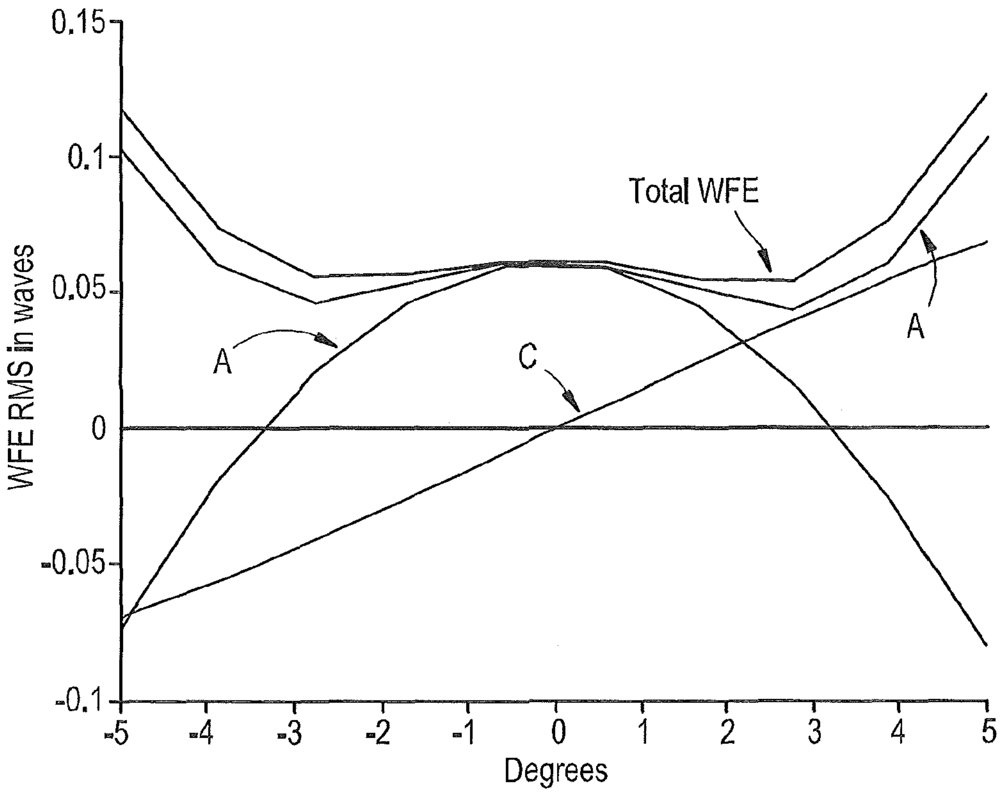
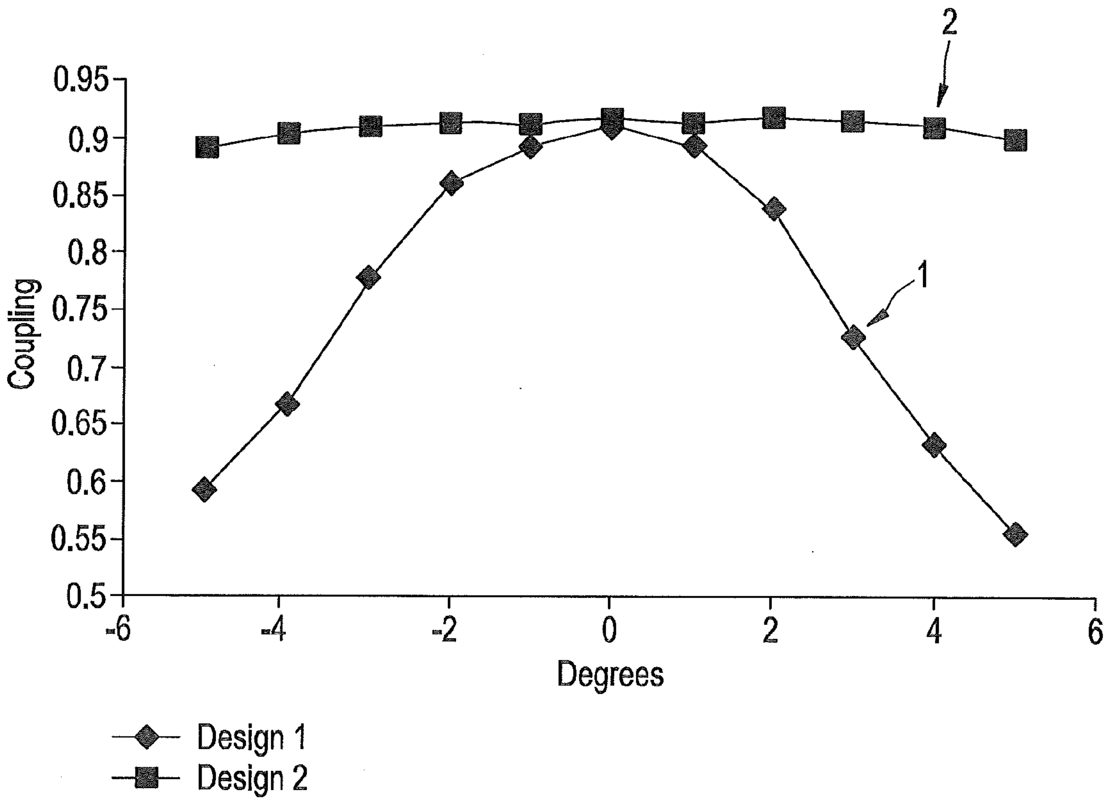

0.15
0.1
0.05
0
-0.05
-0.1
WFE RMS in waves
-5
-4
-3
-2
-1
0
1
2
3
4
5
Degrees
Total WFE
A
A
C

FIG. 20


2
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
Coupling
-6
-4
-2
0
2
4
6
Degrees
Design 1
Design 2

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2011/045156

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01S5/022 H01S5/00
ADD. G02B6/42 G02B26/08 G02B3/02 G02F1/377

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)
H01S G02F 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, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2009/151558 A1 (CORNING INC [US]; CHAPARALA SATISH C [US]; HUGHES LAWRENCE C JR [US]) 17 December 2009 (2009-12-17) paragraphs [0020] - [0031]; figures 1B-1E	1-15
Y	US 2009/190131 A1 (GOLLIER JACQUES [US] ET AL) 30 July 2009 (2009-07-30) paragraphs [0014] - [0021], [0038], [0039]; figures 1-4	1-15
X,P	WO 2010/127060 A1 (CORNING INC [US]; ALMORIC ETIENNE [FR]; GOLLIER JACQUES [US]; HUGHES L) 4 November 2010 (2010-11-04) the whole document	1-15
	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 October 2011	28/10/2011

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Riechel, Stefan

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2011/045156

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	WO 2010/099252 A2 (CORNING INC [US]; GOLLIER JACQUES [US]) 2 September 2010 (2010-09-02) the whole document -----	1-15

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2011/045156

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2009151558 A1	17-12-2009	NONE	
US 2009190131 A1	30-07-2009	CN 101960347 A	26-01-2011
		EP 2238490 A1	13-10-2010
		JP 2011511318 A	07-04-2011
		KR 20100106604 A	01-10-2010
		WO 2009097109 A1	06-08-2009
WO 2010127060 A1	04-11-2010	NONE	
WO 2010099252 A2	02-09-2010	US 2010214652 A1	26-08-2010