Reshaping of a second-harmonic curve in periodically poled Ti:LiNbO$_3$
channel waveguide by a local-temperature-control technique

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We have demonstrated reshaping and bandwidth control of a second-harmonic (SH) curve in a periodically poled Ti:LiNbO$_3$ (Ti:PPLN) waveguide ($\Lambda = 16.6$ $\mu$m) by using a local-temperature-control technique. With this technique, we have achieved several useful shapes of the SH curve such as an almost ideal sinc function, and double and multipeaks in a 74-mm-long Ti:PPLN waveguide, which has a prechirped SH curve at room temperature. More than 60% improvement of SH conversion efficiency and a 5 nm broadening of SH phase-matching bandwidth were achieved. © 2005 American Institute of Physics. [DOI: 10.1063/1.1842854]

The quasi-phase-matched (QPM) technique allows us to access a large nonlinear coefficient ($d_{33}$) of LiNbO$_3$ that cannot be used in the conventional birefringence phase-matching condition. During the past ten years, various nonlinear applications, such as efficient wavelength conversion,$^{1-3}$ optical pulse compression,$^{4,5}$ and all-optical signal processing$^6$ have been demonstrated in a periodically poled LiNbO$_3$ (PPLN). Recently, owing to the advance of the electric field poling technique to fabricate PPLN, not only uniform QPM gratings but also nonuniform QPM gratings have been widely used for nonlinear applications, such as ultra-short-pulse compression$^{4,5}$ and multiple-channel wavelength conversion.$^7$ To make a nonuniform QPM grating, several different grating design approaches, such as Fibonacci structures,$^8$ modulation of the grating period,$^9$ numerically optimized phase modulation,$^{10}$ and phase reversal$^1$ were proposed. However, it is still difficult to obtain the same QPM grating as originally intended when the QPM mask pattern was designed because of the unexpected errors during the fabrication process. In particular, an unexpected QPM condition in a Ti:PPLN waveguide device results not only from the fabrication fault of the QPM grating, but also from the inhomogeneity of the refractive index along the waveguide.

Recently, a temperature gradient technique was introduced by the authors for broadening of phase-matching bandwidth in a Ti:PPLN waveguide that has a uniform QPM grating. In this letter, we have demonstrated reshaping and bandwidth control of a second-harmonic (SH) curve in a Ti:PPLN waveguide by using a local-temperature-control technique.

A 74-mm-long Ti:PPLN waveguide of 16.6 $\mu$m microdomain period was used to demonstrate reshaping and bandwidth control of the SH curve. The waveguide loss was determined to be 0.14 dB/cm at a 1.53 $\mu$m wavelength (TM polarization) with the Fabry–Perot method. The cross-sectional area of the waveguide is defined by the near-field intensity distribution. The horizontal and vertical full width at half-maximum (FWHM) are measured to be 5 and 4 $\mu$m, respectively, in the case of a TM-polarized beam (1.53 $\mu$m).

After characterizing the Ti:PPLN waveguide, we added antireflection coating to the end faces of the sample not only to avoid the Fabry–Perot interference effect, but also to get more coupling efficiency between the fiber and the Ti waveguide. The details of the fabrication method are described in Ref. 3.

The experimental setup to demonstrate reshaping and bandwidth control of the SH curve is shown in Fig. 1. The wavelength and power of the extended-cavity laser (OSICS-1560, Nettest) were controlled with a personal computer. The polarization of the pump wave was adjusted to TM polarization (to obtain maximum nonlinear interaction with nonlinear coefficient $d_{33}$) and fiber butt-coupled to the Ti:PPLN waveguide. The generated SH signal, guided by a 10× objective lens, was measured by the silicon detector. To obtain the localized temperature in the sample, we used five Peltier devices in a sample holder (see the inset in Fig. 1). The temperatures of the five sections were controlled by temperature control units.

In the case of lossless second-harmonic generation (SHG) process, assuming the slowly varying envelope ap-

![FIG. 1. Experimental setup for SHG. The sample holder consists of five separated Peltier sections to obtain the localized temperature. ECL and PC denote extended-cavity laser and polarization controller, respectively.](image)
where the difference is nonlinear coupling constant, and $k$ follows; the coupled-mode equation is given as the following:

$$\frac{dA_1}{dz} = -i\kappa A_3^* e^{i\Delta k z},$$

$$\frac{dA_3}{dz} = -i\kappa A_1^* e^{i\Delta k z},$$

where $A_1$ and $A_3$ are the field amplitudes ($A_i = (n_i/\omega_i)E_i$, where $l=1,3$) at $\lambda_p$, $\lambda_{SH}$ (P=pump, SH=second harmonic), $\kappa$ is nonlinear coupling constant, and $\Delta k$ is the SHG wave vector mismatch parameter. The theoretical fitting curve (solid line) for the SH curve in Fig. 2 was calculated from the coupled-wave equations (1) and (2) and the extraordinary refractive index of Ti:PPLN waveguide as functions of wavelength and temperature. Through the fitting, we obtained the positive parabolic modulation of refractive index difference ($n_{SH} - n_p$) as shown in the inset box [Fig. 2(a)]. Figure 2(a) shows the SH curve of the 74-mm-long Ti:PPLN waveguide at room temperature. The shorter-wavelength side ripples of a phase-matching peak are influenced by positive parabolic variation of the refractive index difference [see the inset of Fig. 2(a)]. This positive parabolic variation of the refractive index difference in a Ti waveguide is frequently caused by differences in Ti stripe thickness during deposition (thick ends and thin center). This kind of SHG curve distortion, which results from fabrication errors, can be corrected by a local temperature control. Temperature distribution along the Ti waveguide can induce a change of the refractive-index difference ($n_{SH} - n_p$). In the case of uniform refractive-index difference along the waveguide, shown in the inset of Fig. 2(b), which was achieved by heating up the endfaces of Ti:PPLN, almost ideal sinc function of SH curve was observed. In this case, the FWHM of SH curve is 26% decreased and SH conversion efficiency is about 61% improved, compared to the case without temperature control. The negative parabolic variation of the refractive-index difference [see inset of Fig. 2(c)] was achieved by heating up the both end faces of Ti:PPLN waveguide further. In this case, the longer-wavelength side ripples of a phase-matching peak were observed. This refractive index difference control technique by temperature can be explained quantitatively as follows.

The temperature distributions along the waveguide $T(z)$ and wave-vector mismatch parameter $\Delta k(z)$ can be expressed as follows:

$$T(z) = T_i, \text{ where } (i - 1) \frac{L}{N} < z \leq i \frac{L}{N}, \quad i = 1, 2, \ldots, N,$$

$$\Delta k(z) = \frac{4\pi}{\lambda_p} \left[ n_{SH}(T,z) - n_p(T,z) \right] - \frac{2\pi}{\Lambda(z)},$$

where $L$ and $N$ are the length of sample and the number of divided sections in sample holder, respectively, and $\Lambda(z)$ is the QPM-grating period. Influence of the temperature change of QPM material can be described as follows:

$$\delta(\Delta k \Lambda) = \delta(\Delta k) \cdot \Lambda + \Delta k \cdot \delta \Lambda$$

$$= 2\pi \left[ \frac{dn_{SH}dT - dn_pdT}{n_{SH} - n_p} + \alpha \right] \delta T,$$

where $\delta T$ and $\alpha$ are the differential of thermal expansion and the coefficient of thermal expansion, respectively. In the case of PPLN, the influence of the thermal expansion [second term in right-hand side of Eq. (5)] to the effective grating period is one order of magnitude smaller than that of the changes in refractive indices [first term in right-hand side of Eq. (5)]. Therefore, we neglected the thermal expansion of the grating period. The dual peaks of the SH curve, which is useful especially for selective channel dropping and wavelength conversion, was obtained by a local-temperature-control technique in the Ti:PPLN waveguide shown in Fig. 3(a). The temperatures of the five sections were 23.5, 22.2, 20, 20.3, and 21.9 °C respectively. We also demonstrated the multiple peaks of the SH curve by changing the temperatures of five sections [see Fig. 3(b)]. This kind of multiple phase-matching condition allows several useful nonlinear application fields, such as multichannel wavelength conversion and multichannel switching.

Another application of PPLN is ultra-short-pulse amplification and pulse compression by the broadening of the SH phase-matching bandwidth. Figure 4 shows the broadening of SH phase-matching bandwidth by a local temperature control. We obtained about 5 nm broadening of the SH phase-matching bandwidth in a 74 mm Ti:PPLN waveguide (which has 0.21 nm bandwidth at uniform temperature). However, one cannot avoid a trade-off between conversion efficiency and bandwidth and large oscillation of conversion efficiency.
efficiency along the wavelength. This large oscillation comes from the limitation of number of localized temperature sections. This problem can be solved by increasing the localized-temperature-control sections or temperature gradient techniques.\(^{11}\) The localized-temperature-control technique provides reshaping of the SH curve as well as broadening of the SH curve, while the other known techniques, such as using a chirped grating, shorter device, and gradient temperature can only provide the latter.

In conclusion, we have demonstrated reshaping and bandwidth control of the SH curve in a periodically poled Ti:LiNbO\(_3\) waveguide by using a localized-temperature-control technique. With this technique, we have achieved several useful shapes of the SH curve, such as an almost ideal sinc function, and double and multiple-peaks in a 74-mm-long Ti:PPLN waveguide, which has a prechirped SH curve at room temperature. More than a 60% improvement of SH conversion efficiency and a 5 nm broadening of the SH phase-matching bandwidth were achieved. We believe that this localized-temperature-control technique will be very useful to make an arbitrary SH curve in QPM devices. Further research is needed for integrating the heating section on the Ti waveguide to increase the number of localized-temperature-control sections.

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