New kind of WDM laser source by optical parametric 
oscillation in aperiodically poled lithium niobate

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ABSTRACT
A new method based on aperiodically poled lithium niobate is suggested to provide multiple wavelengths for WDM optical communications applications. In this paper, we theoretically investigate the method for generating multi-wavelength source based on optical parametric oscillation (OPO) in aperiodically poled lithium niobate (APLN). We also check the effect of errors caused by the room-temperature electric poling process. The relationship between the line-width and the block length is also discussed.

Keywords: wavelength-division-multiplexed (WDM), quasi-phase-matched(QPM), optical parametric oscillation (OPO), aperiodically poled lithium niobate (APLN).

Stable multi-wavelength optical sources with high frequency stability are essential in large capacity optical wavelength-division-multiplexed (WDM) all-optical networks, especially for dense WDM system. Currently used DFB diode lasers are very expensive because their wavelengths have to be chosen to meet the requirement of ITU standard. To develop low cost and reliable laser source for WDM applications is an interesting topic. Two main schemes for obtaining the new WDM source have been proposed and investigated. One is the DFB laser array which integrates multi-wavelength into a chip[1], each wavelengths are adjust to meet ITU standard by special wavelength tuning technique, but this kind of approach is difficult for fabricating and is still too expensive for its low fabrication yield. The other alternative approach is the spectral slice method which filters out the multi-wavelength laser source components from a single broaden-band source in which a pulse laser with pico-second or femo-second pulse duration and specially designed dispersion optical fibers are need[2].

As well known, Quasi-phase-matched(QPM) is a potential approach to generate new coherent laser source[3]. It is an alternative technique to birefringent phase matching for compensating phase velocity dispersion in frequency conversion applications. In a first-order quasi-phase-matched device, the nonlinear coefficient is modulated with a period twice the coherence length of the interaction to offset the accumulated phase mismatch. A significant advantage of quasi-phase matching is that we can get precise output wavelength by control the temperature and the domain inversion period. Another benefit is that the interacting waves can be chosen so that coupling occurs through the largest element of the $\chi^{(2)}$.
Tunable infrared laser source based on OPO in periodically poled lithium niobate or other periodically poled ferroelectric material was obtained by temperature tuning[4]. In this case, only one wavelength can be obtained in a fixed temperature. Recently, frequency conversion in an aperiodically poled ferroelectric material was suggested[4], which can provides more spatial Fourier components than that of the periodically poled material.

In this paper, A promising method for generating multi-wavelength source based on optical parametric oscillation(OPO) in aperiodically poled lithium niobate(APLN) is theoretically investigated[7,8] This APLN is constructed with the opposite ferroelectric domains, whose length is less then coherence length of OPO process. Simulated annealing(SA)[9,10] method is applied to optimize the sequence of this ferroelectric domain structure, which provide plenty of reciprocal vectors to compensate for the mismatch between the interactive waves. Thus, it may be expected that multi-wavelength laser source for WDM optical fiber communications can be obtained with the pre-designed domain-inverted structure in APLN.

![Fig 1. Domain structures in lithium niobate. The arrows in each unit block indicate the domain orientation. And \( \Delta x \) is the thickness of each unit block. (a) structure of periodically poled lithium niobate. (b) structure of aperiodically poled lithium niobate(APLN).](image)

![Fig 2. A schematic diagram of the setup for OPO experiments with a APLN.](image)

Fig 1 shows two kinds of one dimensional microstructures in Z-cut lithium niobate. The thickness of each unit block is the same. The microstructure showed in Fig 1(b) is aperiodic and it contains more reciprocal vectors than the periodic structure in Fig 1(a). The microstructure shown in Fig 1 is designed to get some reciprocal vectors which can lead to needed quasi phase matching process in which
multi-wavelength can be generated simultaneously in the material through OPO process. The schematic diagram of the setup for OPO experiments with an APLN is shown in Fig. 2.

Considering a OPO process in bulk APLN. An APLN sample is put into an optical resonator; and the pump laser beam is incident from the left onto the surface of the APLN sample and the generated signal laser beams begin to oscillate in the optical resonator while the pump power exceeds the oscillation threshold. In the limit of low gain the single-pass parametric power amplification in the sample of length $L$ is

$$G = \frac{|E_r(L)|^2}{|E_r(0)|^2} - 1$$

where $I_\rho$ is the pump intensity; where $\Phi(x)$ represents the orientation of each block, and it only takes binary values of 1 or -1. In our calculation, we consider the reduced effective nonlinear coefficient $d_{\text{eff}}$ for OPO process in APLN.

$$d_{\text{eff}} = \frac{1}{L} \left| \int dx e^{2\pi i \Phi(x)} \right|$$

where $N$ is the number of the blocks in sample; $\Delta x$ is the thickness of each block. The first term is Sinc function, where $\alpha = \pi/(2Lc)$, $Lc$ is the coherent length of the fundamental wavelength. For the perfect first order periodical QPM, $\Delta x = Lc$, it equals $2\pi$; in the APLN case, the length of the each block can be chosen artificially, for example, $\Delta x = Lc/3$, the value of the Sinc function is increased to $3\pi$, 50% than that of the perfect QPM. The second term is determined by the interference effect of all domains, which is globally dependent on the sequences and the sign of every domain. Using simulated annealing method we can get optimized arrangement of the domain orientations of the blocks in the sample.

We first apply the method to design APLN structure used in generating CWDM laser source. The parameters are set as below: the thickness of each block is 10 $\mu$m; the number of the blocks is 3000, the total length of the bulk lithium niobate is 30 mm, the refractive indices of the each interactive wave of the OPO process are from Sellmeier equation[6]. The four wavelength for CWDM laser sources are chosen with the interval of 10 nm (1290 nm, 1300 nm, 1310 nm, 1320 nm) and 20 nm (1490 nm, 1510 nm, 1530 nm, 1550 nm), respectively. The optimal consecutive order of the domains is obtained by the choice of the appropriate objective function in SA method. Fig.3 displays the calculated $d_{\text{eff}}$ after scanning a wide range of wavelength. Four pre-designed peaks in Fig.3(a) and Fig.1(b), the line-width of all the peaks in Fig.3 is about 1 nm. Because OPO process can be operated only when its gain is larger than the oscillation threshold, the line-width of the generated signal will be even shorter. The effective nonlinear coefficient for the four pre-designed wavelength is about 0.20 which is only about 1/3 of that for the perfect QPM in which the ideal maximum value of the effective nonlinear coefficient should be $2/\pi$. This
is because of the trade-off between the multi-wavelength phase-matching and the OPO conversion efficiency.

![Simulated results of OPO process in AOS sample with SA method. N=3000, Δχ = 10μm. (a) The peak wavelength space is 10nm. The line-width of each peak is appropriately 1 nm. (b) The peak wavelength space is 20nm. The line-width of each peak is appropriately 1 nm.](image-url)
With the same purpose and method, we also design APLN OPO to generate DWDM laser source. We adopt the length of each layer 10μm and the number of the blocks is 3000, the total length of the bulk lithium niobate is also 30mm. The four wavelengths with ITU standard for DWDM laser sources are chosen with the interval of 400GHz (3.2nm) as 1565.5nm; 1562.2nm; 1559.0nm and 1555.8nm (ITU channel 15, 19, 23 and 27). The stimulated annealing results are displayed in Fig. 4. The line-width of each peak is appropriately 1 nm which can fulfill the requirement of the laser source for DWDM applications. The reduced effective nonlinear coefficient for the four pre-designed wavelength is about 0.20 due to the trade-off between the multi-wavelength phase-matching and the OPO conversion efficiency.

![Fig. 4. Calculated results of OPO process in AOS sample with SA method with DWDM peak wavelengths. Wavelength space is 3.2nm. N=3000; Δx = 10μm.](image)

![Fig. 5. Simulated results of OPO process in AOS sample with SA method with DWDM peak wavelengths. Wavelength space is 1.6nm. N=2300; Δx = 25μm](image)
Fig. 5 shows the effective nonlinear coefficient as a function of the wavelength by optimally choosing appropriate sequence of the domains in APLN. The eight wavelength peak in the Fig. 5 is accordingly consistent with the pre-set DWDM laser source with the ITU wavelength, channel 29, 27, 25, 23, 21, 19, 17 and 15. To obtain the multi-wavelength for DWDM applications, the line-width of all the peaks should be narrow enough to prevent the crosstalk between the wavelength channels. We found that the wide block length will be helpful to decrease the line-width. The length of each layer 25μm are adopted, and the line-width of each peak is about 0.6nm.

![Graph showing effective nonlinear coefficient as a function of wavelength](image)

**Fig. 6.** Several peak wavelengths propagate in the APLN sample. The wavelengths chosen for calculation are shown in Fig. 3 (a) with wavelength space of 10nm.

It is interesting to investigate the signal waves propagating along the aperiodic grating. Fig. 6 describes several wavelengths propagating in APLN together. From the plot, each curve tend to the same end through different ways. This clearly manifests that these wavelengths can all globally be phase-matched by the interference effect of all constructed domains, but undergo different interference process.
In our calculation we found that the block length $\Delta x$ has great influence on the line-width of each peak. Fig. 7 describes the variation of block length as a function of the linewidth. The smaller of the domain block the more reciprocal vectors are with a fixed length of the sample. So, the reciprocal vectors in the APLN with short blocks should be denser than those in APLN with longer blocks. The curve in Fig. 5 implies that we can sharpen the output peaks by enlarge the size of each block.

![Diagram](image)

**Fig. 7** Variation of line-width of the peaks in the simulated result of CWDM with 20nm wavelength space with block length $\Delta x$.

We also investigate the effect of errors caused by the room-temperature electric poling process. As is well known, the inverted domains typically grow beyond the width of the metal electrode defined by...
pre-designed patterns [4]. Since the error of domain lengths is inevitable under the current room-temperature poling techniques, we take into account the resultant domain size after the poling process. We assume that the inverted domains extend its edge into adjacent layers of opposite sign, and the non-inverted domains correspondingly are shortened. The influence of this extension by the fabrication process is depicted in Fig. 8. We found that the block uncertainty do not arouse the walk-off of the peaks, but change the height of each peak. The figure also shows that the effective nonlinear coefficient doesn't decrease monotonically as the uncertainty of the domain increases. From the Figure, we found that the uncertainty is about 12% as the full width at half maximum and the effect of domain errors caused by the room-temperature electric poling is relative low.

In APLN OPO process, the beams with different wavelength should be oscillating simultaneously. According to the theory of optic resonator designing, we get Equation (3)

\[ \Delta v_q = \frac{c q}{2 nd} \] (3)

where \( \Delta v_q \) is the frequency interval; \( c \) is the speed of light in vacuum; \( d \) is the length of the optic resonator; \( n \) represents the refractive index of the wave propagating in the resonator; and \( q=1,2,3,\ldots \). So, the length of the optical resonator for the multi-wavelength demands can be calculated. For example, we adopt four peaks with wavelength space \( \Delta v_q =400\text{GHz} \) as shown in Fig. 5, and assume that resonator is in vacuum so \( n=1 \). According to Eq.(3), we get \( d=7.50\text{cm} \) as \( q=200 \).

In conclusion, we have demonstrated that APLN can help to generate multiple wavelengths through OPO process. The laser source with precise wavelength meeting the pre-designed wavelength can be obtained by the optimal arrangement of the domain orientations of the blocks along the sample. This method shows the potential application for CWDM and DWDM application because of its low cost, reliability and flexibility.

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Reference