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Parameters for efficient growth of second harmonic field in nonlinear photonic crystals

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ABSTRACT

The ultrashort pulse propagation and nonlinear second harmonic generation under the undepleted pump approximation in a quadratic nonlinear photonic crystal (NPC) structure is theoretically investigated and the optimized parameters for high second harmonic generation conversion efficiency are extracted. The transfer matrix method is used for the numerical formulation for oblique angle of incidence. A unique set of material combination GaInP/InAlP is selected as alternating nonlinear and linear layers. The NPC parameters like incident angle and layer thickness are manipulated to obtain the exact phase matching using double resonance condition for a fixed number of layers with known experimental material parameters.

1. Introduction

In recent years the nonlinearities in photonic crystals (PCs) have gained significant importance in the study of light–matter interaction leading to the development of nonlinear optoelectronic device design. Owing to the property of field amplification in micro- or nano-scale nonlinear region within the photonic crystal, they are more favorable for the higher harmonic wave generations. A number of studies on the second harmonic generation (SHG) in NPCs have been carried out both theoretically [1–7] and experimentally [8–10]. Most of these works have focused on efficient SHG in order to achieve more conversion efficiency. Several theoretical models have been implemented to study SHG in nonlinear PCs, for instance, Green's function analysis [1,11] the rigorous coupled wave analysis [12], an effective index transfer matrix method (TMM) [3] and finite element method [13]. The main challenge to achieve SHG is to obtain the phase matching between the wave vectors of interacting waves. The quasi phase matching (QPM) condition emerged as a good method to achieve the phase matching in bulk material, where the periodically inverted nonlinear coefficient leads to the phase matching condition. Recently, to obtain highly efficient SHG in the QPM structure, a mathematical model of TMM [14] and its extended model have been proposed [15]. The method is based on the pump depletion leading to very high conversion efficiency of about 96% [16,17] but has a major limitation that it cannot be implemented for any arbitrary angle. Hence the method cannot be applied to centrosymmetric materials which inhibit SHG along normal incidence angle. Also, the QPM structures are millimeter long hence not suitable for nano-scale photonic device design. Here again the multilayer photonic crystals get renewed importance in order to achieve high conversion efficiency of harmonic generation in nano- or micro-scale length.

A one-dimensional bilayer nonlinear photonic crystal can be designed by the periodic spatial alteration of optical constant with one of the medium possessing high nonlinear coefficient. These structures possess certain frequency region where the propagation of optical modes are absent known as the photonic bandgap. They are identified as a good source for efficient second harmonic generation [8–10] with their unique property of high density of optical modes in the band-edge transmission resonance. With proper bandgap engineering one can achieve exact phase matching in these multilayer structures. One can use a mixed quarter- and half-wavelength thick linear and nonlinear medium to tune the fundamental field at the first transmission peak of the first-order band-edge and second harmonic density of modes at the second transmission peak of next band-edge which is exactly the half of the wavelength of the fundamental field [9]. This is known as the double resonance and it has globally emerged as the most effective way to achieve phase matching condition. However, considerable manipulation is required in the geometrical parameters to obtain this phase matching in the case of material dispersion.

This paper attempts to optimize the parameters of a one-dimensional NPC with material dispersion for highly efficient second harmonic generation with a unique double resonance

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condition. We also analyze the sensitiveness of conversion efficiency with obtained NPC parameters. Since the total size of the structure is very small we assume non-depletion of the pump while interacting with the nonlinear layer. The theoretical model is based on the Transfer matrix method [18]. For oblique angle of incidence, other studies seem to be more complex, while our model is easy to proceed. We assume fundamental field (FF) incident on the structure and the polarization in the nonlinear layer leads to the generation of second harmonic (SH) field. Here the propagation equations for FF wave and generated SH wave have been solved separately and then their respective matrices are derived. We also take into account phase changes arising from the reflections at boundaries as well as regenerations at the nonlinear layer. We design the structure in such a way that the FF field and the generated SH fields are satisfying double resonance condition. The NPC parameters like incident angle and layer thickness are manipulated for an exact phase matching condition; accordingly, for a fixed number of layers and with known experimental material parameters, we take this as a basic unit cell number. To obtain NPC parameters for high conversion efficiency we increase the number of layers in the multiple of the basic unit cell number. Such a condition leads to considerable increase in conversion efficiency. A similar multilayer NPC was earlier introduced in Ref. [5] where they used the alternate layers with quarter- and half-wave thickness with adjusted linear dispersion material parameters whereas in our model we have introduced modification in thickness from the quarter- and half-wave thickness of layers and experimental dispersion parameters to achieve exact phase matching condition. Since the thicknesses of individual layers are small in comparison with the wavelength of interacting wave, the depletion of pump is negligible at low input intensities. Also it is known that under high intensity the depletion of pump wave leads to the decrease in efficiency due to strong feedback from high refractive index contrast of the constituent layers which causes the total conversion efficiency to saturate [19].

We have considered GaInP/InAlP bilayer nonlinear photonic crystal. While this combination of layers has not been explicitly used before, the GaInP nonlinear medium possesses a substantial second-order nonlinear coefficient of 220 pm/V. Under the undepleted pump approximation, comparatively high conversion efficiency with a less number of periods is achieved. This study is important from the perspective of implementing different material combination with high $\chi^{(2)}$ nonlinear layer for designing compact nano-photonic devices for active SHG. The phase matching condition that we consider can also be used for designing photonic microcavity to ensure high conversion efficiency.

2. The method

The one-dimensional NPC structure comprises of N periods of alternate linear (n_l) layer with thickness d_l and nonlinear (n_{nl}) layer with thickness d_{nl} with a periodic spatial modulation along Z axis. The incident field is TM polarized, where the electric field is in the plane of incidence.

An incident pulse propagating through the structure undergoes reflection and transmission at each interface due to the refractive index mismatch, and there will be interference of propagating and counter propagating waves. In the nonlinear layer the incident pulse gives rise to nonlinear polarization and then according to the phase matching conditions there will be generation of second harmonic field. We calculate separately the reflected and transmitted fundamental fields as well as the generated second harmonic field.

We begin with the propagation equations for the fundamental field using TMM. The ultrashort pulse is incident on the bilayer photonic crystal from air superstrate making an angle θ with

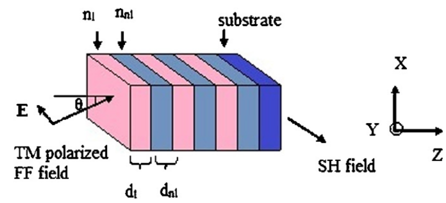

Fig. 1. Schematic diagram of one-dimensional NPC with TM polarized incident field.

Z axis, which we consider as the propagation axis as shown in Fig. 1.

$$\vec{E}_i = \vec{E}_{i0}(\omega, z)\exp(ik_{iz}z) + \text{c.c.}, \tag{1}$$

where $\vec{E}_i$ obeys the wave equations as follows:

$$\left[\frac{\partial^2}{\partial z^2} + \omega^2\mu_0\varepsilon_o\right]\vec{E}_i = 0, \tag{2}$$

$$\left[\frac{\partial^2}{\partial z^2} + \omega^2\mu_0\varepsilon_o\right]\vec{E}_i = -\mu_0\omega^2\vec{P}_i^{(NL)}. \tag{3}$$

From Eq. (1) we get the field in the ith layer as the superposition of the propagating and counter propagating FF wave as given below

$$E_{ix}(\omega, z, t) = \left[E_{ix}^f(\omega, z)\exp(ik_{iz}z) + E_{ix}^b(\omega, z)\exp(-ik_{iz}z)\right] \times \exp\left[i(k_x x - \omega t)\right] + \text{c.c.}, \tag{4}$$

where E_{ix} is the transverse magnetic (TM) component of the field in the XZ plane in ith layer, f and b represents the propagating and counter propagating waves, respectively. The transfer matrix T_0 connects the fields in the superstrate and the first linear layer. At each interface the incident pulse suffers reflection and transmission. T_{LN} and T_{NL} are the transfer matrices that connect the fields at the boundaries between linear and nonlinear layers.

$$T_{NL} = \frac{1}{t_{NL}}\begin{pmatrix} 1 & r_{NL} \\ r_{NL} & 1 \end{pmatrix}, \qquad T_{LN} = \frac{1}{t_{LN}}\begin{pmatrix} 1 & r_{LN} \\ r_{LN} & 1 \end{pmatrix}, \tag{5}$$

where r_{NL} and r_{LN} are the amplitude of reflection coefficients while t_{NL} and t_{LN} are the amplitude transmission coefficients. These coefficients are defined as

$$r_{ij} = \frac{n_i\cos\theta_j - n_j\cos\theta_i}{n_i\cos\theta_j + n_j\cos\theta_i}, \qquad (t_{ij}) = \frac{n_i}{n_j}\left(1 - (r_{ij})\right). \tag{6}$$

The propagation matrices P_L for linear medium and P_{NL} for nonlinear medium connect the fields at one interface to the fields at the other interface within the same layer resulting in the changes in the effective phase of the fields.

$$P_L = \begin{pmatrix} e^{ik_l d_l} & 0 \\ 0 & e^{-ik_l d_l} \end{pmatrix}, \qquad P_{NL} = \begin{pmatrix} e^{ik_{nl} d_{nl}} & 0 \\ 0 & e^{-ik_{nl} d_{nl}} \end{pmatrix}, \tag{7}$$

where $k_i = \frac{n_i\omega}{c}\cos\theta$. The matrix that takes the incident fields from the first interface of the linear layer of a period to the first interface of the linear layer of next period is given by

$$Q = T_{NL}P_{NL}T_{LN}P_L. \tag{8}$$

Finally the resultant fields that are reflected and transmitted out from the structure having N number of periods can be calculated by

$$\begin{pmatrix} E_{out}^f \\ E_{out}^b \end{pmatrix} = T_s P_{NL} T_{LN} P_L Q^{N-1} T_0 \begin{pmatrix} E_{in}^f \\ E_{in}^b \end{pmatrix}, \tag{9}$$

where T_s is the transfer matrix for the interface of the structure with the substrate.