Engineered quasi-phase matching for conversion efficiency optimization of coupled $\chi^{(2)}$ processes

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Abstract: We propose an algorithm to optimize the efficiency of coupled $\chi^{(2)}$ processes in an aperiodic optical superlattice. Frequency tripling efficiency 33% higher than the limit of sequentially periodic structure is numerically demonstrated for the first time.
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1. Introduction

One of the key advantages of quasi-phase matching (QPM) over birefringence phase-matching lies on the flexibility of tailoring the complex phase-matching (PM) spectrum via domain engineering. For example, multi-wavelength second-harmonic generation (SHG) has been realized by phase reversal sequence (PRS) [1], aperiodic optical superlattice (AOS) [2], non-periodic optical superlattice (NOS) [3] and hyperfine AOS (HAOS) [4] optimized by different algorithms, respectively. Optimization becomes more complicated when multiple nonlinear processes are mutually coupled [5]. A relatively well-investigated example is third-harmonic generation (THG) realized by coupled SHG and sum-frequency generation (SFG) processes, which can be applied to carrier-envelope phase (CEP) characterization [6] and ultraviolate laser generation [7]. The THG conversion efficiencies achieved by existing techniques, such as Fibonacci optical superlattice [8] and generalized quasi-periodic optical superlattice (QPOS) [9], remain lower than that (η_0) of a sequentially periodic (SP) structure consisting of two (first-order) single-period QPM gratings for cascaded SHG and SFG. In this contribution, the iterative domino algorithm with unprecedented computation efficiency [4] is generalized from uncoupled multi-wavelength SHG to coupled SHG/SFG processes. Our simulation shows that the new degree of freedom (SHG and SFG can be interacted throughout the entire crystal) enables a record THG efficiency of 1.33 η_0 (to the best of our knowledge).

2. Theory

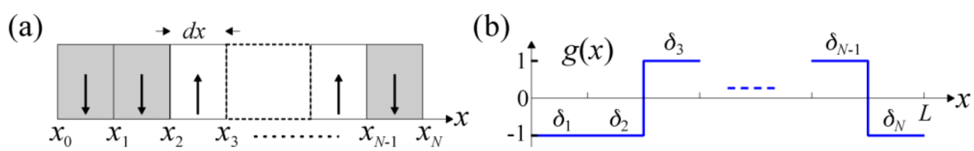

Fig. 1 Schematic diagrams of (a) HAOS with N blocks, and (b) the corresponding orientation function.

Divide a crystal of length L into N blocks with unit length dx ($L=N\times dx$) and orientation function $g(x)=\{\pm1\}$ (Fig. 1). In the absence of pump depletion [$E_1(x)=E_1$], the second-harmonic (SH) field at position $x_m\equiv m\times dx$ is

$$E_2(x) = -j\kappa_2 E_1^2 \int_0^x g(x') \times e^{j\Delta k_2 x'} dx' = -j\kappa_2 E_1^2 \sum_{n=1}^{m} \delta_n \times z_n^{(2)} \ , \qquad (1)$$

where $\Delta k_2 \equiv k_{2\omega}-2k_\omega$, $\delta_n \equiv g(x_n)=\{\pm1\}$, and $\delta_n \times z_n^{(2)} = g(x_n)\times[\exp(j\Delta k_2 x_n)-\exp(j\Delta k_2 x_{n-1})]/\Delta k_2$ represents the contribution from the nth block. Calculation of the third-harmonic (TH) field at the crystal exit needs a double integral (2D series)

$$E_3 \equiv E_3(L) = -j\kappa_3 E_1 \int_0^L g(x)\times e^{j\Delta k_3 x} \times E_2(x) dx = -\kappa_3\kappa_2 E_1^3 \sum_{m=1}^{N} \left[\delta_m \times z_m^{(3)} \times \left(\sum_{n=1}^{m} \delta_n \times z_n^{(2)} \right) \right], \qquad (2)$$

where $\Delta k_3 \equiv k_{3\omega}-k_\omega-k_{2\omega}$ and $z_m^{(3)} \equiv [\exp(j\Delta k_3 x_m)-\exp(j\Delta k_3 x_{m-1})]/\Delta k_3$. Equation (2) indicates that the TH filed locally generated at x depends on the product of local SH field $E_2(x)$ and local phase-matching contribution $g(x)\times e^{j\Delta k_3 x}$. If the qth block is inverted ($\delta_q \rightarrow -\delta_q$), the TH output field can be easily updated by two 1D series

$$E_3' = E_3 - 2z_q^{(3)} \sum_{n=1}^{q-1} \delta_n \times z_n^{(2)} - 2z_q^{(2)} \sum_{n=q+1}^{N} \delta_n \times z_n^{(3)} \ . \qquad (3)$$

The block inversion is preserved (abandoned) if $|E'_3| > |E_3|$ ($|E'_3| > |E_3|$). In each iteration, all the blocks are sequentially tested (q=1~N). The iteration continues until none of the N blocks needs to be inverted.

3. Results

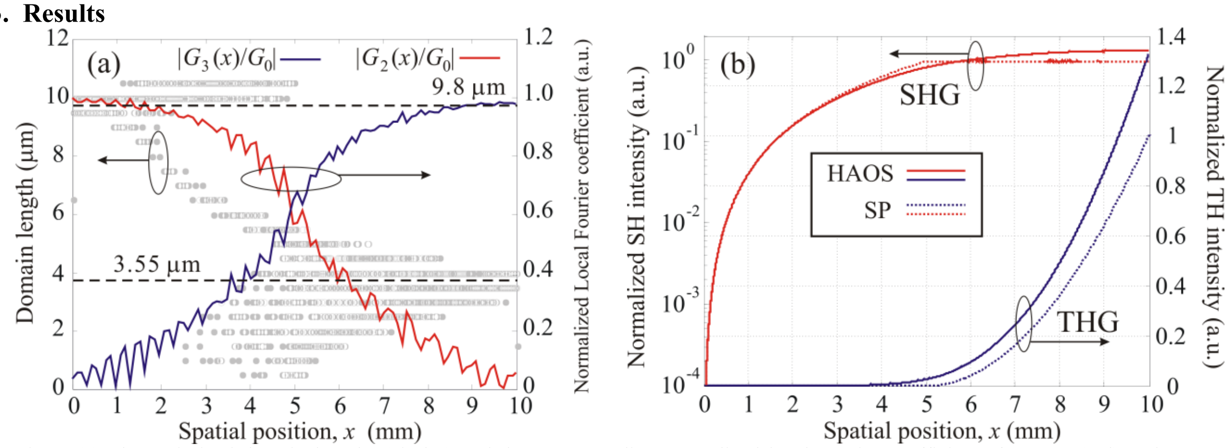

Fig. 2 (a) The optimized domain lengths (circles) and the corresponding normalized local Fourier coefficients for SHG (red) and THG (blue), respectively. $G_0=2/\pi$ means the Fourier coefficient due to a first-order QPM grating of 0.5 duty ratio. The dashed lines indicate the domain lengths of the first-order QPM gratings in an SP structure. (b) Normalized SH (red) and TH (blue) intensities in HAOS (solid) and SP (dotted), respectively.

We considered THG of 1560 nm at a pump intensity of 10 kW/cm^2 in a HAOS made of 5% MgO doped congruent lithium niobate with L=10 mm and N=2000 (dx=500 nm). For an SP structure, the poling periods (domain lengths) needed for SHG and SFG are 19.6 μm and 7.1 μm (9.8 μm and 3.55 μm), respectively. The generalized iterative domino algorithm approaches the optimal solution $\{\delta_n\}$ in just 17 iterations (~25 s), showing the extremely high computation efficiency. Figure 2(a) shows the resulting domain length distribution (circles), where the majority of domain lengths are close to 9.8 μm (3.55 μm) in the first (second) half of the crystal. The performance of the optimized HAOS is verified by numerically solving the coupled wave equations with the account of negligible pump depletion. Figure 2(b) shows that the TH intensity grows up since the very beginning (instead of the middle) of the HAOS (blue solid), and becomes 1.33 times of that obtained by SP (blue dotted). Table 1 compares the simulated THG efficiencies achieved by SP, PRS, QPOS and HAOS, where the 1.33η_0 of HAOS is the first exceeding the SP limit. The key to the unprecedented THG conversion efficiency in HAOS lies on the spatial tailoring of the local Fourier coefficients $G_i(x)= (\Delta L)^{-1}\int_x^{x+\Delta L} g(x')\times e^{j\Delta k_i x'}dx'$ (i=2,3) for the two nonlinear processes. As shown in Fig. 2(a) (solid curves), $|G_2(x)|$ and $|G_3(x)|$ are dominant in the first and second halves, respectively. In contrast, all the other schemes (SP, PRS, QPOS) have nearly constant $G_2(x)$, $G_3(x)$ throughout the entire crystal. In view of the fact that THG mainly relies on the SFG efficiency once SH intensity is sufficiently strong, continuous investment on SHG [i.e. a big $|G_2(x)|$] in the latter part of the crystal is actually a waste of resource.

Table.1 THG conversion efficiencies achieved by different schemes.

Scheme	SP	PRS	QPOS	HAOS
η_{THG}/η_0	1	0.64	0.22	1.33

4. Conclusion

We numerically demonstrated the generalized iterative domain algorithm applicable to coupled $\chi^{(2)}$ processes in HAOS. The spatial tailoring of local Fourier coefficients enables THG efficiency 33% larger than the SP limit, which is the record to the best of our knowledge. This work is supported by Ministry of Science and Technology (Taiwan) under grant 104-2112-M-007-012-MY3.

5. References

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