Generation of multi-wavelength light sources for optical communications in aperiodic optical superlattice

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A method for generating multi-wavelength light source is theoretically investigated by optical parametric oscillation (OPO) in aperiodic optical superlattice (AOS). The effects of domain errors caused by the room-temperature electric poling process are checked. The relationship between the linewidth and the block length is also discussed.

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Multi-wavelength optical sources with high frequency stability and low cost are essential in large capacity optical wavelength-division-multiplexed (WDM) all-optical networks, especially for dense WDM (DWDM) system. Distributed feedback (DFB) diode lasers are widely used now in DWDM system, but it is expensive because their wavelengths have to be chosen to meet the requirement of International Telecommunication Union (ITU) standard. To develop low cost and reliable laser source for WDM applications remains an interesting research 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 wavelength is adjusted to meet ITU standard by special wavelength tuning technique. This kind of approach is difficult in fabricating process 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 broad-band source in which a pulse laser with picosecond or femtosecond pulse duration and specially designed dispersion optical fibers are needed[2].

As well known, quasi-phase-matched (QPM) nonlinear optics process is a potential approach to generate new coherent laser source[3−5]. It is an alternative technique to birefrigent phase matching for compensating phase velocity dispersion in frequency conversion applications. In a first-order QPM device, the nonlinear coefficient is modulated with a period twice of the coherence length to offset the accumulated phase mismatch. A significant advantage of QPM is that we can get precise output wavelength by control the temperature and the domain inversion period. Another benefit is that the interactive waves can be chosen so that coupling occurs through the largest element of the $\chi^{(2)}$ tensor. Tunable infrared laser sources based on optical parametric oscillation (OPO) in periodically pole lithium niobate and other periodically poled ferroelectric material were obtained by temperature tuning[6−8]. In this case, only one wavelength can be obtained in a fixed temperature. Recently, frequency conversion of light in an aperiodically poled ferroelectric material was suggested[9−11], which can provide more spatial Fourier components than that of the periodically poled material.

In this paper, a promising method for generating multi-wavelength light sources based on OPO in aperiodic optical superlattice (AOS) is theoretically investigated. The AOS is constructed with the opposite ferroelectric domains, whose length is less than coherence length of OPO process in periodically poled materials. Simulated annealing (SA) method is applied to optimize the sequence of this ferroelectric domain structure, which provides plenty of reciprocal vectors to compensate 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 AOS.

Figure 1 shows one-dimensional (1D) microstructures of periodic optical superlattice (POS) and AOS. In the following discussions, we use lithium niobate crystal as an example, the crystal structures depicted as in Figs. 1(a) and (b) are called periodically poled lithium niobate (PPLN) and aperiodically poled lithium niobate (APPLN), respectively. Figure 1(a) shows a periodically domain inversion structure. The domain length ΔX is determined by phase mismating between interactive waves in a nonlinear optical process. The microstructure shown in Fig. 1(b) is AOS. The thickness $\Delta X'$ of each unit block is the same and always smaller than that in POS

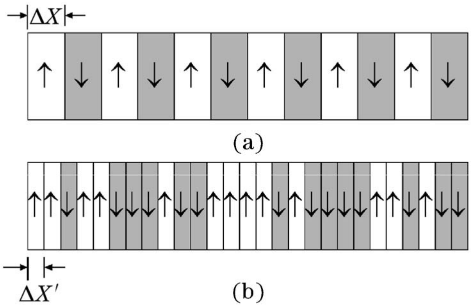

Fig. 1. Schematic diagram of domain structure in lithium niobate. The arrows in each unit block indicate the domain orientation. ΔX and $\Delta X'$ are the thicknesses of each unit block. (a) POS microstructure of PPLN, (b) AOS microstructure of APPLN. The block length is chosen from 2 to 10 μm.

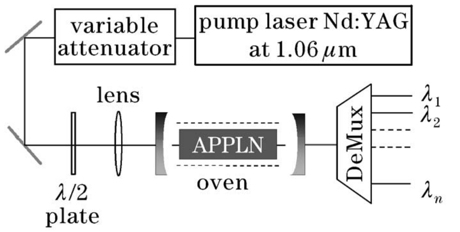

Fig. 2. Schematic diagram of the setup for OPO experiments with an APPLN.

structure[9,11]. It contains more reciprocal vectors than that of POS structure in Fig. 1(a). The microstructure shown in Fig. 1(b) can be designed to get some reciprocal vectors which can lead to pre-designed QPM process by which multiple wavelengths can be generated simultaneously in AOS through OPO process. The schematic diagram of the setup for OPO experiments with an APPLN is shown in Fig. 2.

As shown in Fig. 2, an APPLN sample is put into an optical resonator. The pump laser beam is incident from the left onto the surface of the APPLN sample and the generated signal laser beams begin to oscillate in the optic resonator once the pump power exceeds the oscillation threshold. We consider that in the APPLN all interactive waves are the extraordinary waves that are polarized parallelly to the z-axis. The energy conservation and the momentum conservation can be described as $\omega_{\rm p} = \omega_{\rm s} + \omega_{\rm i}$ and $\Delta k = k_{\rm p} - k_{\rm s} - k_{\rm i} - k_{\rm g}$, where Δk is the phase mismatching, ω_j (k_j) (j =p, s, i) are the angle frequencies (wave vectors) of pump wave, signal wave, and idle wave, $k_{\rm g}$ is the reciprocal vector provided by APPLN crystal.

In the limit of low gain, the single-pass parametric power amplification in the sample of length L is given as[6]

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

$$\approx \frac{8\pi^2 d^2 I_{\rm p} L^2}{c\varepsilon_0 \lambda_{\rm s}\lambda_{\rm i} n_{\rm s} n_{\rm i} n_{\rm p}} \left| \frac{1}{L}\int_0^L {\rm d}x {\rm e}^{i(k_{\rm p}-k_{\rm s}-k_{\rm i})x} \Phi(x) \right|^2, \quad (1)$$

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

$$d_{\rm eff} = \frac{1}{L}\left| \int_0^L {\rm d}x {\rm e}^{i2\pi\alpha x}\Phi(x) \right|$$

$$= \frac{1}{N}\left| {\rm sinc}\,[\alpha\Delta X] \times \sum_{q=0}^{N-1} \Phi(x_q) {\rm e}^{i[2\pi\alpha(q+0.5)\Delta x]} \right|, \quad (2)$$

where N is the number of the blocks in sample, ΔX is the thickness of each block. The first term is Sinc function, where $\alpha = \pi/2L_{\rm C}$, $L_{\rm C}$ is the coherent length of the fundamental wavelength. For the perfect first order periodical QPM, $\Delta X = L_{\rm C}$, the value of sinc function equals $2/\pi$. In the APPLN case, the length of each block can be chosen artificially, for example, $\Delta X = L_{\rm C}/3$, the value of the sinc function is increased to $3/\pi$, 50% more than that of the perfect QPM. The second term is determined by the interference effects of all domains, which is globally dependent on the sequences and the sign of the every domain. Using SA method we can get optimal arrangement of the domain orientations of the blocks in the sample.

We first apply the method to design APPLN structure used in generating coarse WDM (CDWM) laser sources. The parameters are set as follows: the thickness of each block is 10 μm, the number of the blocks is 3000, the total length of the bulk lithium niobate is 30 mm, the refractive indices of the interactive waves for the OPO process are from Sellmeier equation[12]. The four wavelengths for CWDM laser sources are chosen as the signal waves with the interval of 10 nm (1290, 1300, 1310, 1320 nm) and 20 nm (1490, 1510, 1530, 1550 nm), respectively. If APPLN is pumped by a laser with a wavelength of 532 nm, the wavelengths of the corresponding idle waves are 905.4, 900.5, 895.8, 891.2 nm and 827.4, 821.4, 815.6, 810.0 nm. The optimal consecutive order of the domains is obtained by the choice of the appropriate objective function in SA method. Figure 3 displays the calculated $d_{\rm eff}$ after scanning a wide range of wavelength. Four pre-designed peaks are shown in Figs. 3(a) and (b). The linewidths of all the peaks in Fig. 3 are about 1 nm. Because OPO process can be operated only when its gain is larger than the oscillation threshold, the linewidth of the generated signal will be even shorter. The effective nonlinear coefficients for the four pre-designed wavelengths are about 0.20, about 1/3 of that for the perfect QPM PPLN 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.

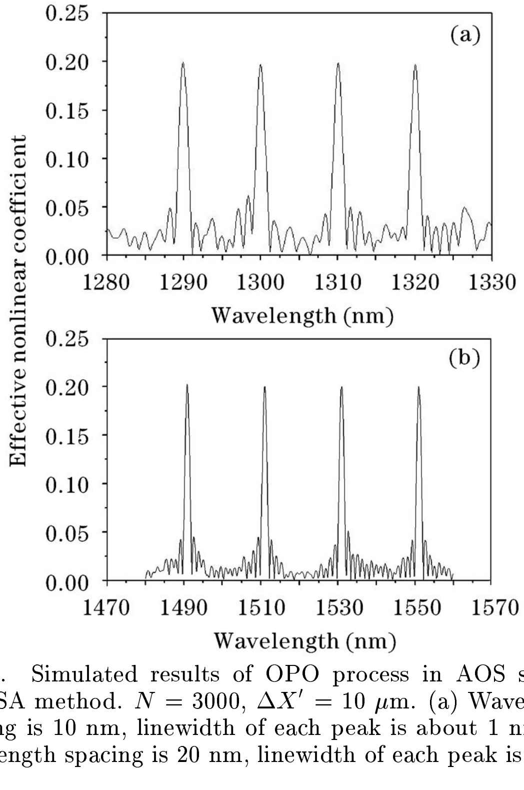

Fig. 3. Simulated results of OPO process in AOS sample with SA method. N = 3000, $\Delta X'$ = 10 μm. (a) Wavelength spacing is 10 nm, linewidth of each peak is about 1 nm, (b) wavelength spacing is 20 nm, linewidth of each peak is about 1 nm.

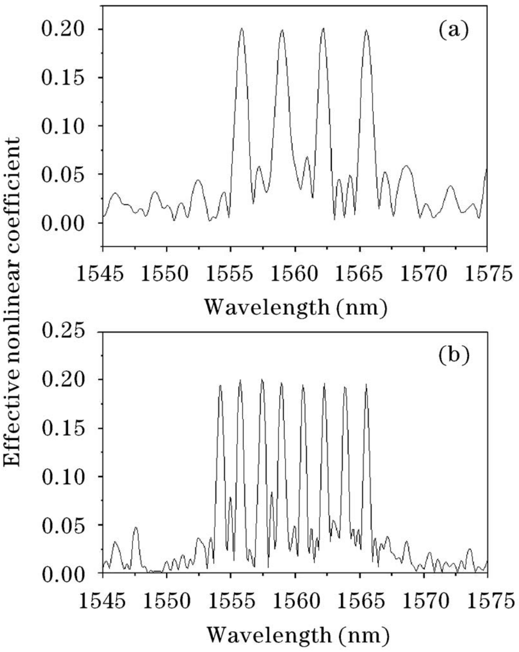

Fig. 4. Calculated results of OPO process in AOS sample with SA method with DWDM peak wavelengths. (a) 4 ITU wavelengths, wavelength spacing is 3.2 nm (400 GHz). $N = 3000$, $\Delta X' = 10$ μm. (b) 8 ITU wavelengths, wavelength spacing is 1.6 nm. $N = 2300$, $\Delta X' = 25$ μm.

With the same purpose and method, we also design APPLN OPO to generate DWDM laser sources. We adopt that the length of each layer is 10 μm, the number of blocks is 3000, and the total length of the bulk lithium niobate is also 30 mm. The four wavelengths with ITU standard for DWDM laser sources are chosen with the interval of 400 GHz (3.2 nm) as 1565.5, 1562.2, 1559.0, and 1555.8 nm (ITU channels 15, 19, 23, and 27). Pumped by a laser with wavelength of 532 nm, the wavelengths of the corresponding idle waves are 805.9, 806.7, 807.6, and 808.4 nm, respectively. The SA results are displayed in Fig. 4(a). The linewidth of each peak is about 1 nm, which can fulfill the requirement of the laser source for DWDM applications. The reduced effective nonlinear coefficients for the four pre-designed wavelengths are about 0.20 due to the trade-off between the multi-wavelength phase-matching and the conversion efficiency. Figure 4(b) shows the effective nonlinear coefficient as a function of the wavelength by optimally choosing appropriate sequence of the domain in APPLN. The eight wavelength peaks in Fig. 4(b) are accordingly consistent with the wavelengths of pre-set DWDM laser sources with the ITU standard, channels 29, 27, 25, 23, 21, 19, 17, and 15. To obtain the multiple wavelengths for DWDM applications, the linewidth of all the peaks should be narrow enough to prevent the crosstalk between the wavelength channels. We found that the wide block length is helpful to decrease the linewidth. If we adopt the length of each layer of 25 μm, the linewidth of each peak can decrease to about 0.6 nm.

It is interesting to investigate the signal waves propagating along the aperiodic grating. Figure 5 describes several wavelengths propagating in APPLN as shown in Fig. 3(a) for CWDM light sources. From the plot, each curve tends to the same end through different ways. This clearly manifests that these wavelengths can all be phase-matched globally by the interference effect of all constructed domains, but undergo different interference processes.

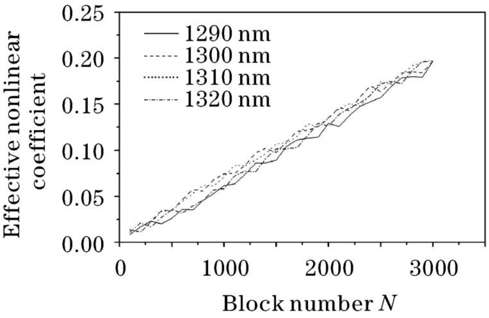

Fig. 5. Schematic diagram of several peak wavelengths propagating in the APPLN sample. The wavelengths chosen for calculation are shown in Fig. 3(a) with wavelength spacing of 10 nm.

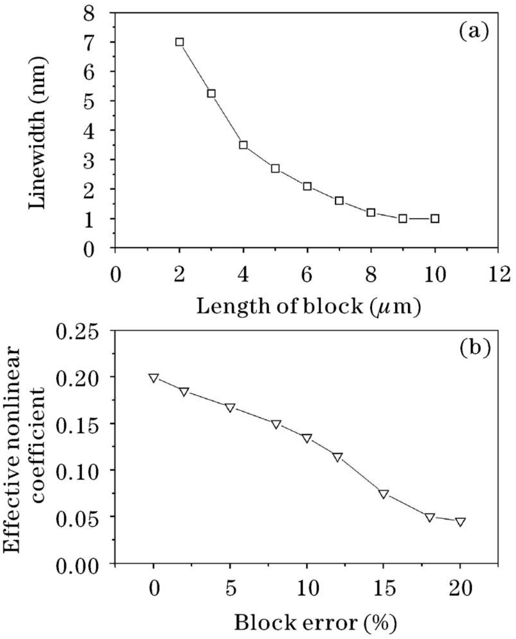

Fig. 6. (a) Linewidth of the peaks versus block length $\Delta X'$ in the simulated result of CWDM with wavelength spacing of 20 nm. (b) Effective nonlinear coefficient versus block error in the simulated result of DWDM with 1.6-nm wavelength spacing. Block error is referred as the proportion of the extended part to the original one at each edge.

The influence of block length $\Delta X'$ and the fabrication error on the performance of OPO process in APPLN are given in Figs. 6(a) and (b). In our calculation we found that the block length $\Delta X'$ has great influence on the linewidth of each peak. Figure 6(a) describes the variation of block length as a function of the linewidth. The smaller the domain block is, the more the reciprocal vectors are with a fixed length of the sample. So the reciprocal vectors in the APPLN with short blocks should be denser than those in APPLN with longer block. The curve in Fig. 6(a) implies that we can sharpen the output peaks by enlarging the size of each block. We also investigate the effect of error caused by the room-temperature electric poling process. As well known, the inverted domains typically grow beyond the width of the metal electrode defined by pre-designed patterns[6]. Since the error of the domain length is inevitable under the current room-temperature poling techniques, the influence of such error on the performance of multi-QPM process should be taken into account. We assume that the inverted domains extend its edge into adjacent layers of opposite sign, so that the adjacent non-inverted domains correspondingly are shortened. The influence of this extension by the fabrication process is depicted in Fig. 6(b). We find that the block errors 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 decreases when the errors of the domain increase. We also find that the error is about 12% as the full-width at half maximum. The effects of domain errors caused by the room temperature electric poling on the performance of device are relatively low.

If the length of the optical resonator is adopted around 10 cm, the frequency interval of the optical resonator $\Delta\nu = c/2nd$ is about 1 GHz, much smaller than the frequency interval for DWDM light sources (several hundred GHz). So, in APPLN OPO process, the beams with different wavelengths for WDM light sources can oscillate simultaneously.

In conclusion, we have demonstrated that APPLN is helpful to generate multiple wavelengths through OPO process. The laser source with precise wavelength meeting the pre-designed wavelengths can be obtained by the optimal arrangement of the domain orientations of the blocks along the sample. As the technique of the room temperature electric poling becomes mature, this method will show its potential application for WDM applications owing to low cost, reliability, and flexibility.

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