**Broadband Second-Harmonic Generation with Group-Velocity Matching in 5mol% MgO-doped Aperiodic Poled Lithium Niobate**

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**Abstract** In this paper, we design an aperiodic poled lithium niobate by using genetic algorithm to increase the acceptance bandwidth of second harmonic generation in 5mol% MgO-doped with group-velocity matching, and an acceptance bandwidth of 243.3nm is obtained finally, which is enhanced to be 4.5 times of that in periodic structure.

1. **Introduction**

Broadband quasi-phase matching (QPM) is widely used in many applications, such as multi-wavelength, second harmonic generation (SHG), ultrashort pulse SHG and optical communications [1-2]. To date, several approaches have been proposed to increase the QPM acceptance bandwidth of SHG. One method is to realize broadband SHG under the conditions that the QPM and group-velocity matching (GVM) of the fundamental (FM) and second harmonic waves are satisfied simultaneously [3-5]. For instance, Yu et al. obtained a bandwidth of 52nm at the communication band in 5mol% MgO-doped periodically lithium niobate (MgO: PPLN) with appropriate temperature, FM wavelengths and QPM grating period [6]. Another way is to compensate the phase-mismatch of SHG by designing a proper structure of nonlinear crystal, which was confirmed by several studies. For example, Dang generated a wide flattop SHG bandwidth of 5.5nm in MgO-doped aperiodic lithium niobate (MgO: APPLN) by simulated annealing algorithm [7]; Bostani designed a special apodized chirped PPLN with which SHG spectra over 30nm could attain [8]; Vyunishev analyzed the theory of SHG under nonlinear Raman-Nath diffraction and designed a chirped 2D nonlinear optical superlattice to supports broadband multiple SHG [9]. However, the requirement of QPM bandwidth is nearly a hundred nanometers with the nonlinear crystal of 10mm for frequency doubling of tens femtosecond ultrashort pulse, and the methods mentioned above are difficult to meet the requirement.

In this paper, we propose an efficient method to realize wider acceptance bandwidth of SH with APPLN in the telecommunication band. Firstly, conditions of GVM and QPM in 5mol% MgO: PPLN are analyzed, and simulation shows that the bandwidth is about 53.9nm for 10mm crystal. An aperiodic structure of lithium niobate was selected to increase the acceptance bandwidth of SH. The APPLN has 3333 uniform domains, whose polarization directions are optimized designed by genetic algorithm to obtain the desired profile of nonlinear coefficient in 1550nm. And then we present a method of...
optimizing the aperiodic poled crystals by adjusting the positions and quantities of the fundamental wavelengths appropriately to broaden the acceptance bandwidth of SH. The simulation results show that the maximum bandwidth of SH is about 243 nm for type-I (o+o→e) interaction of QPM around the wavelength of zero group-velocity dispersion, increased by 189 nm with the optimal structure of 5 mol% MgO: APPLN.

2. Theory

With small signal approximation, the QPM conversion efficiency of SHG is proportional to \( \sin c^2(\Delta k_{QPM} L / 2) \), here, \( \sin c(x) \equiv \sin x / x \) [10], and \( \Delta k_{QPM} \) is the wave vector mismatching which defined as:

\[
\Delta k_{QPM} = \Delta k(\lambda) - k_m = k_{2\omega} - k_{\omega} = \frac{4\pi}{\lambda} (n_{2\omega} - n_{\omega}) - k_m
\]

(1)

here, \( \lambda \) is the wavelength of FM, \( \Delta k(\lambda) \) is the phase mismatch between FM and SH waves, \( k_m \) is the reciprocal vector provided by poled nonlinear crystals, \( k_{\omega} \) and \( k_{2\omega} \) represent the wave vectors of the FM and the SH waves respectively. \( L \) represents the length of nonlinear crystal, \( n_{\omega} \) and \( n_{2\omega} \) are the index of refraction of the FM and SH waves.

The wavelength derivative of phase mismatch is given by [3]:

\[
\frac{d\Delta k(\lambda)}{d\lambda} = \frac{4\pi c}{\lambda} \delta_{n,2\omega}
\]

(2)

here, \( \delta_{n,2\omega} = 1 / \nu_{\omega} - 1 / \nu_{2\omega} \) is defined as group-velocity (GV) mismatch with \( \nu_{\omega} \) and \( \nu_{2\omega} \) represent the group velocity of the FM and the SH waves respectively. The GV mismatch \( \delta_{n,2\omega} = 0 \) can be achieved when \( \nu_{\omega} = \nu_{2\omega} \) (when the GVM condition is satisfied, we call the corresponding wavelength the GVM point), which means the GVM condition is satisfied at the corresponding FM wavelength.

From the theory of Fourier transformation, crystals with an aperiodic optical structure can supply reciprocal vectors flexibly and match more optical parametric processes simultaneously. Therefore, it can increase the acceptance bandwidth of SH effectively. With the small signal and the slowly varying approximation, the conversion efficiency \( \eta \) of SHG is proportional to [11]:

\[
d_{\text{eff}}^2(\lambda) = \left| \frac{1}{L} \int_0^L d(z) e^{i\Delta k(\lambda)z} dz \right|^2
\]

(3)

here, \( d_{\text{eff}}(\lambda) \) is called effective nonlinear coefficient, and \( d(z) \) represents the orientation of each domain taking binary values of 1 or -1, the length of each block is supposed to be \( \Delta L \), and the crystal is divided into \( N \) blocks, then \( d_{\text{eff}}(\lambda) \) can be expanded as:

\[
d_{\text{eff}}(\lambda) = \left[ \frac{1}{L} \int_0^L d(z) e^{i\Delta k(\lambda)z} dz \right] = \frac{1}{L} \sum_{q=0}^{N-1} d(z) \int_{z_q}^{z_{q+1}} d(z) e^{i\Delta k(\lambda)z} dz
\]

\[
= \frac{1}{L} \sum_{q=0}^{N-1} d(z) e^{i\Delta k(\lambda)z_{q+1}} - e^{i\Delta k(\lambda)z_q}
\]

(4)

Here, \( q = 0, 1, 2, \ldots, N \), and the position of each block is located between \( z_q \) and \( z_{q+1} \), the desired structure of aperiodic crystal will be get by optimizing \( d(z) \). And then take domain structure functions into the equation (4), the harmonic conversion efficiency curve can be obtained.
3. Simulations and results

In this paper, a 5mol% MgO-doped LiNO$_3$ (5mol% MgO: LN) crystal is used with the temperature set at 20°C. The Sellmeier equation of 5mol% MgO: LN is given by [12]. As is shown in Fig.1, the GVM wavelength is located at 1.560μm for type-I ($o^+o→e$) QPM after analyzing the dispersion property of the 5mol% MgO: LN.

![Schematic diagram of 5mol% MgO: APPLN.](image)

Fig.1. GV-mismatching as a function of fundamental wavelength for type-I QPM in 5mol% MgO: LN.

The schematic diagram of APPLN is illustrated in Fig.2. The length of APPLN is about 10mm which is divided into 3333 uniform domains with the domain width chosen as 3μm. The arrows which represent the direction of polarization are optimized by genetic algorithm [13]. Then the conversion efficiency will be obtained after substituting the optimal structure into Eq. (3).

![Schematic diagram of 5mol% MgO: CAPPLN.](image)

Fig.2. Schematic diagram of 5mol% MgO: CAPPLN.

Subsequently, broadband QPM SHG’s property is investigated with the aperiodic structure we designed at the waveband around 1.560μm. Firstly, we set the FM wavelength at 1.560μm, 1.720μm, the optimal structure will be get after genetic operations, such as selection, crossover and mutation procedure implemented. Then substitute the optimal structure into Eq (3). The normalized conversion efficiency curve for the optimized 5mol% MgO: APPLN and the phase mismatch Δk(λ) as a function of FM wavelength is shown in Figs.3. Here the acceptance bandwidth of SH is defined as the FM wavelength range of the full width at half maximum (FWHM) of the normalized conversion efficiency [14], as it can be seen from the blue line in Fig.3(a), two QPM SHG peaks with bandwidth of 52.2nm and 6.1nm can be acquired at the position of the predesigned FM wavelength, however, another QPM SHG peak at 1.432μm with acceptance bandwidth of 3.8nm can also be achieved without predesigned wavelength at the position, for this position has almost the same value as 1.720μm which is shown in Fig.3(b). Besides, as shown in the red line in Fig.3(a), two broadband QPM SHG peaks with the same bandwidth of blue line in Fig.3(a) can be obtained with the absence of the broader QPM SHG peak at the GVM wavelength with FM wave of 1.720μm selected only. Consequently, the following simulations
are carried out with the the GVM wavelength of 1.560μm fixed, and the predesigned wavelength on the right side is chosen as an example. Fig.4 shows the simulation results as the right wavelength shifts to the GVM wavelength. We find that bandwidth of the two broadband QPM SHG peaks become wider and wider as the wavelength close to the GVM point. If the interval between the right FM wavelength and the 1.560μm small enough, those three broadband QPM SHG peaks would overlap to a single broader bandwidth peak but with a significant ripples on the top which will gets smaller as the interval becomes closer, and when the right FM wavelength moves to 1.600μm, a wide flattop QPM SHG bandwidth of 98.1nm is obtained as shown in Fig.4.

![Conversion efficiency and Phase-mismatch curve.](image)

Fig. 3. Conversion efficiency and Phase-mismatch curve.

![Conversion efficiency curve as the predesigned wavelength shifts.](image)

Fig. 4. Conversion efficiency curve as the predesigned wavelength shifts.

In order to further broaden the acceptance bandwidth of SH, simulations are performed with 1.560μm, 1.600μm fixed and one more FM wave added every 5nm on right side. Fig. 5(a)-(f) shows the broadband SHG obtained with the number of 1, 7, 13, 18, 22 and 24 FM waves added, respectively. It is shown that the acceptance bandwidth of SH would broaden with the number of FM wavelength increased and reaches the maximum of 243.3nm with 18 wavelengths added. However, bandwidth of SH will become narrow when further wavelength added.
Fig. 5. (a)-(f) SHG bandwidth with 1.5601 μm and 1.600 μm fixed and the number of 1,7,13,18,22,24 FM wavelengths are added every 5 nm on the right side.

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Reference
[1] B.Q. Chen, C. Zhang, C.Y. Hu, R.J. Liu, Z.Y. Li 2015 Phys. Rev. Lett. 115 083902
[2] L.Y. Zhang, Y.J. Liu, J.J. Huang, S.Z. Pu, Z.Y. Yang 2014 J. Opt. Soc. Am. B 31 1202
[3] Kwang-jo Lee, Choon Sup Yoon and Fabian Rotermund 2005 Jpn. J. Appl. Phys. 44 1264
[4] J.F. Zhang, Y.P. Chen, F. Lu, W.J. Lu, W.R. Dang, X.F. Chen, Y.X. Xia 2007 Appl. Opt. 46 7792
[5] Sung Hak Bae, In Hyeong Baek, Sun Young Choi, Won Bae Cho, Fabian Rotermund, Choon Sup Yoon 2010 Opt. Comm. 283 1894
[6] Nan E Y, Jung H R, Myoungsik C , Sunao K, Takunori T 2002 Opt. Lett. 27 1046
[7] W.R. Dang, Y.P. Chen, X.F. Chen 2012 Photon. Technol. Lett. 24 347
[8] Bostani A, Ahsawat M, Tehranchi A, Morandotti R, Kashyap R 2015 Opt. Express 23 5183
[9] Andrey M. Vyuminhev, Vasily G. ArkhipkinR, Anotoly S. Chirkin2015 J. Opt. Soc. Am. B 32 2411
[10] Martin M. Fejer, G. A. Magel, Dieter H. Jundt, Robert L. Byer 1992 J. Quant. Electron. 28 2631
[11] X.F. Chen and F. Wu 2004 Phys. Rev. A 69 0117018
[12] Q. Gayer,Z. Sacks, E. Galun, A. Arie 2008 Appl. Phys. B 91 343
[13] J.Y. Lai, Y.J. Liu, H.Y. Wu, Y.H. Chen, S.D. Yang 2010 Opt. Express 18 5328
[14] J. Jiang, J.H. Chang, S.J. Feng, L. Wei, Q.H. Mao 2010 Opt. Express 18 4740