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Frequency tuning of optical parametric generator in periodically poled optical superlattice $LiNbO_3$ by electro-optic effect

Yan-qing Lu,[a)] Jian-jun Zheng, Ya-lin Lu, and Nai-ben Ming
National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, People's Republic of China

Zu-yan Xu
Institute of Physics, Chinese Academy of Science, Beijing 100080, People's Republic of China

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Frequency tuning of optical parametric generators in periodically poled $LiNbO_3$ by applying a periodic electric field was demonstrated. Remarkable wavelength change was achieved. The dependence of the wavelength shift on the applied field shows a linear relationship. The tuning rates exceeding 3 nm/(kV/mm) were obtained. The phenomenon of dispersion in electro-optic tuning was predicted. Possible applications were discussed. © *1999 American Institute of Physics.* [S0003-6951(99)04701-4]

Recently, more and more research interests have been paid on a new artificial nonlinear material: the periodically poled optical superlattice $LiNbO_3$ (PPLN). Since the sign of the nonlinear optical coefficient of PPLN is modulated, the quasiphase-matching (QPM) technique can be used in frequency conversion applications instead of the conventional birefringent phase matching.[1] A significant advantage of the QPM technique is that any interaction within the transparency range of the material can be noncritically phase matched at a specific temperature by using the largest nonlinear coefficient.[2] In PPLN, the effective nonlinear coefficient reaches to 21.6 pm/V, which is much larger than many common nonlinear crystals including BBO and KTP.[2,3] Although there was concern that scattering or absorption induce by the periodic domain structure could contribute noticeable loss, careful measurement had shown that periodic poling adds no loss.[4] Since the intrinsic material loss of $LiNbO_3$ over most of its transparency range is negligible (absorption coefficient $\alpha \approx 0.002\,\mathrm{cm}^{-1}$)[5,6] and even some research results showed that the PPLN has higher photorefractive damage threshold than single domain $LiNbO_3$,[7] thus the PPLN is really a good candidate for high performance optical parametric generators (OPG), which include optical parametric oscillators (OPO) and optical parametric amplifiers (OPA). In a 50-mm-long PPLN with the modulation period of 31 μm and with the pump intensity low to $1\,\mathrm{GW/m^2}$ which can be achieved by compressing 10 W pump light to be a 110-μm-diam beam), the calculated single pass parametric power amplification is:

$$G(L)=\frac{|E_s(L)|^2}{|E_s(0)|^2}-1\approx \mathrm{Sinh}^2\left(\sqrt{\frac{2\omega_s\omega_i d_Q^2 I_p}{n_s n_i n_p \varepsilon_0 c^3}L^2}\right)=0.97, \tag{1}$$

where d_Q is effective nonlinear coefficient of PPLN, I_p is the pump intensity, and L is the sample length. Comparing the results with that of other materials with the same sample length and pump intensity [e.g., for angle-tuned $LiNbO_3$ OPO at the nominal 47° phase-matching angle,[8] $G(L)\approx 0.044$; for type-II noncritically phase-matched KTP OPO,[9] $G(L)\approx 0.037$], the power gain of PPLN is so high that it makes the related devices more efficient. The pump threshold of an PPLN OPO can even be decreased to continuous wave (cw) level which is difficult to be achieved in ordinary crystals. In fact, in addition to various pulsed PPLN OPGs,[10–12] even the cw single resonant OPO pumped by a 1064 nm laser based on a 50-mm-long PPLN has already been developed by Bosenberg *et al.*[13] When the pump light was 13 W with the beam waist of 97 μm, the 1.25 W idler light at 3.25 μm and 0.36 W signal light at 1.57 μm were generated. (See Fig. 2 in Ref. 13) However, almost all the devices above are tuned by changing the temperature, which is very slow and complicated. The reliability and stability are also not very good. These shortages limited the usage of the PPLN. It is very beneficial to find an alternative tuning method which is simple, rapid, and stable. Although the angle tuning has been widely used in conventional OPGs, it has not been applied in PPLN devices because of the beam deviation and Poynting vector walk off.[14] Electro-optical tuning of an OPG is also particularly attractive since it is nonmechanical and can be done very rapidly. This idea was firstly suggested in 1965[15] and demonstrated two years after.[16] A recent report by Ewbawk *et al.* showed that the electro-optic tuning range of up to ± 44 nm can be achieved in $LiNbO_3$ with the applied voltage up to ± 5 kV.[17] As for PPLN, to the best of our knowledge, the electro-optic tuning technique has not been proposed yet.

In this letter, OPG frequency tuning by applying a periodic electric field along the z direction of the PPLN sample was proposed. The detailed tuning properties were studied. Possible applications were discussed.

The PPLN sample fabricated by the electric poling method[4] usually has the thickness of about 0.3–0.5 mm along the z direction. The ferroelectric domain boundaries are at the y-z plane. In the typical QPM frequency conversion applications, all waves involved are the extraordinary waves. For simplifying the discussion, we assumed the pump wave normally injected into the crystal and propagated along

a)Electronic mail: yqlu@nju.edu.cn

the x axis, then produced the signal wave and idler wave along the same direction.

For a QPM OPG, the waves involved should satisfy the energy conservation condition and the QPM condition:

$$\Delta\omega = \omega_p - \omega_s - \omega_i = 0, \tag{2}$$

$$\Delta k \cdot \Lambda = (k_p - k_s - k_i) \cdot (l_p + l_n) = 2m\pi \quad (m = 1,2,3\ldots), \tag{3}$$

where Δk is the wave vector mismatch, ω is the frequency, k is the wave vector, and subscripts p, s, and i represent the pump, signal, and idler wave, respectively. Λ is the modulation period which is the sum of the positive domain thickness l_p and the negative domain thickness l_n. If an electric field E is applied along the z axis, the new refractive index of the extraordinary light is

$$n_e' = n_e - \tfrac{1}{2} n_e^3 \gamma_{33} E, \tag{4}$$

where $\gamma_{33} = 30.9\,\mathrm{pm/V}$[18] is the electro-optic coefficient of $LiNbO_3$. Since all the waves involved are extraordinary waves, the wave vectors of the pump, signal, and idler wave were changed subsequently

$$k'_{p,s,i} = \frac{1}{c}\omega_{p,s,i} n'_{p,s,i} = \frac{1}{c}\omega_{p,s,i}\left(n_{p,s,i} - \frac{1}{2} n^3_{p,s,i}\gamma_{33}E\right). \tag{5}$$

However, just as the nonlinear optical coefficient, the electro-optic coefficient also has the different signs in different domains. Thus the wave vector in positive domains is different from that in negative domains. In such a inhomogeneous media, the revised QPM condition[19] is:

$$\Delta k' l_p + \Delta k'' l_n = 2m\pi \quad (m = 1,2,3\ldots), \tag{6}$$

where $\Delta k'$ and $\Delta k''$ are the wave vector mismatch at the positive domain and at the negative domain, respectively, when applying the electric field. Assuming the domains have the same thickness $l_p = l_n = \Lambda/2$ and considering the different signs of γ_{33} in different domains, Eq. (6) becomes:

$$(\Delta k' + \Delta k'')\frac{\Lambda}{2} = \Delta k \Lambda = 2m\pi \quad (m = 1,2,3\ldots), \tag{7}$$

where Δk is the unperturbed wave vector mismatch. Equation (7) is just the same as the QPM condition without the electric field, which means the refractive indices of the signal wave and the idler wave do not need to change. Thus the electro-optic tuning cannot be accomplished.

A method that can solve the problem is applying a specific periodic electric field on the crystal. As we know, in the electric poling process, a periodically patterned electrode and a flat electrode were deposited on the $\pm z$ surface of the single domain wafer to make the spontaneous polarization be selectively reversed.[4] In the frequency conversion process, by using the same electrodes, we can apply the electric field only on one kind of domain, e.g., the positive domain. Under this circumstance, the QPM condition is

$$\Delta k' l_p + \Delta k l_n = \Delta k \Lambda - \frac{\Lambda}{4c}\gamma_{33}E(\omega_p n_p^3 - \omega_s n_s^3 - \omega_i n_i^3) = 2m\pi \quad (m = 1,2,3\ldots). \tag{8}$$

To maintain the efficient OPG conversion, the energy conservation and the QPM condition should be satisfied which caused frequency shifts of the signal wave and the idler wave. Thus the electro-optic frequency tuning of a PPLN OPG is achieved. The detailed tuning curve can be obtained by solving Eqs. (2) and (8).

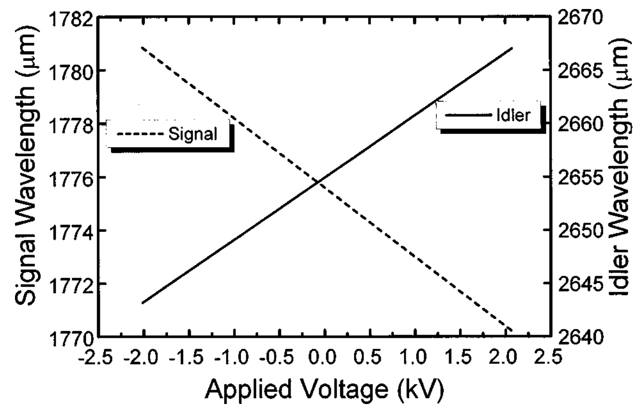

FIG. 1. Wavelength tuning for signal and idler waves at room temperature as a function of applied voltage in a 1064 nm pumped OPG based on a PPLN with the modulation period of 31 μm.

Figure 1 shows the calculated electro-optic wavelength tuning curve as a function of applied voltage on an OPG based on a typical 0.5-mm-thick PPLN with the modulation period of 31 μm, which is just the same as that in Ref. 10. The wavelength of the pump light is 1064 nm. From the figure, the wavelength shifts of both the signal wave and the idler wave exhibit a near-linear dependence on the applied field. A tuning bandwidth of $\pm 10\,\mathrm{nm}$ was achieved in the idler wavelength for an applied voltage of $\pm 1.7\,\mathrm{kV}$. The tuning rate (defined as the wavelength shift normalized by the applied electric field) is about 3 nm/(kV/mm). The above results are obtained at the room temperature $T = 300\,\mathrm{K}$. When temperature changes (e.g., owing to optical absorption) the zero-field wavelength of the OPG changes subsequently. However, the electro-optic frequency tuning can also be achieved. The results in the same crystal are plotted in Fig. 2. Near-linear dependence of wavelength shift on applied electric field was observed at each temperature. However, the slopes of these lines differed slightly. The temperature dispersion of the electro-optic tuning rate is given in Fig. 3, where the data are expressed in the wave number so that the signal and the idler tuning rates are identical.

Besides OPG, the electro-optic tuning technique may be

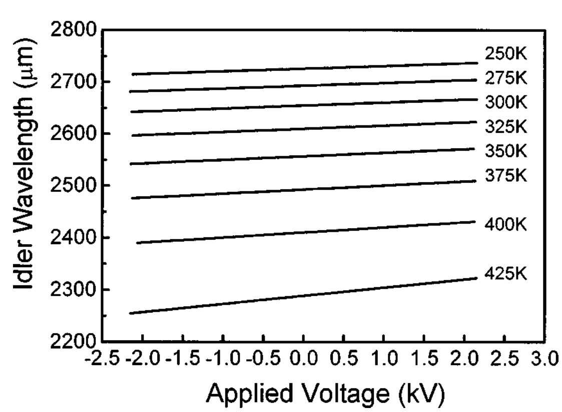

FIG. 2. Idler wavelength tuning as a function of applied voltage at different working temperatures.

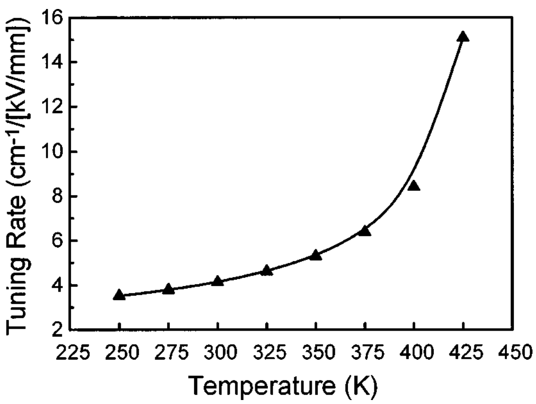

FIG. 3. Dependence of signal (or idler) tuning rate on working temperature.

extended to other frequency conversion applications. For example, in an intracavity frequency doublor[20] or a self-frequency doublor[21] based on PPLN, the periodic electric field can influence both the second harmonic generation (SHG) power and the fundamental light output. The ratio of the fundamental light power and the SHG power is dependent on the intensity of the applied field so that a novel dual-wavelength source can be obtained. If applying this technique on a PPLN OPG or difference frequency generator[22] which has the output wavelength at 1.55 μm, the different intensity of the electric field is just corresponding to different output near the communication window, which means the multichannel wavelength conversion is possible. The most important usage of such a source is in the wavelength division multiplexing (WDM) optical networks.

In addition to above usage, another application is the possibility of constructing a novel ultrashort light source. As we know, the high peak power ultrashort pulses are obtained by compressing after amplifying the frequency-chirped laser pulses. The chirping is generated by complicated process, which makes the devices very expensive. However, in a PPLN OPA, if we applied a periodic electric field as we described when the pump pulse arrived in the crystal, the output signal and idler wave were modulated by the electric field. If the field was changed linearly, the wavelength output of the light formed a linear frequency sweep across the pulse, i.e., frequency chirping, which means we can even get tunable chirped pulses by using this technique. The obtained chirped pulse then might be compressed to generate ultrashort pulse directly. For example, from Fig. 1, applying a linearly electric pulse from -1.7 to 1.7 kV with the same pulse width of the pumping light (e.g., several nanoseconds) will result in a linear chirping with the span of 20 nm. The minimum pulse width that can be compressed is $\tau = 1/\Delta\omega = \lambda^2/(2\pi C\Delta\lambda) \approx 190$ fs.[23]

Although the electro-optic tuned PPLN devices have many applications, it will be more practical if the applied field can be decreased or the tuning range can be enlarged by choosing more adapt materials. Perhaps $Sr_{1-x}Ba_xNb_2O_6$ (SBN) is a good alternative. Its electro-optic coefficient is about 45 times larger than $LiNbO_3$ and their nonlinear coefficient were in the same order,[24] which means that the tuning rate may increase greatly, since the periodic domain structure can also be formed in SBN.[25] If this technique is applied in a periodically poled SBN, perhaps the performance of the devices will be better.

In conclusion, we proposed an electro-optic tuning technique that can tune the output wavelength of PPLN OPG quickly by applying a periodic electric field on the crystal. The dependence of the wavelength shift on the intensity of the applied electric field of an PPLN sample shows a near-linear relationship. The tuning rates excess 3 nm/(kV/mm) are obtained. The phenomenon of dispersion in electro-optic tuning was predicted.

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