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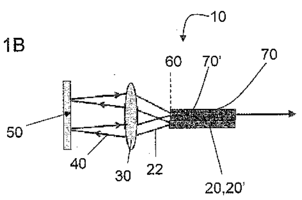
Fig. 1B



(57) **Abstract**: An optical system having an optical axis, the optical system comprising: (I) a light source; (II) a reflector; (III) a lens component situated between the light source and the reflector; (IV) a receiver, wherein the light source and the receiver are situated substantially symmetrically and are decentered with respect to the optical axis, and are separated by a distance d from one another; 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 receiver through the lens; and such that the collimated beam is at an angle Θ' to the optical axis; and (c) the lens component 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 is not misaligned with respect to the average emission angle of the light source; and (ii) astigmatism of less than 0.05 for tilt angles of 2 to 5 degrees, when the lens component is tilted by of 2 to 5 degrees with respect to the average emission angle of the light source.

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FOLDED OPTICAL SYSTEM AND A LENS FOR USE IN THE OPTICAL SYSTEM

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention relates generally to optical systems and more particularly to folded laser system and lenses for use in such systems.

Technical Background

[0002] Generation of green laser light can be achieved by non-linear frequency doubling of infrared light. Typically, as illustrated in laser system of **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. In order to provide the light from the infrared diode laser to the non-linear optical crystal a lens 6 is placed between the infrared diode laser (3) and the non-linear optical crystal 4. The lens 6 intercepts the infrared light from the diode laser 3, and couples this light into the non-linear optical crystal 4.

[0003] However, because the laser systems utilize small optical waveguides that are used to confine the light in both the diode laser and the non-linear optical crystal, alignment tolerances for the components (lens, the non-linear crystal and the diode laser) are on the order of a few tenths of microns or less. This presents a challenge both for initial assembly of the laser system and for maintaining component alignment over the laser's lifetime.

SUMMARY OF THE INVENTION

[0004] One aspect of the invention is an optical system having an optical axis, the optical system comprising: (I) a light source; (II) a reflector; (III) a lens component situated between the light source and the reflector; (IV) a receiver, wherein the light source and the receiver are situated substantially symmetrically and are decentered with respect to the optical axis, and are separated by a distance d from one another; 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 receiver through the lens; and such that the collimated beam is at an angle Θ' to the optical axis; and (c) the lens component 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 is not misaligned with respect to the average emission angle of the light source; and

(ii) astigmatism of less than 0.05 for tilt angles of 2 to 5 degrees, when the lens component is tilted by of 2 to 5 degrees with respect to the average emission angle of the light source.

[0005] According to some embodiments the optical 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 green light.

[0006] We have also discovered that the fine structure on the input facet (i.e., the front facet) of the waveguide portion of the non-linear optical crystal can scatter light back toward the diode laser and may cause the diode laser wavelength to undergo mode hops, which can greatly affect IR-to-green conversion efficiency and hence introduce image artifacts.

[0007] In some embodiments of the present invention, the optical path length OPL from the output facet of the diode laser to the input facet of the non-linear optical crystal is approximately (within ±10%) equal to n times the optical path length inside the diode laser itself, where n is an integer. Preferably n=1.

[0008] Some advantages provided by the exemplary green laser embodiments of the optical system of the present invention is relatively loose angular alignment tolerances for the reflector and the lens component (e.g., on the order of 5 degrees) and low sensitivity to parasitic reflections occurring on the input facet of the non-linear crystal.

[0009] In another aspect, the present invention includes a lens situated on an optical axis, the lens comprising: (I) a front surface; (II) a rear surface separated from said front surface by a distance T; the lens being structured to: (A) provide, when imaging an off-axis source displaced by a distance d' from the optical axis, a collimated beam exiting said rear surface, such that the collimated beam is at an angle Θ' to the optical axis; and (B) to intercept said collimated beam, when coupled with a reflective surface, and to provide an image of the off-axis source, the image having:

(a) astigmatism of more than 0.05 waves RMS when the lens component is not misaligned with respect to the optical axis; and

(b) astigmatism of less than 0.05 waves RMS for tilt angles of 2 to 6 degrees when the lens component is tilted by 2 to 5 degrees with respect to either (i) the optical axis, or (ii) the average emission angle of the source.

[0010] 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.

[0011] 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

[0012] Figure 1A illustrates a prior art optical system;

[0013] Figure 1B illustrates schematically a folded optical system according to one 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 cross-sectional view of a lens component according to one embodiment of the present invention;

[0016] Figure 4 illustrates coupling performance of the lens component of Figs. 2 and 3;

[0017] Figure 5 is a is a cross-sectional view of a lens component according to another embodiment of the present invention;

[0018] Figure 6 is a is a cross-sectional view of a lens component according to yet another embodiment of the present invention;

[0019] Figure 7 illustrates the evolution of aberrations (wave front error) as a function of the tilt of an exemplary lens component;

[0020] Figure 8 illustrates the evolution of aberrations (wave front error) as a function of the tilt of an exemplary lens component;

[0021] Figure 9 is a plot of coupling efficiency as a function of the tilt of an exemplary lens component;

[0022] Figure 10A illustrates astigmatism component which arises from the tilt of the lens component and its evolution with changes in tilt angles; and

[0023] Figure 10B illustrates the dependency of astigmatism on the field of view (FOV).

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0024] 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 exemplary embodiment of the optical system of the present invention is shown in **Figure 1B**, and is designated generally throughout by the reference numeral **10**.

[0025] The optical system **10** in this exemplary embodiment is a frequency doubled green laser that has a folded configuration. In the optical system **10** light is emitted from a light source **20** in this example, an infrared (IR) diode laser **20′**) in the form of the divergent light beam **22**, and is captured and collimated by a single lens component **30**. In this embodiment, the divergent light beam **22** provided by the light source **20** is characterized by the emission divergence half angle Θ at $1/e^2$, for example 20° in one direction and 7° in the other (perpendicular) direction. The collimated (infrared) 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, $0.05\ \text{Rad} \leq \Theta' \leq 0.2\ \text{Rad}$, and more preferably $0.09\ \text{Rad} \leq \Theta' \leq 0.17\ \text{Rad}$. 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 receiver **70**, which in this embodiment is the input facet of the waveguide portion of a non-linear optical crystal **70′**, for example a second harmonic generator (SHG) crystal. 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 green light **5**. Adjustment 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 entrance facet of the non-linear optical crystal **70′**.

[0026] 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 (within ±100 μm) with respect to the optical axis. More specifically, the output facet of the waveguide of the infrared diode **20′** and the input facet of the waveguide of the non-linear optical crystal **70′** are separated by a small distance **d** compared to the focal length f of the lens **30** (i.e., **d<<f**), in order to minimize aberrations of the light beam at the receiver **70** (at the image plane). Preferably, the focal length f of the lens **30** is 1 to 5 mm (1mm≤ **f** ≤ 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. 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).

[0027] The folded laser design configuration shown in **Figure 1B** has the advantage of reducing the overall length of the laser cavity (and hence reduces the package size of the laser), because the optical path is folded upon itself. The folded laser configuration also advantageously minimizes the effect of anti-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 non-linear optical crystal **70′**. Given stable and accurate attachment techniques, the optical system **10** may be completely passive (i.e., it may include no moving components). (Such design is illustrated schematically in **Figure 1B**). Alternatively, the optical system **10** may easily utilize a MEMS mirror as reflector **50**, to actively align the image on the input facet of the non-linear optical crystal **70′** in the two lateral directions. The MEMS mirror may be, for example, magnetically actuated, and may tilt by about 1°.

[0028] Practical realization of folded optical configurations creates a number of challenges. First, because the folded configuration requires that the non-linear crystal **70′** and the diode laser **20′** to be located off lens component's the optical axis (i.e., they are decentered), off-axis optical aberrations are present and can be difficult to control. However, the optical aberrations from the folded configuration must be kept small in order to achieve high coupling efficiency between the diode laser **20′** and the non-linear optical crystal **70′**. One advantage of the green laser embodiment of the present invention is that off-axis aberrations are kept small, even if the lens component **30** is misaligned. In this exemplary embodiment, there are no actuators that control the focus of the optical beam by moving either the reflector **50** or the lens component **30**. Advantageously, the optical system **10** of this embodiment is not sensitive to focal shifts (otherwise coupling and hence optical output power may be lost). Finally, the optical system **10** of **Figure 1B** can also advantageously control or minimize optical feedback. For example, in the green laser embodiments described herein back reflections and scattering of IR light from the input facet of non-linear optical crystal **70′** do not induce undesirable mode hopping behavior from the infrared diode **20′**. Thus, some advantages provided by the exemplary green laser embodiments of optical system of the present invention are relatively loose angular alignment tolerances for the reflector **50** and/or the lens component **30** (on the order of 5 degrees, for example ±0.15 mm and ±3.5 degrees) and low sensitivity to the parasitic reflections occurring on the input facet of non-linear crystal.

[0029] In some laser system embodiments of the present invention, the optical path length OPL from the output facet of the diode laser **20′**to the input facet of the non-linear optical crystal **70′** is approximately (within ±10%) equal to an integer (n) times the optical path length inside the diode laser itself. The optical system **10** shown in **Figure 1B** is designed such that the optical path length OPL between the light source **20** (the output facet of diode laser **20′**) and receiver **70** (input facet of SHG crystal) has about the same optical path length as the diode laser's cavity (i.e., n=1). (Please note that $OPL=D_i \times N_i$,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 optical system **10** of **Figure 1B** is designed to work in a 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′** has the same optical path length as that of the diode laser's cavity. Thus, for example, if the optical path lens through the diode laser crystal is 9.5 mm, then the optical path length through the optical 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, then the optical path length (OPL) from the light source to the lens component **30**, through the lens component **30**, and to reflector **50** is ½ of the OPL of diode laser. The advantage of this configuration is to minimize the laser wavelength instability created by the parasitic reflection off the input facet of crystal waveguide**70′A** of the non-linear optical crystal **70′**.

[0030] Preferably, the lens component **30** has numerical aperture NA between 0.35 and 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 the 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**. For example, BWD may be 0.8 mm, 1 mm, 1.2 mm, 1.5 mm, 1.7 mm, 2 mm, or 2.5 mm. Preferably lens component **30** is situated to image the light source at a magnification M, and $0.9 \leq |M| \leq 1.1$, more preferably $0.95 \leq |M| \leq 1.05$.

[0031] Preferably, the reflector **50** is located in the focal plane of the lens component **30** such that the direction of the average emission angle (i.e., the centroid) of the light source **20** is parallel to the average beam angle on the receiver **70** (i.e., it is parallel to the centeroid of the converging light cone intercepted by the input facet of the non-linear optical crystal **70′**). Preferably, if the light source **20** provides a diverging beam with a maximum half angle Θ, the reflector is located in the focal plane of the lens component **30**, such that the direction of the average emission angle of the light source is parallel to the average beam angle on the receiver **70**. Preferably, when a decentered light source is located in the focal plane of the lens component, and up to 750 μm off-axis, the lens component **30** is structured to provide a collimated beam such that the collimated beam is at an angle Θ' (with respect to the normal to the reflector surface) such that: 0.05 RAD $\leq \Theta'$ is $\leq$ 0.2RAD.

[0032] 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 is not, or not tilted with respect to the average emission angle of the light source; and (ii) astigmatism of less than 0.05 for tilt angles of 2 to 5 degrees, when the lens component is tilted by of 2 to 5 degrees with respect to the average emission angle of the light source. It is noted that at least in some embodiments the optical axis of the lens component is parallel 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 optical system **10**, the RMS wave front error on the receiver is $\leq 0.1\lambda$ (over the lens component's NA of 0.4), where λ is the central wavelength provided by the light source **20**.

[0033] 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.

Examples

[0034] The invention will be further clarified by the following examples.

EXAMPLE 1

[0035] **Figure 2** illustrates a portion of the exemplary folded cavity green laser system, similar to that depicted in **Fig. 1B**. **Figure 3** illustrates the lens component **30** shown in **Figure 2**. More specifically, a non-linear optical crystal **70′** (a periodically poled lithium niobate (PPLN) is placed adjacent to and over the infrared diode laser **20′** in a cantilevered position. IR light is emitted from an infrared diode laser, and is captured and collimated by a lens component. The collimated infrared beam is then reflected off the reflector **50** (planar mirror, **Fig. 3**) and traverses back into through same lens component **30**, where it gets focused onto the input facet of a waveguide in non-linear optical crystal **70′**. The mirror may be a conventional fixed mirror, or it may be a mirror with actuation of its tip/tilt angle, for example a micro-electrical mechanical system (MEMS) mirror. We note that coupling of light between the diode waveguide and the crystal waveguide 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 itself may be tilted. Because the mirror is located in the collimated space of 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 PPLN crystal converts a substantial fraction of the infrared light into green light, which is emitted from the output facet of the crystal (not shown). Such a design allows small ($<<1cm^3$) laser system packages to be made that can emit greater than 50 mW of green light. Modulation at high rates (100MHz) for scanned projection displays may be made by modulating the current input to infrared diode itself.

[0036] 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.

[0037] The radii of curvature (r_1, r_2), thickness T (vertex to vertex) and aspheric coefficients of the lens component **30** are selected to advantageously:

1. minimize coma and astigmatism;
2. obtain a large field of view: low field aberration combined to a large aperture (e.g., NA=0.4), such that the optical 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′**;
3. provide proper combination of focal length and thickness to allow the optical 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.

[0038] 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 $|r_1| > |r_2|$.

[0039] The lens component **30** of **Figures 2** and **3** has the following characteristics: (I) it allows the optical 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 **Th** (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) full NA = 0.61; (vii) outer diameter of the lens component is 2.5 mm to 3 mm.

[0040] 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.

[0041] The surface parameters of the lens component **30** of **Figures 2** and **3** are given in Table 1 below.

[0042] 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

[0043] **Figure 4** illustrates the performance of the lens component **30** of **Figure 2**, and also the performance of two exemplary commercial aspherical lenses (lenses 1 and 2) typically used for coupling applications. As described above, the output facet of the waveguide of the infrared diode **20′** and the input facet of the waveguide of the non-linear optical crystal **70′** are separated by a small distance d. **Figure 4** illustrates that the lens component **30** has a higher coupling efficiency than two commercial aspherical coupling lenses with similar focal lengths. For example, the lens component **30** maintains coupling efficiency of about 90% or higher when the output facet of the waveguide of the infrared diode **20′** and the input facet of the waveguide of the non-linear optical crystal **70′** are separated by the distance d of up to 450 μm (0.45 mm), while the other two lenses maintain 90% coupling efficiency for d values of only 350 μm and 215 μm respectively. Similarly, lens component **30** maintains coupling efficiency of about 80% or higher when the output facet of the waveguide of the infrared diode **20′** and the input facet of the waveguide of the non-linear optical crystal **70′** are separated by the distance d of about 560 μm, while the other two lenses maintain 80% coupling efficiency for d values of only about 360 μm and 270 μm respectively.

EXAMPLE 2

[0044] **Figure 5** illustrates the lens component **30** suitable for use in the optical systems of **Figures 1B and 2**. The lens component **30** of **Figures 2** and **3** has the following characteristics:

(I) it allows the optical system to be in a coupled cavity condition (OPL between the diode laser and the non-linear optical 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 1.821 mm; (iii) focal length: f = 1.4 mm; (iv) glass index of refraction N at 1060 nm is 1.78; (v) NA = 0.4.

[0045] The surface parameters of the lens component **30** of **Figure 5 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(diode 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

[0046] **Figure 6** illustrates the lens component **30** suitable for use in the optical systems of **Figures 1B and 2**. The lens component **30** of **Figures 2** and **3** has the following characteristics:

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

(II) and has the following parameters: (i) FWD = 1.101 mm; (ii) thickness Th (vertex to vertex) of 1.58 mm; (iii) focal length: f = 1.789 mm; (iv) glass index of refraction N at 1060 nm is 1.503; (v) NA = 0.4.

[0047] The surface parameters of the lens component **30** of **Figure 6** are given in Table 3 below.

Table 3

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(diode 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

[0048] A conventional way to optimize lens systems consists in putting all the optical components 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 try 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.

[0049] 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.

[0050] 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).

[0051] **Figure 7** illustrates the evolution of the wave front error as a function of the tilt of the lens calculated for exemplary design of the lens component. In this configuration, 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, amplitudes of both the coma and astigmatism (which are the predominant aberrations) increase. As a consequence, the wave front is very small when there lens component is tilted, but it rapidly degrades as the tilt increases.

[0052] In order to relax the tolerances, we tried another optimization method. The lens components **30** (See Figs 3, 5 and 6) that resulted from this optimization do not require tight tolerances. That is, tolerance analysis indicates that tolerances on lens tilt, and mirror angle angle, are relaxed by at least a 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 component. As can be seen on **Figure 8,** the astigmatism curve is not at a minimum when the tilt is at zero and 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.

[0053] The consequence is that the total aberrations remain relatively flat over a wide range of angular tilt of the lens. In other words, the lens component **30** can advantageously accommodate a much larger range of positioning tolerances.

[0054] **Figure 9** illustrates the coupling efficiency calculated for both types of lens components (i.e., one optimized conventionally [design #1], and one with residual astigmatism [design #2]) versus respectively, the tilt of the lens component and the tilt of the mirror. As can be seen, when the optical system utilizes a lens component with a small amount of astigmatism (see, for example, Figs. 3, 5 and 6) tolerances are dramatically improved without any significant impact on the coupling.

[0055] This analysis shows that positioning tolerances can be dramatically improved by introducing some residual astigmatism into the optical system design. That astigmatism compensates the one that is generated by the components' misalignments which makes the system much more forgiving to positioning tolerances. For example, wherein the image spot at the receiver has astigmatism and the astigmatism includes a field induced astigmatism component and a lens tilt induced component, the lens component **30** is preferably structured such that when one of these astigmatism components is positive, the other astigmatism component is negative, for all lens component tilt angles between 2 to 6 degrees. This is shown, for example in **Figures 10A and 10B.** More specifically, **Figure 10A** illustrates an astigmatism component that is induced by the tilt of the lens component **30**. **Figure 10B** illustrates astigmatism component versus field of view (FOV).

[0056] 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. An optical system having an optical axis, said optical system comprising:

(I) a light source;

(II) a reflector; and

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

(IV) a receiver, wherein the light source and the receiver are situated substantially symmetrically and are decentred with respect to the optical axis and are separated by a distance d from one another;

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 receiver through the lens; and such that the collimated beam is at an angle Θ' to the optical axis; and (c) the lens component is structured to provide on the receiver an image of the light source, said image characterised by

(i) astigmatism of more than 0.05 waves RMS, and less than 0.1 waves RMS, when the lens component is not misaligned with respect to the average emission angle of the light source; and

(ii) astigmatism of less than 0.05 for tilt angles of 2 to 5 degrees, when the lens component is tilted by of 2 to 5 degrees with respect to the average emission angle of the light source.

2. The optical system according to claim 1, 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.

3. The optical system according to claim 1, wherein the front working distance FWD is 0.3 mm to 3 mm.

4. The optical system according to claim 1, wherein the back working distance BWD is 0.5 mm to 3 mm.

5. The optical system according to claim 12, wherein 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.

6. The optical system according to claim 1, wherein said astigmatism of the lens component is not misaligned is created by: (i) wedge in the lens, or (ii) decentration of one of said surfaces relative to another, or (iii) by one of said surfaces being tilted relative to another.

7. The optical system according to claim 1, wherein said lens is structured to provide a collimated beam 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 a decentered point source located in a focal plane of said lens, and up to 750 μm off-axis.

8. The optical system according claim 7, wherein said angle Θ' is: 0.09 RAD $\leq\Theta'$ is $\leq$ 0.17 RAD;

9. The optical system of claim 2, wherein said light source is a diode laser, and the OPD of lens plus the distance to said reflective surface is substantially equal (within 10%) to the OPD of diode laser.

10. The optical system of claim 9, wherein optical path distance OPD is: less than 10 mm.

11. The optical system of claim 1, wherein the light from said light source traverses the lens component twice before it reaches said receiver.

12. The optical system of claim 1 wherein said lens component is situated to image at a magnification M, and $0.9\leq |M| \leq 1.1$.

13. A lens situated on an optical axis, said lens comprising:

(I) a front surface;

(II) a rear surface separated from said front surface by a distance Th;

the lens being structured to (A) provide, when imaging an off-axis source displaced by a distance d' from the optical axis, a collimated beam exiting said rear surface, such that the collimated beam is at an angle Θ' to the optical axis; and (B) to intercept said collimated beam, when coupled with a reflective surface, and to provide an image of the off-axis source, the image having:

(a) astigmatism of more than 0.05 waves RMS, when the lens component is not misaligned with respect to average emission angle of the source; and

(b) astigmatism of less than 0.05 waves RMS for tilt angles of 2 to 6 degrees when the lens component is tilted by 2 to 6 degrees with respect to the average emission angle of the source.

14. The lens according to claim 13, wherein 25 μm $\leq d' \leq 750$ μm and 0.05 RAD $\leq \Theta' \leq$ 0.2RAD.

15. The lens of claim 13, wherein the astigmatism includes a field induced astigmatism component and a lens tilt induced component, and said lens is structured such that when one of these astigmatism components is positive, the other astigmatism component is negative, for all tilt angles between 2 to 6 degrees.

16. The lens of claim 13, wherein said lens is structured such that the field induced astigmatism component is approximately equal to a negative of the lens tilt induced astigmatism at least one tilt angle between 2 to 6 degrees.

17. The lens of claim 13, said lens having

(a) a front aspheric surface and a rear aspheric surface;

(b) NA of 0.35 to 0.5; and

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

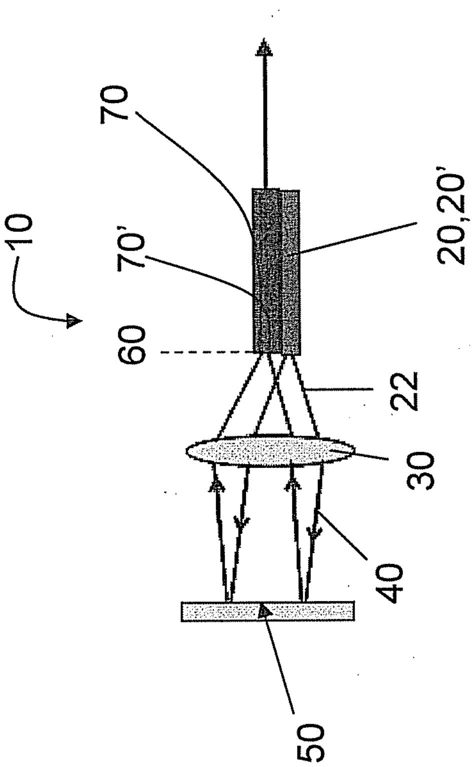


Fig. 1B

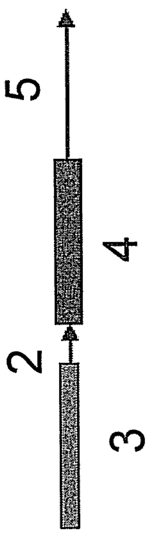


Fig. 1A

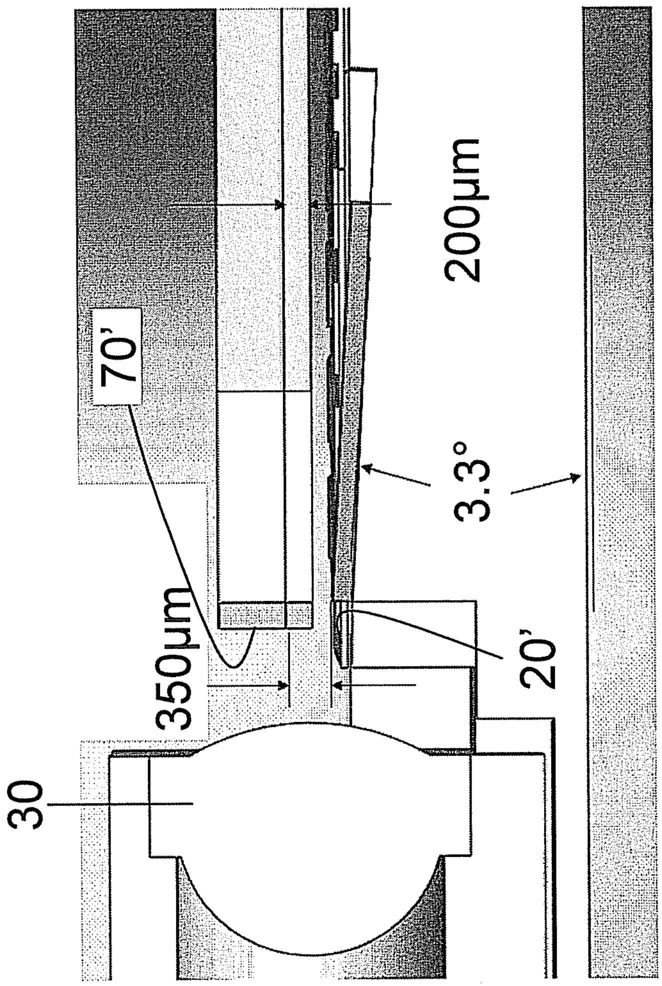


Fig. 2

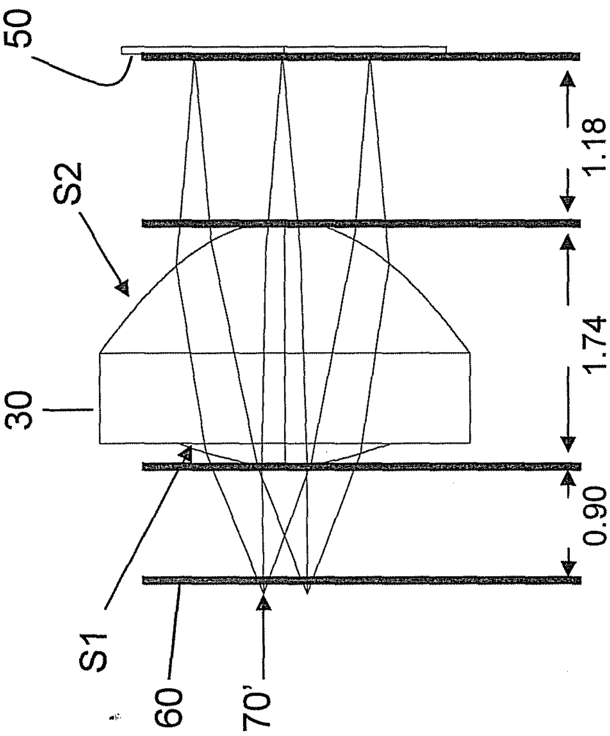


Fig. 3

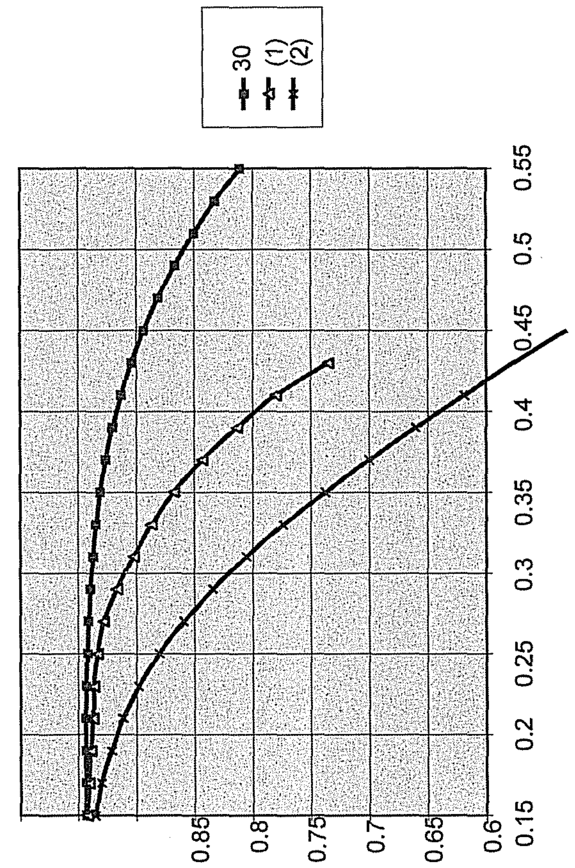


Fig. 4

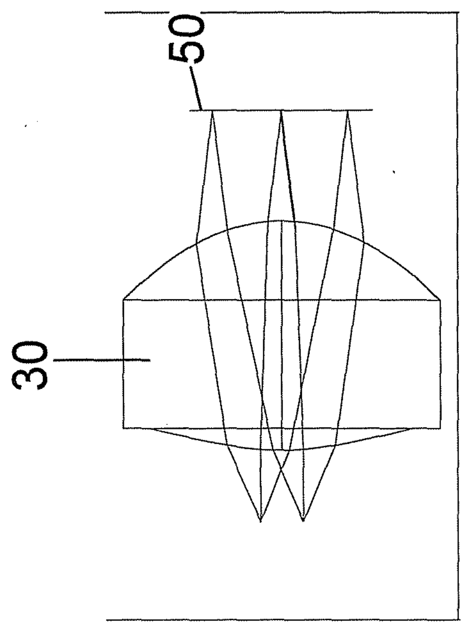


Fig. 5

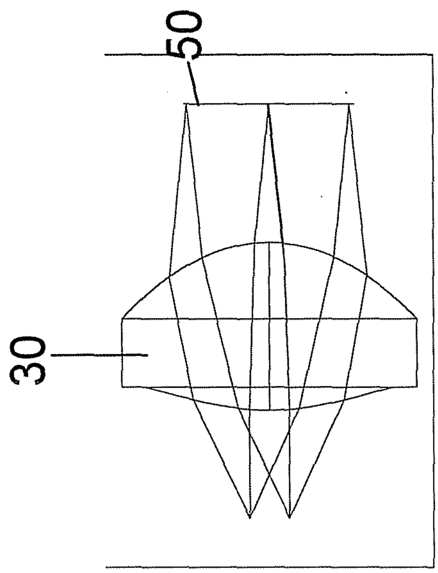
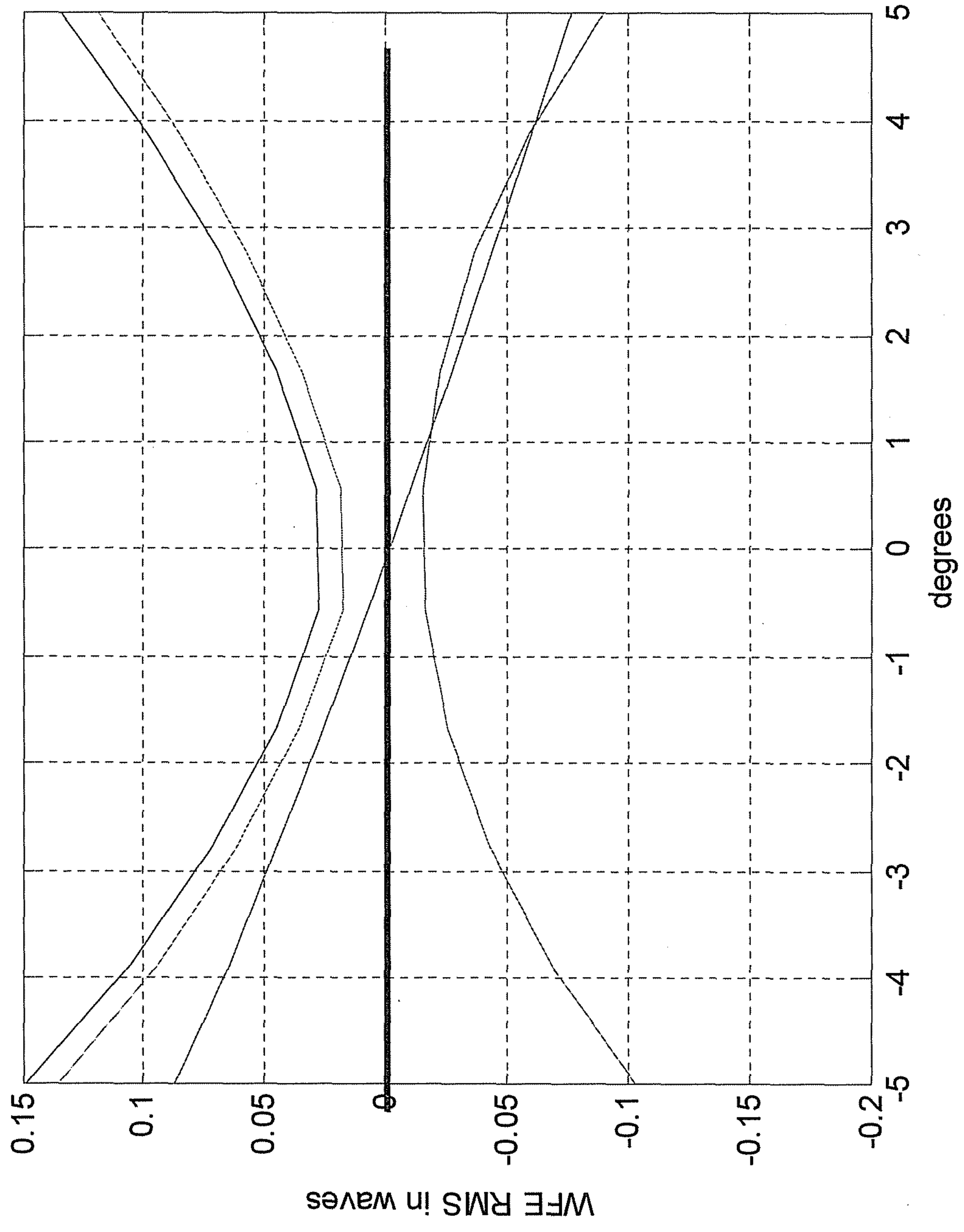


Fig. 6



WFE RMS in waves
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
degrees
-5
-4
-3
-2
-1
0
1
2
3
4
5

Fig. 7

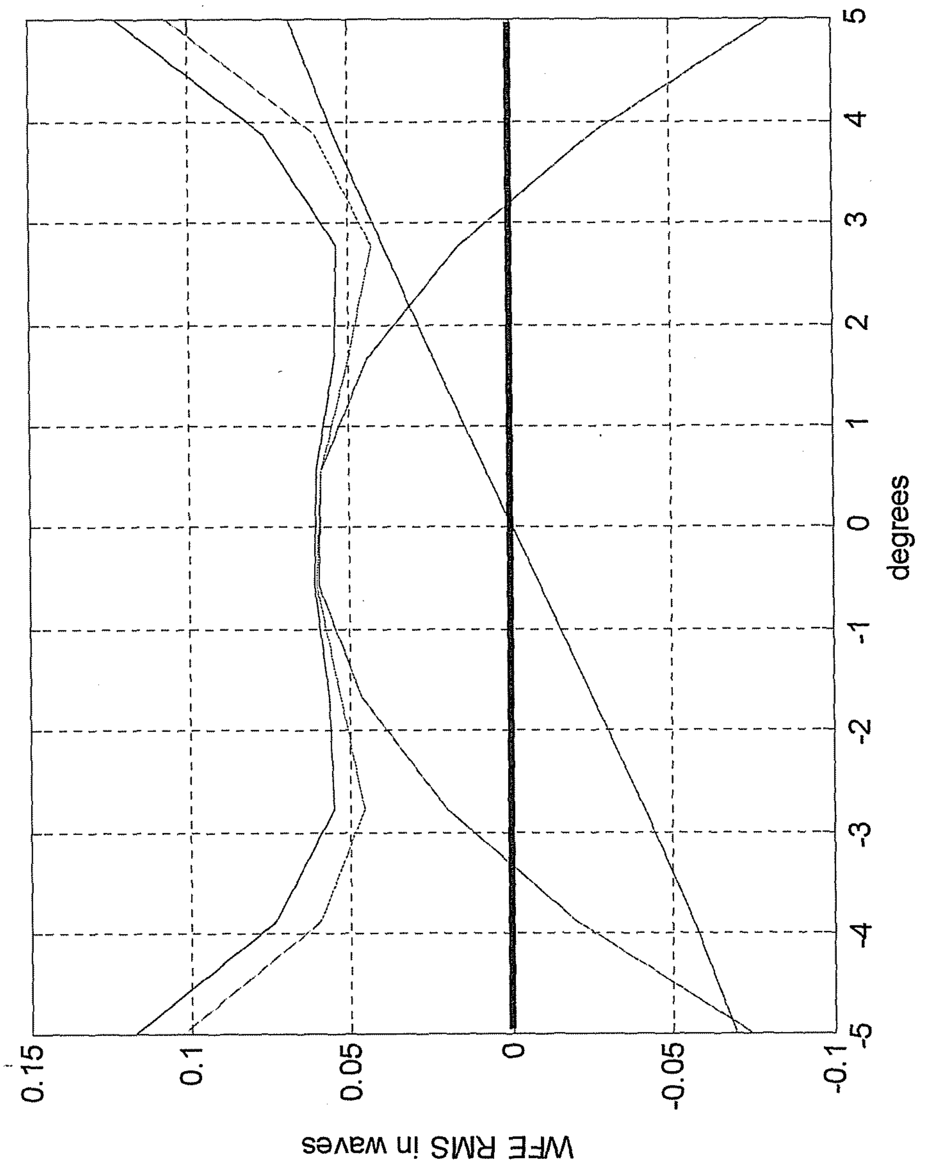


Fig. 8

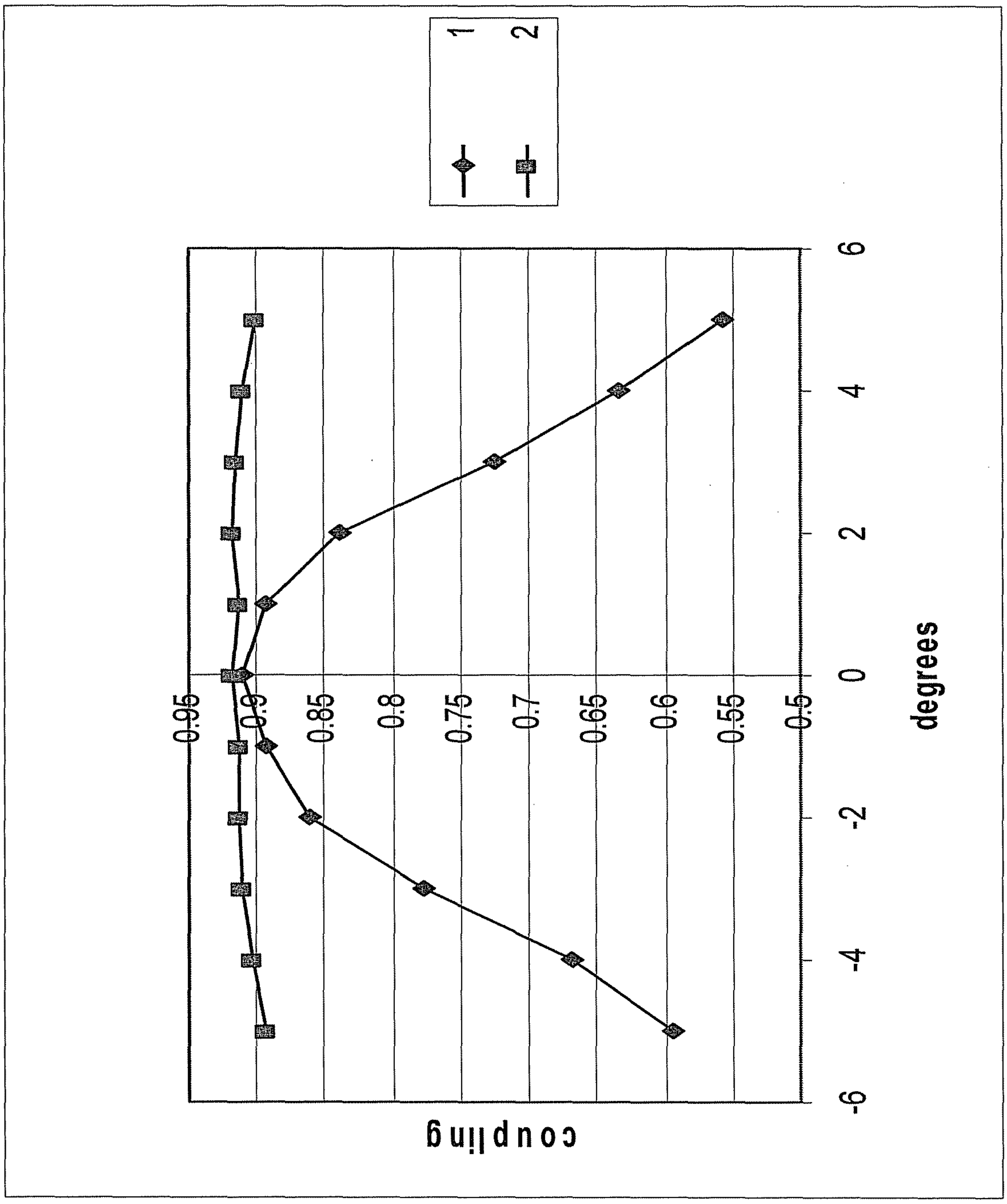


Fig. 9

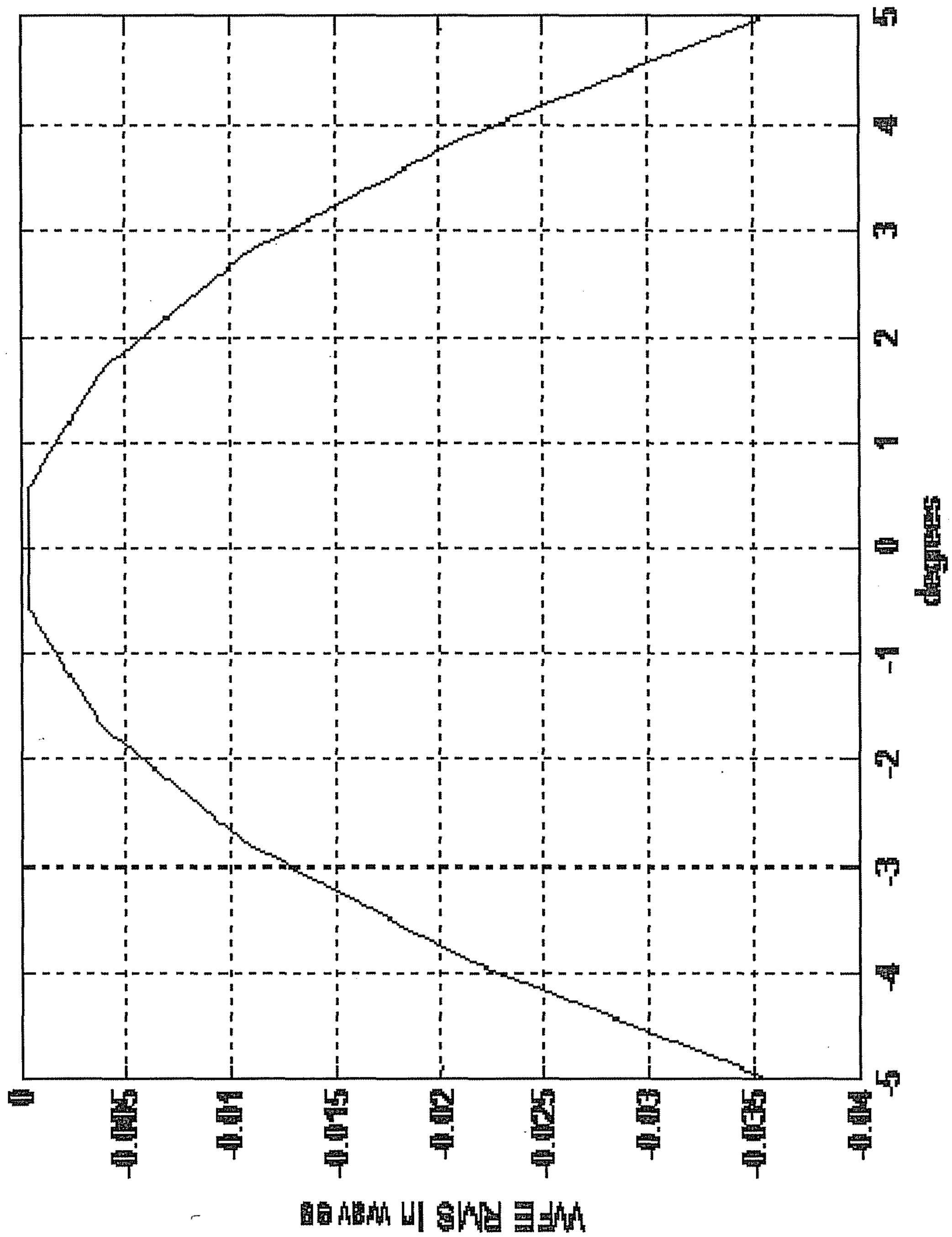

WFE RMS in waves
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
-0.035
-0.04
degrees
-5
-4
-3
-2
-1
0
1
2
3
4
5

Fig. 10A

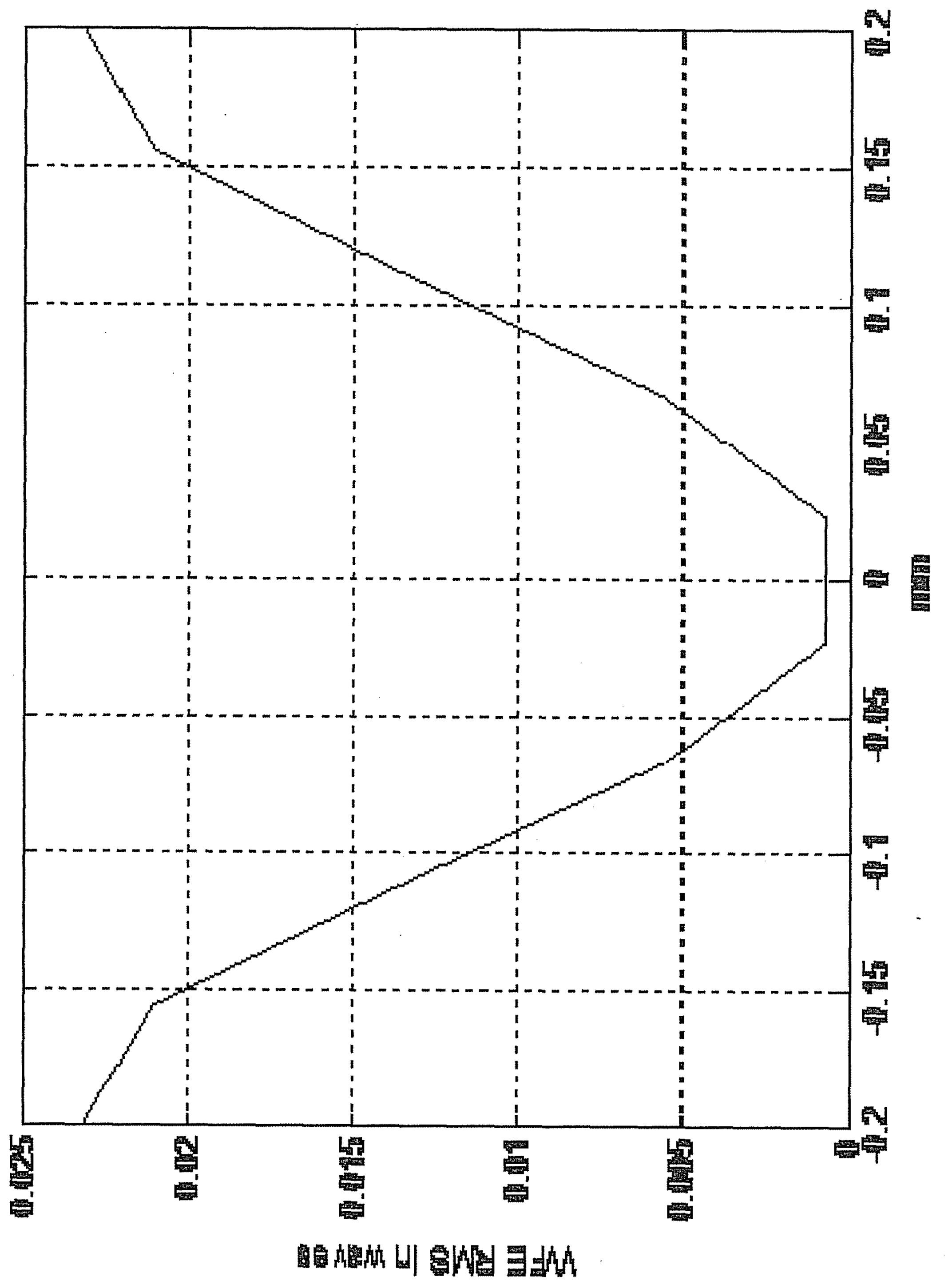

0.025
0.02
0.015
0.01
0.005
0
WFE RMS in waves
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
mm

Fig. 10B