Hyperfine aperiodic optical superlattice optimized by iterative domino algorithm for phase-matching engineering

Cheng-Wei Hsu, Jui-Yu Lai, Shang-Da Yang*
Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 30013, Taiwan
shangda@ee.nthu.edu.tw

Abstract: We propose hyperfine aperiodic optical superlattice optimized by iterative domino algorithm to achieve arbitrary discrete and continuous phase-matching power spectra. This schmem can handle >10^5 unit blocks and improves the record overall efficiency by 9%.
OCIS codes: (230.7405) Wavelength conversion devices; (230.4320) Nonlinear optical devices; (160.3730) lithium niobate

1. Introduction

Quasi-phase-matching (QPM) in ferroelectric materials has been widely used in plenty of wavelength conversion processes [1]. In applications of gas sensing using several absorption lines [2] and high-sensitivity ultrashort pulse measurement [3], one needs discrete phase-matching (PM) peaks at pre-specified positions and a continuous PM spectrum with broad bandwidth, respectively. There have been some techniques, such as aperiodic optical superlattice (AOS) optimized by simulated annealing (SA) [4] and nonperiodic optical superlattice (NOS) optimized by genetic algorithm (GA) [5], capable of achieving arbitrary discrete PM peaks. However, their performances (conversion efficiency, spectral fidelity, and complexity of target PM peaks) are subject to the limited number (~several thousands) of unit blocks or domains that can be practically optimized by SA or GA, and no continuous PM spectrum has been demonstrated accordingly. In this paper we propose a new scheme, hyperfine AOS (HAOS) optimized by iterative domino (ID) algorithm, which can optimize hundreds of thousands unit blocks in 15 minutes by typical PCs. The high computation efficiency enables the use of a very small unit block length (~0.1 μm, limited by the resolution of the photolithographic mask) and a large number of target PM peaks (~100), while all the domains are still made longer than the minimum domain size that can be reliably poled (~4 μm). As a result, the HAOS+ID scheme can realize arbitrary discrete PM peaks and continuous PM power spectra with unprecedented conversion efficiency (~25% and 9% higher than those of AOS and NOS, respectively) and nearly perfect spectral fidelity. We also numerically demonstrated that our scheme can arrive at a quasi-optimal solution, which can only be slightly improved by impractically long computation time.

2. Theory

Without loss of generality, we demonstrate the HAOS+ID scheme by investigating second-harmonic generation (SHG) in a congruent $LiNbO_3$ bulk of length L. The crystal is divided into N unit blocks of the same length dx. If the pump is non-depleted, the conversion efficiency at fundamental wavelength λ is given by:

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

where η_{norm} is the normalized efficiency in units of %/W, Δk (a function of λ) is the wave vector mismatch, and $d(x)$ (taking values of +1 or -1) represents the spatial distribution of domain orientations. For HAOS (and AOS), the reduced effective nonlinear coefficient $d_{R\text{-}eff}$ can be rewritten as:

$$d_{R-eff}(\lambda) = \frac{1}{L}\left|\sum_{n=1}^{N} z_n(\Delta k)\right|,\quad z_n(\Delta k) = \delta_n\frac{e^{i\Delta k\cdot x_n} - e^{i\Delta k\cdot x_{n-1}}}{\Delta k}, \tag{2}$$

where δ_n (=1 or -1) and x_n=$n\cdot dx$ denote the orientation and right boundary of the nth unit block, respectively; and $z_n(\Delta k)$ is a complex number contributed by the nth unit block at a fundamental wavelength λ corresponding to some wave vector mismatch Δk. When one of the N blocks (say the qth unit block) of the sample is inverted, i.e. $\delta_q' = -\delta_q$, the reduced effective nonlinear coefficient (thus the conversion efficiency) can be easily updated by:

$$d_{R-eff}' = d_{R-eff} - 2z_q(\Delta k)\cdot \tag{3}$$

Eq. (3) enables our ID algorithm to efficiently optimize the domain orientations block by block, instead of all blocks at a time as performed in SA and GA [4,5]. A fitness function F is used in the ID algorithm to quantitatively estimate the appropriateness of a sample:

$$F = \sum_{\alpha=1}^{M}\left|\frac{\eta_\alpha - \eta_\alpha^{(0)}}{\eta_\alpha^{(0)}}\right|^p \quad (p \text{ is a positive integer}), \tag{4}$$

where $\eta_\alpha^{(0)}$ ($\sum \eta_\alpha^{(0)} = 1$) and η_α represent the target and achieved conversion efficiencies normalized to the peak efficiency η_0 of a periodic QPM grating of the same length L [5]. We employ the overall efficiency $\eta_{tot} \equiv \sum_{\alpha=1}^{M} \eta_\alpha$ and the average shape error $\Delta\eta \equiv \sum_{\alpha=1}^{M} \left| \eta_\alpha - \eta_{tot} \times \eta_\alpha^{(0)} \right| / \eta_{tot}$ to quantitatively measure the performance of the sample [5]. The ID algorithm is initialized by a "best" sample with N positively oriented blocks $S_{best}=\{\delta_n=1;\ n=1,\ldots,N\}$ and a trial sample S_{trial} made by inverting the orientation of block-2 (δ_2 = -1) while keeping the remaining blocks intact, corresponding to fitness values F_{best} and F_{trial}, respectively. S_{best} is unchanged or replaced by S_{trail} if $F_{trial} \geq F_{best}$ or $F_{trial} < F_{best}$ occurs. This procedure applies from block-2 to block-N in the first iteration, and is repeated until there is no block inverted in a single iteration. The ID algorithm guarantees the optimal solution in terms of inverting one unit block at a time. However, our simulations showed that the probability of further improvement by inverting 2 (3) blocks at a time is only ~10^{-5} (~10^{-7}). It will take impractically long time to get very nominal improvement.

3. Results

In all of our simulations, we used L=1.89 cm, p=16 [Eq. (4)], and restricted all the domains longer than 4 μm. When there is only one target PM peak at 1550 nm, HAOS+ID gives a periodic QPM grating of period 18.9 μm as expectation. In designing five PM peaks distributed in V-shape as in [5], HAOS+ID with unit block length dx=0.1 μm and N=189,000 (Fig. 1, solid) achieves both unprecedented overall efficiency (η_{tot}=94%) and nearly perfect spectral fidelity ($\Delta\eta$=5×10^{-5}). The overall efficiency is 25% and 9% higher than those of AOS (dotted, η_{tot}=75%) and NOS (dashed, η_{tot}=86%), respectively. The minimum domain length is 8.9 μm, well above the limit of poling techniques [6,7]. In this design, the ID algorithm continues for 1,586 iterations, taking ~30 minutes by a typical PC (~14 times faster than NOS+GA). To demonstrate the uniqueness of HAOS+ID, we designed a grid of 101 PM peaks uniformly distributed within λ=1547-1572 nm by using dx=0.2 μm and N=94,500. Such a high complexity is intractable for the previous schemes. Fig. 2 (solid) shows that the resulting PM tuning curve is continuous, for the peak spacing (0.25 nm) is smaller than the width of individual peak (0.6 nm). The passband ripple $\Delta\eta_{rip}$, defined as ±0.5[max(η_α)–min(η_α)]/mean(η_α) for $\lambda_\alpha \in$[1547,1572] nm, is only ±3.4%, smaller than that obtained by apodization (~±8%) [6]. $\Delta\eta_{rip}$ <±0.5% is feasible (Fig. 2, dashed) if using the state-of-the-art poling technique [7].

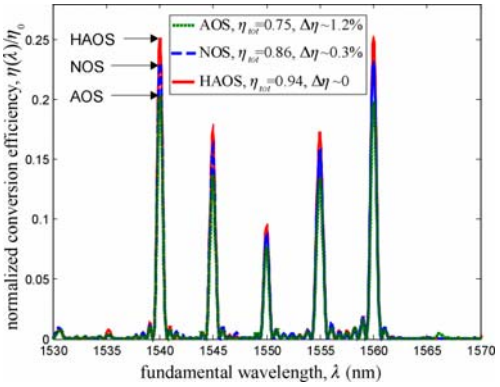

Fig. 1. The normalized conversion efficiency spectrum of three samples designed by AOS (dotted), NOS (dashed), and HAOS (solid), respectively.

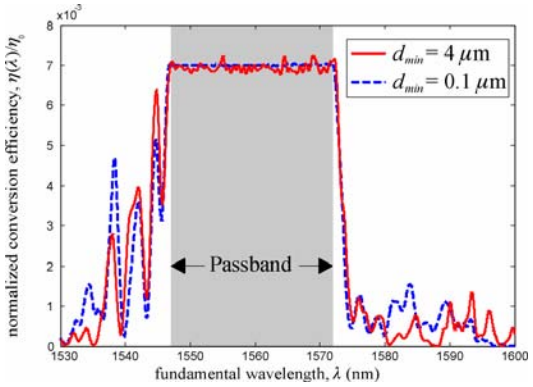

Fig. 2. The normalized conversion efficiency spectra of 101 equally-spaced PM peaks with minimum domain length d_{min} of 4 μm (solid) and 0.1 μm (dashed). The shaded area represents the passband.

4. Conclusions

We demonstrated that HAOS+ID can achieve arbitrary discrete PM peaks and continuous PM power spectra with unprecedented conversion efficiency and target complexity. The algorithm has high computation efficiency and can converge to a quasi-optimal solution. Experiment is ongoing and promising for each domain is longer than the limit of our poling technique [5]. This work is supported by NSC-Taiwan under grant 97-2221-E-007-028-MY3.

5. References

[1] D. S. Hum, M. M. Fejer, C. R. Physique **8**, 180-198 (2007).

[2] M. Asobe, et. al., Opt. Lett. **32**, 3388-3390 (2007).

[3] H. Miao, et. al., J. Opt. Soc. Am. B **25**, A41-A53 (2008).

[4] Y. W. Lee, et. al., Opt. Lett. **27**, 2191-2193 (2002).

[5] J. -Y. Lai, et. al., Opt. Express **18**, 5328-5337, (2010).

[6] T. Umeki, et. al., J. Opt. Soc. Am. B **25**, 2315-2322 (2009).

[7] G. Rosenman, et. al., Appl. Phys. Lett. **82**, 103-105 (2003).