平成１１年度　分子科学研究所研究会

「高機能全固体レーザーとその応用」
―「非線形光学材料／素子の新展開」―

New aspects of nonlinear optical materials and devices

主催：分子科学研究所

Organized by Institute for Molecular Science

協賛：レーザー学会

Approved by the Laser Society of Japan

岡崎国立共同研究機構岡崎コンファレンスセンター

OKAZAKI Conference Center, OKAZAKI National Research Institutes

平成 11 年 10 月 29 日

Program

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「高機能全固体レーザーとその応用」
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– New aspects of nonlinear optical materials and devices –

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開会の辞　Opening Remarks

10:10-10:40
"Material potential of stoichiometric $LiTaO_3$ and $LiNbO_3$ for bulk quasi-phase matching devices"
Yasunori FURUKAWA, Kenji KITAMURA, Syunji TAKEKAWA (NIRIM)

10:40-11:00
"Second-order nonlinearity in stoichiometric $LiNbO_3$ and $LiTaO_3$"
Takumi FUJIWARA, Akira J. IKUSHIMA, Yasunori FURUKAWA*, Kenji KITAMURA*
(Toyota Institute of Technology, *NIRIM)

11:00-11:20
"Exact measurement of electroopic coefficients in $LiNbO_3$ crystals
－nonstoichiometric dependences and effect of doping Ce- or Fe-ions－"
Yukiko KONDO, Yuri YAMASHITA, Takeshi FUKUDA, Yasunori FURUKAWA*, Kenji KITAMURA*, Hirochika NAKAJIMA (Waseda Univ., *NIRIM)

11:20-11:40
"Large second-order optical nonlinearity in thermally poled silica glass"
Akihiro KAMEYAMA, Atsushi YOKOTANI, Kou KUROSAWA (Miyazaki Univ.)

11:40-12:00
"Sublattice-reversal epitaxy for QPM devices"
Shinji KOH, Takashi KONDO (Univ. of Tokyo)

12:00-12:20
Photo-induced damage in GdYCOB and its circumvention
M. YOSHIMURA, H. FURUYA, H. NAKAO, I. YAMADA, Y. F. RUAN, Y. K. YAP, Y. MORI, T. SASAKI (Osaka Univ.)

昼食　Lunch　(13:15 **写真撮影 commemorative photo taking)**

分子研レーザーセンター長挨拶　Introduction of *"Institute for Molecular Science"*

13:30-14:00
Special talk: "Future prospects of fiber lasers and LD arrays"
Prof. Ken-ichi UEDA (Univ. of Electro-Communications)

14:00-15:00
Special talk: "Recent developments in microstructured nonlinear materials and their applications"
Prof. Martin M. FEJER (Stanford Univ.)

Coffee Break

15:20-15:40
"Miniatuarized SHG blue laser and application to optical disk"
Kazuhisa YAMAMOTO, Yasuo KITAOKA, Kiminori MIZUUCHI (Matsushita Electric Industrial Co., Ltd.)

15:40-16:00
"QPM-SHG device using periodically poled $MgO-LiNbO_3$"
Yasukazu NIHEI, Akinori HARADA, Shin'ichiro SONODA, Masami HATORI, Koji KAMIYAMA,
(Fuji Photo Film Co., Ltd.)

16:00-16:20
"Liquid phase epitaxial growth of $LiNbO_3$ thin films for QPM-SHG devices"
T. KAWAGUCHI, K. MIZUUCHI*, M. IMAEDA, K. YAMAMOTO*, T. FUKUDA+
(NGK Insulators, *Matsushita Electric Industrial Co., Ltd., +IMR, Tohoku Univ.)

16:20-16:40
"1.5 μm-band quasiphase matched $LiNbO_3$ wavelength converters for optical communication systems"
Chang-qing XU (Oki Electric Industry Co., Ltd.)

閉会の辞　Closing Remarks

Abstracts

Material potential of Stoichiometric $LiTaO_3$ and $LiNbO_3$ for bulk quasi-phase matching devices

Yasu Furukawa and Kenji Kitamura

(National Institute for Research in Inorganic Materials)

Lithium tantalate ($LiTaO_3$) and lithium niobate ($LiNbO_3$) are of interest for surface acoustic wave (SAW) devices, piezoelectric devices and in nonlinear optical applications because of their large electro-optic and nonlinear optical coefficients. Among these applications, wavelength conversion by quasi-phase matching (QPM) using periodically poled $LiNbO_3$ (PPLN) and $LiTaO_3$ (PPLT) crystals has attracted as promising methods to realize tunable frequency conversion devices with high efficiency. Although the domain switching by applying electric field is a practical method for fabricating periodically poled domain structure, high electric field (above 21 kV/mm) required for domain switching and large internal field in both cases of $LiNbO_3$ and $LiTaO_3$ pose limitations on the sample thickness and the ability to control domain periodicity.

We will report newly developed stoichiometric $LiTaO_3$ crystal as one of the most promising material for bulk quasi-phasematching because of its low coercive field for ferroelectric domain switching, increased nonlinear constant and reduced photorefraction as compared to congruent crystals.

Near stoichiometric $LiTaO_3$ crystal were grown from a Li-rich melt using a novel double crucible Czochralski method. The ferroelectric domain shape and domain wall smoothness were compared between the conventional and near sotichiometric $LiTaO_3$ crystals. It turned out that the domain shape under the electric field at room temperature strongly depended on the densities of nonstoichiometric defects. The domain shape in the conventional $LiTaO_3$ is basically triangular while it is hexagonal in the stoichiometric $LiTaO_3$. The sides of hexagon in the stoichiometric $LiTaO_3$ are perpendicular to the crystallographical X axes, that is, parallel to the X faces. Therefore, considerably smooth domain walls can be obtain in the stoichiometric $LiTaO_3$ when the periodical domain structure is designed as each domain elongates along the Y axis. This result is promising a great improvement by using stoichiometric $LiTaO_3$ in fabricating quasi-phase matching wavelength conversion devices with high performances.

[Notes]

Second-Order Nonlinearity in Stoichiometric $LiNbO_3$ and $LiTaO_3$

Takumi FUJIWARA, Akira J. IKUSHIMA,
*Yasunori FURUKAWA, and *Kenji KITAMURA

(Toyota Institute of Technology, *NIRIM)

$LiNbO_3$ and $LiTaO_3$ single crystals have caught much attention to be applied to electro-optic (EO) and second-harmonic generation (SHG) devices such as optical switches, modulators, and SHG light sources, and also volume holographic memories. This is because the crystals has good mass producibility and a relatively high second-order nonlinearity and photorefractive sensitivity. For possible enhancements, EO effect and photorefractivity have previously been studied in $LiNbO_3$ with various dopants. However, $LiNbO_3$ crystals so far studied was nonstoichiometric, where usually congruent composition was obtained from a melt with 48.6 mol.% Li_2O. This is because the crystals with stoichiometric composition have hardly been grown by the conventional Czochralski method.

Kitamura et al. have reported a novel crystal growing technique to yield stoichiometric $LiNbO_3$ and $LiTaO_3$ crystals of high quality, where the stoichiometry is achieved by the continuous-charge double-crucible Czochralski method with 58.0 mol.% Li_2O melt. Stoichiometric $LiNbO_3$ has advantages: photorefractivity has been thought to be enhanced, and much of previous work has focused on this important issue. Recently, the stoichiometric crystal shows a larger photorefractive gain and a faster response time than those in the commercially available Fe-doped congruent one.

The photo-induced index change should be closely related to the EO effect, and therefore quantitative measurement of the EO coefficients is strongly demanded to clarify the origin of large photorefractivity. In addition, possible increase of the EO and SHG coefficients in $LiNbO_3$ crystals has to be confirmed for photonic devices with much higher efficient EO effect and frequency conversion than those to date. In a present work we have examined the EO and SHG coefficients in both the stoichiometric and congruent $LiNbO_3$ and $LiTaO_3$ crystals.

[Notes]

Exact Measurement of Electroopic Coefficients in $LiNbO_3$ Crystals －Nonstoichiometric Dependences and Effect of Doping Ce- or Fe-ions－

Yukiko KONDO, Yuri YAMASHITA, Takeshi FUKUDA,
*Yasunori FURUKAWA, *Kenji KITAMURA,
and Hirochika NAKAJIMA

(Waseda University, *NIRIM)

The composition dependence of the electrooptic coefficients in $LiNbO_3$ (LN) crystals, and the influence of doping with Ce-ions and Fe-ions were investigated. Several samples with different compositions were prepared for the measurement. The composition of the LN crystals ranges from stoichiometric (Li/(Li+Nb)=0.5) to highly nonstoichiometric (Li/(Li+Nb)=0.479). In order to grow single LN crystals with a stoichiometric composition (SLN), a double cruicible method was used. Samples doped with Ce- or Fe-ions were also prepared for the measurement.

The electrooptic coefficients were measured with the Mach-Zehnder interferometer. He-Ne laser (633nm, 8mW) was used as a light source. An AC voltage of 175 Hz was applied to the crystal by a pair of electrodes with an air gap on the crystal. The interference pattern was observed by a photodetector and an oscilloscope. The electrooptic coefficients were derived from the measured half-wave voltage.
The electrooptic coefficient r_{33} increases with an increase in Li/Nb ratio, while r_{13} seems to be almost independent of the crystal composition. The electrooptic coefficient r_{33} in LN crystal with almost stoichiometric structure was 1.14 times as large as that in congruent LN crystal whose electrooptic coefficient is 32.6 pm/V. The electrooptic coefficient also increases by Ce-ion doping of less than 500 ppm and Fe-ion doping. An increase of more than 30% in electroptic coefficients (from those in nondoped congruent LN) can be obtaind by doping with Ce- or Fe-ions.

The lattice constants of the LN crystals were determined by the X-ray diffraction method. The lattice constant along the c-axis decreases with an increase in Li/Nb ratio, or by doping with Ce- or Fe-ions. In this way, the crystal structure changes into the less symmetric structure whose electro-optic coefficient is very large. This might be the reason why the electrooptic coefficient increases with an increase in Li/Nb ratio or by doping Ce- or Fe- ions.

[Notes]

Large second-order optical nonlinearity in thermally poled silica glass

A.Kameyama, A.Yokotani, and K.Kurosawa

(Dept. of E&E Eng., Miyazaki University)

Silica glass has become the most attractive material for photonics engineering, since a function of a permanent strong second-order optical nonlinearity has generated in thermally poled silica glasses in addition to high transparency and high band-gap energy. The origin of the nonlinearity is considered to be electric-field-induced second-order nonlinearity, $\chi^{(2)} = \chi^{(3)}E_{dc}$, in which the space charge field comes from SiO-(NBO-) and metallic ion. The $\chi_{33}^{(2)}$ was around 1 pm/V in silica glass made from natural quartz (including much metallic ion), but no nonlinearity was observed in high-purity silica glass synthesized from $SiCl_4$. It is required to generate the strong optical nonlinearity in high-purity silica glass in optics. We have reported the nonlinearity in high-purity synthesized silica glass which induced defects by X-ray irradiation before poling, but $\chi_{33}^{(2)}$ was only 0.24 pm/V. Furthermore, silica glass is impossible to generate large second harmonic wave light because silica glass can't satisfy phase-matching condition, fine structures such as nonlinear gratings are required for the practical devices. Some groups have reported a quasi-phase-match second harmonic generation from the fine structures made by electrode of periodic structure in the silica glass. The signal intensity was very smaller than the ideal value for the random of periodic pitch and the poling process must carry out in the vacuum. Dell et al. have reported that when poled silica glass exposed to UV light, the nonlinearity was reduced. The erasure process are very simple and are useful to make the fine structures to allow strong second harmonic generation. We report large second-order optical nonlinearity of $\chi_{33}^{(2)} = 0.71$ pm/V in a high-purity synthesized silica glass which was heated up and exposed by a KrF excimer laser, and the nonlinearity decreased for the KrF excimer laser irradiation after poling.

[Notes]

Sublattice Reversal Epitaxy for QPM devices

Shinji KOH, and Takashi KONDO

(Faculty of Engineering, The University of Tokyo)

Compound semiconductors are promising materials for fabricating quadratic nonlinear optical devices because sophisticated crystal growth and processing technologies available for semiconductors should allow us to exploit their large optical nonlinearity. Monolithic integration of such nonlinear optical devices and semiconductor lasers will lead to a new class of novel compact laser sources for optical communications and other optical data processing applications. The phase matching problem arising from the optical isotropy of zincblende-type semiconductors can be solved by using quasi-phase-matching (QPM) methods, which require spatial modulation of the optical nonlinearity. The best way to utilize the large optical nonlinearity is to achieve periodic domain inversion. We have demonstrated sublattice reversal epitaxy to fabricate domain-inverted structures in the GaAs/Ge/GaAs system.[1]

The idea is to trick the Ga and As atoms of overgrown GaAs into forgetting their sublattice sites that they have occupied in the substrate by inserting a thin Ge intermediate layer in the GaAs epitaxial growth. Sublattice-reversed GaAs crystal has been reproducibly grown in the lattice-matched GaAs/Ge/GaAs (100) and (111) systems. Sublattice reversal was confirmed by reflection high energy electron diffraction (RHEED) and preferential etching. The quality of the sublattice-reversed GaAs crystal is investigated using cross-sectional transmission electron microscopy (XTEM). A method to fabricate a periodically domain-inverted structure using sublattice reversal epitaxy is demonstrated for the GaAs/Ge/GaAs (100) system.

References:

[1] S. Koh, T. Kondo, M. Ebihara, T. Ishiwada, H. Sawada, H. Ichinose, I. Shoji and R. Ito, Jpn. J. Appl. Phys. Vol. **38** L508 (1999).

[Notes]

Photo-induced Damage in GdYCOB and its Circumvention

M. YOSHIMURA, H. FURUYA, H. NAKAO, I. YAMADA, Y. F. RUAN, Y. K. YAP, Y. MORI, and T. SASAKI

(Department of Electrical Engineering, Osaka University)

The development of all-solid-state UV lasers is important for industrial and medical applications. Re $Ca_4O(BO_3)_3$ (Re: rare-earth atom) is an attractive nonlinear optical borate family stirring considerable interest in solid-state laser community because of its moderate nonlinearity, nonhygroscopicity, and ease in growing large crystal. Recently, we have developed a substitutional solid solution of $Gd_xY_{1-x}Ca_4O(BO_3)_3$ (GdYCOB) crystal in order to control the birefringence. The increase of the compositional parameter x could change the phase-matching angles of third-harmonic generation (THG) of Nd:YAG laser to the y axis. As a result, GdYCOB (x=0.28) achieved noncritically phase-matched (NCPM) type-I THG at room temperature [1]. However, during high-power THG operation, degradation of THG output power and distortion of beam pattern occurred due to photo-induced damages and thermal dephasing. We have found two types of photo-induced damages. One was gray-track, which was formed by high peak power THG. Another was photorefractive damage induced by THG at high repetition rate frequency. It seems that these damages were similar to that of $KTiOPO_4$ (KTP) crystal [2]. Thermal dephasing of GdYCOB is due to damage-induced and the intrinsic absorption. GdYCOB at elevated temperature can circumvent the photorefractive damage and thermal dephasing. THG output as high as 0.5 W was obtained at 62.5 kHz, which is comparable to that of type-II LBO. We can expect proper polishing process and optical coatings lead to higher UV output.

References:

[1] M. Yoshimura, H. Furuya, T. Kobayashi, K. Murase, Y. Mori, and T. Sasaki, Opt. Lett., **24**, 193 (1999).

[2] B. Boulanger, I. Rousseau, J. P. Feve, M. Maglione, B. Menaert, and G. Marnier, IEEE J. Quantum Electron., **35**, 281 (1999).

[Notes]

Future prospects of fiber lasers and LD arrays

Ken-ichi UEDA

(Institute for Laser Science, University of Electro-Communications)

1. Direction and Background

One of the most critical issues on laser technology and science is how to control the light generation and propagation. The principle of laser amplification is stimulated emission. Coherent addition is the realization of this principle in the scale to laser devices. Is it possible or not to realize the coherent addition in the device scale? This is the issue I want to discuss in this symposium.

I have an experience to develop an extremely stabilized laser source for gravitational detection. In this experiment, we achieved a very good frequency stability of the order of micro Herz. We also tried to make an experiment of coherent addition by using a pair of stabilized lasers. But the result was not so good as expected. We learned that the frequency and phase control was relatively easy, but the spatial mode control was critical. This is the starting point of our proposal of coherent addition.

In principle the intrinsic light generator is an atom. Every atom generates a single photon. So, the light emission in the conventional light source is incoherent because the light emission from atoms are random in time and space. How to generate the coherent light? Stimulated emission solved this problem. In the amplification process, the stimulated emission process is effective for the coherent addition of emission from atoms in time and space. Please imagine that a large number of atoms of 10^{19} /cm^3 generate the same quality of photons.

I have another experience about fiber laser development. In this development I learned that the multiple-beam output is better than the single beam output from the view of the energy extraction. It means that multiple beam output is better if these beams can be combined coherently like lasing process. This is our target.

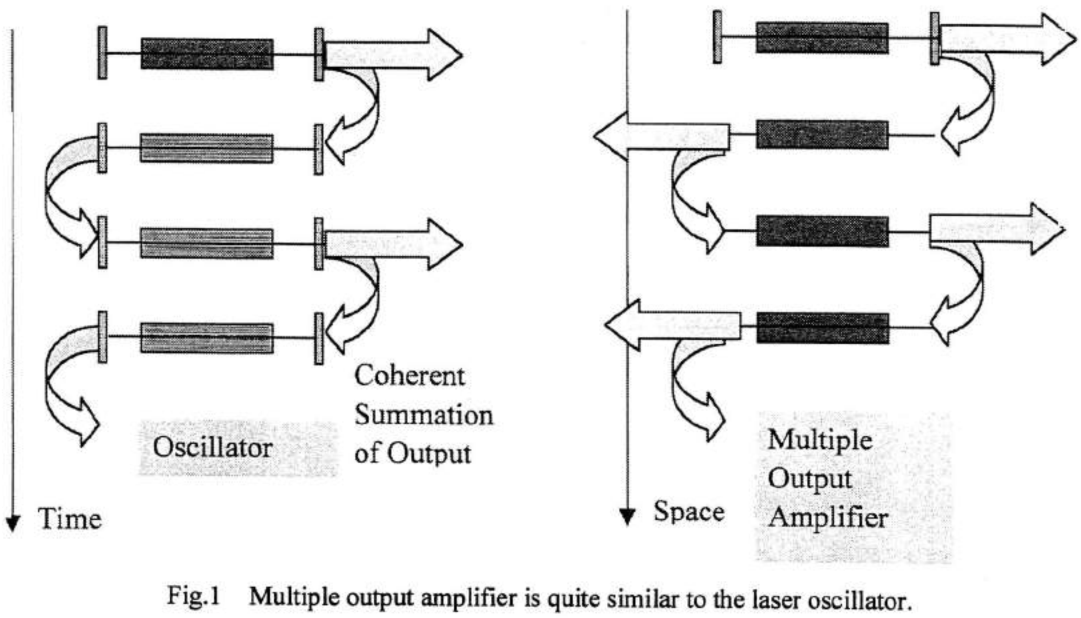

Fig.1 Multiple output amplifier is quite similar to the laser oscillator.

(a) laser oscillator in time domain and (b) multi-output amplifier in space domain.

2. Discussion

I present the concept of multiple beam output laser system here. As shown in Fig. 1 (a), the single output beam of a typical laser resonator is the result of the coherent superposition of multiple output beams with time coherence. If we apply the same concept to the multi-element amplifier system, we have a very similar picture as shown in Fig.1 (b). The every beams has the same frequency and spatial quality, but the phase is not locked. Yes, my idea is different from the traditional one in this point. I believe we can correct the phase in the final stage of amplifiers.

Multiple output system is promising in laser diode (LD) amplifiers. High power LD system contains many small power LDs. SDL developed a high power LD technology by expanding active area. But, this method has a limited potential of expanding of output power because the current confinement in the large volume is not scalable. In principle the fully saturated amplification can extract the energy from the amplifier material. LD amplifier can control the phase directly by the driving current control. This is a big advantage.

How to measure the phase condition? When we apply the intensity modulation with a certain frequency on two beams, the heterodyne signal gives us the phase locked condition through the spectrum analyzer. So, by means of multichannel analyzing is available to adjust the phase of multiple beams.

There are several kinds of multiple output laser system, series, parallel and series parallel arrangement. Which is better? It depends on the future technological development.

The similar concept is able to be realized in the fiber lasers. In the fiber laser technique the fiber combining and branching is relatively easy. So, the series parallel branching amplifier is good enough. The output of fiber laser is divided into the seed beams of multiple branched fiber amplifiers. At the final stage of bundled fiber amplifiers in the side pump scheme we need the phase control optics.

3. Future, fusion technology of laser and adaptive optics

I want to mention that the phase control of multiple beams realizes the real active optics for adaptive optics. The phase control produces the parallel, conversing and diverging beams easily. The beam scanning is also possible. In this lecture I present several aspects of such real active optics.

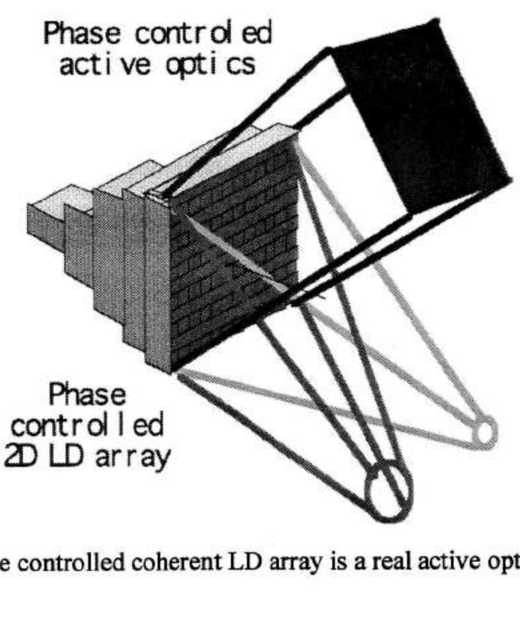

Fig.2 Phase controlled coherent LD array is a real active optics.

Recent Developments in Microstructured Nonlinear Materials and Their Applications

Martin M. FEJER

(Stanford University)

Over the past several years, compact sources of coherent radiation based on microstructured nonlinear materials have become relatively well known. Recently, applications in other areas such as signal processing devices for optical communications, and ultrafast pulse generation and shaping have emerged. Two important classes of microstructured materials are periodically poled ferroelectrics and orientation patterned semiconductors. In this talk, we will discuss the current status of these microstructured materials, and present results in some of the recent applications areas.

While the periodically-poled ferroelectrics are increasingly well developed, and have found commercial applications, there remain issues in with respect to material properties, especially for high average power or short wavelength uses. After describing basic patterning techniques and applications, improved patterning based on "backswitch" poling, and characterization of linear and nonlinear absorption in ferroelectrics will be discussed.

Near-degenerate difference frequency generators in PPLN waveguides can perform functions at optical frequencies analogous to those performed by RF mixers at lower frequencies, i.e. they generate an output field proportional to an input signal (around 1560 nm) and a local oscillator field (around 780 nm). Applications to WDM systems as wavelength convertors, to TDM systems as gated mixers, and to correction of dispersion as spectral inverters are all possible. Device and system demonstrations of such functions will be presented.

Patterned materials based on III-V or II-VI semiconductors offer transparency much deeper into the infrared than do oxide ferroelectrics, as well as having large nonlinear susceptibilities, and high thermal conductivity. All-epitaxial methods are emerging for growth of thick and thin films of orientation-patterned semiconductors, suited to bulk and waveguide applications, respectively. Recent results in this area will be presented as well.

[Notes]

Miniaturized SHG blue laser and application to optical disk

Kazuhisa YAMAMOTO, Yasuo KITAOKA, and Kiminori MIZUUCHI

(Optical Disk Systems Development, Center Matsushita Electric Industrial Co., Ltd.)

High-density optical disk systems with storage capacity of over 10GB are focused on as next DVD system. 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. We have concentrated our attention to development of the shorter wavelength coherent light source. It is required for the light source to gain continuous wave with low noise and good focusing characteristics, and also pulsed power of over 10mW at frequency of maximum modulation frequency of over 10 MHz.

We propose an SHG blue laser of quasi-phase-matched (QPM)-second harmonic generation (SHG) waveguide devices and tunable distributed-Bragg-reflector (DBR) laser diodes. The SHG blue laser is an attractive short-wavelength light source for generating high power blue light with low noise and good focusing characteristics. The tunable DBR laser diode oscillates in a single longitudinal mode to yield very low noise characteristics for blue light as harmonic wave. The QPM-SHG waveguide devices offer high conversion efficiency due to long interaction length and good focusing characteristics of diffraction limited spot size, because fundamental wave is strongly confined in an optical waveguide and the generated blue light is 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.

In this paper, we demonstrate miniaturized SHG blue laser by use of butt-coupling configuration, which consists of a tunable DBR laser diode and a QPM-SHG waveguide device in x-cut Mg doped $LiNbO_3$. Also, readout characteristics of a high-density ROM disk, and recording marks on a phase-change optical disk using the SHG blue laser will be reported.

[Notes]

QPM-SHG device using periodically poled $MgO-LiNbO_3$

Yasukazu NIHEI, Akinori HARADA,
Shin'ichiro SONODA, Masami HATORI, and Koji KAMIYAMA

(Miyanodai Technology Development Center, Fuji Photo Film Co., Ltd.)

The full color laser scanning exposure technology is attracting attention as a high performance image printing system in the field of digital full color printing. Now we developed very stable blue and green solid-state lasers sufficient for high-speed color photographic printers. And the newly developed Digital Lab System "FRONTIER" with high speed color photographic printer was accomplished.

The main feature of our newly developed blue and green lasers is that advanced bulk periodically poled $MgO-LiNbO_3$ (PPMGLN) is used as a frequency doubling crystal which is superior to conventional $KNbO_3$ or KTP crystals. And PPMGLN has higher resistance to photorefractive damage at room temperature. We have successfully fabricated bulk type of PPMGLN by using a novel corona discharge method. And it was turned out that the electrical resistance of $MgO-LiNbO_3$ after periodically domain inversion decreased greatly. For $MgO-LiNbO_3$ having this feature we find that the corona discharge technique is more suitable for fabricating uniform bulk periodic domain inversion than the conventional electric-field poling technique. Consequently we commercially developed blue and green solid-state lasers using PPMGLN for the first time.

The basic scheme of our blue and green solid-state lasers is an intracavity frequency doubling of a laser diode pumped solid-state laser. The maximum output power of over 17 mW for blue (at the wavelength of 473 nm) and over 90 mW for green (at the wavelength of 532 nm) were achieved, respectively, at a laser diode power of 500mW. And a high stability of laser power against temperature and a low noise, which are very important for the full color laser scanning system, have also been achieved.

For the similar applications, we study another laser module with a butt coupling structure of QPM-SHG devices and a laser diode. This laser module has more simple structure and an additional function of optical modulation. Formation of a domain inversion was achieved in off-cut $MgO-LiNbO_3$ for the first time. The depth of the domain inversion was about 2.5 times deeper than that in an X-cut substrate. By forming a waveguide, a blue light of wavelength 475 nm, and a power 37 mW has been obtained and a normalized second harmonic conversion efficiency was 300%/W cm^2 with interaction length of 10 mm. And EOM-SHG integrated device was demonstrated.

[Notes]

Liquid Phase Epitaxial Growth of $LiNbO_3$ Thin Films for QPM-SHG Devices

T. KAWAGUCHI, K. MIZUUCHI*, M. IMAEDA, K. YAMAMOTO*, and T. FUKUDA+

(NGK Insulators, *Matsushita Electric Industrial Co., Ltd., +IMR, Tohoku University)

Introduction

LN single crystals show excellent properties for use as optical waveguide devices which utilize electro-optic or nonlinear optical effects. Because the performance of these devices is closely related to the quality of substrate crystals, extensive fundamental investigations are in progress, such as the doping and/or the stoichiometry control. However, up to now, the choice of substrates has been limited to the commercially supplied nondoped LN or 5 mol% MgO-doped LN with congruent composition, both of which are grown by the CZ method. This is because the growth of doped or off-congruent bulk crystals encounters many difficulties in achieving compositional uniformity and high crystalline quality. Another approach is to epitaxially grow a doped and/or stoichiometry-controlled LN thin-film on a conventional LN substrate. Liquid phase epitaxy (LPE) is a suitable technique because 1) a large number of dopants can be selected, 2) it provides a thin-film with high crystalline quality and 3) 3-inch sizes wafers with compositional and thickness uniformity can be achieved. These provide the compatible availability in conventional device fabrication processes. Quasi-phase-matched (QPM) second-harmonic generation (SHG) device is one of the most attractive applications of LN optical waveguides. Controlling its ferroelectric domain and suppressing optical damage have attracted great interest. In this paper, several approaches of LPE-LN in optical applications are introduced, with our main focus on QPM-SHG applications.

Ferroelectric domain control

Domain-inverted film growth is observed in several film/substrate combinations. We proposed a new fabrication process for the QPM-SHG device by forming a periodic groove structure on a Z-cut substrate followed by the growth of a domain-inverted LN thin-film by LPE. A first order SHG of 440nm wavelength with a grating period of 3.6_m was demonstrated. Periodically switching spontaneous polarization on X-cut LN substrate was also formed by modulating the substrate orientation.

Optical damage resistance of Zn-doped LN thin-film

A maximum of about 8 mol% ZnO could be doped into the films without any degradation of surface morphology. Since a threshold concentration of 4 - 6 mol% ZnO is effective in suppressing the optical damage in CZ-grown LN, the ZnO content in the films obtained by LPE is expected to be sufficient to suppress optical damage. In contrast to the fact that the optical damage level for the device using an undoped LN film is not more than about 10 _ W, the device using Zn:LN film does not show any reduction in SHG properties up to output power levels of the mW order. This indicates that a significant improvement (> 10^2 times) of the resistance to optical damage is achieved using the Zn:LN film.

Thin-film optical waveguide

Although optical waveguides in LN substrates are usually formed by proton-exchange or Ti-indiffusion technique, crystal structure change or damage from these diffusion processes causes the degradation of optical properties such as the reduction of electro-optic constants. The thin-film LN waveguide is attractive because it has almost the same properties as LN crystal itself. In addition, a step-index profile and independent controllability of the waveguide depth and width are favorable in designing devices. A ridge-type multi-layered waveguide structure was fabricated by micro-machining. Rectangular cross-sectional shaped step-index waveguide was realized without diffusion processes.

Summary

Control of ferroelectric domain, doping of beneficial materials, flexibility in the structural design and control of crystalline properties (refractive index, crystallinity, ...) are important in the development of new LN optical waveguide devices. LPE is an attractive technique for this purpose.

[Notes]

1.5 μm-band quasiphase matched $LiNbO_3$ wavelength converters for optical communication systems

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Wavelength converters are considered necessary components in future wavelength demultiplex (WDM) systems. For use in cross-connect networks, the wavelength converters should exhibit high conversion efficiency, low noise, high transparency to signal bit-rate and signal data format, broad tunable range of the converted signal, and signal polarization insensitivity. On the other hand, for use in long-haul transmission networks, additional properties such as high speed, multi-channel conversion and large conversion span are required. Compared to other wavelength conversion methods, wavelength conversion based on quasiphase matched (QPM) difference frequency generation (DFG) offers several advantages (i.e. high speed, low noise and high transparency), however further improvements of the QPM-DFG wavelength converters are necessary. For QPM-DFG based wavelength conversions around 1.55 μm, if a pump light at a wavelength of λp (ex. λp=0.775 μm) is used, a signal light at λs (ex. λs=1.54 μm) can be converted to λc (i.e. $\lambda c = 1/(1/\lambda p - 1/\lambda s) = 1.56$ μm). Since the QPM-DFG based wavelength conversion involves a nonlinear interaction process and the phase matching condition can only be satisfied for a finite pump wavelength, high speed, low noise, and multi-channel wavelength conversions can easily be obtained.

In this paper, our recent results on insertion loss of $LiNbO_3$ waveguide and optical damage in the wavelength converters are reported, and some system applications of the present devices are proposed. It is shown that a fiber-to-fiber insertion loss of less than -3.5 dB can be obtained for a wavelength converter module with a 40 mm-long device. Also, It is found that optical damage occurs even at a pump power level of less than 10 mW, indicating that optical damage problem has to be solved before practical applications.

[Notes]

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