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

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We proposed and experimentally demonstrated the iterative domino algorithm to optimize optical superlattice with $>10^5$ unit blocks to achieve arbitrary target phase-matching power spectrum. This scheme can achieve unprecedented overall conversion efficiency and spectral fidelity with extremely high computation efficiency. © 2012 Optical Society of America

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The ability of tailoring phase-matching (PM) response by engineering the spatial distribution of nonlinear coefficient is one of the key advantages of quasi-phase-matching (QPM) over the birefringence PM in wavelength conversion processes [1]. This is of particular importance in some applications, such as gas sensing using several absorption lines [2], where several discrete PM peaks at prespecified wavelengths and with desired relative efficiencies are required. This goal can be realized by some existing techniques, such as periodic continuous phase modulation [2], aperiodic optical superlattice (AOS) optimized by simulated annealing (SA) [3], and nonperiodic optical superlattice (NOS) optimized by genetic algorithm (GA) [4]. However, the spacing between PM peaks due to phase modulation is limited by an integral multiple of some unit value determined by the modulation period. AOS suffers from lower conversion efficiency, and worse spectral fidelity for the domain size can only be an integral multiple of some unit block length dx restricted by the poling technique (e.g., $dx = 3.5$ μm in [3]). NOS allows for analogue domain size and generally outperforms AOS [4]. However, the computation time of GA increases with the number of domains and the genetic pool size nonlinearly, seriously restricting the complexity of target PM spectra (e.g., ≤5 PM peaks in [4]).

We proposed a new scheme, coined as hyperfine aperiodic optical superlattice (HAOS) optimized by iterative domino (ID) algorithm, to overcome the aforementioned problems. The extremely high computation efficiency of the ID algorithm permits very small unit block length ($dx \geq 0.1$ μm in this work) and very complicated target PM spectrum (≤21 PM peaks here), while all the domains are still made longer than the minimum domain size $dx_{\min}$ (4.5 μm here). In the design of five PM peaks, the overall conversion efficiency (average shape error) achieved by HAOS + ID is 9% and 25% higher (2–3 orders of magnitude lower) than those of NOS + GA and AOS+ SA, respectively. Besides, HAOS + ID can exceed the overall conversion efficiencies achieved by NOS + GA and AOS + SA with 2–3 orders of magnitude less computation times.

Figure 1(a) shows the schematic of HAOS consisting of N unit blocks $\{b_n,\ n = 1, 2, \ldots, N)$ of length dx, where $g(x)$ represents the spatial distribution of domain orientations. The ID algorithm is utilized to determine the N binary numbers $\{\delta_n = \pm 1\}$ such that the target PM tuning curve [Fig. 1b] composed of M peaks centered at arbitrary wavelengths $\{\lambda_\alpha\}$ and with relative efficiencies $\{\eta_\alpha^{(0)}\}$ $(\alpha = 1, 2, \ldots, M)$ can be achieved.

Assuming plane waves and nondepleted pump, the SHG efficiency of a QPM grating at fundamental wavelength λ is

$$\eta(\lambda) = \eta_{\text{norm}}(\lambda) \times |G(\lambda)|^2, \quad G(\lambda) = \frac{1}{L}\int_0^L g(x) e^{i\Delta k \cdot x} \mathrm{d}x, \quad (1)$$

where η_{norm} is the normalized efficiency accounting for the input intensity, crystal nonlinearity, and grating length, G is the complex mismatch function, and Δk is the λ-dependent wavevector mismatch. For a periodic QPM grating of 50% duty-cycle, $\eta(\lambda)$ is roughly a sinc^2 function with a peak value of $\eta_0 = \eta_{\text{norm}}(\lambda_0) \times (2/\pi)^2$ at the central PM wavelength λ_0. For a general HAOS device, $G(\lambda)$ can be calculated by the summation of N complex numbers:

$$G(\lambda) = \sum_{n=1}^{N} \delta_n \times z_n(\Delta k), \quad z_n(\Delta k) = \frac{e^{i\Delta k \cdot x_n} - e^{i\Delta k \cdot x_{n-1}}}{\Delta k \times L}, \quad (2)$$

where $\delta_n \times z_n(\Delta k)$ represents the contribution of the nth unit block b_n. If $G(\lambda_\alpha)$ denotes the mismatch function value at λ_α of an HAOS device, the new coefficient $G'(\lambda_\alpha)$ due to domain inversion of b_n (while all the other

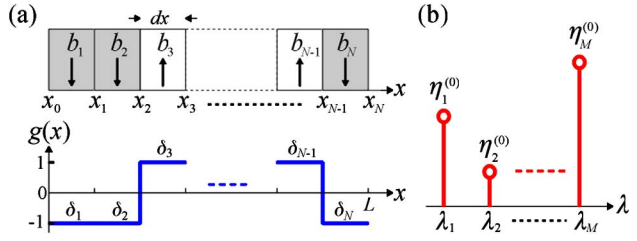

Fig. 1. (Color online) (a) Schematic of HAOS and the corresponding domain orientation distribution function. (b) The conceptual target PM tuning curve.

$N-1$ unit blocks remain unchanged) can be easily calculated by a subtraction:

$$G'(\lambda_\alpha) = G(\lambda_\alpha) - 2z_n(\Delta k). \tag{3}$$

Equation (3) makes ID algorithm much faster than SA and GA.

The ID algorithm starts with a device D consisting of N positively oriented blocks, i.e. $D = \{\delta_n = 1; n = 1, 2, \ldots, N\}$. The conversion efficiencies relative to η_0 at the M target wavelengths, i.e. $\{\eta_\alpha = \eta(\lambda_\alpha)/\eta_0, \alpha = 1, 2, , \ldots, M\}$, are calculated by Eqs. (1) and (2). The appropriateness of the device is quantitatively estimated by a fitness function:

$$F_1 = \sqrt[p]{\sum_{\alpha=1}^{M} \left| \frac{\eta_\alpha - \eta_\alpha^{(0)}}{\eta_\alpha^{(0)}} \right|^p} \qquad (p \geq 2), \tag{4}$$

where the target conversion efficiencies $\eta_\alpha^{(0)}$ are normalized according to $\sum_{\alpha=1}^{M} \eta_\alpha^{(0)} = a \leq 1$ and a larger p value can result in a better spectral fidelity at the cost of longer computation time. The trial device D' is initialized by inverting the first block b_1 of D. Since D' only differs from D by one unit block, the corresponding effective nonlinear coefficient G' can be evaluated by Eq. (3). One can then calculate the relative conversion efficiencies η'_α and the fitness value $F_1(D')$ accordingly. The device D is updated by D' if $F_1(D') < F_1(D)$. The same process applies to all the N unit blocks in sequence within one iteration. More iterations are repeated until no block is inverted in one iteration. To ensure that all domains are longer than $dx_{\min}$, an extra iteration is performed where D remains unchanged if $F_1(D') < F_1(D)$ but the domain ended by b_{n-1} is still shorter than $dx_{\min}$. The performance of a device is quantitatively measured by overall conversion efficiency η_{tot} and average shape error $\Delta\eta$. In this Letter, we considered two HAOS devices made by 18.9-mm-long congruent lithium niobate and restricted all the domains longer than $dx_{\min} = 4.5$ μm. The parameter p of Eq. (4) was chosen 16. Figure 2(a) shows the first target spectrum S_1 consisting of 5 PM peaks distributed in a V shape (open circles), where the total target efficiencies are normalized to $a = 1$. By using a unit block length of $dx = 0.1$ μm ($N = 189,000$ blocks), HAOS + ID gives a nearly perfect result (solid) with overall conversion efficiency $\eta_{\text{tot}} = 0.94$ and average shape error $\Delta\eta = 4 \times 10^{-5}$. The minimum domain length is 8.9 μm. The results of NOS + GA (dashed-dotted) and AOS + SA (dashed) designed with $dx_{\min} = 4.5$ μm and 4.82 μm are also shown for comparison [4], where values of $\eta_{tot}(\Delta\eta)$ are 9% and 25% (2–3 orders of magnitude) worse than those of HAOS + ID. The computation efficiency of the ID algorithm is remarkably high. Figure 2(b) shows the evolution of η_{tot} (left axis) and the number of inverted blocks within one iteration (right axis) during the ID optimization process. It only took two iterations (~2 s) and 47 iterations (~53 s) to have η_{tot} exceed 0.75 and 0.86, which were achieved by AOS + SA and NOS + GA with eight minutes and 430 minutes, respectively. The overall efficiency η_{tot} kept on increasing until the 1601th iteration (~30 minutes) where no block inversion occurred. Our simulation also showed that the probability of further improvement

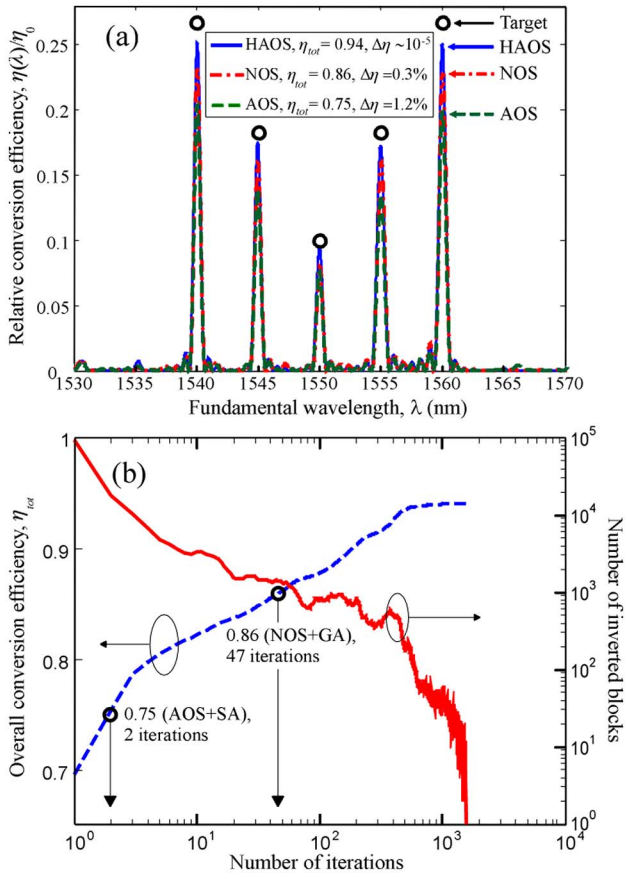

Fig. 2. (Color online) (a) Simulated PM tuning curves of three devices designed by HAOS + ID (solid), NOS + GA (dashed-dotted), and AOS + SA (dashed), respectively. The target spectrum S_1 (open circles) consists of five peaks distributed in a V-shape. (b) The overall conversion efficiency (dashed) and the number of inverted blocks (solid) versus number of iterations.

by simultaneously inverting two (three) unit blocks at one time is only ~10^{-5} (~10^{-7}). It will take an excessively long time to get a marginal improvement.

Figure 3 shows the target spectrum S_2 composed of 21 equally high PM peaks uniformly distributed between 1530 nm and 1590 nm (open circles). An additional parameter, ripple contrast, is used to characterize the flatness of the resulting PM spectrum:

$$\Delta\eta_{\text{rip}} \equiv \pm 0.5 \times [\max(\eta_\alpha) - \min(\eta_\alpha)]/(\eta_{\text{tot}}/M).$$

By using the simulation parameters $dx = 0.2$ μm , $a = 1$, and the fitness function F_1, we got a result with $\eta_{\text{tot}} = 0.92$, $\Delta\eta = 1.26\%$, and $\Delta\eta_{\text{rip}} = \pm 3.23\%$ (solid) within 502 iterations (12 minutes). If the spectral fidelity is critical, one can use $a < 1$ and (or) a hybrid fitness function:

$$F_2 = F_1 + b \times \sum_{\alpha=1} |\eta_\alpha - \eta_{\text{tot}} \times \eta_\alpha^{(0)}| \qquad (b > 0). \tag{5}$$

The determinations of a and b depend on the trade-off between the spectral fidelity and the overall conversion efficiency. With $a = 0.91$ and $b = 0.2$, we got $\eta_{\text{tot}} = 0.87$, $\Delta\eta = 1.21\%$, and $\Delta\eta_{\text{rip}} = \pm 2.66\%$ within 11 minutes. On the other hand, GA is too slow to handle the 21-peak

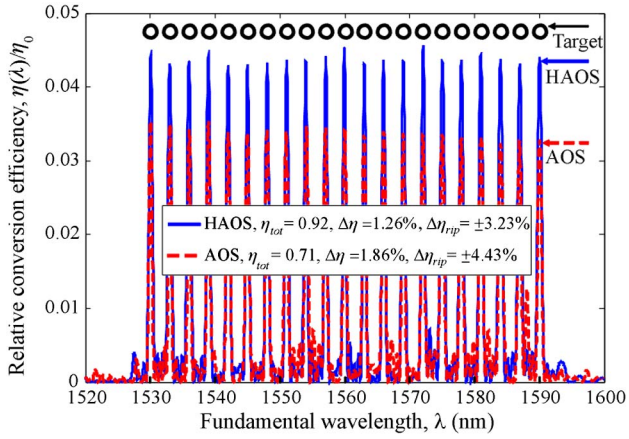

Fig. 3. (Color online) Simulated PM tuning curves of two devices designed by HAOS + *ID* (solid) and AOS + SA (dashed), respectively. The target spectrum S_2 (open circles) consists of 21 uniformly distributed peaks during 1530–1590 nm.

target, while AOS + SA only achieved $\eta_{\text{tot}} = 0.71$, $\Delta\eta = 1.86\%$, and $\Delta\eta_{\text{rip}} = \pm 4.43\%$ within 70 minutes (dashed).

We used the standard electric-field poling technique to fabricate $LiNbO_3$ QPM samples based on the simulation results. A reference QPM grating of constant period $\Lambda = 18.8\ \mu$m (domain length $l = \Lambda/2$) was fabricated on each sample such that η_0 can be experimentally measured. The second-harmonic yield was measured as a function of fundamental wavelength to get a PM tuning curve.

Figure 4(a) shows the experimentally measured PM tuning curves of three devices designed for the target spectrum S_1 by HAOS (solid), NOS (dashed-dotted), and AOS (dashed), respectively. The corresponding values of $\eta_{tot}(\Delta\eta)$ are 0.94, 0.80, 0.70 (2.5%, 5.5%, 6.2%), respectively. These results show that HAOS can be well implemented by standard fabrication technology and outperforms NOS and AOS. Figure 4(b) shows the experimentally measured PM tuning curve (solid) of HAOS designed for S_2 (optimized with $a = 0.91$ and $b = 0.2$), where all the 21 peaks are clearly resolvable. Discrepancy between simulation and experiment is mainly due to the fabrication error. The normalized random duty-cycle (RDC) error $\bar{\sigma}_l$ of a periodic QPM grating can be estimated by the pedestal level of its PM tuning curve [5]. For QPM gratings composed of a wide variety of domain lengths, the variation of domain expansion speed can further degrade the poling quality. PM pedestal measurement of our reference QPM gratings of constant period gave $\bar{\sigma}_l = 20\%$ for both samples. The effects of RDC error were simulated by introducing a Gaussian random variable of zero mean and standard deviation of $\sigma_{\delta l} = l \times \bar{\sigma}_l = 1.88\ \mu$m to distort each domain boundary. Ten random trials were performed to calculate the mean value of each performance parameter. For the HAOS designed for S_1, both simulation (with $\sigma_{\delta l} = 1.88\ \mu$m) and experiment arrived $\eta_{\text{tot}} = 0.94$, $\Delta\eta = 2.5\%$. In contrast, the experimental results of NOS and AOS ($\eta_{\text{tot}} = 0.80, 0.70$, $\Delta\eta = 5.5\%, 6.2\%$) are worse than those obtained by simulation ($\eta_{\text{tot}} = 0.85, 0.75$, $\Delta\eta = 3.2\%, 3.4\%$). The better robustness of HAOS results from the smaller variation of domain lengths (standard deviations σ_l of HAOS, NOS, AOS are 0.15 μm, 0.73 μm, 1.37 μm, respectively). For a complicated target

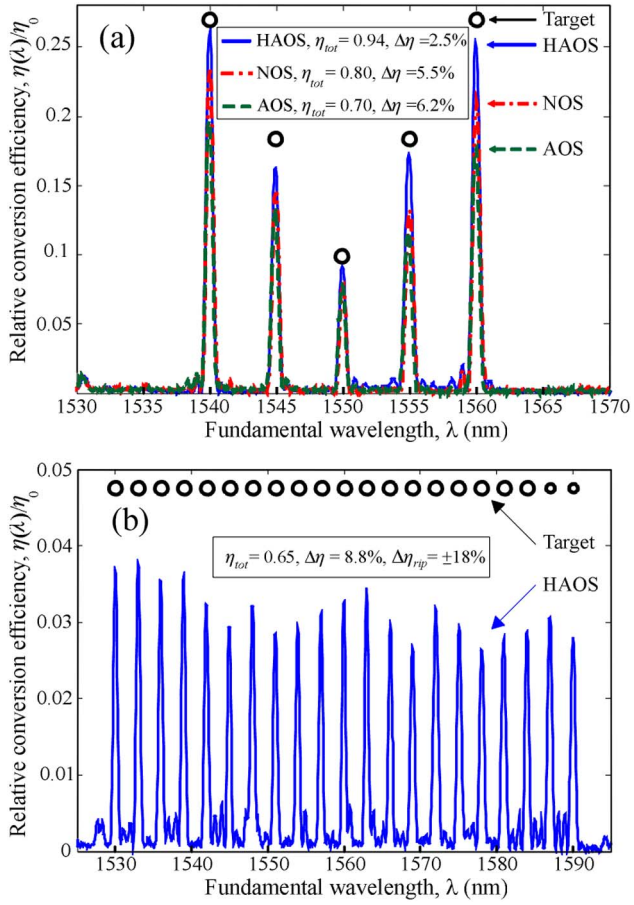

Fig. 4. (Color online) Experimentally measured PM tuning curves designed for target spectra (open circles) (a) S_1 and (b) S_2 by HAOS + *ID* (solid), NOS + *GA* (dashed-dotted), and AOS + SA (dashed), respectively.

spectrum S_2, the experimental results of HAOS are much worse than the simulated counterparts ($\Delta\eta = 5.9\%$, $\Delta\eta_{rip} = \pm 13\%$) because of the larger σ_l (1.10 μm). These problems can be solved by using poling techniques with ultrahigh resolution [6].

We proposed and experimentally demonstrated HAOS + ID scheme for PM spectral engineering. It can achieve unprecedented overall efficiency, spectral fidelity, and computation efficiency. The experimentally measured PM tuning curve agrees well with the 5-peak target spectrum, while the discrepancy in the 21-peak case is mainly attributed to the fabrication error.

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References

1. D. S. Hum and M. M. Fejer, C.R. Physique **8**, 180 (2007).
2. M. Asobe, O. Tadanaga, T. Umeki, T. Yanagawa, Y. Nishida, K. Magari, and H. Suzuki, Opt. Lett. **32**, 3388 (2007).
3. Y.-W. Lee, F.-C. Fan, Y.-C. Huang, B.-Y. Gu, B.-Z. Dong, and M.-H. Chou, Opt. Lett. **27**, 2191 (2002).
4. J.-Y. Lai, Y.-J. Liu, H.-Y. Wu, Y.-H. Chen, and S.-D. Yang, Opt. Express **18**, 5328 (2010).
5. J. S. Pelc, C. R. Phillips, D. Chang, C. Langrock, and M. M. Fejer, Opt. Lett. **36**, 864 (2011).
6. G. Rosenman, P. Urenski, A. Agronin, Y. Rosenwaks, and M. Molotskii, Appl. Phys. Lett. **82**, 103 (2003).