Quasi-phase-matched second harmonic generation device in Mg-doped LiNbO₃ and its application to high-density optical disk system

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Abstract. The resistance to photorefractive damage is investigated for several nonlinear crystals. A quasi-phase-matched (QPM) second harmonic generation (SHG) waveguide device is fabricated in 5 mol% Mg-doped LiNbO₃, which has high resistance to optical damage. The SHG blue laser of the QPM-SHG waveguide device and a tunable distributed Bragg reflector (DBR) laser diode is demonstrated, wherein output stability of continuous blue light is measured. The SHG blue laser, using the QPM-SHG waveguide device with broadened flat matching response, shows good modulation characteristics. The pulsed peak power of 23 mW with rectangular modulated waveform is generated. The SHG blue laser is installed to an optical head, and good recording and readout characteristics are demonstrated. Moreover, butt-coupled SHG blue laser is examined to gain a miniature module with volume of 0.8 cc.

Keywords. Quasi-phase-matched (QPM); second harmonic generation (SHG); Mg-doped LiNbO₃; optical waveguide; high-density optical disk systems.

1. Introduction

High-density optical disk systems are needed for efficient and storage capacity of data files, as well as of software and media packages. Several high-density optical disk technologies have been reported, such as cross-talk canceller technology, magnet super-resolution technology, and use of higher numerical aperture of objective lens and shorter-wavelength light source (Kaneko *et al* 1992; Kasazumi and Kato 1997; Osato *et al* 1998). Among these, we have focussed on development of the shorter-wavelength coherent light source. The light source has to attain continuous wave with low noise and good focussing characteristics, and also pulsed wave of over 10 mW with maximum modulation frequency of over 10 MHz.

We propose second harmonic generation (SHG) blue laser of quasi-phase-matched (QPM)-(SHG) waveguide devices and wavelength locked laser diodes. Frequency doubling of laser diodes, using QPM-SHG waveguide devices, is a promising method for efficient blue light generation (Lim *et al* 1989; Mizuuchi *et al* 1997). The QPM-SHG waveguide devices offer high conversion efficiency and good focussing characteristics of diffraction limited spot size, because fundamental wave is strongly confined to an optical waveguide, and the generated blue light is in a guided mode. Also, direct frequency doubling without solid-state laser materials makes it possible to modulate the generated blue light directly in high-frequency regions.

It is essential to realize an output stability and long life time of the SHG blue laser in order to apply it to the several application systems. In the QPM-SHG device, the wavelength allowance range for phase-matching to generate blue light efficiently was very narrow to be <0.1 nm. Therefore, the refractive index change of the substrate due to photorefractive damage resulted in the fluctuation of output power of blue light. This necessitated employing of ferroelectric materials, which show high resistance to the photorefractive damage, as the substrate of the QPM-SHG device. Also, since the wavelength fluctuation of the fundamental wave yields the unstable output power, it is essential to lock and tune the wavelength in the wavelength allowance by using a diffraction grating and an optical bandpass filter (Kitaoka *et al* 1994). It is also important to broaden the phase matching allowance range in order to attain the output stability and good modulation performance. Moreover, because the blue light power is in proportion to the square of the fundamental power, the coupling efficiency of the fundamental wave to the waveguide in the QPM-SHG device effects the output stability. Therefore, it is necessary to mount the QPM-SHG device and the laser diode on a module firmly so that the coupling efficiency is maintained for the change of surroundings, and butt-coupling of the laser diode and the waveguide is a promising method to realize mechanical stability and downsizing.

In this paper, we demonstrate a stable and compact SHG blue laser by use of QPM-SHG waveguide device in Mg-doped LiNbO₃ and a tunable distributed Bragg

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reflector (DBR) laser diode. The high resistance to photorefractive damage of Mg-doped LiNbO_3 is investigated, and stable continuous blue light and high-power pulsed blue light are demonstrated. By installing the SHG blue laser to optical disk systems we have demonstrated its readout and recording characteristics. Finally, a butt-coupled SHG blue laser without coupling lenses has also been realized.

2. Stabilization of SHG blue laser

2.1 QPM-SHG device

The SHG blue laser consisted of the waveguide-type QPM-SHG device and the tunable DBR laser diode as shown in figure 1. The QPM-SHG waveguide device had a proton-exchanged waveguide and periodically domain-inverted regions, which were fabricated in X-cut 5 mol% Mg-doped LiNbO_3 . In general, an inhomogeneity in refractive index, i.e. photorefractive damage, is caused by electro-optic effects, when ferroelectric materials such as LiNbO_3 and LiTaO_3 are illuminated by laser light (Ashkin *et al* 1966; Chen 1969). It is very essential for the substrate to be highly resistant to photorefractive damage in order to generate high power blue light. The change in refractive index, owing to photorefractive damage, causes the fluctuation of output power and the distortion of the guided transverse mode. In order to stabilize the output power of the blue light, it is important to use the ferroelectric material with high resistance to the optical damage as the substrate of the QPM-SHG device.

At first, we investigated the resistance to photorefractive damage of several nonlinear materials, such as LiNbO_3 , LiTaO_3 , domain-inverted LiTaO_3 , Mg-doped LiNbO_3 (grown by Kyocera Corporation), and domain-inverted Mg-doped LiNbO_3 , by observing the distortion of transmitting beam in the crystal, using the experimental setup shown in figure 2. This phenomenon due to photorefractive damage was reported by Ashkin (1966). The light beam radiated from Ar laser, wavelength of 457.9 nm, was focussed on the samples by a lens with

Figure 1. Configuration of SHG blue laser consisting of a QPM-SHG waveguide device and a tunable DBR laser diode.

a focal length of 120 mm, and the spot size in the sample was 60 μm (full width at half maximum: FWHM). The temperature of the sample was kept constant by a pertier cooler in order to protect it from pyroelectric effect. The focussed power was changed by the ND filter. The transmitted light beam was monitored by CCD camera and the beam size (FWHM) was calculated by a personal computer. Before the measurement, the transmitted beam size was measured at Ar laser power < 0.1 mW. The Ar laser power was subsequently increased to the measured power, and the sample was illuminated for 60 sec. The transmitted beam size was measured once again and compared with the beam size before illumination. When the distortion of transmitting beam in the sample was 20% for the compared beam size, the threshold of photorefractive damage (PRth) for the sample was defined.

The experimental results are summarized in table 1. The LiTaO_3 crystal showed higher resistance to photorefractive damage than the LiNbO_3 crystal. The PRth for the LiTaO_3 crystal was 15 mW. For the domain-inverted LiTaO_3 crystal, beam distortion of transmitted light could not be observed for illuminated power (50 mW) of the measurement limited power, and the resistance to photorefractive effect was improved by forming the periodically domain-inverted regions on the substrate.

Figure 2. Experimental setup for investigating the resistance to photorefractive damage.

Table 1. Resistance to the photorefractive damage for the measured samples. Threshold was defined when the distortion of transmitting beam in the sample was 20%.

	PRth for 457.9 nm (mW)	PRth for 488 nm (mW)
LiNbO_3	0.5	—
LiTaO_3	15	35
Domain-inverted LiTaO_3	> 50	> 1700
7.9 mol% Mg : LiNbO_3	> 50	—
5.7 mol% Mg : LiNbO_3	> 50	—
5.0 mol% Mg : LiNbO_3	> 50	> 1700
3.4 mol% Mg : LiNbO_3	0.1	—
1.05 mol% Mg : LiNbO_3	0.2	—
Domain-inverted 5 mol% Mg : LiNbO_3	> 50	> 1700

We consider this as the reason why the space charge fields produced by illumination of laser light are compensated in the periodically domain-inverted regions. By using higher power Ar laser (488 nm, 1.7 W), the improvement due to the periodically domain-inverted regions was examined. The PRth for LiTaO₃ crystal was 35 mW, and on the other hand the photorefractive damage could not be produced for domain-inverted LiTaO₃ crystal. We found that the periodically domain-inverted regions suppressed the photorefractive damage strongly and the effect was over 50 times. The photorefractive effect for the Mg:LiNbO₃ crystal heavily depended on the doping ratio. For more than 5 mol% Mg-doped LiNbO₃ crystal, the PRth was over 50 mW of the measurement limited power at the wavelength of 457.9 nm. We also did not observe any beam distortion by illumination of higher power Ar laser (488 nm, 1.7 W). These results agreed fairly well with those reported by Bryan *et al* (1984). For the domain-inverted Mg:LiNbO₃ crystal, the photorefractive effect could also not be observed.

We have researched the QPM-SHG device on the LiTaO₃ substrate. However, it is difficult to maintain the output power over 10 mW stably. The Mg-doped LiNbO₃ crystal showed high resistance to photorefractive damage. Therefore, we focussed on research on the QPM-SHG waveguide device in Mg-doped LiNbO₃ in order to generate the blue light over 10 mW. We fabricated the QPM-SHG waveguide device using X-cut 5 mol% Mg:LiNbO₃ as a substrate and examined the SHG characteristics, because it was easier to grow an uniform crystal based on refractive index distribution and Mg concentration.

The uniform domain-inverted regions, with period of 3.2 μm , depth of 1.9 μm and interaction length of 10 mm, were formed by use of two-dimensional high-voltage application (Mizuuchi *et al* 1997). The proton-exchanged waveguide was fabricated perpendicularly along the periodically domain-inverted regions. The depth and the width of the waveguide were 1.9 μm and 4 μm , respectively. Because the proton-exchanged channel waveguide in the X-cut substrate allows the TE mode fundamental wave to guide in, the light beam from the laser diode in TE mode can be coupled to the waveguide without a half-wave plate. The proton-exchanged high refractive index cladding was formed on the waveguide to attain high conversion efficiency by increasing overlap between the fundamental wave and the harmonic wave.

The SHG characteristics of the QPM-SHG waveguide device in the 5 mol% Mg:LiNbO₃ was measured by using a Ti:Al₂O₃ tunable laser. Blue light of 10 mW was generated for the coupling fundamental power of 35 mW, which corresponded with conversion efficiency of 29% (900%/W). The wavelength allowance width for the phase-matching was 0.08 nm (FWHM). The shift of the phase-matching wavelength could not be also

observed. These results indicate that the 5 mol% Mg:LiNbO₃ is a promising substrate to gain the QPM-SHG waveguide device, by which high-power blue light is stably generated.

2.2 Tunable DBR laser diode

It is essential that the wavelength locked lasers are employed as a fundamental wave in the SHG blue laser, because the wavelength allowance range for the phase-matching of the QPM-SHG device is very narrow. However, the tilt of the wavelength selective means causes the wavelength shift to fluctuate the output power. We have proposed SHG blue laser using a tunable DBR laser diode as the wavelength-locked laser diode. This laser diode consists of the active region and the DBR region with separated electrodes. The functions of locking and tuning the wavelength were monolithically integrated in the DBR structure. Therefore, it makes possible to realize the downsizing of the SHG blue laser and suppress the fluctuation of output power. The tunable DBR laser diode has been specifically developed for this application by SDL Inc., San Jose, California (Gulgazou *et al* 1997). The wavelength and output power were 852 nm and 100 mW, respectively, and the tunable wavelength range of 2 nm was obtained by changing the input current to the DBR region, while a single longitudinal mode could be maintained for the output power of 100 mW.

2.3 Blue light generation

2.3a Continuous blue light: The SHG characteristics of the QPM-SHG device was examined by using the tunable DBR laser diode. The light beam from the tunable DBR laser diode was collimated by a lens with numerical aperture (NA) of 0.5, and focussed on the facet of the QPM-SHG waveguide device by a lens with NA = 0.39. The wavelength of the laser diode could be adjusted within the phase-matching wavelength allowance range by controlling the input current to the DBR region. Figure 3 shows the generated blue light power as a function of power of the tunable DBR laser diode for the 10 mm long QPM-SHG device. The fundamental wave of 50 mW was coupled to the waveguide of the QPM-SHG device to generate blue light (426 nm) of 12 mW, which corresponded to conversion efficiency of 24% (480%/W). The obtained conversion efficiency was less than that obtained for the Ti:Al₂O₃ laser. That is the reason why the Ti:Al₂O₃ laser oscillates in multi-longitudinal mode. The relative intensity noise of generated blue light (−144 dB/Hz), was low enough to be applicable to the high-density optical disk systems. The focussing characteristics were examined, where the blue light was collimated by a lens with focal length of 12 mm and focussed by a lens with NA = 0.6. The

diffraction limited focal spot size of $0.39 \times 0.39 \mu\text{m}$ (FWHM) was obtained.

The wavelength allowance width for the phase-matching of the QPM-SHG was 0.08 nm (FWHM) for the 10 mm long device. Narrow allowance range makes it difficult to maintain the output stability. We assembled a module of the SHG blue laser using the 6 mm long QPM-SHG waveguide device and the 100 mW tunable DBR laser diode, and measured the output stability. The module temperature was maintained constantly by a pertier cooler. Generated output power of blue light was 3.2 mW. Figure 4 shows the output stability of the SHG blue laser. The power fluctuation was less than 5%. It was found that the 5 mol% Mg : LiNbO₃ has high resistance to photorefractive damage to be a suitable substrate to gain high-powered SHG blue laser.

2.3b Pulsed blue light: Because the longitudinal mode spectrum of the modulated conventional Fabry–Perot laser diodes is multi-mode to expand wider beyond the wavelength allowance range for the phase-matching, direct intensity modulation of generated blue light by modulating the laser diode as a fundamental wave has not been so far attained. The DBR region in the tunable DBR laser diode suppresses the expansion of the longitudinal mode spectrum within ~ 0.1 nm. However, since the wavelength allowance range for the phase-matching of the QPM-SHG device is very narrow, it is difficult to attain high conversion efficiency and rectangular waveform for modulated blue light constantly. Recently, the QPM-SHG waveguide device with broadened flat quasi-phase matching response has been reported, where the phase-shifted

segments were inserted in the periodic domain-inverted region (Mizuuchi and Yamamoto 1998). The dependence of the harmonic wave intensity on the fundamental wavelength is flat near peak conversion efficiency. The device length was 10 mm, where the domain-inverted region was divided into 3 segments ($L_1 = 1.38$ mm, $L_2 = 7.24$ mm, $L_3 = 1.38$ mm) with 2 phase-shift segments ($t_1 = 1.3 \mu\text{m}$, $t_2 = 1.9 \mu\text{m}$). The flat matching response was evaluated by using a Ti : Al₂O₃ laser. The flat peak bandwidth (the full width at 95% maximum) was 0.13 nm and the conversion efficiency was 380%/W.

The direct intensity modulation of the blue light was examined by using the QPM-SHG waveguide device with broadened flat matching response in 5 mol% Mg : LiNbO₃ and the tunable DBR laser diode. The light beam from the tunable DBR laser diode was coupled to the waveguide of the QPM-SHG device by a lens system. The driving current of the tunable DBR laser diode was directly modulated to generate the pulsed blue light. The peak power and the duty of the laser diode at the modulation were determined so that average power was less than 100 mW. The pulsed blue light of the wavelength 426 nm was generated by tuning the wavelength of the laser diode in the phase-matching wavelength allowance range of the QPM-SHG device. Figure 5 describes the modulated blue output with modulation frequency of 10 MHz and pulse duty of 33%. The rectangular modulated waveform for the generated blue light could be obtained where the rise time was less than several ns to satisfy the specification of high density optical disk systems. That is the reason why the oscillated wavelength during the modulation was maintained within the broadened wavelength allowance range of the QPM-SHG waveguide device. Figure 6 shows an example of measured peak power of the pulsed blue light dependence on the peak power of the tunable DBR laser diode. The

Figure 3. Measured blue light power plotted against coupling power of fundamental wave.

Figure 4. Output stability of SHG blue laser.

modulation frequency was 10 MHz and the duty was 33%, respectively. Maximum peak blue power of 23 mW was obtained for the coupling peak power of 165 mW. The longitudinal mode spectrum remained to be locked in the broadened wavelength allowance range, to attain highly efficient wavelength conversion. This result indicates that the SHG blue laser, using the tunable DBR laser diode, is capable of recording data both on phase-change disk as well as on magneto-optical disk.

3. Application to optical disk systems

3.1 Readout characteristics

Applicability of SHG blue laser to optical disk system was examined. Coherent light source in the optical disk system is needed to satisfy severe specifications such as output power stability, noise characteristics and focussing characteristics. We have installed the SHG blue laser into an optical head with an objective lens of NA = 0.6, and demonstrated readout of a high-density ROM disk. The carrier to noise (C/N) of 51 dB was obtained for pit length of 0.25 μm in the pure-tone signal. Figure 7 shows the readout characteristics of random signal on the ROM disk, whose thickness was 0.6 mm. Minimum pit length and track pitch in the random signal were 0.29 μm and 0.74 μm , respectively. This eye-pattern was obtained without filtering. The signal amplitude for minimum pit length was 40% of the envelop of the eye-pattern, which agreed well with the calculated result. The jitter for the random signal was 8.8% after filtering.

Figure 5. Modulated waveform of generated blue light with modulation frequency of 10 MHz and duty of 33%.

The SHG blue laser offered good performances in both basic optical properties and readout characteristics of optical disk. We consider that SHG blue laser is one of essential key technologies to realize the high-density optical disk systems with storage capacity of over 10 GB.

3.2 Recording characteristics

Recording pure-tone marks on the phase-change optical disk was performed by using the SHG blue laser with capability of direct intensity modulation. Phase change optical disk, with GeSbTe as recording layer and Au as reflection layer, was designed and fabricated by Matsushita group, so that the absorption and the reflectivity in both crystal and amorphous condition are suitable

Figure 6. Measured peak power of modulated blue light plotted against coupling peak power of fundamental wave.

Figure 7. Readout characteristics of the random signal on the high-density ROM disk using SHG blue laser.

for the blue light. The substrate thickness was 0.6 mm, same as that of DVD disk. The spacing of land and groove was $0.33\text{ }\mu\text{m}$. Figure 8 is an example of the recorded marks on both the land and the groove, observed by transmission electron microscope (TEM). The mark length was $0.24\text{ }\mu\text{m}$. This result shows the feasibility of realizing high-definition DVD-RAM with storage capacity of 15 GB per side on a 12 cm phase-change optical disk. However a new technology, such as cross-talk canceller technology (Kasazumi and Kato 1997), is needed in order to readout high-density data with storage capacity of 15 GB, using a blue light source. Therefore, we examined the recording and the readout of pure-tone signal with $0.3\text{ }\mu\text{m}$ mark length on the phase change optical disk with the track pitch of $0.35\text{ }\mu\text{m}$. These parameters are proportional to the wavelength ratio of $425\text{ nm}/650\text{ nm}$ (red laser in DVD) and this storage capacity corresponds to 11GB (4.7 GB in DVD). The readout signal is shown in figure 9. The C/N of 52 dB was obtained indicative of uniform marks, which were recorded on the phase change optical disk using the SHG blue laser. This confirms the capability of direct intensity modulation of the SHG blue laser, and indicates the applicability of the SHG blue laser to the rewritable optical disk system.

Figure 8. Recording marks observed by transmission electron microscope (TEM).

Figure 9. Readout characteristics of pure-tone signal recorded by SHG blue laser.

4. Butt-coupled blue light source

The lens-coupled SHG blue laser consists of two lenses, the laser diode, and the QPM-SHG waveguide device. Because the blue light power is in proportion to the square of the fundamental power, it is therefore necessary to maintain the coupling efficiency of the fundamental wave for the change of surroundings so as to stabilize the blue light power. In the lens-coupled SHG blue laser, the lens shift due to mechanical stress causes the change of the coupling efficiency. Therefore, butt-coupling of the laser diode and the waveguide without the coupling lenses is a promising method to realize mechanical stability. In this configuration, downsizing and ease to fabricate the module are also realized to make them adequate for commercial use and mass production of SHG blue laser.

We examined the butt-coupling characteristics of the tunable DBR laser diode and the QPM-SHG waveguide device. In order to couple the laser beam to the waveguide directly, the guided mode in the waveguide of SHG device have to coincide with the transverse mode of the laser diode. In our configuration, the X-cut substrate was used to guide in TE mode, and the laser diode oscillated in TE mode. Also, the function of locking and tuning the wavelength to the phase-matching wavelength was integrated on the tunable DBR laser. Therefore, it makes possible to mount both the laser diode and the QPM-SHG device on the same submount.

We measured the coupling efficiency in the butt-coupled configuration. The laser diode beam was directly coupled to the waveguide of SHG device without lens systems. The coupling efficiency for the QPM-SHG waveguide device in $\text{Mg}:\text{LiNbO}_3$ substrate is shown in figure 10.

Figure 10. Butt-coupling characteristics using QPM-SHG device in X-cut $\text{Mg}:\text{LiNbO}_3$ and tunable DBR laser diode.

Figure 11. 0.8 cc butt-coupled SHG blue laser.

This figure shows the coupling efficiency vs the distance between the laser diode and the waveguide. Maximum coupling efficiency of 75% could be realized and the efficiency was 50% at the distance of 4 μm . The results show good agreement with the coupling characteristics using the lens system.

The 0.8 cc butt-coupled SHG blue laser is shown in figure 11. The DBR laser diode chip on the 5.6 mm ϕ stem and the QPM-SHG waveguide device with conversion efficiency of 110%/W were mounted on the 0.8 mm stainless module. The distance between the laser diode chip and the waveguide was 4 μm , and the coupling efficiency of 50% was obtainable. The blue light of 2.7 mW was stably generated for laser diode power of 100 mW.

The possibility of a planar-type SHG blue laser as our final target was explored where both the tunable DBR laser diode chip and the QPM-SHG waveguide device are mounted in junction-down on Si sub-mount. This configuration has been employed for the coupling of the laser diode and the optical fibre in the optical communication field. It makes possible to mount the laser diode chip and the QPM-SHG device by passive alignment. The mechanical stability of the SHG blue laser would be realized by the butt-coupled and the planar-type configuration.

5. Conclusion

We realized the stabilization of blue light power of the SHG blue laser with the QPM-SHG waveguide device in the 5 mol% Mg-doped LiNbO_3 and the tunable DBR laser diode. It was found that the >5 mol% Mg-doped LiNbO_3 crystal has higher resistance to the photorefractive damage and the domain-inverted regions improve the resistance considerably. The oscillated wavelength of the tunable DBR laser diode was locked in the wavelength allowance range for the phase-matching to attain output stability in 100 h. The direct intensity modulation of the blue light with rectangular waveform was confirmed by using the QPM-SHG waveguide device with broadened flat matching response and the tunable DBR laser diode. The SHG blue laser was installed to the optical pickup. The readout of the high-density ROM disk and the recording on the phase-change optical disk was examined to confirm the applicability of the SHG blue laser to the optical disk systems. Finally, butt-coupled SHG blue laser was examined to gain a butt-coupled miniature module with volume of 0.8 cc that showed mechanical stability.

References

- Ashkin A, Boyd G D, Dziedzic J M, Smith R G, Ballman A A, Levinstein J J and Nassau K 1966 *Appl. Phys. Lett.* **9** 72
- Bryan D A, Gerson R and Tomaschke H E 1984 *Appl. Phys. Lett.* **44** 847
- Chen F S 1969 *J. Appl. Phys.* **40** 3389
- Gulgazov V M, Zhao H, Nam D, Major J S and Koch T L 1997 *Electron. Lett.* **33** 58
- Kaneko M, Aratani K and Ohta M 1992 *Jpn J. Appl. Phys.* **31** 568
- Kasazumi K and Kato M 1997 *Proceeding of international symposium on optical memory, Yamagata Th-Q-06* p. 204
- Kitaoka Y, Mizuuchi K, Yamamoto K and Kato M 1994 *Opt. Rev.* **1** 227
- Lim E J, Fejer M M, Byer R L and Kozlovsky W J 1989 *Electron. Lett.* **25** 731
- Mizuuchi K and Yamamoto K 1998 *Opt. Lett.* (to be published)
- Osato K, Yamamoto K, Ichimura I, Maeda F and Kasami Y 1998 *Proceeding of optical data storage WA2-1* p. 131