Wavelength Conversion Devices Using Quasi-phase-matched $LiNbO_3$

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Abstract

This paper describes recent progress in research on wavelength converters that employ quasi-phase-matched $LiNbO_3$ (QPM-LN) waveguides. The basic structure and operating principle of these devices are also explained. The wavelength conversion characteristics, resistance to photorefractive damage, and optical parametric amplification characteristics of an annealed proton exchanged waveguide are presented. Polarization-independent wavelength conversion using a ridge waveguide fabricated on epitaxially grown $LiNbO_3$ is also introduced. QPM-LN-based wavelength converters have several advantages: for example, they can convert high-speed signals of 1 THz or more, have no signal-to-noise ratio degradation and no modulation format dependence, and can simultaneously convert broadband wavelength division multiplexing channels. Therefore, they will be key devices in future photonic networks.

1. Introduction

In recent years, there has been considerable progress in the research and development of technology for constructing large-capacity optical communications systems by wavelength division multiplexing (WDM) of high-speed optical signals. To be flexible and efficient, future networks will require photonic network technology that can process optical signals directly without converting them into electrical signals. Wavelength conversion devices are promising for achieving this. Various types of wavelength conversion devices have been proposed and studied, but quasi-phase-matched $LiNbO_3$ (QPM-LN) waveguides are superior to the others. They can convert high-speed signals of 1 THz or more, have no signal-to-noise ratio (SNR) degradation and no signal format dependence, and can simultaneously convert a group of broadband wavelengths.

In this paper, we describe the structure and operating principle of wavelength conversion devices that employ QPM-LN waveguides and report on the research being conducted on them at NTT Photonics Laboratories.

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2. Overview of wavelength conversion devices that use QPM-LN waveguides

Wavelength conversion using QPM-LN waveguides is based on a second-order nonlinear optical effect called the difference frequency generation (DFG). When a signal light with frequency ω_1 (wavelength $\lambda_2 = 2\pi c/\omega_2$) and a pump light with frequency ω_3 (wavelength $\lambda_3 = 2\pi c/\omega_3$) are injected into a second-order nonlinear material, this effect can be used to generate a converted light with a wavelength ($\lambda_2 = 2\pi c/\omega_2$) equal to the difference between the angular frequencies of the two beams: $\omega_2 = \omega_3 - \omega_1$. To achieve a highly efficient device that employs the interaction of three lightwaves in such a second-order nonlinear crystal, it is essential that the phase mismatch $\Delta\beta$ given by the following equation is zero, which corresponds to the phase matching condition.

$$\Delta\beta = 2\pi\,(n_3/\lambda_3 - n_2/\lambda_2 - n_1/\lambda_1), \tag{1}$$

where n_1 is the refractive index at the signal light wavelength λ_1, n_2 is the refractive index at the converted light wavelength λ_2, and n_3 is the refractive index at the pump light wavelength λ_3.

In the field of solid-state lasers, wavelength conversion has been achieved by making use of birefringent phase matching (BPM), which employs the birefringence of crystals. However, this method can only satisfy the phase matching condition for certain combinations of signal and pump wavelengths. Quasi-phase-matching (QPM) relaxes the phase matching constraint and allows wavelength conversion of arbitrary wavelength combinations in the wavelength region where the material is transparent. In QPM wavelength conversion, the nonlinear coefficient is modulated with period Λ so as to make $\Delta\beta$ in Eq. 2 equal to zero. This is known as the quasi-phase-matching condition,

$$\Delta\beta = 2\pi (n_3/\lambda_3 - n_2/\lambda_2 - n_1/\lambda_1 - 1/\Lambda). \quad (2)$$

Using this technique, we can achieve highly efficient conversion between various wavelengths by varying Λ. For example, wavelength conversion between the 1.3- and 1.55-µm bands and between the 1.55- and 1.58-µm bands can be achieved using the same material. QPM structures can be formed from various materials, including oxide ferroelectrics such as $LiNbO_3$ (LN) and $LiTaO_3$ [1] and semiconductors such as AlGaAs [2], but the most promising material is $LiNbO_3$. The advantages of $LiNbO_3$ are i) its transparency in the 0.6–0.8-µm band, which is the pump light wavelength for wavelength conversion in the communication wavelength band and ii) its large nonlinear coefficient.

The basic structure of the device is shown in Fig. 1. An optical waveguide is formed on a substrate on which a QPM structure was previously formed by periodically reversing the spontaneous polarization of the $LiNbO_3$. For conversion from the 1.55-µm band to the 1.58-µm band, for example, a 0.78-µm pump light is injected into the waveguide together with the signal light. The wavelength conversion efficiency as a function of the phase mismatching in Eq. 2 is given by Eq. 3.

$$\eta = \eta_{max} [\sin (\Delta\beta L/2)/(\Delta\beta L/2)]^2, \quad (3)$$

where η_{max} is the efficiency at the QPM wavelength and L is the length of the waveguide.

Figures 1(b) and (c) show a typical arrangement of the signal light, the pump light, and the converted light on the wavelength axis. Even if the signal light is a group of WDM wavelengths, all of the signal lights can be converted, so batch conversion of a multi-wavelength signal group is possible.

Figure 1 also shows the dependence of the wavelength conversion efficiency on the pump and signal wavelengths when a 30-mm-long LN waveguide is used. When the pump wavelength changes, the phase mismatch changes sharply due to dispersion in the refractive index of LN. Thus, the range of wave-

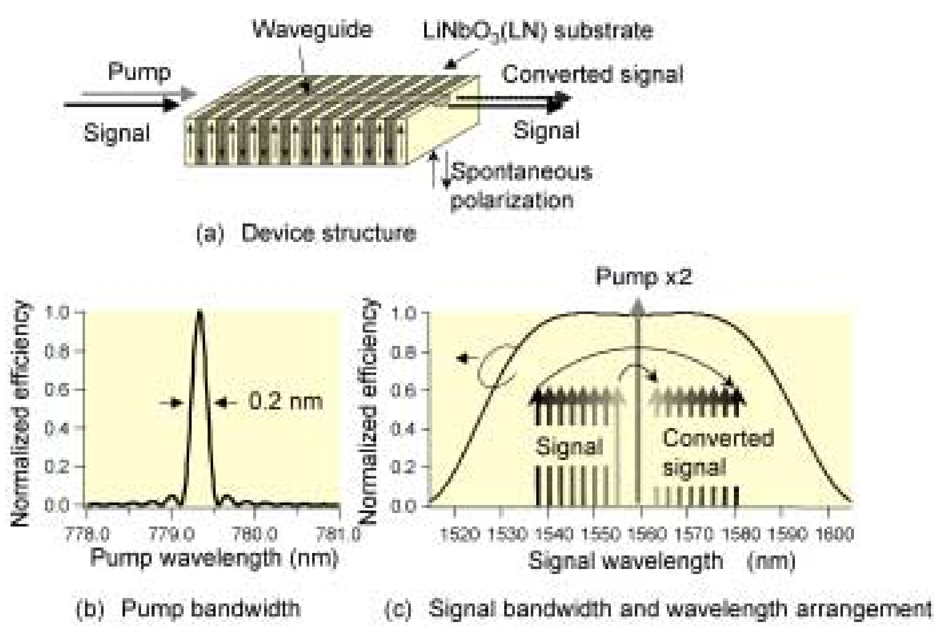


Fig.1. Structure and operating principle of a QPM-LN wavelength conversion device.

lengths available for pumping is very narrow: only 0.2 nm, as shown in Fig. 1(b). On the other hand, when the signal wavelength is changed, the refractive index changes for the signal and converted signal wavelengths cancel each other out, so conversion over a very wide wavelength range (60 nm) is possible, as shown in Fig. 1(c). This is wide enough to enable easy conversion of even high-speed signals of 40 Gbit/s or more.

Furthermore, because the phase information of the input signal light is preserved in the conversion process, there is no dependence on the modulation format, even for signals that take full advantage of phase modulation. For example, this device can handle the CS-RZ [3] or duo-binary [4] formats, which have been studied recently for transmission at 40 Gbit/s or above. Another merit of the QPM-LN device is that very little noise is added to the optical signal during the wavelength conversion process, because the device itself produces virtually no spontaneous emission.

The 1.55-μm-band wavelength conversion requires a 0.78-μm light source for the pump light. However, few laser diodes emit a single wavelength in this wavelength band. Moreover, waveguides that are single-mode in the 1.55-μm band are multimode at about half that wavelength (*i.e.*, in the 0.78-μm band). This makes it difficult to obtain external pumping solely in the fundamental mode. It is possible, however, to use a 1.55-μm light source as an external pump light with a cascade scheme, which converts the 1.55-μm light to a 0.78-μm internal pump light in the waveguide by second harmonic generation (SHG). Wavelength conversion is achieved by DFG between the internal pump light and the signal light. In SHG, the wavelength of the pump light (1.55 μm) coincides with the degenerative wavelength at which the signal and converted signal wavelengths become the same in the DFG process. Thus, the QPM conditions for the SHG and DFG processes are satisfied simultaneously by the same poling period, so internal pump light generation by SHG and wavelength conversion by DFG can be accomplished in the same waveguide.

Next, we consider the efficiency of wavelength conversion. If the attenuation of the pump light in the DFG process is negligible (small signal approximation), then the power of the converted light P_3 is given by Eq. 4 in terms of the signal and pump light powers P_1 and P_2.

$$P_3 = \eta L^2 P_1 P_2 / 100, \quad (4)$$

where η represents the conversion efficiency per unit length of the device and is normally expressed in units of %/W/cm$_2$. The overall efficiency of the device ηL^2 improves in proportion to the square of the waveguide length and is expressed in units of %/W.

If we assume that the attenuation due to the wavelength conversion of the fundamental wavelength can be disregarded (small signal approximation), then the power of the SH light P_2 is given in terms of the power of the fundamental wave P_4 by

$$P2 = \eta L^2 P_4^2 / 100. \quad (5)$$

The efficiency of the SHG process is, in principle, the same as that of the DFG process. Therefore, the easily measured SHG conversion efficiency is used to evaluate the conversion efficiency of the device.

In the cascade scheme, pump light generation by SHG and wavelength conversion by DFG are accomplished in parallel as the signal and external pump lights propagate within the waveguide, so the conversion efficiency cannot be predicted by analytical equations such as Eqs. 4 and 5. Nevertheless, because the internal pump light is roughly proportional to the square of the external pump light power, the increase in the power of light converted by the cascade scheme is approximately proportional to the square of the pump light power.

This approximation of the conversion efficiency of the DFG and SHG processes is valid only in the low power region, where the attenuation of the pump light is negligible. With strong pumping, which produces the high conversion rates at which pump light attenuation occurs, the converted light power saturates, so the conversion efficiency does not follow Eqs. 4 and 5.

3. QPM-LN waveguide fabrication technology

A QPM structure can be formed in ferroelectric materials such as $LiNbO_3$ by periodically reversing the spontaneous polarization. $LiNbO_3$ that has this kind of structure is called periodically poled lithium niobate (PPLN). Various methods have been used in attempts to fabricate such structures, but in recent years a method has been established in which an electric field is applied directly to the substrate using a periodic electrode [5]. This method is capable of forming periodically poled structures over the entire surface of a three-inch wafer. We tried various kinds of LN substrate to achieve good device performance and succeeded in forming uniform periodically poled structures for LN substrates doped with Mg, Zn, *etc.*, which have proved difficult to achieve by conventional methods.

Two methods of fabricating this waveguide have been tried. In the annealed proton exchange (APE) method [6], a mask pattern made of SiO_2 or another such material is formed on the LN substrate by photolithography and the substrate is then immersed in a proton donor such as benzoic acid at high temperature to form a high-index layer on the substrate by the exchange of Li^+ ions and H^+ ions. To recover the nonlinear coefficient, which is degraded by excessive proton exchange, the waveguide is annealed at a high temperature to diffuse the protons. This method has a relatively simple process and can fabricate waveguides over a large surface area with good uniformity. This method is also known to have much better resistance to photorefractive damage than the Ti diffusion method used for LN optical modulators. It enables us to obtain a large change in refractive index and thus achieve strong optical confinement [7]. With the APE method, only the refractive index for the extraordinary light beams increases, so only the TM mode is guided when a Z-cut substrate is used. To obtain polarization independence, it is therefore necessary to achieve polarization diversity by using two waveguides.

To solve such problems, ridge waveguides that use epitaxially grown LN have also been studied [7]. This method uses Zn-doped LN film grown by liquid phase epitaxy (LPE) on an Mg-doped LN-clad substrate. After the periodic poling of this substrate by the application of an electric field, a ridge structure is formed by dry etching to create the waveguide. Doping the LN with Zn increases both the ordinary and extraordinary indices, so both TE and TM polarizations can be guided by a single waveguide. However, it is technically difficult to obtain uniform film thickness and waveguide size over a large area with the LPE ridge waveguide.

4. Wavelength conversion devices that use APE

As described in section 2, the efficiency of a wavelength converter that employs second-order nonlinear optical effects improves in proportion to the square of the waveguide's length. Accordingly, techniques for fabricating long waveguides are important for making highly efficient devices. If the refractive index is not uniform over the entire length, then the QPM wavelength will vary along the waveguide and the effect of the long waveguide will not be fully realized. We recently succeeded in fabricating a 5-cm-long waveguide device that uses an undoped $LiNbO_3$ substrate and has an SHG efficiency of 1300%/W by improving the temperature uniformity during the proton exchange and annealing processes [8].

We performed wavelength conversion of WDM signals on six 40-Gbit/s channels. Figure 2 shows the output spectrum. C-band signals on all six channels were simultaneously converted to the L band. This was achieved by using a 5-cm waveguide pumped with a CW light beam generated by a 1.55-µm LD combined with an erbium-doped fiber amplifier (EDFA). The input optical signal, the eye pattern of the converted light, and the bit error rates before and after wavelength conversion are shown in Fig. 3. There was no waveform degradation after wavelength conversion in this device. Furthermore, the power penalty of 0.3 dB, which was barely within the measurement limits, confirms that the noise introduced by the wavelength conversion process was negligible. The ability to convert the wavelengths of high-speed signals independent of the modulation format and without signal degradation is a special feature of this device. In addition, the bandwidth for the optical signal wavelength is over 60 nm, as described in section 2, so for WDM with a 100-GHz interval (0.8-nm interval), for example, 36 signal light wavelength channels can be converted as a group. This means that a large-capacity signal of 1.4 Tbit/s can be handled by a single device at a signal speed of 40 Gbit/s per channel.

Next, we describe the resistance of the device to photorefractive damage. When high-power light is injected into a second-order nonlinear crystal such as

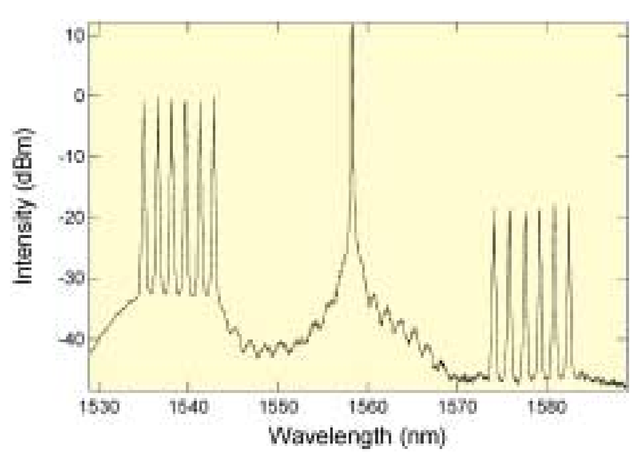
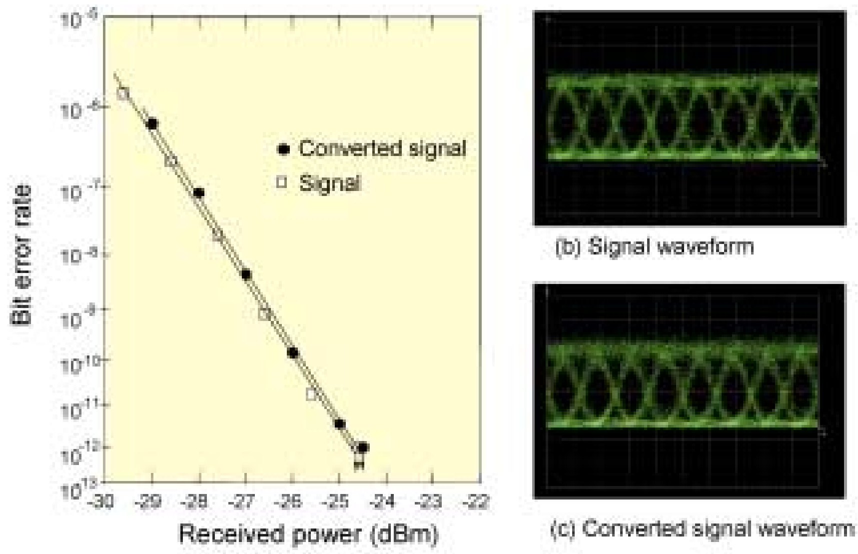


Fig. 2. Spectrum for multiple wavelength conversion with a cascade pump.



(a) Bit error rate performance

Fig. 3. Wavelength conversion characteristics for a 40-Gbit/s optical signal.

LN, the refractive index changes because of the photorefractive effect. The main cause of the effect is carriers excited from defects in the crystal. Because the photorefractive effect causes beam distortion in bulk crystal, this is also referred to as photorefractive damage [7]. Optical confinement in a waveguide device depends on the waveguide structure, so unless there is a very large change in the refractive index, beam deformation is not likely to occur in the waveguide. Nevertheless, if there is a change in refractive index in a QPM device, the QPM conditions obtained in Eq. 1 change, which gives rise to a change in the QPM wavelength. In DFG wavelength conversion, the pump wavelength band is relatively narrow, as shown in Fig. 1, so the change in the QPM wavelength may reduce conversion efficiency. Devices that employ undoped $LiNbO_3$ must be operated at nearly 100 ˚C to avoid the wavelength shifting due to photorefractive damage. To solve this problem, we developed a device that employs a Mg- or Zn-doped LN substrate to allow a lower operating temperature and achieve highly efficient wavelength conversion using high power pumping. Doping LN with Mg or Zn is known to increase resistance to photorefractive damage by compensating for the carriers created by the defects [7]. By using Zn-doped LN, we have already made APE waveguides with an efficiency of 450%/W.

To evaluate the improvement in resistance to photorefractive damage, we measured the change in QPM wavelength when a short-wavelength light near the pump wavelength was injected [9]. Figure 4 shows the experimental setup. When the broadband amplified spontaneous emission from the EDFA is injected into the QPM-LN device, only the wavelength component that matches the QPM wavelength is converted by SHG. Accordingly, by observing the spectrum in the vicinity of 0.78 µm with an optical spectrum analyzer, we can instantaneously measure a QPM curve such as that shown in Fig. 1(b). The temporal change in the QPM wavelength can be measured by monitoring the SH spectrum at constant intervals while injecting a 784-nm light beam, which is slightly different from the QPM wavelength. The temporal change in the QPM wavelength is shown in Fig. 5(a). In this case, a 20-mW pump light was injected at room temperature. The undoped device experienced a very large wavelength shift of 3 nm at

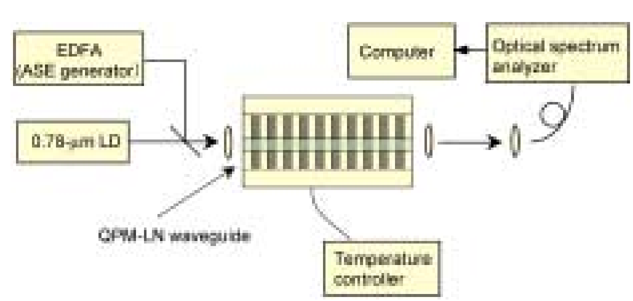
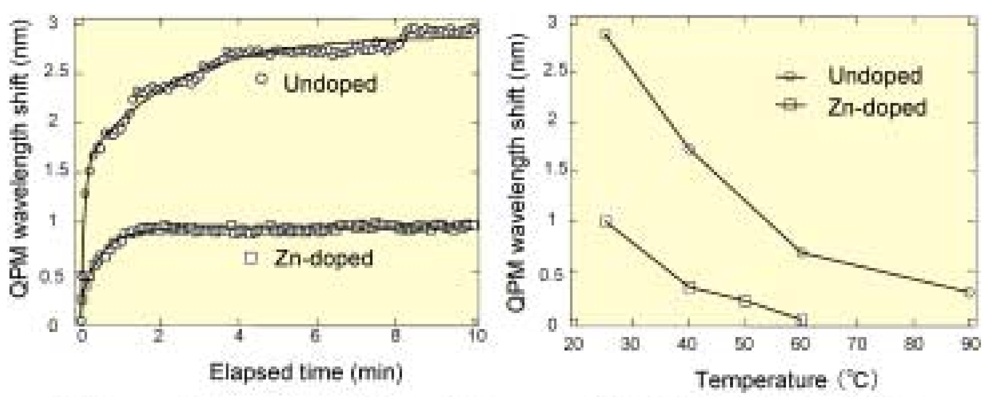


Fig. 4. Experimental setup for measuring optical damage.

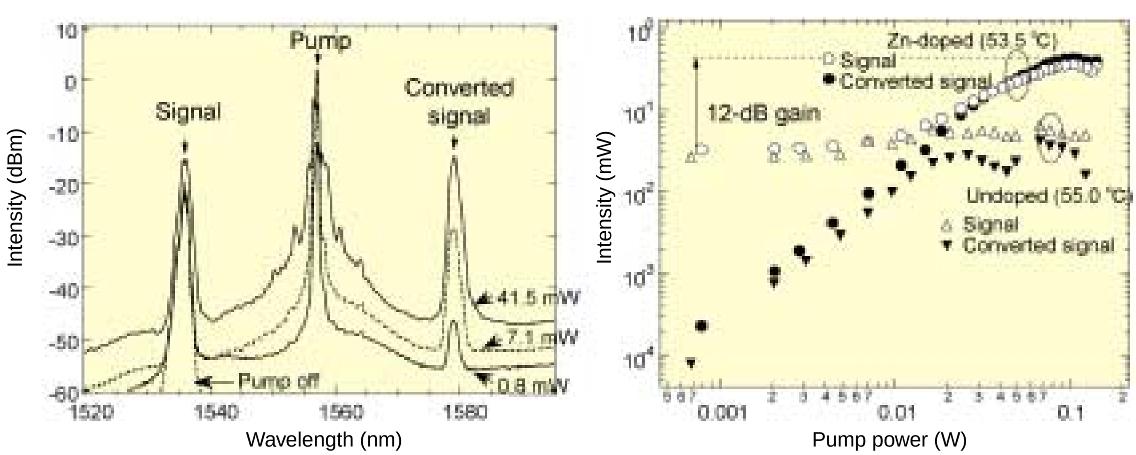
room temperature, but when a Zn-doped LN substrate device was used, the shift was reduced to 1 nm. However, a 1-nm change in wavelength is still not sufficiently small in relation to the pump wavelength bandwidth. Therefore, we investigated the characteristics at elevated temperature. The dependence of the QPM wavelength shift on device temperature is shown in Fig. 5(b). Although the shift decreased as the device temperature increased, it was not possible to eliminate the wavelength shift completely in the undoped device even at 90 ˚C. With the device using a Zn-doped substrate, on the other hand, it was possible to eliminate it completely at 60 ˚C. Using a doped LN substrate improves resistance to photorefractive damage and allows operation at a more practical temperature.

With the DFG process, if the pump power is increased until the intensity of the converted signal approaches that of the signal, the DFG from the converted light to the signal light occurs at the same time. As a result, parametric amplification of the signal and converted signal is possible. To confirm this operation, we previously investigated strong pumping using a picosecond pulse [10]. To simplify pulse synchronization, a 1.55-µm light source was used for both the pump and signal lights. Gain switching with a DFB-LD was used to generate signal and pump light beams with pulse widths of 5 and 13 ps, respectively. These pulses were amplified with an EDFA, their timing was adjusted to superimpose them temporally, and then they were injected into the QPM-LN device. The device used in the experiment was 10 mm



(a) Temporal change at room temperature (b) Temperature dependence

Fig. 5. Change in QPM wavelength caused by optical damage.



(a) Output spectrum with different pump powers (b) Pump power dependence

Fig. 6. Parametric amplification with pulsed pump.

long.

Figure 6(a) shows the output spectrum for several pump powers. At a pump intensity that produced a sufficiently large converted signal, both the signal and converted signal were amplified above the input signal level. Fig. 6(b) shows the output intensities of the signal and converted signal as a function of pump power for devices employing undoped and Zn-doped LN. In the region where the pump power was relatively low, the converted signal increased in proportion to the square of the pump power. When the converted signal intensity reached the same level as the input signal, both the signal and converted signal were amplified.

As shown in Fig. 6(b), parametric amplification with a gain of 12 dB was obtained in the device with the Zn-doped LN substrate. This figure also shows that when the device with the undoped LN substrate was operated at the same temperature, the QPM wavelength shifted due to the photorefractive effect, and sufficient gain was not obtained. Thus, devices that use doped LN, which provides high resistance to photorefractive damage, can achieve efficient wavelength conversion without any SNR degradation.

5. Ridge waveguide wavelength conversion devices that use LPE-grown $LiNbO_3$

To confirm the feasibility of QPM-LN wavelength conversion devices that employ LPE-LN, we have fabricated prototypes and are testing the principle of polarization-independent operation [11].

An example of the near-field pattern of a waveguide with TE and TM polarization is shown in Fig. 7. Virtually the same mode size is obtained for both polarization modes. Furthermore, a 10-mm-long waveguide device exhibits an SHG efficiency of 40%/W/cm^2, which is comparable with that of a device fabricated by the APE method. In addition, there was no photorefractive-effect-induced change in the QPM wavelength during parametric amplification experiments using a pulse pump because we used photorefractive damage resistant Zn-doped LN for the waveguide core of this device. We were thus able to confirm that stable amplification was achieved with the waveguide.

Next, we describe this device's polarization-independent operation (Fig. 8). The signal light is injected into the waveguide via a circulator. The signal light emitted from the waveguide passes through a quarter-wavelength plate and is reflected by a dichromatic mirror. The reflected signal light passes through the quarter-wavelength plate again, so the polarization is rotated by 90˚ relative to the original emitted light. It then propagates back through the waveguide in the reverse direction and is output from the circulator. The 0.78-µm pump light with TM polarization is launched from the opposite side to the signal light. The pump light is reflected by dichromatic mirrors formed at the waveguide ends, so it propagates back and forth in the waveguide. Because there is wavelength conversion due to DFG when

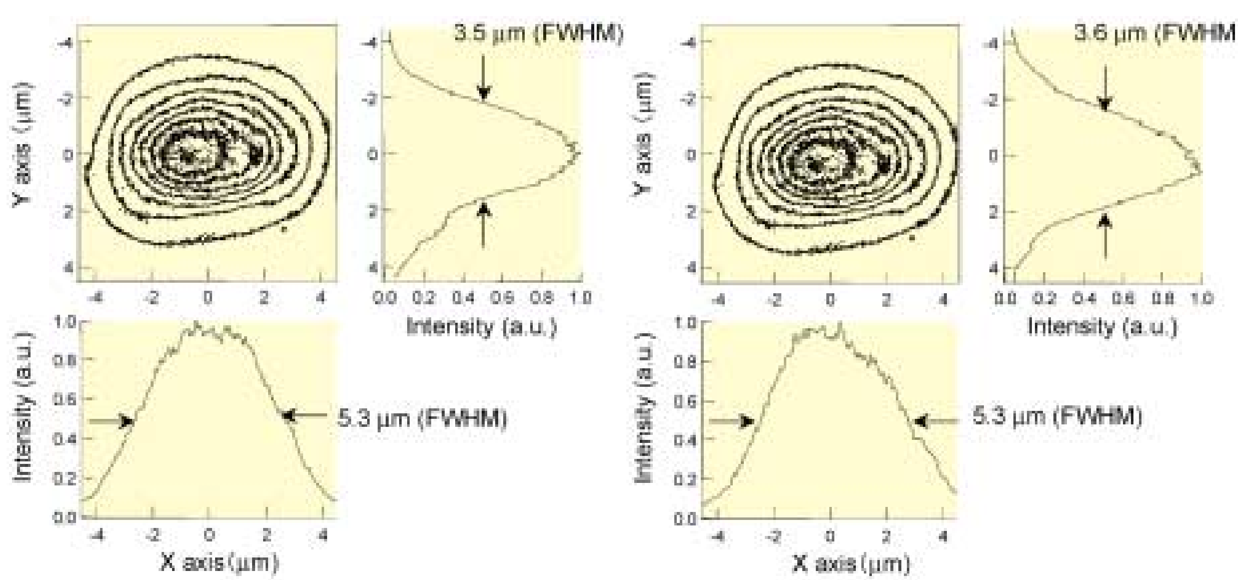


Fig. 7. Waveguide mode using an LPE-LN substrate (FWHM: full wave at half maximum).

both the pump and signal are TM polarized, the TM component of the signal is converted during forward propagation and the TE component is converted during backward propagation. In this way, a signal with any polarization can be converted by DFG. Fig. 9 shows the DFG spectrum for TE and TM polarized optical signals. Although it is necessary to improve the wavelength conversion efficiency by lengthening the waveguide, virtually the same conversion efficiency was achieved for both polarizations.

6. Conclusion

We presented an overview of QPM wavelength conversion devices and the current state of research in this area. Although we introduced QPM-LN devices in terms of wavelength conversion, a wide variety of other applications such as dispersion compensation [12], time slot conversion [13], optical sampling [14], wavelength shifting [8], multiplexing [15], and demultiplexing[16] have also been reported. We believe that the high efficiency, broad bandwidth, high SNR, transparency and other such excellent characteristics possessed by these devices ensure that their importance will continue to increase in the future. We must continue to pursue higher efficiency and greater functionality, while keeping in mind the various uses of these devices.

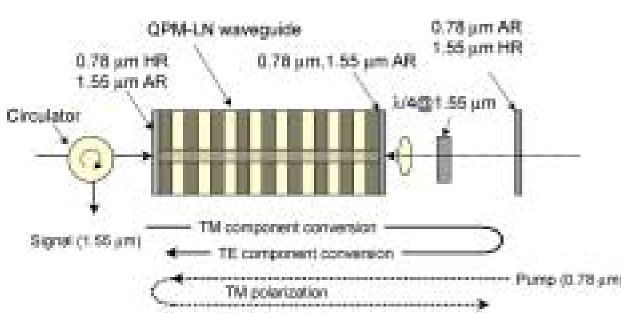


Fig. 8. Structure of a polarization-independent device with an LPE-LN waveguide. HR: highly reflective facet; AR: anti-reflection coated.

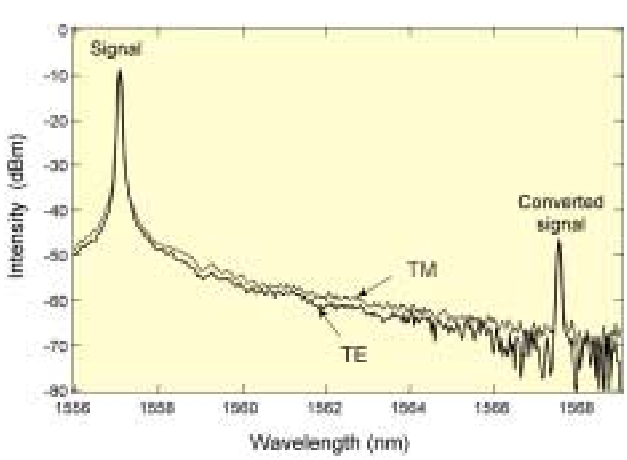


Fig. 9. DFG spectrum in a polarization-independent device.

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