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Reflectivity control via second-order interaction process in one-dimensional photonic band-gap structures

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Abstract

We exploit the nonlinear reflectivity of a pulse at the fundamental frequency induced by a second harmonic signal in one-dimensional photonic band gap structures for applications to fast control of light-by-light and all optical signal processing. We find that the enhancement of nonlinear gain near the band edge, coupled with a suitable choice of the relative phases between the input pulses, leads to significant reflectivity and transmittivity changes of the input pump pulse for structures only a few microns in length. © 2000 Published by Elsevier Science B.V.

Nonlinear interactions with second-order nonlinearities have recently been proposed as an alternative to intensity dependent changes induced in cubic nonlinear materials [1] for at least two reasons: speed, and primarily because of low-loss properties, in contrast with third-order processes. The possibility of lossless operation is attractive, because it can help revive the idea of fast control of light-by-light for all-optical signal processing. In this regard, devices that aim to control the reflectivity of a pump beam have been proposed [2–4]. These devices are based on the nonlinear interaction that arises when an intense second harmonic (SH) field is injected together with a weak fundamental field (FF). Ref. [2] refers to an optical loop mirror filled with a $\chi^{(2)}$ medium. Ref. [3] discusses the effect for a single interface, while Ref. [4] addresses reflectivity control in a microcavity geometry. Ideally, a nonlinear mirror that is independent of the relative phase between the input beams is desirable, as Cojocaru et al. [4] clearly sought to achieve. However, phase dependence is one of the hallmarks of second-order processes, and difficult if not impossible to override.

Thus, we seek to exploit phase properties to our advantage, in order to achieve control of the reflective and transmissive properties of a one-dimensional (1-D) photonic band gap (PBG) structure doped with a $\chi^{(2)}$ material. We assume incident pulses at the FF and SH frequencies interact under suitable phase matching conditions near the band edge. PBG crystals [5] have been the subject of intense investigations regarding

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electromagnetic wave propagation phenomena at optical frequencies. Many practical applications of these structures have been suggested in one dimension for linear and nonlinear systems. We mention the photonic band edge laser [6], a nonlinear optical limiter and diode [7], an efficient nonlinear frequency converter [8,9]. We note that recently there was a demonstration of increased nonlinear conversion efficiency near the band edge of a 1-D structure [9]. These results are encouraging, and thus lead us to believe that devices based on the physics of the band edge, i.e., field localization, group velocity reduction, and the availability of exact phase matching conditions make these devices extremely promising for both linear and nonlinear optical applications [10,11].

In this paper, we will show that in a regime of undepleted SH intensity, a proper choice of the *effective phase matching* conditions between FF and SH fields (as discussed in Ref. [10]) can lead to a significant increase of nonlinear gain and dramatic reflectivity and transmittivity changes of the FF over a distance of only a few microns. The "simplified" numerical method presented in this paper has been tested by direct integration of the equations of motion in the time domain in a manner similar to the method developed in Ref. [8].

In the example that we discuss, threshold intensities of the control SH pulse are taken to be on the order of 1 GW/cm^2, with a $\chi^{(2)}$ of order of 20–30 pm/V. However, we note that the threshold intensity can be *reduced by several orders of magnitude by increasing the density of modes* [11], which can be achieved by simply increasing the linear refractive index contrast or the number of periods, N.

The effect that we discuss is related to the enhancement of gain near the band edge [6], and a SH amplification process that occurs near the band edge in a phase matched, 1-D PBG structure [8,11]. A phase dependent de-amplification regime is also examined. We consider a 1-D, finite, N-period structure consisting of pairs of alternating layers of high- and low-linear refractive indices, and possibly different $\chi^{(2)}$ responses; we assume the nonlinearity is located in the high index layers. Layer thicknesses are taken to be a and b; $\Lambda = a + b$ is the length of the elementary cell, and for N periods, the length of the structure is $L = N\Lambda$. The geometry that we consider satisfies *effective phase matching* conditions similar to those described in Refs. [8,11], where the FF ω_1 is tuned at the low-frequency band edge, and the SH $2\omega_1$ is tuned at the second resonance with respect to the second-order band gap. Following the formalism discussed in Refs. [8,10], we assume the two pulses co-propagate in the presence of large index discontinuities. We further assume that the bandwidth of incident pulses is much narrower than the bandwidth of the band edge transmission resonance [8,10]. In this quasi-monochromatic regime, the equations of motion can be cast as follows:

$$\begin{aligned}
&\frac{\mathrm{d}^2 E_{\omega_1}(z)}{\mathrm{d}z^2} + \frac{\omega_1^2}{c^2}\widetilde{N}^2(z,\omega_1)E_{\omega_1}(z) = 0,\\
&\frac{\mathrm{d}^2 E_{2\omega_1}(z)}{\mathrm{d}z^2} + \frac{4\omega_1^2}{c^2}\widetilde{N}^2(z,2\omega_1)E_{2\omega_1}(z) = 0,
\end{aligned} \tag{1a}$$

where

$$\begin{aligned}
&\widetilde{N}^2(z,\omega_1) = n^2(z,\omega_1) + 8\pi\chi^{(2)}(z)\frac{E^*_{\omega_1}(z)E_{2\omega_1}(z)}{E_{\omega_1}(z)},\\
&\widetilde{N}^2(z,2\omega_1) = n^2(z,2\omega_1) + 4\pi\chi^{(2)}(z)\frac{E^2_{\omega_1}(z)}{E_{2\omega_1}(z)}.
\end{aligned} \tag{1b}$$

Here, $n(z,\omega)$ is the linear refractive index of the layered structure. $\widetilde{N}(z,\omega)$ plays the role of total refractive index, with a linear and a nonlinear part. For *large index contrast*, typically of order unity or more, the nonlinear contribution remains a weak perturbation even in the depleted pump regime and prevent any cumulative nonlinear phase shift. Therefore, for the realistic $\chi^{(2)}$ values and field amplitudes we use, the nonlinear contribution is several orders of magnitude smaller compared to the linear refractive index contrast. As a consequence of this, shifts of the band edge, which are proportional to the nonlinear index change, are negligible (and inconsequential) compared to resonance bandwidth.

We have tested the regime of validity of this approximation by direct integration of the equations of motion in the time domain in a manner similar to the method developed in Ref. [8]. Using an FFT beam propagation method, which assumes slowly varying amplitudes in time (SVEAT) only, and which takes into account reflections to all orders, we find good agreement with the results we present here. In fact, the direct integration of the wave equations reveals that shifts of the band edge remain negligible and inconsequential even in the depleted pump regime.

Under these circumstances, we expand Eq. (1b) and obtain

$$\begin{aligned}\widetilde{N}(z,\omega_1) &= n(z,\omega_1) + \frac{4\pi\chi^{(2)}(z)}{n(z,\omega_1)}\left|E_{2\omega_1}(z)\right| \\ &\quad\times \mathrm{e}^{\mathrm{i}(\varphi(z)-2\mathrm{i}\phi(z))}, \\ \widetilde{N}(z,2\omega_1) &= n(z,2\omega_1) + \frac{2\pi\chi^{(2)}(z)}{n(z,2\omega_1)}\frac{\left|E_{\omega_1}(z)\right|^2}{\left|E_{2\omega_1}(z)\right|} \\ &\quad\times \mathrm{e}^{-\mathrm{i}(\varphi(z)-2\mathrm{i}\phi(z))},\end{aligned} \tag{2}$$

where

$$E_{\omega_1}(z) = \left|E_{\omega_1}(z)\right|\mathrm{e}^{\mathrm{i}\phi(z)}, \qquad E_{2\omega_1}(z) = \left|E_{2\omega_1}(z)\right|\mathrm{e}^{\mathrm{i}\varphi(z)}$$

are the linear field eigenmodes at the frequencies ω_1 and $2\omega_1$, respectively. The eigenmodes are obtained with a simple application of the matrix transfer method. The nonlinear refractive index is different from zero if the field at the SH frequency is not zero. Further, the index $\widetilde{N}(z,\omega) = n(\omega) + \Delta n(z,\omega)$ is a complex quantity that depends on the relative phases of the fields.

In order to obtain gain at the FF frequency, we impose the following input condition on the relative phases between FF and SH fields: $\varphi(2\omega) - 2\varphi(\omega) = -\pi/2$. Therefore, assuming that the SH field is orders of magnitude more intense than the FF, and that the SH field remains undepleted during the interaction, we can easily and accurately estimate the refractive index $\widetilde{N}(z,\omega_1)$ of the FF. In particular, we can evaluate the real and imaginary parts of $\Delta n(z,\omega_1)$ once the linear field eigenmodes are known. We stress that shifts of the band edge can be neglected due to the relative small nonlinear index change compared to linear index contrast. Coherence between the fields is maintained inside the device thanks to the fact that the spatial extent of a ps pulse (several mm) is much larger compared with the physical length of the device (typically of the order of few microns).

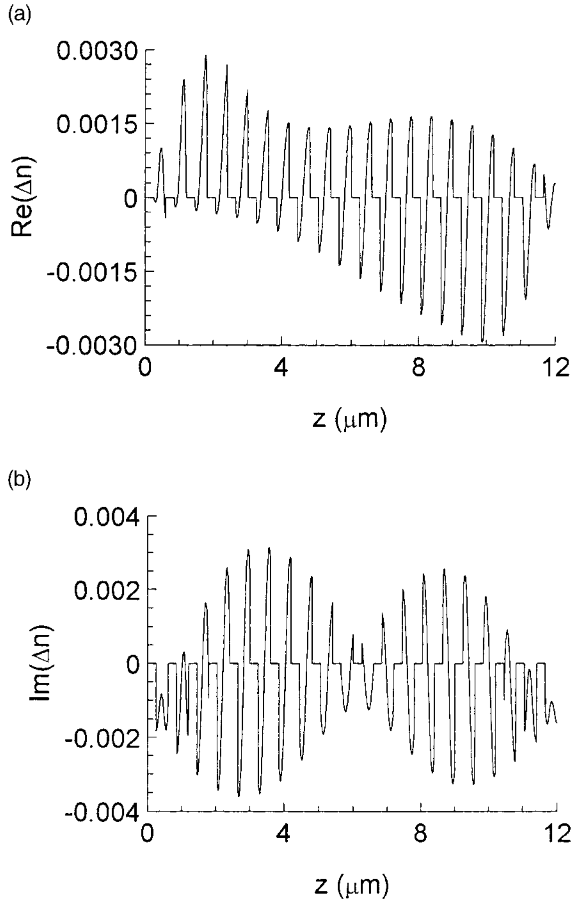

Fig. 1. (a) $\mathrm{Re}[\Delta n(z,\omega_1)]$ vs. position, (b) $\mathrm{Im}[\Delta n(z,\omega_1)]$: the structure consists of a 20-period half-quarter wave stack, with layers of high ($n_2 = 1.42857$) and low ($n_1 = 1$) refractive index, $\chi^{(2)} = 25$ pm/V in the high index layer. Thicknesses are $a = \lambda/(4n_1)$ and $b = \lambda/(2n_2)$. Input amplitudes are taken to be 10^4 V/m for the FF, and 10^8 V/m amplitude for the SH beam.

An example of the behavior of the nonlinear index $\Delta n(z,\omega_1)$ is shown in Fig. 1. For illustration purposes, we choose $N = 20$, and a mixed half-wave–quarter-wave stack, with alternating refractive indices $n_1(\omega_1) = 1$ and $n_2(\omega_1) = 1.42857$, respectively. The fields are tuned as in Refs. [8,10], near their respective band edges. In Fig. 1a, we show the real part of $\Delta n(z,\omega_1)$ as a function of position inside the structure, while the imaginary component, which represents gain (or loss), is shown in Fig. 1b. The amplitudes of the SH and FF fields are chosen to be 10^8 and 10^4 V/m, respectively, and $\chi^{(2)} = 25$ pm/V. We observe that the calculated maximum value of $\Delta n(z, \omega_1)$ is more than two orders of magnitude smaller compared to the linear index contrast. Once the *perturbation* $\Delta n(z, \omega_1)$ has been calculated, we apply the matrix transfer method appropriately modified to contain the new spatial modulation of the index, and calculate the modified, nonlinear transmission spectrum. We repeat the procedure assuming that pulse bandwidth is well contained within the band edge transmission resonance. This allows us to work with the same eigenmode for all frequencies contained within the pulse. All the results have been tested by direct integration of the equations of motion in the time domain, as discussed in Ref. [8].

The novelty of this approach consists in the fact that we can easily access states that display relatively modest but significant amplification of the fundamental field at the band edge in both forward and backward directions, with a gain coefficient that changes nonlinearly with N [8,10–12] and the refractive index contrast, under phase matched conditions. Fig. 2 shows the behavior of the FF pulse transmission as a function of N, under the amplification regime. An increase in the number of periods induces an increase in the transmitted pulse intensity, thanks to the large increase of the density of modes (DOM) [12]. Thus, with a suitable selection of material parameters, such as number of periods, the magnitude of $\chi^{(2)}$, input intensity of the SH field, and most importantly, phase matching conditions [8,10], the numerical method described above allows us to easily calculate the amplitude of the transmitted and reflected components of the FF.

We find that the resulting nonlinear interaction leads to nonlinear mirror and/or optical switch behavior in that, a state of complete transmission can be modified into a state where both transmission and reflection display significant amplification. This device can also effectively operate as

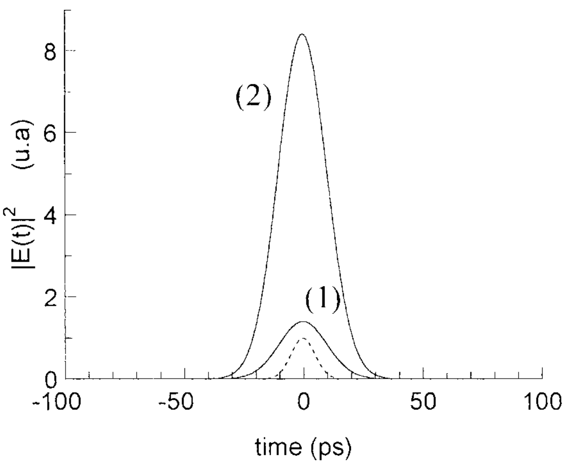

Fig. 2. Pulse transmittivity (given in terms of $|E|^2$) at the FF as a function of N, the number of periods, with $\varphi_{2\omega}(z=0) - 2\varphi_\omega(z=0) = -\pi/2$. Linear (- - -), and nonlinear transmission (—) for (1) $N = 20$ periods and (2) $N = 35$ periods. The parameters used are those of Fig. 1.

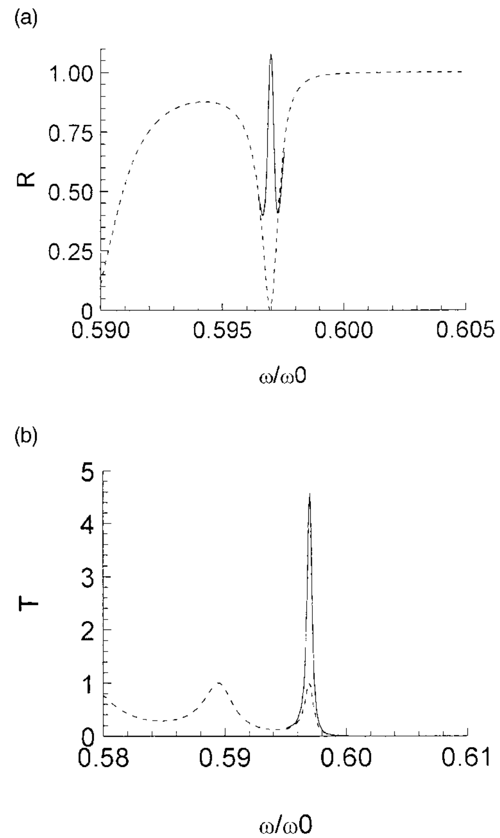

Fig. 3. (a) Reflectivity vs. normalized frequency (dotted line is the linear regime), (b) transmittivity vs. normalized frequency (dotted line is the linear regime), for the geometry of Fig. 1, with $n_2 = 1.42587$ and $n_1 = 1$, $\chi^{(2)} = 20$ pm/V, input FF and SH field amplitudes as shown in Fig. 1; pulse duration is 10 ps.

an efficient nonlinear mirror or switch in the following way. We refer to Fig. 3, which we obtain using the numerical procedure described above. We choose a geometry composed of 35 periods of a mixed-half-quarter wave stack, with refractive indices of $n_1(\omega_1) = 1$ and $n_2(\omega_1) = 1.42857$; we have introduced some dispersion in the refractive index such that $n_1(2\omega) = 1$, $n_2(2\omega) = 1.524$, and tuned the pump field to $\omega/\omega_0 = 0.597$. ω_0 corresponds to a wavelength of 1 μm so that the conditions of Refs. [8,11] are reproduced. $\chi^{(2)}$ is taken to be 20 pm/V. Fig. 3a shows the reflectivity in the linear (dotted line) and in the nonlinear (solid line) amplification regimes. The input SH and FF field amplitudes are as in Fig. 2. The duration of both input pulses is 10 ps. The relative input phase difference is $-\pi/2$. In Fig. 3b, the dotted line represents transmission in the linear regime; the nonlinear transmission is represented by the solid line. Therefore, we note that it is possible to obtain a large contrast in the reflection coefficient with a reduction of the threshold intensity, with a modest $\chi^{(2)}$ value (20 pm/V). If we use a $\chi^{(2)}$ of 100 pm/V, the threshold intensity needed for 100% reflection would be lowered to the 10–100 MW/cm^2.

In Fig. 4 we depict the transmission as a function of relative input phases, $\delta\phi$. The figure suggests that the transmission is a periodic function of $\delta\phi$, as expected. This effect might also be viewed as a de-amplification process that can be controlled via the adjustment of $\delta\phi$. The transmittivity is given for the same parameters of Fig. 1. We note that this input dependent de-amplification process occurs for a relative input phase difference of $-3/2\pi$.

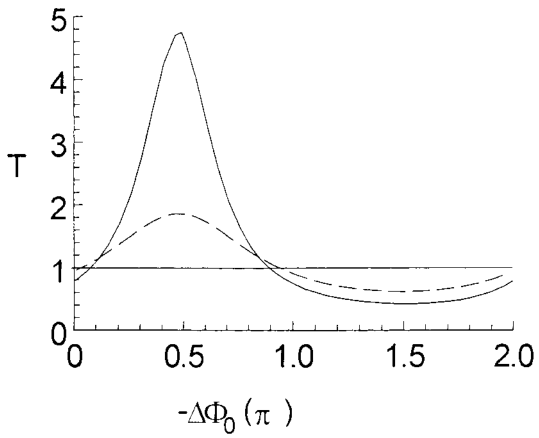

Fig. 4. Transmittivity of the FF vs. relative phase difference for different values of the input SH field amplitude for the same geometrical parameters of Fig. 3.

In conclusion, group velocity reduction near the band edge can give rise to a very efficient nonlinear amplification scheme induced by the coupling between an FF and an SH fields. The high DOM and the particular phase matching conditions that can be accessed near the photonic band edge makes it possible for PBG structures to be considered highly likely candidates as efficient, phase sensitive nonlinear mirrors. We note that although we have analyzed periodic structures and simple second-order processes, we predict that the same effects can occur for structures that are not necessarily periodic or 1-D, or that contain metals as in metal–dielectric multilayer stacks [13]. A control beam whose intensity is on the order of a few MW/cm^2 can in principle be easily achieved in these structures by using a large refractive index contrast or larger number of periods.

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