Collimation of Cerenkov-SHG Blue Light with a Parabolic Mirror

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SYNOPSIS

Proposed here is a convenient optical system to collimate the crescent shaped blue laser beam radiated from a Cerenkov SHG in channel waveguide configuration. This collimation system is consisted of a parabolic mirror and has a very large tolerance to the mirror displacement. The anisotropy of the nonlinear crystal on which the waveguide is fabricated has been taken into account. The optimum mirror location is given to obtain a collimated blue laser beam with an aberration less than 0.07λ. By using an objective lens, the collimated beam can be focused down to a thin beam with the spot size less than $1\mu m$.

1. INTRODUCTION

Compact sources of blue laser light are required in many applications, such as data storage, undersea communication and full color display etc. Although it has achieved a lot to develop the direct blue light source–laser diode with wavelength less than $0.5\mu m$, it is not commercially available. The most popular approach now for the blue light sources is wavelength up-conversion. When the infrared light from a laser diode is injected into a nonlinear crystal, some part fraction of it is converted to the blue light. This process depends on the nonlinear optical susceptibility of the optical crystal and is called second harmonic generation(SHG).

There are several configurations of SHG. Among them, the guided wave configurations are often used. The waveguides are fabricated by titanium indiffusion or proton exchange(PE) in the substrate of lithium niobate which has large nonlinear

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coefficients. SHG in Cerenkov configuration in PE waveguides has been reported to be more efficient[1,2,3]. Most important, Cerenkov SHG has an advantage of automatic phase matching.

On the other hand, the rays of SH light form a part of Cerenkov cone because of the channel waveguide. The cross section of SH light beam shapes a cresent. It has to be collimated for practical applications.

In order to collimate the Cerenkov SH light, one direct efficient method is using a conic lens[4]. This method leads to a well collimated beam under a strict condition that the wavelength of the harmonic light source has to be steady without variation.

This paper proposes a convenient optical system consisted of a parabolic mirror, to collimate the crescent shaped beam radiated from the Cerenkov SHG. Chapter 2 introduces simply the principle of Cerenkov SHG and the conceptional model of virtual light source used in this paper. Chapter 3 and 4 express how the convenient collimation system works and how to reach an optimum collimation condition. Chapter 5 gives the focused beam, which shows that the collimated beam can be focused down to a thin beam with the spot size less than 1μm.

2. CERENKOV SHG AND VIRTUAL LINEAR SOURCE OF ITS CRESCENT SHAPED BEAM

In a waveguide, when the nonlinear polarization has a phase velocity faster than that of a free wave at the harmonic frequency, a second harmonic will be radiated to the substrate at an angle (Fig.1). This process is somewhat like the Cerenkov radiation, so it is called as Cerenkov SHG and the angle Cerenkov angle denoted here as α.

When SH light is radiated to the substrate, SH and the harmonic phase velocities keep equal in a certain direction(Fig.2). This relationship is usually called as phase matching and expressed as

$$v_{\mathrm{pf}} = v'_{\mathrm{ps}} \tag{1}$$

where v_{pf} is the harmonic phase velocity along the channel waveguide and v'_{ps} is that of SH light along the same direction. Referring to Fig.2, eq.(1) turns out to be

$$N = n_{\mathrm{ce}} \cos\alpha \tag{2}$$

where N is the effective refractive index of the harmonic light in the waveguide, and n_{ce} is the refractive index of SH light in the substrate.

Theoretically, the shape of SH light beam depends on the characters of the waveguide and the substrate where SH light is radiated. In a Cerenkov SHG consisted of

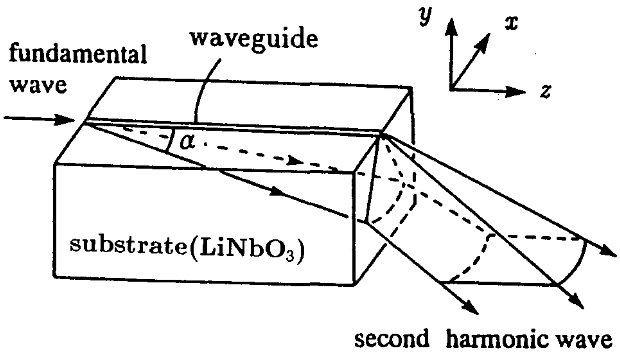

Fig.1 Cerenkov channel waveguide SHG. When the fundamental wave (the harmonic) is injected into the waveguide fabricated on $LiNbO_3$ by proton exchange, the second harmonic wave is radiated into the substrate.

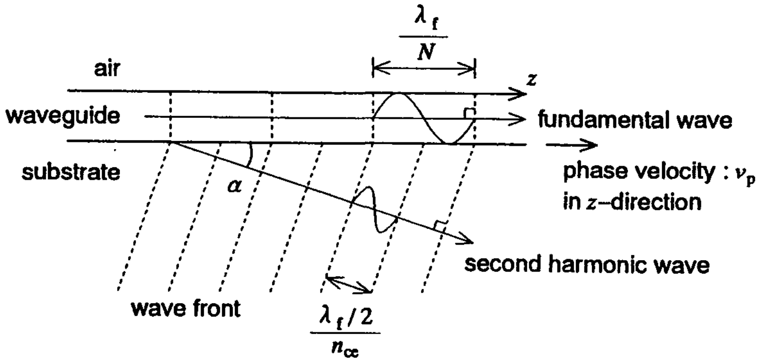

Fig.2 Phase matching in Cerenkov SHG. The harmonic phase velocity v_{pf} along its propagating direction is ω/β_ω, and the component v'_{ps} of SH phase velocity in the same direction is $2\omega/\beta'_{2\omega}$.

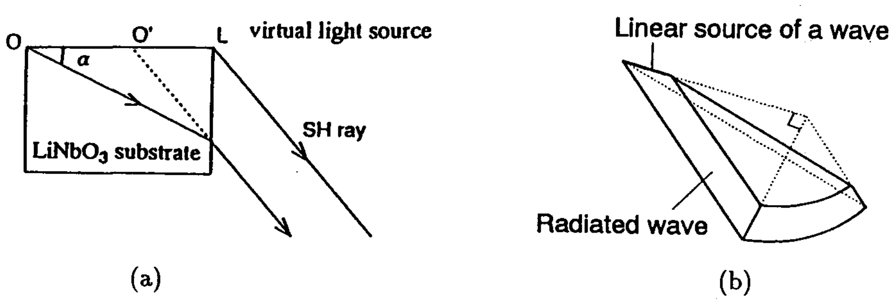

Fig.3 Virtual linear source $O'L$ of SH light(a) and the crescent shaped SH light beam(b).

the channel waveguide fabricated on the lithium niobate($LiNbO_3$), the waveguide can be considered as a line shaped light source for its width is far smaller than its length. Hence we can consider only the refraction in the direction perpendicular to that SH light is radiated along. Because Cerenkov radiation forms a Cerenkov cone, its cross section shapes a crescent[4](Fig.3).

3. COLLIMATION OF SH BEAM WITH A PARABOLIC MIRROR

3.1 Configuration of Collimation System

For practical applications, the crescent shaped SH beam of Cerenkov SHG has to be collimated. Here we propose a convenient collimation system consisted of a parabolic mirror. The configuration and principle are shown in Fig.4. The crescent shaped SH beam is reflected by a parabolic mirror located beside the SHG device. If only the substrate of SHG device is of isotropic, the geometrical reflection turns out a perfect collimation. In this case, the only requirement is keeping the focal axis of the mirror coincident with the linear light source, i.e., the channel axis of the waveguide.

In principle, the wavefront of SH beam reflected by the mirror is independent to the focal length of the mirror. This gives a freedom to choose the focal length. It can be chosen in accordance with the beam spot size needed practically.

For practical application, the collimated beam should be focused by a lens, as shown in Fig.5. Taking the direction in which the collimated beam propagates as z''-direction, and the plane perpendicular to it as x-y'' plane, we get a new Cartesian coordinate system(x, y'', z''). The circular spot of focused beam requires the same radii on x-y'' plane, denoted by $\omega_1 = \omega_2$. Calculation for this condition gives the focal length f_L of the mirror as

$$f_L = W D_E \sin\gamma / 2\lambda \tag{3}$$

where W is the width of the channel waveguide, λ the wavelength of SH light, D_E the beam width in y'' direction and γ the refraction angle. D_E and γ are given respectively as

$$D_E = L \tan\alpha \cos\gamma \tag{4}$$

$$\gamma = \sin^{-1}(n_{ce} \sin\alpha) \tag{5}$$

3.2 Location Tolerance of the Mirror

Because the wavelength of the laser light is of micro meter, error of the alignment

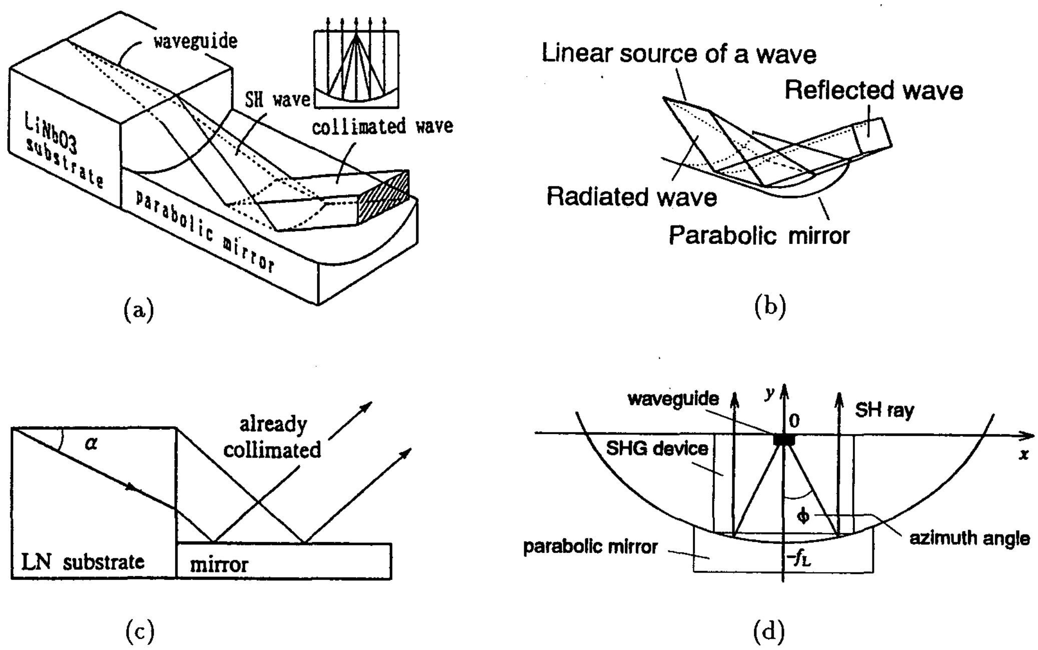

Fig.4 Parabolic mirror collimation configuration for the crescent shaped SH beam. The focal length of the mirror is f_L. The mirror is located so that its focal axis is coincident with the waveguide axis.

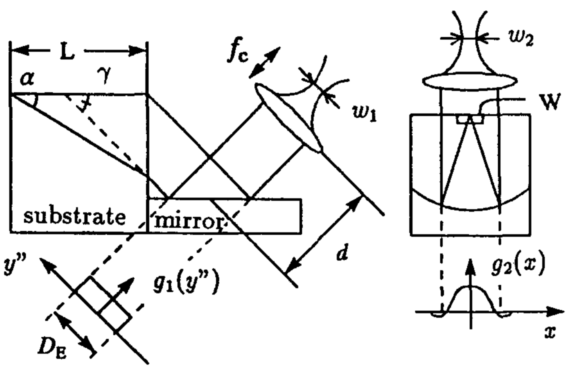

Fig.5 Focusing configuration for the collimated beam by using an objective lens.

between the optical axes of the optical devices is required in an order of sub-micro meter.

In the collimation system of Fig.4, the collimated beam profile distorts with the displacements of the mirror from its optimum location. Directly, displacement in x-direction Δx makes the collimated beam deflected, and that in y-direction Δy results in an expansion of the beam. Both of the effects lead to a distortion in beam intensity profile on the plane perpendicular to the propagation direction.

Taking a criterion that the sidelobes of the distored beam profile are -10dB less than the peak of the mainlobe, the calculation for beam distortion due to the displacements gives a quite satisfactory tolerance:

$$|\Delta x| < 140\mu\text{m} \tag{6}$$

$$-3\mu\text{m} < \Delta y < 7\mu\text{m} \tag{7}$$

Particalarly, the largest displacement Δx of 140μm deflects the beam only 3.7 degree from its propagation axis. Comparing with the tolerance in the order of sub-micro meter required in an optical system, eq.(6) and (7) reveal a high reality in alignment of our collimation configuration.

3.3 Anisotropic Effects in $LiNbO_3$

The nonlinear crystal $LiNbO_3$ used in our SHG device is a kind of anisotropic crystal. Light propagating in it behaves sometimes extraordinarily, which is expressed by the index ellipsoid[5] and the dispersion angle.

According to the index ellipsoid, the refractive index of $LiNbO_3$ to SH light varies with an angle is given as

$$n_{\text{ce}}(\theta_{\text{k}}) = \frac{n_{\text{o}} n_{\text{e}}}{\sqrt{n_{\text{o}}^2 \cos^2 \theta_{\text{k}} + n_{\text{e}}^2 \sin^2 \theta_{\text{k}}}} \tag{8}$$

where, n_{o} and n_{e} are indices of the substrate respectively to the ordinary and extraordinary light, and θ_{k} is the angle between the C-plane(perpendicular to the optic axis) and the normal vector of SH wavefront(Fig.6), given in the form:

$$\theta_{\text{k}} = \sin^{-1}(\sin \alpha(\phi) \cos \phi) \tag{9}$$

In eq.(9), ϕ is called as azimuth angle and determines the radiation range on the plane perpendicular to the waveguide axis(Fig.4). The dispersion angle denoted as θ_{d} is made by the poynting vector and the wavefront vector, and given as

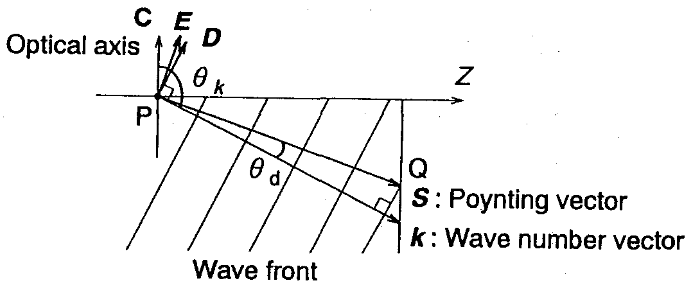

Fig.6 Vectors in anisotropic crystal $LiNbO_3$. Dispersion angle is denoted as θ_d. C is the optic axis and E, D have the same meanings in electromaganetic fields.

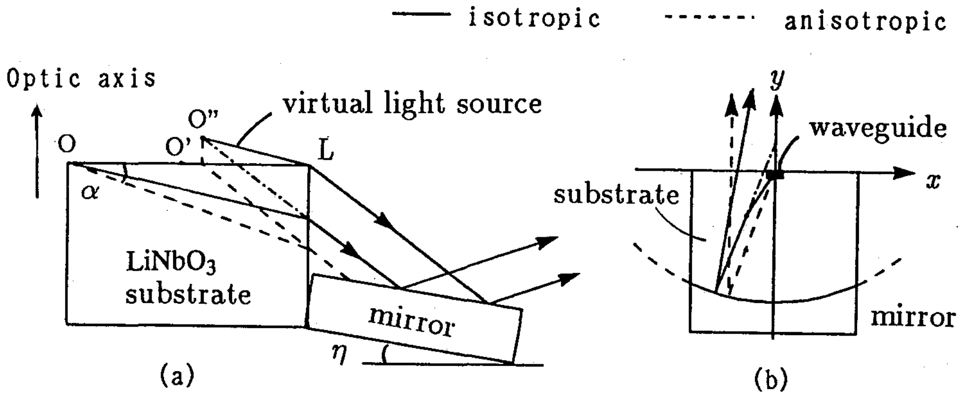

Fig.7 Variation of virtual light source(a) and the focusing effect due to the disperssion angle(b). η is the declining angle to compensate the focusing effect.

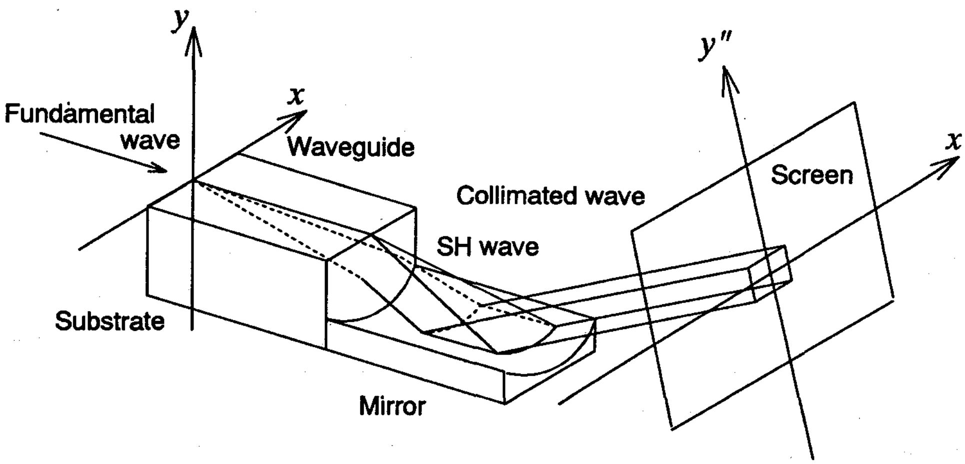

Fig.8 Geometrical optical system for calculation of beam propagation.

$$\theta_{\mathrm{d}}(\phi) = \tan^{-1}\left[\frac{(n_{\mathrm{e}}^2 - n_{\mathrm{o}}^2)\tan(\theta_{\mathrm{k}} + \pi/2)}{n_{\mathrm{e}}^2 + n_{\mathrm{o}}^2\tan^2(\theta_{\mathrm{k}} + \pi/2)}\right] \tag{10}$$

It tells that the poynting vector points to a direction different from that of its wavefront, as illustrated in Fig.6.

Because of the index ellipsoid, Cerenkov angle α and then the elevation angle of the collimated beam varies with the radiation angle ϕ:

$$\alpha(\phi) = \tan^{-1}\frac{n_{\mathrm{o}}}{N}\sqrt{\frac{n_{\mathrm{e}}^2 - N^2}{n_{\mathrm{o}}^2\sin^2\phi + n_{\mathrm{e}}^2\cos^2\phi}} \tag{11}$$

And because of the dispersion angle, the virtual source of SH light now becomes a curved surface instead of a line in an isotropic crystal. Fig.7 shows the virtual source deflecting upward from the position of the isotropic line source, on the plane including the channel waveguide and y axis. The variation of the virtual light source makes the collimated beam focused somewhat, as shown in Fig.7(b).

To compensate the anisotropic effects, the parabolic mirror should be declined with a declining angle η. The details are explained in the following chapter.

4. EVALUATION OF COLLIMATED SH LIGHT BEAM

4.1 Declining Angle to Compensate the Anisotropic Effects

The focal axis of the collimating mirror should be coincident with the virtual linear source to collimate the crescent shaped beam. When the virtual linear source deflects upward from the waveguide channel, the mirror should be declined to keep being coincident with the deflected source. If this could be achieved, then the anisotropic effects can be compensated, and a perfect collimation can be obtained.

Referring to Fig.7, intuitively, the mirror should be declined by an angle η so that its focal axis can coinside with that of the new virtual light source.

The virtual light source in the case of anisotropic $LiNbO_3$, however, shapes a completed curved surface like a part of cone instead of a line. So the declining angle η to compensate the anisotropic effects can not be determined so simply. It is necessary to determine it based on the evaluation to the beam intensity and phase distribution. In other words, the mirror should be declined by an optimum angle so that the most of beam intensity distributes over a region where the phase distribution is flat enough to meet some criterion.

4.2 Aberration of the Collimated Beam

The beam intensity and phase distribution with different declining angles of the collimation mirror were calculated by using the method of geometrical ray tracing. The observing screen to evaluate the beam quality is shown in Fig.8.

The phase distributions with different declining angles are shown in Fig.9. For the initial mirror state with the declining angle being 0 degree, the reflected beam has a warped phase distribution. In the positions where normalized beam intensity falls to exp(-2), the phases advanced in about 20 times of wavelength compared with that in the center. Declining the mirror a little, the phase distribution becomes flatter. When the mirror was declined by 5.5 degree, the aberration of the reflected beam is small, within the Rayleigh limit, i.e., within a quarter of a wavelength.

The aberration of the collimated beam can also be evaluated in terms of another parameter, say RMS(Root Mean Square). When the declining angle is 5.5 degree, RMS reaches its minimum over the region where the normalized beam intensity holds on a level not less than exp(-2). This minimum is 0.06λ(Fig.10), smaller than 0.07λ of Marechal's Criterion.

4.3 Propagation of the Collimated Beam

To obtain an optimum collimated beam, the beam intensity was calculated. Fig.11 shows the spot sizes of the collimated beam propagated with a distance of 1 meter from the mirror, with different declining angles. The spot size of the beam just after reflected by the mirror is 4mm. Referring to Fig.11, the optimum declining angle to hold a same spot size is 5.5 degree.

Calculation of SH beam in different positions gives the beam propagation from the mirror, illustrated in Fig.12. The beam propagation reveals that if the mirror is declined by 5.5 degree, SH light beam reflected by the mirror turns out to be a collimated beam.

5. FOCUSING OF THE COLLIMATED BEAM

Many practical applications, such as direct patterning of optical IC, fine analysis of organism etc., need laser beam with a spot size less than 1μm. On a focusing comfiguration shown in Fig.5, the calculation for beam focusing was carried out with different declining angles, supposing the focusing lens to be an objective lens with

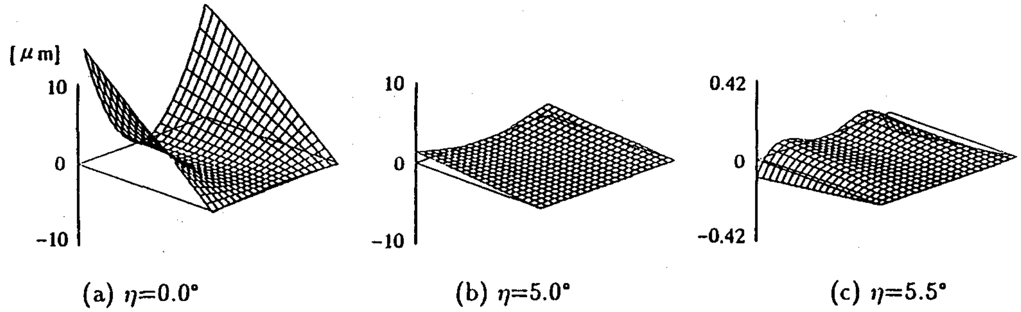

Fig.9 Phase distribution of SH beam reflected by the mirror with the declining angle η varied.

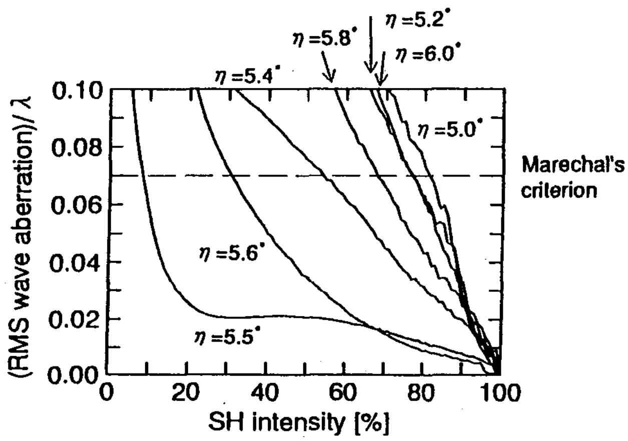

Fig.10 Aberration of the SH beam reflected by the mirror with different declining angles.

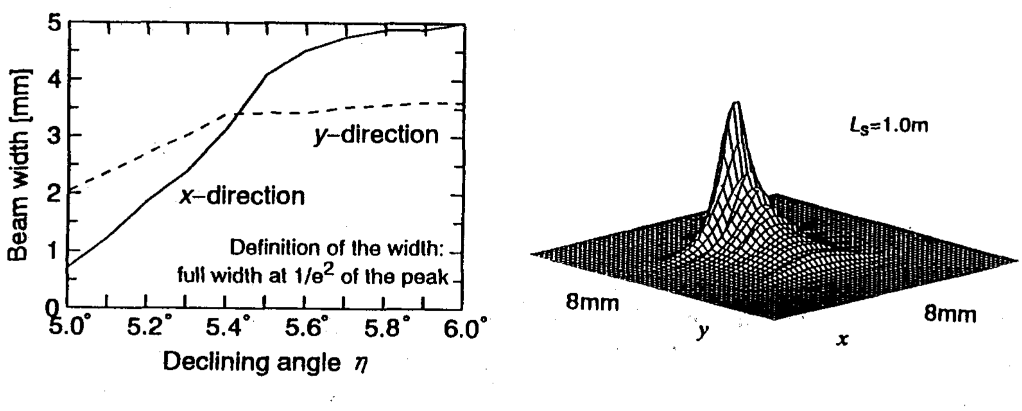

Fig.11 Intensity distribution of the SH beam reflected by the mirror with η varied.

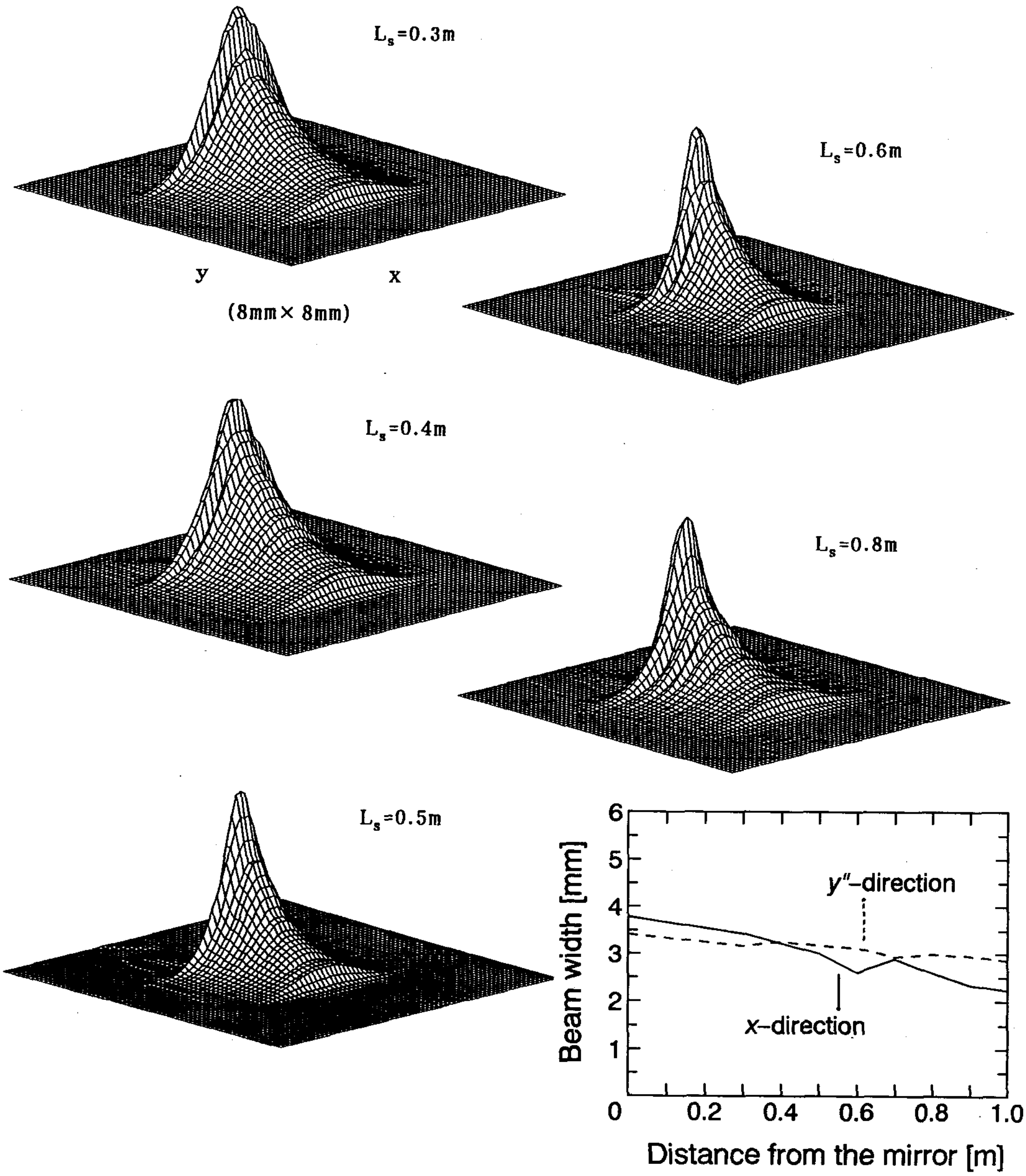

Fig.12 Propagation of SH beam reflected by the mirror with η 5.5 degree.

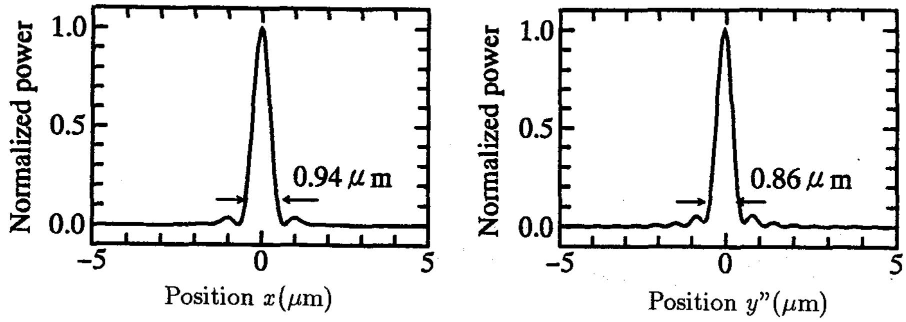

Fig.13 Spot size of the focused beam by using a objective lens with focal length of 5mm and the numerical number 0.5.

focal length of 5mm and the numerical number 0.5. Fig.13 gives the calculated spot size of the focused beam. The minimum spot size in x direction is 0.90μm and that in y'' direction is 0.86μm, both less than 1μm. The correponded declining angle is 5.47 degree, just less than 5.5 degree–the optimum angle to get minimum aberration. By the way, if the aberration of the SH light beam could be zero, the same focusing will give a beam spot size of 0.74μm and 0.88μm respectively in x and y'' direction.

6. CONCLUSION

We have explained a convenient optical configuration consisted of a parabolic mirror to collimate the crescent shaped blue laser beam of Cerenkov channel waveguide SHG. This collimation configuration has a quite large tolerance to the displacements of the mirror. Declining the mirror can compensate the anisotropic effects of the SHG device. With an optimum declining angle, the aberration of the collimated beam achieves a value meeting well the Marechal's criterion. By using an objective lens, this collimated beam can be focused to a thin beam with spot sizes less than 1μm, very near the refraction–limitted beam focusing.

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