Optical parametric amplification of arbitrarily polarized light in periodically poled LiNbO₃

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Abstract: Optical parametric amplification (OPA) of arbitrarily polarized light is proposed in a multi-section periodically poled Lithium Niobate (PPLN). External electric field is applied on selected sections to induce the polarization rotation of involved lights, thus the quasi-phase matched optical parametric processes exhibit polarization insensitivity under suitable voltage. In addition to the amplified signal wave, an idler wave with the same polarization is generated simultaneously. As an example, a ~10 times OPA showing polarization independency is simulated. Applications of this technology are also discussed.

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1. Introduction

Periodically poled LiNbO₃ (PPLN) has been widely used in many nonlinear optical, electrooptic (EO) and piezoelectric devices for light conversion, modulation and switching. Due to the periodic ferroelectric domain structure, it exhibits many unique properties such as quasiphase-matched (QPM) frequency conversion [1–3], polarization rotation [4–6] and macrophonon polarition excitation [7]. Based on the multi-functionality of PPLN, a recent research interest is to investigate the interaction and coupling of different physical processes [8] then to explore new technical applications [9]. For example, a fast tunable PPLN optical parametric

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oscillator (OPO) has been demonstrated by combining PPLN's nonlinear and EO effects together [10]. However, most of the nonlinear optical and coupled processes exhibit evident polarization dependency, which means the related devices only allow the incoming light with a certain polarization state. This barrier actually originates from the fundamental physics. For instance, the nonlinear optical coefficient d_{33} normally dominates the QPM processes in PPLN. Therefore, all interacted waves have to be z-polarized. It would be very interesting in physics and much desired in applications if a quadratic nonlinear optical effect could become polarization independent.

In this work, we propose an optical parametric amplifier (OPA) for arbitrarily polarized light by using a four-section PPLN. The parameters of different sections are well designed so that the first and fourth sections are used for QPM parametric amplification, while EO polarization rotation is realized in two central sections for signal and idler waves, respectively. In this case, not only pump, signal and idler waves coupled together through nonlinear interaction, ordinary and extraordinary lights also exchange their power for EO effect. Five-wave coupling equations are used in our investigation [11]. When a z-polarized pump wave is injected, arbitrarily polarized signal wave could be amplified ten times or even more. The amplification factor keeps constant for a wide range of signal powers with < 1% polarization dependent fluctuation. Applications of this technique are also discussed. Various light sources thus are expected to be frequency-converted and amplified even for vector beams [12].

2. Theory and simulation

Figure 1 shows the schematic diagram of our design. Lights propagate along the x-axis. The PPLN sample has four sections. The first and fourth sections are designed for QPM OPA with a z-polarized pump wave. As we know, the largest nonlinear coefficient of LiNbO₃ is d_{33} , forcing the signal waves to be polarized along the z-axis as well. To realize a polarization independent OPA, the second and third sections of the sample are designed for signal and idler waves EO polarization rotation [4], respectively. In this case, the z-polarized part of the signal wave could be amplified in the first section while the left y-polarized part could be EO rotated 90° then also be amplified in the last section. The overall frequency conversion thus becomes insensitive to the initial signal polarization state.



Fig. 1. Schematic diagram of a four-section PPLN. External electric fields are applied along the y-axis at the second and the third sections, representing EO1 and EO2 in the figure.

In detail, when a z-polarized signal wave is injected into the sample, it will be amplified as long as the QPM condition is satisfied. In the meantime, a z-polarized idler wave is produced simultaneously. In order to keep the conversion continuously, the power of the pump wave must be much larger than that of the signal wave. When the idler wave and the amplified signal wave enter the second and third sections, both of them are converted to y-polarization lights if a suitable voltage is applied. At last, the y-polarized signal and idler waves pass through the last section with no change because the QPM condition is not satisfied for ordinary lights.

On the other hand, when the incoming signal wave is y-polarized, it cannot be amplified in the first section as we mentioned before, thus no idler wave is generated subsequently. However, the signal wave could be converted to z-polarization in the second section, and then

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it is able to be amplified in the fourth section eventually. Likewise, an accompanying zpolarized idler wave is produced.

From analysis above, both y- and z-polarized signals could be amplified in our sample. If the first and the last sections own the same number of periods, they should have the same magnification factor no matter what polarization state is given. Because all lights could be divided into y- and z- polarized components, arbitrary polarization amplification thus could be accomplished.

To investigate the OPA/EO processes just mentioned, we use coupling wave equations to describe the interaction between the five involved waves. Plane-wave approximation is taken.

$$\begin{cases} \frac{dE_{sy}}{dx} = -i\frac{\omega_s}{n_{sy}c} \varepsilon_{23}^{(s)}(x)E_{sz}e^{i\Delta k_1'x},\\ \frac{dE_{sz}}{dx} = -i\frac{\omega_s}{n_{sz}c} [\varepsilon_{23}^{(s)}(x)E_{sy}e^{-i\Delta k_1'x} + d_{33}(x)E_{pz}E_{iz}^*e^{-i\Delta k_2'x}],\\ \frac{dE_{iy}}{dx} = -i\frac{\omega_i}{n_{iy}c} \varepsilon_{23}^{(i)}(x)E_{iz}e^{i\Delta k_3'x},\\ \frac{dE_{iz}}{dx} = -i\frac{\omega_i}{n_{iz}c} [\varepsilon_{23}^{(i)}(x)E_{iy}e^{-i\Delta k_3'x} + d_{33}(x)E_{sz}^*E_{pz}e^{i\Delta k_2'x}],\\ \frac{dE_{pz}}{dx} = -i\frac{\omega_p}{n_{zz}c} d_{33}(x)E_{sz}E_{iz}e^{i\Delta k_2'x}, \end{cases}$$

where c is the speed of light in vacuum. $E_{j\eta}$, $k_{j\eta}$, $\omega_{j\eta}$ and $n_{j\eta}$ (the subscript j = p, s, i refers to the pump wave, the signal wave, and the accompanying idler wave, respectively, and $\eta = y, z$ represents the polarizations) are the amplitudes of waves, the wave vectors, the angular frequencies and the refractive indices, respectively. The converted idler wave is generated at frequency $\omega_i = \omega_p - \omega_s$. $\varepsilon_{23}^{(s)}(x) = -n_{sy}^2 n_{sz}^2 \gamma_{51}(x) E$ for the signal wave and $\varepsilon_{23}^{(i)}(x) = -n_{iy}^2 n_{iz}^2 \gamma_{51}(x) E$ for the idler wave, where $\gamma_{51}(x) = \gamma_{51}f(x)$ is the modulated EO coefficient in PPLN and E refers to the external DC electric field. For no electric field is applied to the first and fourth sections, E should be zero. $d_{33}(x) = d_{33}f(x)$ is the modulated nonlinear coefficient. $\Delta k_1' = k_{sy} - k_{sz}$, $\Delta k_2' = k_{pz} - k_{iz} - k_{sz}$, $\Delta k_3' = k_{iy} - k_{iz}$ are the wave vector mismatch for polarization rotation of the signal wave, the OPA, the rotation of the idler wave, respectively. The asterisk refers to complex conjugation.

The structure function f(x) is important in a PPLN. Its sign changes from + 1 to -1 in different domains. We define G_m (m = 1, 2, 3, 4) as the reciprocal vector that provides. In the first and fourth sections, they are identical, so $G_{1,4}$ ($G_{1,4} = G_1 = G_4$) is used for short.

In our design, $G_{1, 4}$ equals to $k_{pz} - k_{sz} - k_{iz}$, which could compensate the OPA phase mismatch in the first and fourth sections. Likewise, G_2 in the second section is used to compensate the phase mismatch for the signal wave's polarization rotation, which means $G_2 = k_{sy} - k_{sz}$. And G_3 should satisfy $G_3 = k_{iy} - k_{iz}$ for idler wave's EO polarization rotation. In this case, the coupling Eqs. (1) can be simplified as:

$$\begin{cases} \frac{dA_{sy}}{dx} = iK_1 A_{sz} e^{i\Delta k_1 x}, \\ \frac{dA_{sz}}{dx} = iK_1^* A_{sy} e^{-i\Delta k_1 x} - iK_2 A_{pz} A_{iz}^* e^{-i\Delta k_2 x}, \\ \frac{dA_{iy}}{dx} = iK_3 A_{iz} e^{i\Delta k_3 x}, \\ \frac{dA_{iz}}{dx} = iK_3^* A_{iye} e^{-i\Delta k_3 x} - iK_2^* A_{sz}^* A_{pz} e^{-i\Delta k_2 x}, \\ \frac{dA_{pz}}{dx} = -iK_2 A_{sz} A_{iz} e^{i\Delta k_2 x}, \end{cases}$$
(2)

with $A_{j} = \sqrt{\frac{n_{j}}{\omega_{j}}}E_{j}$, $\Delta k_{1} = k_{sy} - k_{sz} - G_{2}$, $\Delta k_{2} = k_{pz} - k_{sz} - K_{iz} - G_{1,4}$, $\Delta k_{3} = k_{iy} - k_{iz} - G_{3}$, and

coefficients used in Eqs. (2) are $K_1 = i \frac{\omega_s g_1 r_{51} E}{2c} \sqrt{n_{sy}^3 n_{sz}^3}$, $K_2 = \frac{d_{33} g_1}{c} \sqrt{\frac{\omega_{sz} \omega_{pz} \omega_{iz}}{n_{sz} n_{pz} n_{iz}}}$

$$K_3 = i \frac{\omega_i g_1 r_{51} E}{2c} \sqrt{n_{iy}^3 n_{iz}^3}$$
 and $g_1 = \frac{2}{\pi}$.

In our simulation, the temperature is set at 20°C. We assume the pump wavelength is 532 nm with 10 MW/cm² intensity. The pump power shouldn't be too large for it may surpass the damage threshold of PPLN. For an 810 nm signal wave, a 1550 nm idler wave is produced. Both of these two wavelengths are right at common lasers' emission peaks, implying this system may have very practical applications. The electric field is set at 710 V/mm for polarization rotation. In addition, although an 810 nm is taken as signal wave, the 1550 nm may also be selected instead. In this case, the signal and idler wavelengths are swapped.

To compensate the phase mismatching, $\Lambda_{1, 4} = 7.45 \ \mu m$, $\Lambda_2 = 9.88 \ \mu m$, $\Lambda_3 = 20.48 \ \mu m$ should be fabricated for the first and fourth, second, third sections, respectively. Furthermore, the first and fourth sections have 1000 periods, the second section has 256 periods, and the third section has 250 periods, respectively. As we know, more domains may give rise to higher OPA amplification factor and lower polarization rotation voltage. However, more domains also mean longer sample, which results in lower fabrication yield and inconvenience in experiments. Deciding the domain numbers thus is the compromise of high amplification, low EO rotation voltage and suitable sample length. In this design, the total length is 22.5 mm that is quite achievable. In our simulation, $d_{33} = 25.2 \ pm/V$ and $r_{51} = 32.6 \ pm/V$ are used.

First, we use 1 W/cm^2 as the intensity of signal wave. In this case, the light is quite weak that needs to be amplified in many applications.



Fig. 2. The light intensity at different positions inside the four-section PPLN when the signal wave is y-polarized (a) or z-polarized (b). Solid, dotted, dash-dotted and dashed curves represent y-polarized signal wave, z-polarized signal wave, y-polarized idler wave and z-polarized idler wave, respectively.

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#171351 - \$15.00 USD (C) 2012 OSA Figure 2 shows the evolution of all waves' intensities in the sample. No matter y- or zpolarized signal wave enters the sample, it is amplified ~10 times in the sample. In addition, an idler wave is produced at the same time. The 3 dB wavelength bandwidth is approximately 1 nm for the signal wave, while it is 7 nm for the idler one. And, the 3 dB temperature bandwidths are approximately 4.4 K for both of the signal and idler waves. From Fig. 2, the ypolarized signal wave still increases gradually in the fourth section. This is because the electric field is applied to all four sections in the simulation to simply the future experiment. Driven by the extra field, there is still some ineffective conversion between the y- and zpolarized signal waves in the first and fourth Sections. The locally converted z-polarized signal also could be amplified through OPA process then further converted to y-polarization successively. Therefore the y-polarized signal wave still could increase slowly.

However, the simulation above only discusses the linear polarization along y and z axes. To well testify the sample's response for arbitrary polarizations, we studied the cases with different intensity ratios and phase differences between the y- and z- polarized components. Figure 3 shows the simulation result. The output amplification ratio of the signal wave varies from 10.326 to 10.340 with only 0.2% fluctuation, *i.e.*, < 0.01 dB polarization dependency. To further suppress the fluctuation, different voltages should be applied to the second and third sections to ensure exact 90° polarization rotation for both the signal and idler waves.



Fig. 3. The amplification factor at arbitrary polarization states. About 0.2% fluctuation is observed.

3. Discussion

In our simulation above, a polarization independent OPA is displayed for a weak 1 W/cm^2 signal wave. However, not only the polarization state, but also the signal power may vary from time to time. It is necessary to testify the OPA's performances under a wide range of signal intensity.

Figure 4 shows the results when the signal wave intensity changes from 1 W/cm² to 25 KW/cm². However, although the signal intensity increases up to 25000 times, the amplification factor still keeps over 10 times with the polarization induced amplification fluctuation of less than 1%. We believe these performances should be suitable for many practical applications. In addition to the amplification factor, the polarization state of the output wave is also important in some applications. From Fig. 2, the y-polarized signal is amplified to be z-polarized light, while the z-polarized signal is converted to y-polarized light. However, their relative phase difference may still keep the same after passing through the sample. Therefore a linearly polarized signal should rotate its polarization direction for 90° after the amplification. For general elliptically polarized light, its principal axis rotates 90° and the revolving direction of light vector is reversed. To retain or further control the output polarization of the amplified waves, one or more extra PPLN sections could be added in the

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sample. Their periods should fit the requirement for EO polarization for signal or idlers waves. Separate voltage should be applied only to the corresponding sections. In principle, arbitrary polarization state could be generated.



Fig. 4. (a) The PPLN OPA's amplification factor at different signal wave intensities. (b) Polarization induced amplification fluctuation as a function of the signal wave intensity.

Along with the 810 nm signal wave, an idler wave at 1550 nm telecom band is also generated. Actually we may also take the 1550 nm light as the signal for amplification. In this case, some fiber-optic applications may be expected. Actually other signal, idler wavelengths and amplification factor also could be achieved as long as we redesign the PPLN or change the pump wave. If the basic four-section structure is kept with EO rotation in the two central sections, polarization independent OPA still could be realized for arbitrarily polarized signal waves. From our analysis, our OPA even may work for vector beams [12] with complicated wavefront. For example, given a radially polarized signal light, we may treat the whole light as many beams with different polarization states. When they enter our sample, all these beams could be amplified with the same magnification ratio no matter what their polarization states are. After the beams pass through the sample, the light power is greatly enhanced while still keeping the vector beams characteristics. As we know, generating vector beams is normally not easy. Due to the limitation of used approach, it is not convenient to obtain the beams in some wavelength band, *i.e.*, infrared region. Furthermore, most of the crystal based active amplification or OPA are sensitive to polarization states, which makes it difficult to amplify vector beams. However, our multi-section PPLN based OPA might open a new window to obtain high power vector beams in new wavelength bands. In addition, our design takes the advantages of PPLN's EO and nonlinear optical properties together. The whole device is controlled by electric field, which means it may also work like an EO modulator for a given input signal. There are really many topics to study in this system. More interesting technical applications are anticipated.

4. Conclusion

In conclusion, we propose a way to amplify arbitrarily polarized wave using a four-section PPLN sample. A DC electric field is applied on selected sections. No matter what polarized direction the signal wave has, it may be effectively amplified with negligible polarization dependency. And, the OPA remains good performance over a wide range of input signal intensities. The accompanying idler wave, producing due to OPA process, can be used in communication and so on. Not only our design can be used in amplifying waves from fibers such as vector beams, but also it is practical in many other fields like EO modulator.

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