Optical Limiting and Switching of Ultrashort Pulses in Nonlinear Photonic Band Gap Materials

Michael Scalora, Jonathan P. Dowling, Charles M. Bowden, and Mark J. Bloemer
Weapons Sciences Directorate Research, Development and Engineering Center, AMSMI-RD-WS, U.S. Army Missile Command, Redstone Arsenal, Alabama 35898-5248
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We numerically investigate nonlinear propagation of ultrashort pulses in a one-dimensional photonic band gap structure. We find that, near the band edge, nonlinear effects cause a dynamical shift in the location of the band gap. We demonstrate that this nonlinear mechanism can induce intensity-dependent pulse transmission and reflections. In addition, pulse reshaping and pulse generation is observed. This phenomenon has important new applications in both optical limiting and optical switching.

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If a multilayer stack of dielectric material is arranged in such a way that alternating layers have a high index of refraction, say n_2, and a low, say n_1, and the thickness of each layer also alternates and is such that $a = \lambda/4n_1$ and $b = \lambda/4n_2$, where λ is the free-space wavelength, then this dielectric stack forms a reflective dielectric coating [1]. Such a structure is usually referred to as a distributed Bragg reflector, and it is depicted in Fig. 1. A range of wavelengths centered at λ will be reflected, that is, propagation of those wavelengths is not allowed inside the structure. This is an example of the phenomenon from which the name "photonic band gap" (PBG) is derived in analogy with electronic band gaps of semiconductor theory [2].

Although this is a well-known phenomenon, we are interested in using the language of photonic band gap theory to study the nonlinear dynamics of a pulse that impinges on such a structure, with its carrier frequency near the gap edge. Theoretical investigations regarding pulse propagation inside a similar structure have been previously carried out to examine a band edge, distributed feedback enhancement of gain in a photonic band edge laser (PBEL) [3]. The example we investigated yielded nearly a factor of 4 enhancement of gain, primarily due to band edge effects. Near the band edge of a one-dimensional PBG structure, the group velocity approaches zero [4]. As a result, a photon sees an increased effective path length due to the many multiple reflections it undergoes, a phenomenon sometimes referred to as photon localization. A pulse at the band edge tends to form a standing wave, whose antinodal intensities have amplitudes several times over the free-space intensity. Other band edge effects, such as anomalous index of refraction effects, have also been studied [4].

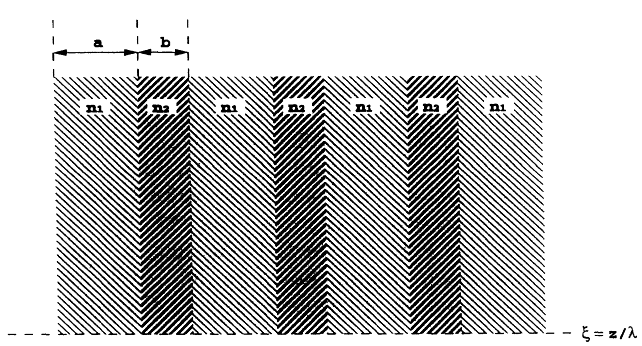

FIG. 1. A one-dimensional periodic array of alternating dielectric layers of indices n_1 and n_2 and widths a and b, respectively, for an overall period of $d = a + b$.

In this Letter, we study the results of including a χ_3 nonlinearity in a one-dimensional PBG structure. Previous studies of nonlinear effects include the investigation of steady state optical bistability and band gap solitary waves [5,6]. We concentrate on the nonlinear dynamics of ultrashort pulses which are only 100 optical cycles long (about 300 fs for $\lambda = 1\ \mu$m). The model we have developed to examine pulse propagation is simple and applicable to a wide range of problems. With the advent of commercially available Kerr lens mode-locked lasers, the understanding of femtosecond pulse propagation is increasingly important to a diverse range of investigators. Aside from the optical limiting and switching behavior, the nonlinear PBG medium causes pulse reshaping and pulse generation due to the wide range of frequencies contained in ultrashort pulses and the anomalous dispersion relation [4]. To our knowledge, the interaction of ultrashort optical pulses with photonic band gap materials has not previously been studied. The dynamic intensity-dependent shifting of the band edge, which leads to optical limiting, can be understood from Fig. 2. Here we show a plot of the infinite lattice transmission coefficient,

$$T(\omega) = 1 - \theta[1 - |f(\omega)|], \tag{1}$$

where $f(\omega)$ is determined by the dispersion relation relating k to ω via [1]

$$\cos[k(a+b)] = f(\omega) \equiv \cos\left[\frac{\omega n_1 a}{c}\right]\cos\left[\frac{\omega n_2 b}{c}\right] - \frac{n_1^2 + n_2^2}{2n_1 n_2}\sin\left[\frac{\omega n_1 a}{c}\right] \times \sin\left[\frac{\omega n_2 b}{c}\right], \tag{2}$$

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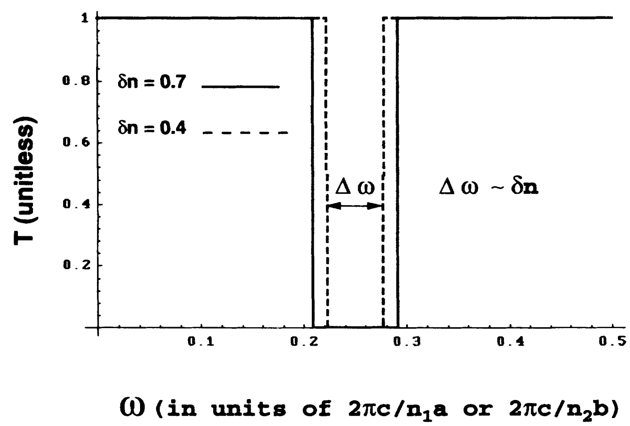

FIG. 2. Transmission curve of the periodic array of Fig. 1 as a function of frequency, for two values of $\delta n = n_2 - n_1$. The width of the gap $\Delta\omega$ is approximately proportional to δn.

and θ is the unit step function. Clearly, total reflection (i.e., a band gap) occurs whenever $|f(\omega)| > 1$ [7]. The first gap in Fig. 2 (dashed line) represents the case $\delta n = 0.41$, and the second gap (solid line) represents the case $\delta n = 0.7$. We fix $n_1 = 1$, and then choose $n_2 = 1.41$ for the first case and $n_2 = 1.7$ for the second. It is clear that a larger index difference widens the gap, while a smaller difference narrows it. Immediately one can see that by doping at least one layer with a medium whose response has a χ_3 nonlinearity, that is, the refractive index changes with the applied intensity, the actual width of the gap can dynamically change by an amount proportional to the local intensity. We will discuss some concrete applications of this effect after we briefly introduce a numerical model below, namely, an optical limiter and optical switch.

For our numerical model we assume the field is paraxial and of the form $E(z,t)e^{i(kz-\omega t)}$ + c.c., where E is an envelope function. Upon direct substitution, and assuming slowly varying envelope functions in time only, Maxwell's equation for the propagation of electromagnetic radiation in a one-dimensional photonic band gap material can be written in dimensionless form as

$$\frac{\partial^2 E}{\partial \xi^2} + 4\pi i \frac{\partial E}{\partial \xi} + 4\pi i \frac{\partial E}{\partial \tau} = -4\pi^2 [n^2(\xi, |E|) - 1]E. \quad (3)$$

Here, $\xi = z/\lambda$ and $\tau = ct/\lambda$ are the scaled length and time coordinates, respectively, and $n(\xi, |E|)$ is the effective refractive index of the medium that contains information regarding the linear as well as the nonlinear response of the structure. We have chosen $k = \omega/c$, while $\lambda = 2\pi/k$ and ω are both the average wavelength and frequency, respectively. For simplicity, the field E is assumed to have a Gaussian profile that is initially located outside the structure traveling with velocity c. Its width at the waist is taken to be about 100 optical cycles, thus insuring that the slowly varying envelope approximation in time is satisfied. While the linear index profile alternates between n_2 and n_1, the nonlinear contribution is of the form

$$n_{\rm NL}^2 = \chi_3 |E|^2. \quad (4)$$

Here, χ_3 is a small coefficient that accounts for nonlinear interactions in the structure and can be chosen to have positive or negative values.

Equation (3) is solved using a split-step modified beam propagation method that is implemented in the time domain [3,8,9]. This method is particularly useful because it handles reflections, while not requiring the introduction of explicit boundary conditions. The boundary conditions are implicitly contained in the equation of motion. If we define

$$\chi_{\rm eff} E = i\pi [n^2(\xi, |E|) - 1]E, \quad (5)$$

the solution of Eq. (3) can then be written as

$$E(\xi, \tau + \delta\tau) = e^{\delta\tau D/2} e^{[\chi_{\rm eff}(\xi,\tau)\delta\tau]} e^{\delta\tau D/2} \times E(\xi,\tau) + O(\delta\tau^3), \quad (6)$$

where the operator D is given by

$$D \equiv \frac{i}{4\pi} \frac{\partial^2}{\partial \xi^2} - \frac{\partial}{\partial \xi}. \quad (7)$$

The method is introduced in Ref. [3], and more details can be found in Refs. [8] and [9]. The most important aspects of the dynamics are included in our solution. In particular, this method handles naturally the reflections that arise in propagation through the one-dimensional photonic band gap material.

We now discuss our main results. Because the index of refraction changes with field intensity, and because the right-hand side of the propagation equation is essentially proportional to the difference of the squares of the refractive indices, the medium response changes dynamically with the incident field. This can be quantified by the following argument. In the frequency domain, the width of the gap is determined by the difference between the refractive indices, as illustrated in Fig. 2. Let us choose $n_2 > n_1$ and assume n_2 is nonlinear. That is,

$$n_2^2 = n_0^2 + \chi_3 I, \quad (8)$$

where χ_3 is a small coefficient, I is the field intensity in the medium, and n_0 is a fixed background index. If $\delta n = n_2 - n_1$, then δn increases with increasing intensity I, if $\chi_3 > 0$, and decreases if $\chi_3 < 0$. Here we consider an incident pulse whose carrier frequency is tuned in the pass band at the band edge. For positive coefficient χ_3 the width of the gap increases with increasing δn. As the pulse enters the structure, a dynamical shift in the size of the gap occurs. The full frequency range that now may fall inside the gap can include the center frequency of the pumping field, i.e., most of the pulse, thus effectively forbidding that frequency from propagating. This process constitutes the basis for an intensity-driven optical limiter.

The optical limiting operation of the device is depicted in Figs. 3(a)–3(d). A Gaussian pulse is launched from the left and is incident on a one-dimensional lattice that has a quarter-wave-type band gap. As the pulse propagates inside the medium, a dynamical widening of the gap occurs, inhibiting transmission. This effect becomes more pronounced with increasing input intensity. In Fig. 3(d) the peak pulse intensity is 16 times larger than in Fig. 3(a). The gap in this case excludes a greater range of frequencies from propagating through the structure, and, hence, the figure shows that reflections increase for these larger intensities. The pulse shape and the number of pulses generated depend on input intensity, pulse width, and tuning of the carrier frequency with respect to the edge of the gap. We found that in the case of a long pulse incident on a nonlinear PBG structure doped with a negative χ_3 in alternating layers, it is possible to generate a train of pulses or induce instabilities [10].

In order to apply this effect to optical switching, we now consider the case where multiple beams of slightly different frequencies are incident on the one-dimensional, nonlinear, photonic band structure described above. We assume that I is the intensity of a strong pump capable of altering the index of refraction of a broadband χ_3 medium, and ω is the pump's carrier frequency. We then apply I_0, the intensity of a probe pulse, such that $I \gg I_0$, and we take the carrier frequency of I_0 to be ω_0. If we assume that both ω and ω_0 are located in the band below the gap, but that ω is relatively far below the gap, while ω_0 is near the band edge, then both beams will initially be transmitted. As the beam of intensity I alters the index of refraction, its effect is to widen the gap, and it will do so to such an extent that ω_0 will be found inside the gap. Beam I_0 then shuts off since its frequency is now part of the forbidden frequency range, where an extremely high percentage of reflection occurs. This constitutes the operation of an optical switch, and the switching dynamics described above is depicted schematically in Fig. 4.

For some dielectric materials, the nonlinear coefficient is found to be negative. That is $n_2^2 = n_0^2 - |\chi_3|I$. This can also be used to generate switchlike behavior on the part of the nonlinear PBG material. In this case, δn decreases with increasing intensity, and the width of the gap will decrease accordingly. If we now select the frequency of operation ω_0 of the probe beam I_0 somewhere near the edge of the gap, but inside of it, none of it can be transmitted initially. Applying the pump beam will tend to decrease the width of the gap, and if a certain power level is surpassed, the probe beam at ω_0 may suddenly be found outside of the gap, in the band, and its transmission is thus allowed. This process also constitutes the basis of an optical switch.

We note that the switching time associated with beam shutdown, or turn-on, depending on the sign of χ_3,

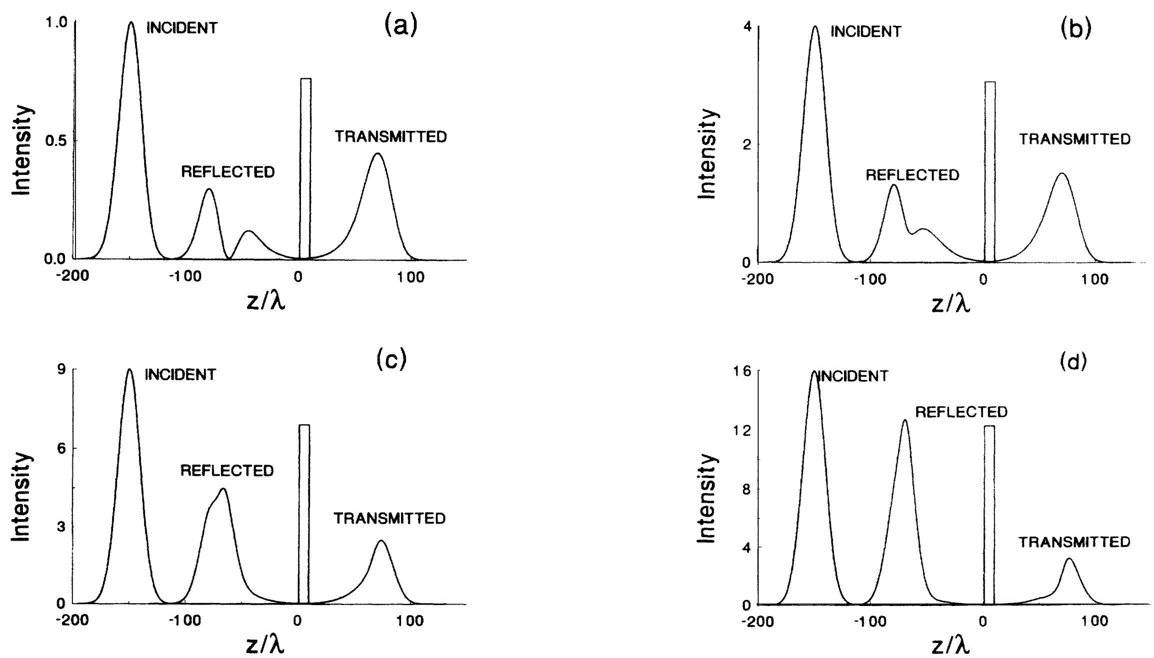

FIG. 3. Incident, transmitted, and reflected pulses for the periodic structure shown in Fig. 1 with the high index regions doped with nonlinear χ_3 material. The structure is about 8λ wide, with each layer about $\lambda/4$. The peak intensities of the incident pulse range from a value of 1 in (a), to a value of 16 in (d). We have chosen $\chi_3 = 0.01$. Note that the reflection increases with the increasing input intensity while transmission decreases, thus demonstrating optical limiting.

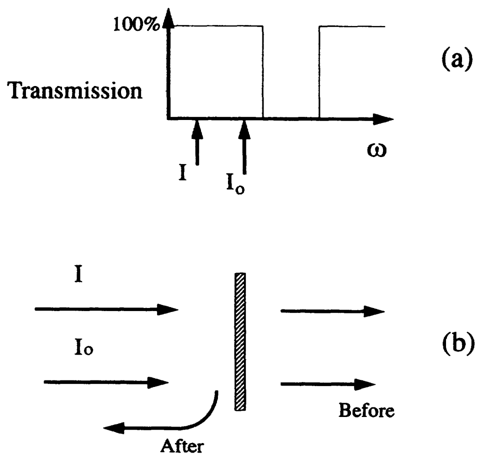

FIG. 4. Schematic operation of an optical switch based on limiter operation of a PBG structure doped with a medium with positive χ_3 nonlinear response. The transmission (a) is initially nearly 100% for both beams because they are both tuned in the pass band below the gap. After the pump beam I is applied, the width of the gap changes, and the range of forbidden frequencies will include ω_0, the probe beam frequency. This will result in reflection of the probe (b).

depends on at least two factors: first, the speed at which the nonlinearity can be excited, and second, structural geometry. The effects of geometry are included in our calculation, while the speed is strictly material dependent. Therefore, since we are using short pulses, ultrafast limiter and switch operation is possible.

Finally, we point out that because interference effects inside the structure yield local intensities that may be several times larger than the input pulse intensity, the fields are not required to be as strong as one might think. This can be significant if energy requirements and material breakdown parameters are considered for actual system design.

In conclusion, we have examined nonlinear wave propagation effects in a one-dimensional photonic band gap structure doped with a χ_3 type of nonlinearity. We find that an external, ultrashort pulse can cause a dynamical shift of the location of the band gap due to nonlinear medium response. As a result, a whole new class of ultrafast devices can be engineered. We have demonstrated numerically a new optical limiter and have illustrated how the process can be applied to a new optical switching mechanism. Because the dynamics we studied were based on ultrashort incident pulses—on the order of 100 optical cycles long—device operation is expected to be ultrafast, and it would only be limited by the speed at which the nonlinear response can be excited.

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