1-2006

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ABSTRACT

We present experimental results of second harmonic generation enhancement through the resonance of the band edge in a photonic crystal based on lithium niobate. Proton exchange technique was used to fabricate a waveguide near the surface of the lithium niobate substrate. The photonic crystal structure over the waveguide was made by UV laser interferometry. Subsequently experiments were designed to quantify the Cerenkov second-harmonic generation (CSHG) radiated into the substrate. The SHG radiated inside the waveguides was also experimentally investigated. In our experiments, the second guided mode of the waveguide was tuned to the band edge resonance to enhance the second harmonic generation. The highest conversion efficiency of CSHG using photonic band gap (PBG) was around 50 times compared to SHG emission from non-patterned lithium niobate. A numerical model was used to corroborate the experimental result. It was also found that the SHG signal in the waveguides is quenched compared to the CSHG signal.

Keywords: Cerenkov second harmonic generation, photonic band gap, lithium niobate, optical waveguide.

1. INTRODUCTION

Sources of coherent light in the short wavelength spectral regions are required in many different applications such as color printing, high-definition projection displays, medicine for fluorescence assays of biological systems, medical sources for photo-excitation therapies, lithography with ultraviolet sources, higher-density optical data storage and optical tomography [1][2].

Present blue-green sources are based mostly on gas lasers or resonantly frequency doubled solid-state lasers. GaN based blue lasers are now becoming available, but they are still expensive devices. Second-harmonic generation (SHG) is an alternative method to convert light from available infrared solid state lasers to the visible. Here we show that a photonic crystal and waveguide geometry can be used to significantly increase the SHG conversion efficiency. There are two modes of emission: 1. from a guided mode at the fundamental frequency into an SH guided mode (guided-guided type of SHG) or 2. from a fundamental guided mode into an SH radiation mode (so-called Cerenkov-type SHG). These conversion scheme offer a simple and inexpensive method of generating high intensity short-wavelengths using well establish nonlinear optics principles. It does so by frequency doubling, using low-cost laser diodes and compact diode-pumped solid state lasers as the pump signal, that are currently available around 1 μm. By using nonlinear optical waveguides, high conversion efficiencies can be obtained even for moderated input powers because of the high optical power density and the long interaction lengths provided by the guided-wave structures.

Lithium niobate ($LiNbO_3$) is an excellent optical material, most commonly used as a substrate for applications in integrated electro-optic and nonlinear optical devices. In a single-mode channel configuration, the fundamental mode of a $LiNbO_3$ based waveguide provides tight optical confinement of the field. Even a modest CW power of 2 mW that couples into a guided mode will result in a power density of the order of 10^6W/cm^2. In the last few years, the quasi-

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Integrated Optics: Devices, Materials, and Technologies X, edited by Yakov Sidorin, Christoph A. Waechter,
Proc. of SPIE Vol. 6123, 61230N, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.646952

phase matching (QPM) technique [3], in which the ferroelectric domains of the material are periodically inverted to compensate for dispersion, has received special attention for SHG to generate blue [4] and green [5] light using nonlinear $LiNbO_3$ waveguides.

The addition of a resonant cavity can further increase the SHG efficiency. This effects causes the increment of the electric field in the waveguide that produces the enhancement of the nonlinear properties of the material. A Bragg grating used as a resonant cavity is an example of a periodic media, i.e. a medium that has a spatially periodic refractive index[6][7]. The transmission through such a periodic medium is characterized by the appearance of stop bands, which indicate that the Bragg condition is satisfied. For an incident wave with wavelength λ, and a grating period of Λ the Bragg condition is given by $\Lambda=m\lambda/2n$ where m is an integer and n is the effective index of the guided mode. Previous theoretical work has stated that the SHG conversion efficiency can be enhanced by several orders of magnitude as a consequence of the resonant effect of the photonic band gap (PBG) structure[[6- 9].

Experiments using $Ga_{0.7}Al_{0.3}As$/AlAs multilayer structure showed that the SHG conversion efficiency was increased by up to 60 times for the TM-TM configuration [10-12]. Although using a grating as a photonic crystal has been predicted to increase the SHG conversion efficiency in the waveguide[8-9], no experiments that matches the theoretical calculations has been reported until now. The recent publications showed that a grating band-gap structure in a planar nonlinear waveguides for SHG can be made using e-beam lithography and reactive ion etching. These reports used atomic force microscopy imaging to analyze the results of the sample preparation[12-13]; however, no SHG experiments were performed with the reported samples.

A giant SHG conversion efficiency of 5000 in a GaN photonic crystal recently was reported in Ref. (14). In this paper there is an especially weak signal without the PBG structure due to the sub-micron layer thickness and a photomultiplier was used to measure the signal. The comparison was done between two cases with different sample conditions when the PBG sample was compared to the film structure. This makes the comparison difficult because the grating significantly increases the interaction length inside the nonlinear layer by coupling light from the vertical into the horizontal direction, also accessing a different component of the nonlinear tensor. Earlier work by Blau et al.[15] reported PBG enhancement in a polymer waveguide, but the enhancement was not quantified. Both of above papers reported the enhancement for the case of SHG reflection, which means only a small amount of nonlinear material is used. In other words their design use very limited path lengths in the nonlinear material.

In this paper, we report our experimental findings on SHG emission with a waveguide geometry and a PBG grating to enhance the conversion efficiency in lithium niobate. We use well characterized samples and compare the results with detailed theoretical calculations. Finally, we find that the SHG enhancement inside the waveguide is weak, compared to the Cerenkov SHG (CSHG) emission, which is radiated into the substrate and satisfies a phase matching condition. We report for the first time a 50 times enhanced signal from the PBG structure in the CSHG process. The research involves several elements: the fabrication of well-controlled proton exchange $LiNbO_3$ waveguide samples; improvements in our characterization of the refractive index profile to ensure consistency between theory and experiment; and optimization of the UV laser lithography on $LiNbO_3$ to control the input coupling efficiency and obtain stronger coupling of the forward- and backward-propagating pump modes. We developed methods to control the optimal design parameters to get higher SHG conversion efficiency.

2. THEORETHICAL BACKGROUND

Nonlinear optics[16] is an extension of conventional linear optics that has been enabled by the arrival of the laser technology. Typically, only lasers have the field intense necessary to modify the optical properties of a material. Nonlinear optical phenomena are “nonlinear” in the sense that they occur when the response of the material to an applied field depends on the strength of the optical field. In the case of second-harmonic generation, the intensity of the light generated has a frequency which is the double of the incident light, and tends to increase as the square of the intensity of the applied laser light.

Under proper experimental conditions, the process of second-harmonic generation can be so efficient that a large percentage of the power in the incident radiation at frequency ω is converted to radiation at the second-harmonic frequency 2ω. The complex second-harmonic polarization amplitude for this case can be expressed in the form:

$$P(2\omega) = \chi^{(2)} E^2 (\omega) , \qquad (1)$$

where $E(\omega)$ is the electric field amplitude of the fundamental frequency and $\chi^{(2)}$ is the nonlinear coefficient. The second-harmonic intensity in the non-depleted pump approximation is related to the pump intensity as

$$I(2\omega) = CI^2(\omega), \qquad (2)$$

where C is a constant that accounts for the material properties and the experimental conditions. The intensity of second harmonic generation is proportional to the s quare of the pump intensity.

Three main methods can be used to achieve a high pump power. One is to use a mode locked laser to produce a train of short pulses that concentrate a very high power in each pulse for the pump. A second is to use a waveguide to confine the pump into a very narrow cross-sectional area. The third is use a resonator to store higher pump power in the material. In our experiment, we design samples that use PBG structures on top of the lithium niobate waveguide as resonators. By combining the above three methods at the same time, a high pump intensity can be produced in the waveguide. According to the Eq. (2), the SHG enhancement can be very high when we optimize the pump intensity. We describe here the effect of PBG structure in the enhancement of SHG.

The phase matching condition is an important element in the efficiency of the SHG. To keep the phases of the waves locked together, the indices of refractions of the both the pump and the second-harmonic signals should be equal. There are several different methods tha can be used to reduce the dispersion of material so that the phase matching condition for two waves can be met.The type I phase matching condition implies:

$$n(\omega) = n(2\omega) \qquad (3)$$

Two generally used methods of phase matching are angle-tuning and temperature-tuning. Another method is the socalled quasi-phase matching condition, which was first proposed by Armstrong et al.[3]. Recently, it was shown that a PBG grating modifies the indices of both pump and SHG at the same time, Eq. (3) can be effectively satisfied by carefully fabricating a PBG in the top of the waveguide, and therefore the conversion efficiency can be improved[6-10].

In this paper we report the observation of so called Cerenkov SHG (CSHG) radiation, which has an automatic phase matching condition. The CSHG signal is visually observed and enhanced through the PBG structure. This phenomenon is natural for the nonlinear optical waveguide. As the name implies the CSHG signal is radiated into the substrate, while the pump intensity remains confined inside the waveguide.

3. PBG FABRICATION ON LITHIUM NIOBATE

A PBG structure can significally enhances the SHG signal. However the fabrication of a PBG structure is always the key problem because of the high precision requirement for the grating period. In our experiments a lithium niobate waveguide was made using the proton exchange method. The PBG structures were fabricated by using a UV laser lithography setup. Subsequently we examined dry etching technology to imprint the grating into the waveguide. A new Cerenkov radiation method devised during this project, in conjunction with other diffraction methods, to analyze the accuracy and tolerance of our PBGs.

The interest in using a guided-wave configuration for nonlinear interactions was recognized early in the development of nonlinear optics. The theory for PBG enhanced SHG in the waveguide was investigated by several groups. When conditions are met he enhancement is predicted to be as high as several orders of magnitude[6-9,12]. The main problem for the fabrication of a PBG structure in this configuration is the accuracy needed for the grating period. One paper mentions an accuracy of 0.0027nm for a fixed-wavelength source with the PBG transmission at 3 GHz wide (or 0.024 nm) at the operating wavelength of 1.55 μm, the tolerance of corresponding pitch is less than 0.0027 nm. Some have pointed out that the tolerance should be in the order 7 ppm (parts in 10^6) to ensure overlapping between the tuning of the fundamental wavelength and the band edge resonance[12]. A new method is developed to achieve a high accuracy of the PBG period in our experiment.

In our experiment, a UV laser lithographic method was used to make a photoresist mask. The grating period was determined by using the Cerenkov radiation method that will be introduced later. Then the results will be compared to the checked by several grating diffraction methods. Finally, the enhancement of SHG in Cerenkov configuration was explored.

3.1 Sample design

The crystal orientation is shown in a 3-dimensional illustration in Fig. 1. Note that the definition of coordinates is totally different from that for the crystallographic designations. For example, the designated +Z (or +C) crystallographic direction of the crystal is actually the +X direction defined in Fig. 1. In the experiments, the waveguide is made on the +Z surface of crystal.. Fig. 1 shows the planar waveguide produced by proton exchange in a photoresist film that was spin coated on the surface. Two different gratings are written on the sample. The grating that couples the pump into the waveguide has a period of 710.0 nm; it couples the pump wave into the waveguide (right side) at an angle around 45˚ as shown in Fig. 1.

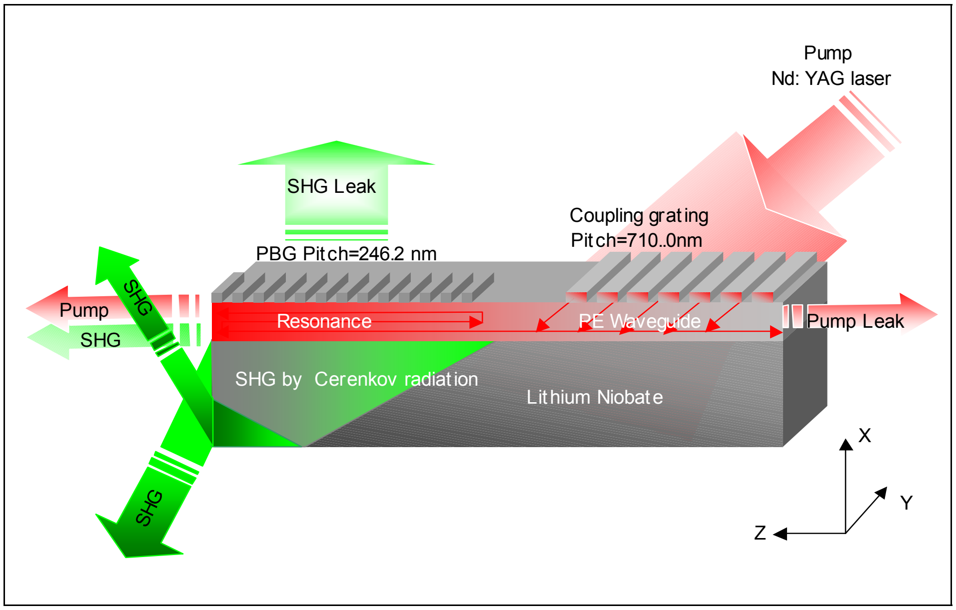


Figure 1 - Principle of experimental sample in a 3-dimensional view for PBG enhanced SHG.

A PBG grating with 246.2 nm period was used for the resonant enhancement of SHG using the band-edge resonance effect (half of left side). The other half of the sample on the left side of the sample and parallel to Y-Z plane also has a homogeneous cladding index. The so-called Cerenkov phase-matching condition, in which a radiating second-harmonic field into the substrate is phase matched to the fundamental field in the waveguide, is met. Therefore, two Cerenkov SHG signals are emitted. A weaker, guided SHG signal emerges at the left edge of sample in X direction. A SHG signal was also weakly diffracted vertically (in the X direction) from the PBG grating surface due to the second-order grating coupling out of the sample.

In Fig. 1 (also see Fig. 6) the thickness of grating is t=100 nm and the thickness of waveguide is h=1.5 µm. A Nd:YAG laser with wavelength of 1.064µm is coupled into the PE waveguide with incident angle $\varphi = 45^o$. The output wavelength is half of the pump signal , i.e. 0.532 µm. The Bragg scattering angles for the pump and SHG light can be described by the following formula:

$$k_0 n_0 \sin(\theta) = \beta - q k_t \ , \qquad (4)$$

where,

$$k_0 = 2\pi / \lambda, k_t = 2\pi / \Lambda \ . \qquad (5)$$

In the above equations, n_o is the refractive index of either air, β is the propagation coefficient of the guided mode in the waveguide, and *q* is an integer denoting the diffraction order. The grating period is $\Lambda = 246.2\ nm$. If *q* is 0 or 1, θ is calculated to be 0 and 90^o respectively. The diffractive rays are observed in our experiments. Cerenkov SHG radiation is emitted at an angle α, and then refracted out from the edge of sample at the angle of α_l. The refractive angle α_l on the left edge of sample can be accurately measured and used to calculate the effective refractive index of modes inside the waveguide.

3.2 Waveguide fabrication

A suitable waveguide for a frequency conversion device in $LiNbO_3$ should preserve the nonlinear susceptibility of the crystal, it must have low loss, as well as resistant to photorefractive damage. The waveguide must be also compatible with the inverted domain structure. Two techniques are mainly used to fabricate waveguides in $LiNbO_3$. The first approach, introduced by Schmidt and Kaminow in 1974, consists of localized titanium using diffusion. The second, proposed by Jackel in 1982, is based on proton exchange (PE) between Li^+-ions of the crystal and H^+-ions obtained from benzoic acid.

However, the well-studied titanium diffused $LiNbO_3$ waveguides are not generally suitable for SHG nonlinear optics for several reasons. For instance, the Ti:$LiNbO_3$ waveguides fabrication enables photorefractive damage in the near-infrared at power levels exceeding tens of milliwatts, thus making them impractical for nonlinear optics applications, the index contrast is typically small, and the index profile is diffuse. As an alternative, the proton exchange (PE) process and annealed proton exchange (APE) in $LiNbO_3$ provide excellent waveguides for these purposes. PE waveguides have a step index profile with a large extraordinary refractive index change ($\Delta n \sim 0.1 \sim 0.14$), which is around 0.1 in our experiment, and are fabricated at temperatures below 350 ^{o}C. Furthermore the best PE and APE $LiNbO_3$ waveguides were reported to have low propagation losses, and their resistance to photorefractive damage are orders of magnitude greater than those of Ti-$LiNbO_3$[17-18].

PE and Annealing PE (APE), using benzoic acid as the proton source, have become popular techniques to fabricate waveguides in $LiNbO_3$. Particularly, their good power handling capability and the possibility of getting high confinement have made these fabrication methods the choice for nonlinear optical applications. In the PE process the $LiNbO_3$ sample is immersed in benzoic acid,(melting point around 215 ^{o}C), for 2 hours (exchange time). During the exchange reaction Li^+-ions diffuse out from the crystal surface, and H^+-ions diffuse into the crystal to replace the Li^+. The ion exchange results in approximately step-like proton concentration and refractive index profiles,. The effective waveguide could not be made if the temperature is lower than 190 ^{o}C in our experiments. Finally, different waveguide depths were found by using different processing times. The waveguide depth can be calculated by using the WKB method; this method will be examined with our results in Section 4. The waveguide depths range between 0.4 μm to 2.0 μm. Finally, a depth close to 1.5 μm was chosen for our experiments, because the second mode in this waveguide exhibited a higher SHG efficiency than the first mode. It will also be shown below that the efficiency in a thinner waveguide with only one mode is also lower than the second mode in a thicker waveguide that supports two modes.

Several papers reported that the PE processing may reduce the nonlinear coefficient d_{33} in the waveguide of $LiNbO_3$[19-21], thus reduce the efficiency of SHG in the waveguide. This is consistent with our findings, which demonstrate, that it is much easier to produce CSHG radiation than SHG in the waveguide. Annealing has been reported to overcome this deficiency, but annealing will also reduce the refractive index of waveguide. Some reports claim only 50% of d_{33} could be recovered. Other reports claim that after heated in BA for more than half hour the d_{33} could not be recovered. The results were tested by making more samples with different PE and annealing times.

Pyrophosphoric acid, was also used instead of benzoic acid for proton exchange. It was widely reported to produce higher index increases of about 0.14. [22-23]. Therefore, in our experiment, the pyrophosphoric acid was also used during the proton exchange processing, but serious damage on the sample's surface was found, which means the waveguide became lossy due to the additional scattering. We decided to avoid further use of pyrophosphoric acid in these experiments. However, this process should be modified and improved to achieve better waveguide characteristics in the future work.

Annealing was attempted in our experiments to recover the d_{33} nonlinearity of $LiNbO_3$, but the result was not as good as we expected. After the samples were annealed at 350 ^oC for several hours (from 1 to 24 hours), the nonlinearity could not be recovered, also the refractive index difference in the waveguide was reduced, which reduces the mode confinement in the waveguide.

To pattern the PBG structure in the waveguide, an Argon ion laser with SHG in the wavelength of 244 nm was used in our lithography setup. The lithography consists basically in a Lloyd's mirror interference setup. By changing the angle of interference, θ (30.30 ^{o} and 9.86, for 246.2 nm and 700 nm respectively) between the two beams we can alter the grating period. The period of the grating can be calculated from the formula:

$$\Lambda = \frac{\lambda}{2\sin(\theta)} \qquad (6)$$

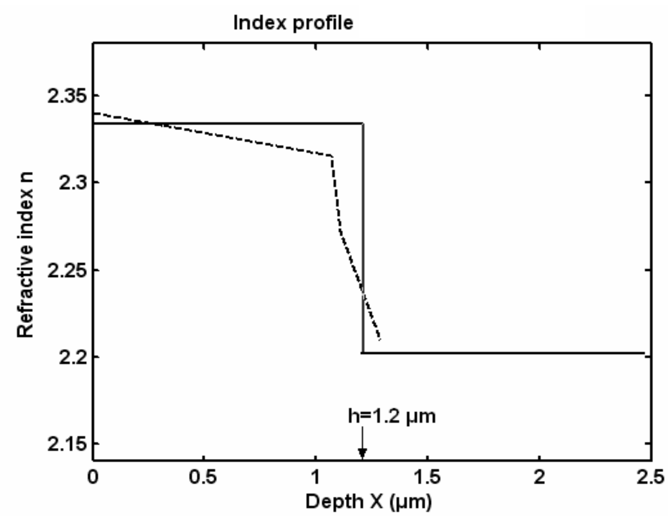


Figure 2 : Profile of the refractive index in a sample waveguide, the dotted line is a WKB fitting and solid line is step shape fitting of the data, h is the depth of this waveguide.

We found that the Cerenkov radiation method can be used to find the effective refractive indexes of the pump signal in the waveguide. The prism coupling and diffraction method can also be used to determine all the effective refractive indices in the waveguide. A WKB method can be used to accurately find the index profile and the depth in waveguide. Figure 2 shows the step profile of the refractive index of the sample.

4. THEORETHICAL CALCULATIONS OF THE CSHG EFFICIENCY

The CSHG signal is radiated into the substrate and therefore is not available for back-conversion to the fundamental frequency. It is a pure loss mechanism. We estimate the SHG field amplitude in the waveguide by the expressions:

$$B^{+} = \mathrm{M}(A_f)^2 \exp\left(i\alpha_f\right) \qquad (7)$$

$$B^- = \mathrm{M}(A_b)^2 \exp(i\alpha_b) \qquad (8)$$

B^+ is the complex field amplitude of the SHG mode in the +Z direction in Figs.1 and 5, B^- is the field amplitude of the SHG mode in the –Z direction, α_f is the phase change between pump and SHG in the nonlinear process in the +Z direction, α_b is the phase change between pump and SHG in the nonlinear process in the -Z direction. M describes the linear coupling and nonlinear processes of the waveguide mode, and includes both physical and experimental parameters, The plus (minus) sign below stands for propagation along the positive (negative) z direction. The total intensity of CSHG signal is:

$$I_B^+ = \int_0^L |B^+(z)|^2 dz, \qquad (9)$$

$$I_B^- = \int_0^L |B^-(z)|^2 dz. \qquad (10)$$

where z is the position of light in Z direction. The normalized conversion efficiency can be expressed by the following expressions:

$$\eta_{rel}^+ = \frac{I_{B\kappa}^+}{I_{B0}^+}, \qquad (11)$$

$$\eta_{rel}^- = \frac{I_{B\kappa}^-}{I_{B0}^+}, \qquad (12)$$

Where, I_{Bk}^+ and I_{B0}^+ are the intensities of the CSHG in +Z direction, with grating ($\kappa \neq 0$) and without grating ($\kappa = 0$). For the second mode with κ=14.8002 (1/cm) the normalized conversion efficiency is plot in the bottom subplot of Fig. 3; the upper subplot is the transmission spectrum for comparison. It's noted that a small change of κ does not affect the shape of two plots, meaning a small variation in the grating will not affect the PBG too much. We also can see from this figure that the relative efficiency is increased 50 times when the wavelength is tuned to the first transmission resonance near the lower-frequency of the band edge.

We determined that the coupling coefficient is around κ =14.80 (1/cm), which fits the model to the second mode in the sample. The maximum relative efficiency is 50 times, bandwidth is about 0.005 nm. Two peaks are at 0.12278 nm and 0.13861 nm. For Δλ =0.12278 nm the relative efficiency is 48.08 times and the transmission of the fundamental field is T = 1.00. Those results will be compared to the experimental results in Section 5.

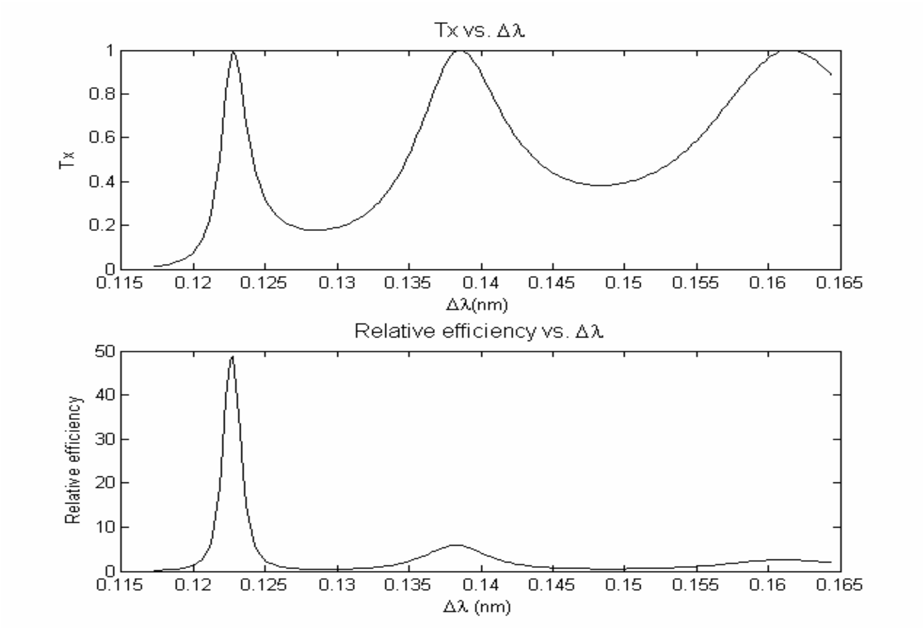


Figure 3: (top) Transmission spectra with detuning in nm units for direct comparison with experiment. (bottom) Relative efficiency with detuning in nm units for direct comparison with experiment.

5. SHG EXPERIMENTAL RESULTS

Fig. 4 shows the experimental setup used to measure the enhancement due to the PBG structure in CSHG. A 150 ps mode locked Nd:YAG laser with a, repetition rate of 78 MHz was used as the pump signal. A polarizer was used after the laser output in order to produce linear polarized pulses. There are only TM modes in the waveguide after the proton exchange processing. In order to get TM coupling a half wavelength plate is applied to rotate the direction of polarization until a TM mode is reached. The laser output was grating coupled into the waveguide and the SHG emission is collected by a fiber optical cable with a diameter of 1 mm that is imaged onto the input slit of a spectrometer.

A vertical emission from the PBG grating is also observed. Its angle was almost perpendicular to the surface of the sample. The pump is then TM coupled into the waveguide around 45^o in X-Z plane through a grating with the pitch of 710 nm, seen in Fig. 5 The depth of waveguide is 1.5 μm, so that two modes can be excited in waveguide. Those two modes can be seen separately by adjusting the coupling angle. The SHG efficiency caused by the second mode is found to be much higher than the first mode.

The second PBG grating with period of 246.2 nm is made for the second guided mode in the waveguide. This period is also very close to the first order Bragg condition in the wavelength of 1.064 μm. The conclusion is that the first-order Bragg condition for the pump is exactly the second-order Bragg condition for SHG. Therefore, there is a diffractive emission vertical to the surface of sample, which can be used to monitor the PBG while turning the angle γ of sample in the X-Y plane during our adjustment of the PBG structure period. Figure 6 shows a photo of the experimental results with the SHG emission pattern observed on a screen.

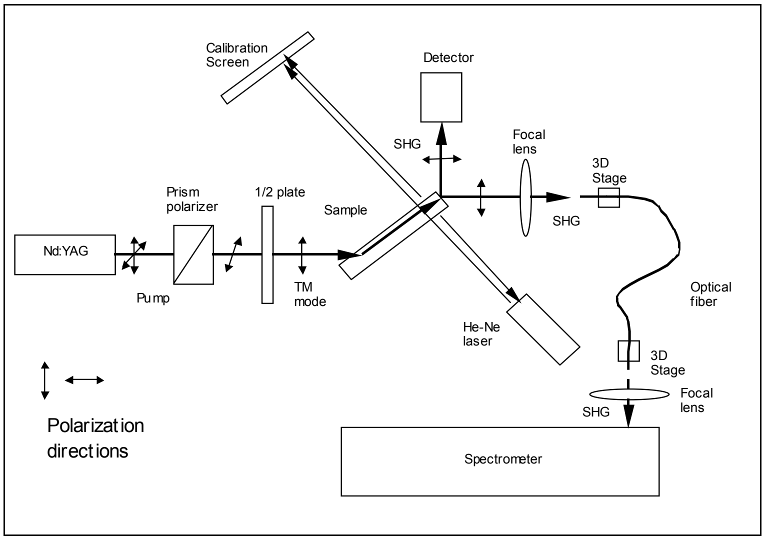


Figure 4 : Experimental setup for the CSHG.

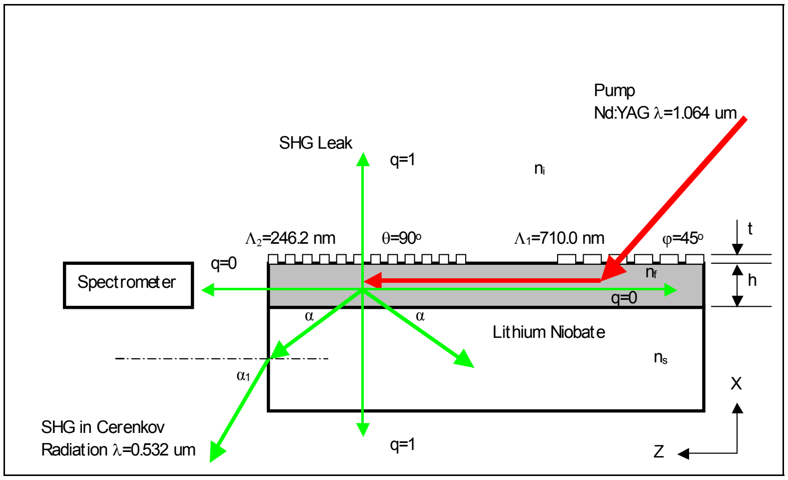
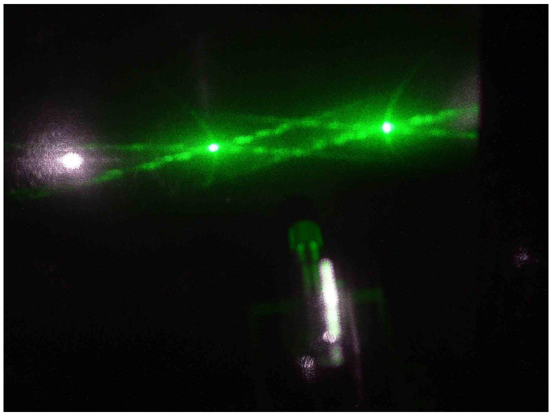


Figure 5: 2D schematic diagram illustrating the principle of Cerenkov radiation in the sample.

A strong pump is coupled into the waveguide at the right edge of sample. It can produce strong SHG either in the waveguide, or emitted as a Cerenkov radiation SHG, which can be seen in angle α_1 in Figs. 1 and 5. The refractive indices for the waveguide and substrate are respectively 2.2300 and 2.1437. The effective indexes for pump in this waveguide are 2.2147 and 2.1661 respectively. Those are smaller than 2.2189, the refractive index of SHG in the substrate. This is the condition for Cerenkov radiation mentioned in Section 4, and a CSHG signal is found in our experiments. The two angles α_1 are calculated theoretically in the previous section, and were found around 7.8430^o and 30.2089^o. The measured angles are 7.83^o and 30.31^o, which are very close to the theoretical result.



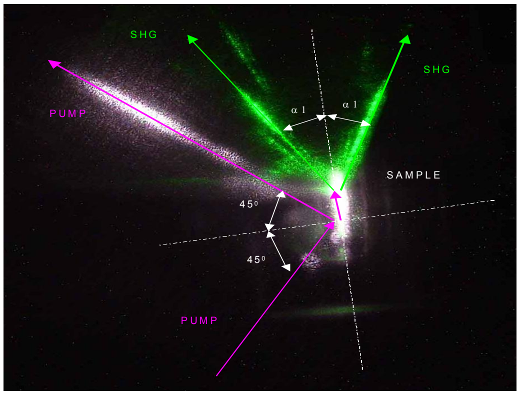
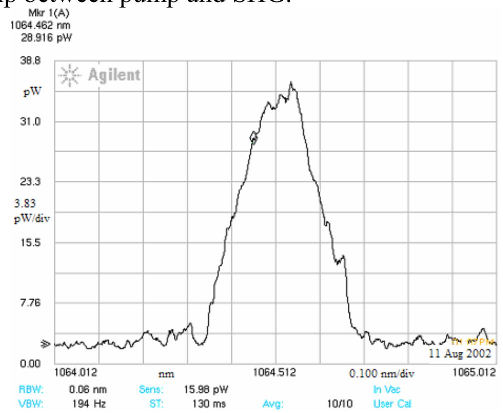


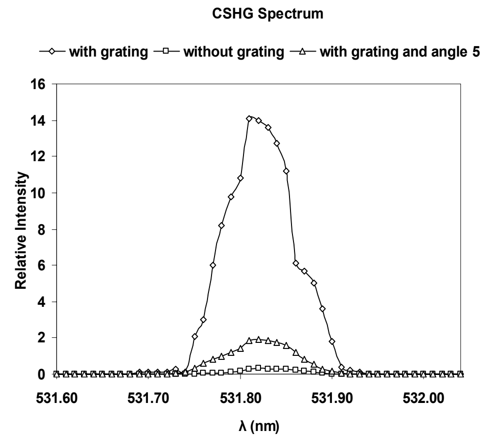
Figure 6: CSHG output on a screen vertical to the direction of beams, viewed in the –Y direction in Fig. 1. The bright spot on the far left is the pump beam reflection.

Figure 7: Photos showing the sample pumped by the YAG and the CSHG output shown in a darkened room, viewed from the Y direction in Fig. 1.

The light reflected at 45^o in Fig. 7 is the IR pump field. The sample illuminated by the laser is a bright line near the center of the picture. The CSHG beams were the strong and well collimated beams of light. The CSHG output shown on a screen in Fig. 6 reveals a complex pattern of SHG that is attributed to the spreading of the SHG signal in the waveguide. The bright spots at the crossing of the lines determine the Cerenkov angle. Note that in this case no spots were observed in the center between the two Cerenkov emission spots. The waveguide SHG is very weak for this sample; this indicates that phase matching is not achieved in the waveguide or that the waveguide nonlinearity may also be weak. Phase matching is normally an important consideration for SHG, but in this case the CSHG adjusts itself to the phase matching condition by the emission angle, The SH field is radiated away from the grating and therefore it does not interact with the pump wave. This provides the efficient SHG that we observe in our experiments.

The spectrum of the pump was measured using an optical spectrum analyzer with a resolution of 0.06 nm. The data shown in Figs. 8(a) and 8(b) portray the pump spectrum and second-harmonic signal intensity, respectively. The three curves in the plot of Fig. 8(b) compare the results when there is no-grating, with a grating and when the pump beam is tuned off resonance from the Bragg condition to an angle of 5^o in the YZ plane shown in Fig. 1. The overall enhancement of the CSHG signal is about 50 times for this sample for the grating/no grating intensity ratio. As the experiment demonstrates detuning the pump from the resonance results in a much reduced SH signal. Comparing Figs. 8(a) and 8(b) we find that the shape of pump spectrum is similar to that of SHG spectrum. The bandwidth of pump is 0.4 nm and the corresponding SHG bandwidth is 0.2 nm. This matches the theoretical result about the bandwidth relationship between pump and SHG.





(a) (b)

Figure (8a): The spectrum of pump, showing the bandwidth of 0.4 nm. Figure 8(b): The CSHG emission spectra.

6. CONCLUSION

We reported the design, fabrication, and demonstration of CSHG in lithium niobate waveguides. In fabricating these devices, we address many of the problems that typically limit these experiments. We presented a brief review of the basic theory underlying the PBG enhancement. The model predicts confinement of the field intensities in the PBG structure when we tune the frequency to the first transmission maximum at the low-frequency band edge. The experimental setup was discussed in some detail a full article with data representing several samples will appear in Ref.(25). We found that SHG generated in a waveguide mode is very weak compared with CSHG radiated into the substrate from the Cerenkov condition. The CSHG spectra were measured under comparable conditions with and without a grating effect, respectively. The intensity ratio from those two cases was used to determine the PBG efficiency improvement. A significant enhancement was found to be up to 50 times. The results are consistent with our numerical model. With etched gratings the grating overlap factor will be increased leading to further improvements in the enhancement; a near-infrared diode laser can be used to pump the device for a compact blue coherent light source. Further dispersion control can be achieved by introducing a two-dimensional PBG for higher SHG conversion.

Acknowledgments

The research described in this publication was made possible in part by Awards no. RP2-2266 and no. RP2-2275 of the US Civilian Research and Development Foundation for the Independent States of the former Soviet Union (CRDF). The work of A.M.Z. was also supported in part by the President of and the Volkswagen Foundation (project I/76 869). Russian Federation Grant no. 00-15-99304, the Russian Foundation for Basic Research project no. 00-02-17567, JWH and CD were funded by a DARPA grant, NSF grant ECS 0140109 and Ohio DAGSI fellowship. CS was funded by INFM –PAIS project. We are grateful to the Air Force Research Laboratory for the loan of the argon ion laser.

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