

Multiple quasi-phase-matching in two-dimensional domain-inverted aperiodic optical superlattice

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Received 16 November 2003; received in revised form 22 December 2004; accepted 27 September 2005

Available online 5 October 2005

Communicated by A.R. Bishop

Abstract

Quasi-phase-matching (QPM) is an alternative approach for nonlinear optical frequency conversion compared to conventional birefringent method in the bulk crystal. In this Letter, two-dimensional aperiodic optical superlattice (2DAOS) for achieving multi-QPM is proposed. A special optical superlattice structure containing pre-designed values of the reciprocal lattice vector \mathbf{G} that can accomplish multi-QPM process is given by using stimulated annealing (SA) algorithm.

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The technique for achieving new frequency laser source by quasi-phase-matching (QPM) [1,2] nonlinear optics has been developing very quickly in the past decades. QPM method can be used to compensate the wave vector mismatch caused by the different phase velocities of the interactive waves involved in a nonlinear process. With the emergence of room temperature electrical poling technique for domain inversion in ferroelectric material, periodically poled crystals such as periodically poled lithium niobate (PPLN) have already been available in the commercial applications. This kind of one-dimensional periodic optical superlattice (1DPOS) provides only one first-order reciprocal vector to compensate the wave vector mismatch in a given nonlinear optical process and has a narrow acceptance bandwidth for pump wavelength and operating temperature. To achieve multi-QPM, one-dimensional quasi-periodic optical superlattice (1DQOS) [3–5] such as Fibonacci structure was suggested in which multiple second harmonic generation (SHG) waves are obtained simultaneously. Then the one-dimensional aperiodic optical superlattice (1DAOS) [6–10] is proposed, which can supply even more reciprocal vectors for multi-QPM than that of 1DQOS. Above phase matching approaches expand the amount of the requisite superlattice reciprocal vec-

tors for QPM greatly and make the multi-QPM available. In the past several years, nonlinear frequency conversion in two-dimensional periodic optical superlattice (2DPOS) was studied [11–15]. It is shown that in-plane quasi-phase-matching process can be established in 2DPOS. 2DPOS extends the applications of QPM technique and provides a new kind of nonlinear optical crystal for various frequency conversion applications by nonlinear optical process. It can be naturally expected that two-dimensional aperiodic optical superlattice (2DAOS), evolving from 1DAOS and 2DPOS, may give even flexible QPM conditions in comparison with currently suggested approaches and may become another novel nonlinear optical materials for nonlinear optical parametric process.

In this Letter, we report a two-dimensional aperiodic optical superlattice. The structure of a 2DAOS is designed to implement multiple second harmonic generation with identical effective nonlinear coefficient.

The nonlinear frequency conversion of SHG process in 2DPOS is reported by Berger [11], the QPM condition appears:

$$\begin{aligned}\omega_2 &= 2\omega_1, \\ \mathbf{k}_2 &= 2\mathbf{k}_1 + \mathbf{G}_{p,q}, \\ \mathbf{G}_{p,q} &= p\mathbf{a} + q\mathbf{b}, \quad p, q = 0, \pm 1, \pm 2, \dots,\end{aligned}\quad (1)$$

where \mathbf{k}_1 (\mathbf{k}_2) is the wave vector of the fundamental (second harmonic) wave in the crystal; $\mathbf{G}_{p,q}$ is the two-dimensional

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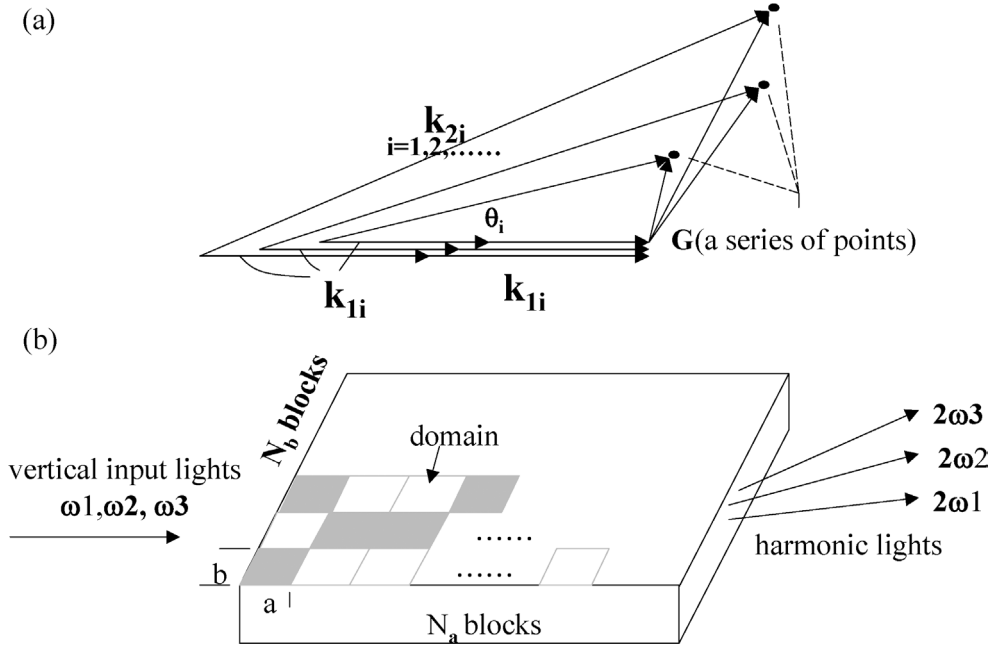


Fig. 1. The sketch map of function and structure about 2DAOS (bottom). (a) Multi-QPM process in SHG. It shows the three QPM conditions by the three triangles. It scratches out a series of points in reciprocal lattice vectors (\mathbf{G}) space. (b) The schematic picture of the design method for 2DAOS. The domain orientation is represented by the coefficient $d(x, y)$ which will be determined by the SA method.

reciprocal lattice vector of the domain superlattice, \mathbf{a} , \mathbf{b} denote the first-order reciprocal vectors of common two-dimensional lattice. In the assumption of slow-wave variation of field amplitudes and the so-called small signal approximation in which the depletion loss of fundamental wave power can be negligible, the efficiency of the SHG generation can be expressed as:

$$\eta_{\text{SHG}} = \frac{I_{2\omega}}{I_{\omega}} = \frac{8\pi^2 |d_{33}|^2 I_{\omega} S^2}{c\epsilon_0 \lambda^2 n_{2\omega} n_{\omega}^2} \left| \frac{1}{S} \iint_S e^{i(\mathbf{k}_{2\omega} - 2\mathbf{k}_{\omega}) \cdot \mathbf{r}} d(\mathbf{r}) dx dy \right|^2, \quad (2)$$

where S is the area of the two-dimensional period and $C(\mathbf{G})$ is Fourier coefficient that represents the efficiency of the corresponding frequency conversion. The larger value the Fourier coefficient $C(\mathbf{G})$ is, the higher efficiency the frequency conversion process will be.

In the 2DPOS, only several first order (in Eq. (1), $p, q = \pm 1$) in-plane QPM can be achieved due to the periodic domain-inverted structure and lack of the QPM vector arbitrariness. In order to obtain multi-QPM in two-dimensional optical superlattice, multiple two-dimensional reciprocal vectors supplied by optical superlattice are necessary. Similar as 1DAOS, we expect that 2DAOS can provide more reciprocal vectors for in-plane multi-QPM nonlinear optics process. The idea of 2DAOS in the process of the SHG is illustrated in the inset of Fig. 1(a). $\mathbf{k}_1(\lambda_1)$ is the wave vectors of the fundamental wave, and \mathbf{k}_2 is the wave vector of the harmonic wave, θ is the angle between the wave vectors \mathbf{k}_1 and \mathbf{k}_2 . When the values of \mathbf{k}_1 and θ is fixed, in order to meet the QPM condition, the reciprocal lattice vector \mathbf{G} provided by the two-dimensional optical superlattice must satisfy $\mathbf{k}_2 = 2\mathbf{k}_1 + \mathbf{G}$.

As shown in Fig. 1(a) $\mathbf{G}(G_x, G_y)$ can be determined by the following triangle relationship when $\vec{k} \parallel \vec{x}$:

$$G_x = k_2 \cos(\theta) - 2k_1, \quad G_y = k_2 \sin(\theta). \quad (3)$$

The following problem is to arrange the domain-inverted pattern on the chip in order that the 2DAOS contains a series of the reciprocal lattice vectors \mathbf{G} whose values can make all multiple QPM effectively. As a result, the phase matching for the above harmonic frequency generations can be implemented simultaneously in one chip of 2DAOS.

We can build up these vectors by pre-designing the pattern of the domains such as in LiNbO_3 . In our design, the 2DAOS is constructed by arrays of rectangle blocks at same size only with different domain orientation where the nonlinear coefficient $d(x, y)$ takes values of d_{33} or $-d_{33}$ in the original or domain-inverted region, respectively. The length and width of the block unit is set to be a and b , the number of blocks in X-axis is N_a , and in Y-axis is N_b . The design method is illustrated in Fig. 1(b). Fourier Analysis (FA) is applied to find the structure of the reciprocal lattice vector \mathbf{G} of 2DAOS for the multi-SHG process derived from Eq. (2) as

$$\eta_{\text{SHG}} \propto C(\mathbf{G})^2 \quad \text{and} \quad C(\mathbf{G}) = \frac{d_{33}}{S} \left| \iint_S \tilde{d}(x, y) e^{-i\mathbf{G} \cdot \mathbf{r}} ds \right|, \quad (4)$$

S is the area of the sample. d_{33} is the nonlinear susceptibility constant of the sample. $\tilde{d}(x, y)$ takes values of 1 or -1 in the original and domain-inverted region, respectively, and may be written as $\tilde{d}(m, n)$ because the values are the same in the area $x \in [ma, ma + a]$, $y \in [nb, nb + b]$ under the division above of the surface. We evaluate the integral Eq. (4) to

$$C(\mathbf{G}) = \frac{d_{33}}{N_a N_b} \left| \text{sinc}(u) \text{sinc}(v) \sum_{mn} \tilde{d}(m, n) e^{-i[(2m+1)u + (2n+1)v]} \right|, \quad (5)$$

$$u = aG_x/2, \quad v = bG_y/2, \quad \text{sinc}(x) = \sin(x)/x.$$

It is evident that the optimal construction in the 2DAOS for SHG can be ascribed as a search for several maximum $C(\mathbf{G})$ at a series of given \mathbf{G} values. Such an optimization nonlinear problem can be solved with the simulated annealing (SA) method [16] and then the favorable arrangement of the domain orientations of the blocks in the sample can be determined completely.

As an example, we choose 5 wavelengths of $\lambda_1 = 1.4 \mu\text{m}$, $\lambda_2 = 1.45 \mu\text{m}$, $\lambda_3 = 1.5 \mu\text{m}$, $\lambda_4 = 1.55 \mu\text{m}$, and $\lambda_5 = 1.6 \mu\text{m}$, with the output angle of $\theta_1 = 10^\circ$, $\theta_2 = 11^\circ$, $\theta_3 = 12^\circ$, $\theta_4 = 13^\circ$ and $\theta_5 = 14^\circ$. The QPM condition satisfied reciprocal lattice vectors \mathbf{G} can be calculated to be $(1.22 \times 10^5, 3.41 \times 10^6)$, $(3.74 \times 10^4, 3.61 \times 10^6)$, $(-4.39 \times 10^4, 3.80 \times 10^6)$, $(-1.23 \times 10^5, 3.97 \times 10^6)$, $(-2.00 \times 10^5, 4.13 \times 10^6)$. To carry out the particular construction of 2DAOS in which the above SHG process at the five wavelengths, we choose $a = 1 \mu\text{m}$, $b = 1 \mu\text{m}$, $N_a = N_b = 300$. The dispersions of the refractive index of material are evaluated according to Sellmeier formula [17]. The objective function in the SA method is chosen as

$$E = \sum_i C_i + A[\max(C_i) - \min(C_i)], \quad (6)$$

where the symbol $\max()$, $\min()$ manifests to take their maximum or minimum value among all the quantities including into $()$. A is a constant to equipoise each C_i .

Fig. 2 is a gray-scale diagram of the constructed 2DAOS in part from the calculated result. The black (white) blocks represent the positive (negative) domains. The constructed 2DAOS is no more a periodic structure. Fig. 3 displays the calculated

effective nonlinear coefficient with the optimized 2DAOS structure as shown in Fig. 2 after scanning a wide range of G_x and G_y . Five strong peaks with almost identical peak value of about 3.8 pm/V at the pre-designed wavelengths and output angles are achieved only at the expense of the reduced effective nonlinear coefficient lower than that of the perfectly periodic QPM grating. For perfect QPM uniform grating, the ideal value of the nonlinear coefficient is 33 pm/V. The effective nonlinear coefficient decreases in 2DAOS is due to the trade-off between the multiple QPM and conversion efficiency.

The same method can also be applied to the other nonlinear optical process such as difference frequency generation (DFG) and optical oscillation amplification (OPA). Because this kind

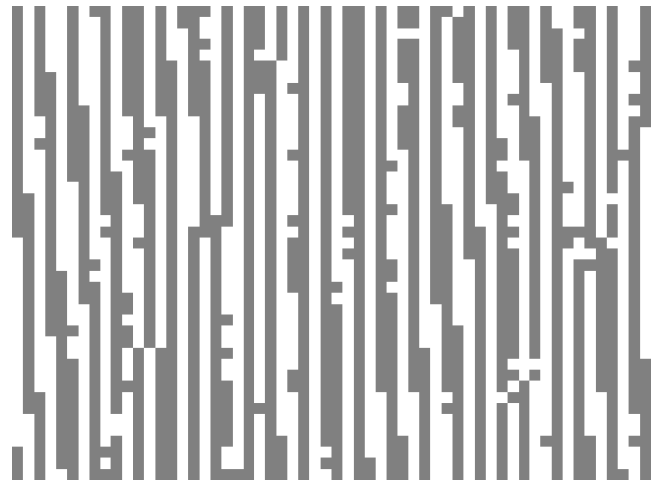


Fig. 2. A gray-scale diagram of the constructed 2DAOS in part. The black (white) blocks represent the positive (negative) domains.

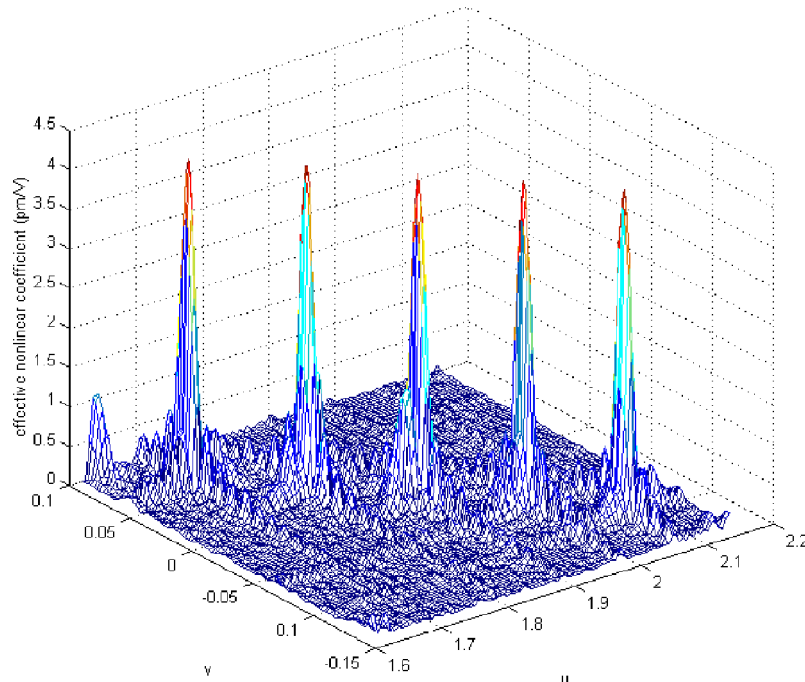


Fig. 3. Effective nonlinear coefficient in the constructed 2DAOS, the calculated peak value of effective nonlinear coefficient at the five given fundamental wavelengths is about 3.8 pm/V.

of quasi-phase-matching can be achieved within a plane with different output angles, wavelength demultiplexing, switching and filtering with the advantages of a wide frequency band can be realized.

In summary, we propose a 2DAOS for achieving multiple phase matching. By using the SA method, a 2DAOS structure is constructed to realize multiple phases matching of SHG. It is shown that 2DAOS can expand the applications of QPM techniques and will be a new nonlinear optical material for optical frequency conversion process.

Acknowledgements

This research was supported by the National Natural Science Foundation of China, No. 60007001 and the Foundation for Development of Science and Technology of Shanghai, No. 00JC14027.

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