Nonperiodic optical superlattice optimized by genetic algorithm for engineered multiwavelength conversion

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Abstract: We experimentally demonstrate engineered multiwavelength conversion using nonperiodic optical superlattice optimized by genetic algorithm with two target functions. This scheme has better spectral shape fidelity and ~15% higher conversion efficiency compared to aperiodic optical superlattice.

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1. Introduction:

Quasi-phase-matching (QPM) in ferroelectric materials has been widely used in a variety of wavelength conversion processes [1, 2]. In some applications, such as gas sensing using several absorption lines [3] and equalized wavelength conversion grids [4], multiple phase-matching (PM) spectral peaks with different heights at specified wavelengths are required, which cannot be accomplished by some of the existing methods [4, 5, 6]. Periodic continuous phase modulation with suppression of undesired PM peaks [3] can meet the aforementioned requirements, however, the spacing between PM spectral peaks is limited by integral multiples of some unit value (determined by the phase modulation period), and is unsuitable in designing PM spectra with a small number of well-separated peaks [2]. Aperiodic optical superlattice (AOS) optimized by simulated annealing (SA) [7] also allows for great design flexibility, but the domain size is limited to integral multiples of some unit block length. In contrast, nonperiodic optical superlattice (NOS) [8] removes the domain size restriction, and might achieve better conversion efficiency and spectral shape fidelity. However, the NOS presented in Reference [8] can only produce PM peaks of equal height and has to be optimized by the combination of SA and genetic algorithm (GA). In this work, we theoretically and experimentally demonstrate NOS solely optimized by GA to achieve arbitrarily distributed PM peaks. Our simulations show that NOS can have an overall efficiency 15% higher than that obtained by an AOS of the same length. We have also investigated the distortion of PM tuning curve in the presence of fabrication errors and pump depletion.

2. Theory:

Without loss of generality, we demonstrate the NOS scheme by examining second-harmonic generation (SHG) in a lithium niobate bulk of length L. The crystal is divided into N blocks with different lengths (to be optimized), and adjacent blocks have opposite domain orientations. If the pump is non-depleted, the conversion efficiency spectrum is given by [5]:

$$\eta(\lambda)=\eta_{norm}(\lambda)\cdot P_\omega\cdot d_{eff}^2(\lambda), \qquad d_{eff}(\lambda)=\frac{1}{L}\left|\int_0^L \tilde{d}(x)e^{i\Delta k(\lambda)\cdot x}dx\right|, \tag{1}$$

where λ is the fundamental wavelength, η_{norm} is the normalized efficiency in units of %/W, d_{eff} is the effective nonlinear coefficient determined by the NOS design, Δk is the wave vector mismatch, and $\tilde{d}(x)$ (taking values of 1 or -1) represents the spatial distribution of domain orientation. To achieve multiple PM peaks at specified wavelengths $\{\lambda_\alpha\}$, we sequentially employ two target functions T_1, T_2 in search of an optimized $\tilde{d}(x)$ by GA:

$$T_1=\sqrt{\sum_{\alpha=1}^{M}\left[\eta_\alpha-\eta_\alpha^{(0)}\right]^2}, \qquad T_2=T_1+\sum_{\alpha=1}^{M}\left|\eta_\alpha-\tilde{\eta}_\alpha^{(0)}\right|, \tag{2}$$

where $\eta_\alpha^{(0)}$ ($\sum\eta_\alpha^{(0)}=1$) and η_α represent the target and achieved conversion efficiencies at λ_α normalized to the peak efficiency η_0 due to a uniform QPM grating of the same length L, $\eta_{tot}=\sum\eta_\alpha$ (<1) denotes the achieved overall efficiency, and $\tilde{\eta}_\alpha^{(0)}=\eta_{tot}\times\eta_\alpha^{(0)}$ is the "damped" target conversion efficiency used to adjust the magnitude of the target PM spectrum (according to the achieved overall efficiency) without changing its shape. Our simulations show that minimizing T_1 can only suppress conversion efficiencies at undesired wavelengths ($\lambda\notin\{\lambda_\alpha\}$), while the resulting PM spectral shape is typically unsatisfactory. This problem can be solved by preserving the elite individuals identified by T_1 and minimizing the difference between the achieved and damped target efficiencies. In this way, the evolution power of GA can be dedicated to improving the PM spectral shape. Using T_2 only, however, might suffer from low overall efficiency though the PM spectral shape can meet the target. In our algorithm, a fixed number of generations N_i is prespecified for the target function T_i (i=1, 2).

3. Simulations and experiments

The genetic pool used in all of our NOS designs, contains 1200 individuals. Each individual consists of 2000 ferroelectric domains, and the minimum domain length is set as 4.5 μm in view of the typical limitations of high-quality e-field poling. Two parameters, the overall efficiency η_{tot} and the average spectral shape error $\Delta\eta$ ($\equiv \sum_{\alpha}\left|\eta_{\alpha}-\tilde{\eta}_{\alpha}^{(0)}\right|/\eta_{tot}$), are used to estimate the performances quantitatively. Table 1 shows the results of designing five PM peaks distributed in V-shape derived by using target function(s) T_1, T_2, T_1&T_2 in NOS scheme, and by using AOS approach, respectively. Using T_1 or T_2 alone suffers from worse spectral shape fidelity ($\Delta\eta$ values are 12-13 times higher than that of using both T_1 and T_2). The overall conversion efficiency is significantly lower if only T_2 is used. Compared to AOS of the same length, NOS optimized by T_1 and T_2 can achieve higher efficiency (η_{tot} =0.86 vs. 0.75) and better spectral shape fidelity ($\Delta\eta$=0.33% vs. 1.15%) owing to the removal of domain length restriction (Fig. 1). We also verified (not shown here) that the performances of NOS can be further improved by increasing the size of genetic pool, while the AOS approach is subject to tradeoff between efficiency and fidelity because of the fixed number of unit blocks for a specified device length.

Table 1. Simulation results of designing five V-shaped PM peaks using NOS (columns 3-5) and AOS (column 6) schemes.

λ_{α} (nm)	$\eta_{\alpha}^{(0)}$	η_{α} (T_1)	η_{α} (T_2)	η_{α} (T_1+T_2)	η_{α} (AOS)
1540	0.2667	0.2333	0.1137	0.2302	0.2036
1545	0.1833	0.1548	0.0858	0.1594	0.1378
1550	0.1000	0.0678	0.0453	0.0864	0.0756
1555	0.1833	0.1523	0.0793	0.1576	0.1350
1560	0.2667	0.2355	0.1251	0.2299	0.1984
η_{tot}	1	0.8437	0.4492	0.8635	0.7504
$\Delta\eta$	0	4.43%	4.05%	0.33%	1.15%

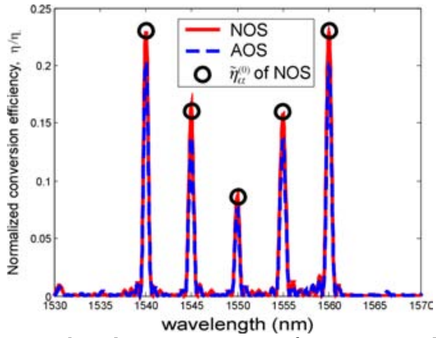

Fig. 1 V-shaped PM tuning curves of NOS optimized by T_1 and T_2 (solid) and AOS (dashed), respectively.

Our simulations also show that the performances of NOS are slightly deteriorated in the presence of fabrication errors (uniform domain broadening and random domain size error), in agreement with those in Reference [7]. When the conversion efficiency is high, eq. (1) is no longer valid because of pump depletion. The general features of distorted PM spectrum are narrower main lobes and amplified noise at unwanted wavelengths. We use the relative target efficiency $r_{targ}\equiv A_{targ}/A_{tot}$ to quantitatively measure the PM spectral distortion under high conversion efficiency, where A_{targ} and A_{tot} represent the summation of the areas of the M target main lobes and the total area of the PM power spectrum, respectively. Fig. 2 shows that the performance of NOS design (open circles) is similar to that of a periodic QPM grating (with analytic solution [9]), where the relative target efficiency dramatically drops as the peak conversion efficiency approaches 90%.

We fabricated 19-mm-long lithium niobate NOS samples with 2000 domains by e-field poling technique. PM tuning curves were characterized by measuring second-harmonic power as a function of fundamental wavelength. Fig. 3 shows the experimentally measured PM tuning curves (solid) for the two different target spectra (open circles in Fig. 3a and Fig. 3b). The corresponding spectral shape errors are very low ($\Delta\eta$=4.39%, and 3.04%), confirming the feasibility of our NOS scheme.

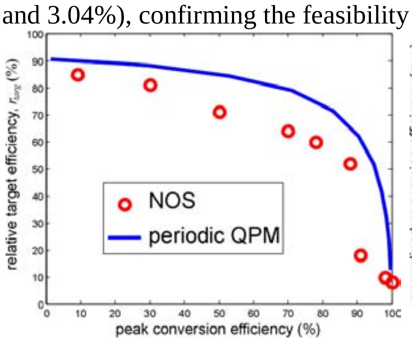

Fig. 2. Relative target efficiencies versus peak conversion efficiency for an NOS device (open circles) and a purely periodic QPM grating (solid),

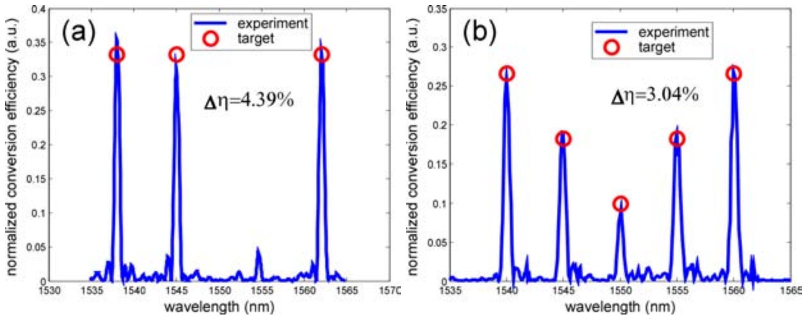

Fig. 3. Experimentally measured PM tuning curves (solid) for (a) three unequally-spaced, equally-high PM peaks, and (b) five equally-spaced, V-shape distributed PM peaks. The open circles represent the damped target efficiencies $\tilde{\eta}_{\alpha}^{(0)}$.

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