Modeling of Z-scan characteristics for one-dimensional nonlinear photonic bandgap materials

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We propose a Z-scan theory for one-dimensional nonlinear photonic bandgap materials. The Z-scan characteristics for this material are analyzed. Results show that the Z-scan curves for photonic bandgap materials with nonlinear refraction are similar to those of uniform materials exhibiting both nonlinear refraction and nonlinear absorption simultaneously. Effects of nonlinear absorption on reflected and transmitted Z-scan results are also discussed. © 2009 Optical Society of America

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The Z-scan technique proposed by Sheik-Bahae *et al.* [1,2] has proved to be one of the most convenient methods for measurements of nonlinear refraction and nonlinear absorption because of its simplicity and high accuracy. It has been extensively used to measure nonlinear optical properties of bulk materials [2,3] and films [4,5] as well as one-dimensional (1D) nonlinear photonic bandgap (PBG) materials [6–9].

1D PBG materials are periodic structures that enable engineering of the most fundamental properties of electromagnetic waves through selective trapping or "localization of light." Their nonlinear optical properties are widely studied by the Z-scan technique because of applications in the all-optical switching and limiting [10,11]. However, previous works are mainly focused on the experiments [6], and most of the experimental results are simulated by the standard Z-scan theory [2]. This neglects the fact that both open- and closed-aperture Z-scan curves of 1D nonlinear PBG materials are quite different from those of uniform materials in particular when the light frequency is in a range that is close to the band edge of the 1D nonlinear PBG material. Some authors started to consider the effects of PBG material in the simulations of the experimental results [7].

Hwang and Wu [8] proposed a Z-scan theory by analyzing the dispersion relation and intensity-dependent wavenumber in a 1D nonlinear PBG material, but only open-aperture Z-scan curves were discussed. Based on the finite-difference time-domain method, Meng *et al.* [9] extended the Z scan for bulk materials to 1D PBG materials by incorporating the frequency- and power-density-dependent reflections into the linear and nonlinear absorptions. However, the closed-aperture curves they obtained needed to be modified further by a symmetric method, which is suited only for the case of a small nonlinear phase shift.

In this Letter, we present a Z-scan theory that can be used to simultaneously calculate open- and closed-aperture Z-scan curves for 1D nonlinear PBG materials. We analyzed the Z-scan characteristics for PBG materials with refractive and absorptive nonlinear optical coefficients. The results show that the Z-scan curves for PBG materials with nonlinear refraction are similar only to those of uniform materials exhibiting both nonlinear refraction and nonlinear absorption simultaneously. Applying our model enables one to optimize nonlinear PBG structures for particular applications such as optical limiting.

The central part of Z-scan theory is to obtain the distribution of amplitude and phase of the electric field at the exit surface of the sample, which determine the open- and closed-aperture Z-scan curves, respectively. We consider a plane wave that is propagating in the z direction and normally incident on a 1D nonlinear PBG material (the inset of Fig. 1). We choose the field to be polarized in the y direction so that $\mathbf{E}=E(z)\hat{\mathbf{y}}$ and $\mathbf{H}=H(z)\hat{\mathbf{x}}$ hold. Then, for a 1D PBG material with a $\chi^{(3)}$ nonlinearity, Maxwell's equations (in Gaussian cgs units) are [12]

$$\mathrm{d}E/\mathrm{d}z = ikH, \tag{1}$$

$$\mathrm{d}H/\mathrm{d}z = ik[\varepsilon_{\mathrm{lin}}(z) + 12\pi\chi^{(3)}_{1111}|E|^2]E, \tag{2}$$

where $k=\omega/c$ and $\varepsilon_{\mathrm{lin}}$ is the linear dielectric constant.

We can assume the transmitted electric field at the exit surface of the sample is $Et=E_t\exp(i\phi_t)$, where E_t and ϕ_t are the amplitude and the phase of the transmitted light. Then, the electric and the magnetic field at the exit surface of the sample can be written as follows:

$$E(L) = Et, \tag{3}$$

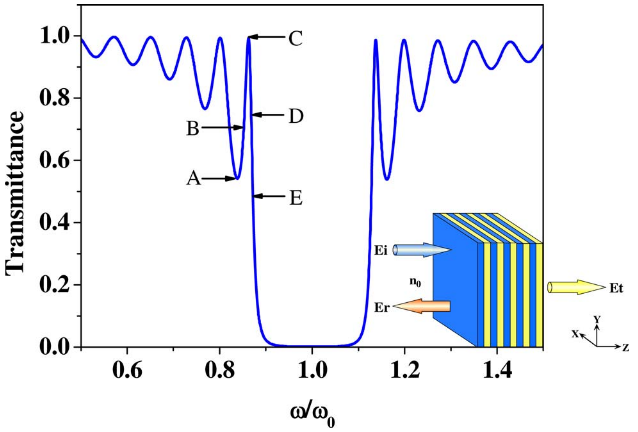

Fig. 1. (Color online) Linear transmission of the quarter-wave reflector. Inset, schematic of the considered configuration with 1D nonlinear PBG material. Marked are the normalized frequencies near the band edge: $A=0.8380\omega_0$, $B=0.8523\omega_0$, $C=0.8627\omega_0$, and $D=0.8683\omega_0$.

$$H(L)=n_0Et, \tag{4}$$

where n_0 and L are the linear refractive index of the surrounding medium and the thickness of the sample, respectively.

Treating Eqs. (3) and (4) as the initial conditions, the electric field $E(0)\exp(i\phi_t)$ and the magnetic field $H(0)\exp(i\phi_t)$ at the incident surface of the sample can be obtained by solving Eqs. (1) and (2). Meanwhile, the incident electric field can be written as $Ei=E_i\exp(i\phi_i)$, where E_i and ϕ_i are the amplitude and the phase of the incident light. According to the external boundary condition, the incident field can be expressed as follows:

$$Ei=E_i\exp(i\phi_i)\equiv\frac{1}{2}[E(0)+H(0)/n_0]\exp(i\phi_t). \tag{5}$$

Therefore the phase relation between transmitted and incident fields can be written as

$$\phi_t=\phi_i-\arg[E(0)+H(0)/n_0]. \tag{6}$$

Accordingly, the phase relation between reflected and incident fields can be written as

$$\phi_r=\phi_i-\arg[E(0)+H(0)/n_0]+\arg[E(0)-H(0)/n_0], \tag{7}$$

where $\arg[E(0)\pm H(0)/n_0]$ is the phase angle of the complex variable $[E(0)\pm H(0)/n_0]$.

The Z-scan configuration is the same as that in [2]. Assuming a fundamental TEM_{00} Gaussian beam traveling in the $+z$ direction, we can write E as [2]

$$E(z,r,t)=E_0(t)\frac{w_0}{w(z)}\exp\left[-\frac{r^2}{w^2(z)}-\frac{ikr^2}{2R(z)}\right]\times\exp[-i\varphi(z,t)], \tag{8}$$

where $w^2(z)=w_0^2(1+z^2/z_0^2)$ is the beam radius, w_0 is beam waist radius, $R(z)=z(1+z_0^2/z^2)$ is the radius of curvature of the wave front at position z, and $z_0=kw_0^2/2$ is the diffraction length. $E_0(t)$ denotes the electric field at the focus and contains the temporal envelope of laser pulse. The term $\exp[-i\varphi(z,t)]$ contains all the radially uniform phase variations.

Curves for the amplitude and phase relations between the transmitted and the incident fields can be obtained by integrating Eqs. (1) and (2) backward from $z=L$ to $z=0$. Considering Eq. (8) as the incident field, we can calculate the distribution of the amplitude and phase of the electric field at the exit surface of the sample by the interpolation method. In analogy to the standard Z-scan theory, we can successively obtain open- and closed-aperture Z-scan curves by analyzing the electric field distribution after the sample.

In the following, we present the Z-scan results for a quarter-wave reflector consisting of 12 dielectric layers with a linear refractive index $n=\sqrt{2}$ and a nonlinear refractive index $\mathrm{Re}(\chi^{(3)})=1\times10^{-12}$ (esu) that are separated by air. The linear transmission of the quarter-wave reflector is shown in Fig. 1. Figure 2 gives the Z-scan curves for four different normalized frequencies (as indicated in Fig. 1), where the nonlinear absorption index $\mathrm{Im}(\chi^{(3)})$ is set to zero. The beam waist radius w_0 and the on-axis peak intensity at the focus are 45 μm and 191 GW/cm^2, respectively.

Figures 2(a) and 2(b) demonstrate that the Z-scan curves for this 1D PBG material are similar to those of a uniform material with both nonlinear refraction and nonlinear absorption. Distinct open-aperture Z-scan profiles can be found in curves B, C, and D of Fig. 2(a) that would indicate the presence of nonlinear absorption in a uniform medium, but in fact are results from multiple scattering by means of Bragg diffraction. The normalized frequencies B and D in Fig. 1 correspond to the spectral positions with maximum peak and valley, respectively. The effective frequency dependence induced by the layered structure can be utilized to realize various applications of PBG materials at characteristic frequencies such as laser cavities (B), all-optical limiting (C), and optical switching (D).

To present more details of the Z-scan characteristics, the open-aperture Z-scan curves for different

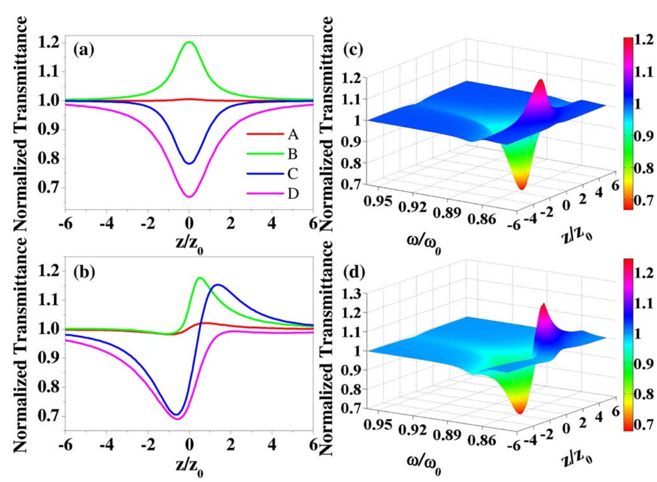

Fig. 2. (Color online) Z-scan curves assuming purely refractive nonlinearity. (a), (c) Open-aperture Z scan; (b), (d) closed-aperture Z scan.

normalized frequencies near the band edge from $0.84\omega_0$ to $1\omega_0$ are shown in Fig. 2(c). We can see that the open-aperture Z-scan changes its shape from a peak to a valley with increasing normalized frequency, which would correspond to an interpretation as optical gain and induced absorption (IA) in uniform materials. This observation highlights the necessity of our theoretical model for a correct interpretation of Z-scan measurements on 1D PBG structures. Peaks and valleys are suppressed at various frequencies in the closed-aperture Z scan [Fig. 2(d)] because of multiple scattering between the layers.

It is well known that the reflection of the 1D PBG material cannot be ignored. To fit the experimental data, we need to monitor the reflected signal from the sample as well as the transmitted signal in the Z scan. Figure 3 gives the Z scan including the reflected and transmitted signal for different nonlinear absorption coefficients at spectral position E. From the open-aperture Z scan in Fig. 3(a), we can see that the IA ($\mathrm{Im}(\chi^{(3)})<0$) in the material can suppress the peak of the reflected Z scan and deepen the valley of the transmitted Z scan, respectively. To extract the nonlinear absorption from the open-aperture Z scan, the total (reflected+transmitted) Z-scan signal is monitored, which is given in Fig. 3(a). If there is only pure nonlinear refraction in the material, the open-aperture Z scan will be a straight line. In contrast, the IA can deepen the valley of the open-aperture Z scan. The IA can lead to a shift for the reflected and transmitted closed-aperture Z scan, as shown in Fig. 3(b). For the closed-aperture Z scan, the total energy is not conserved even if we monitor the reflected and transmitted signal simultaneously. We cannot easily obtain the useful information by this way. Therefore we don't give the total closed-aperture Z scan in Fig. 3(b). With our approach it is possible to include both nonlinear refraction and absorption in the analysis of experimental Z-scan data, and nonlinear optical material parameters and PBG structural design can be combined to engineer the nonlinear optical response of PBG materials for a particular application such as optical limiting.

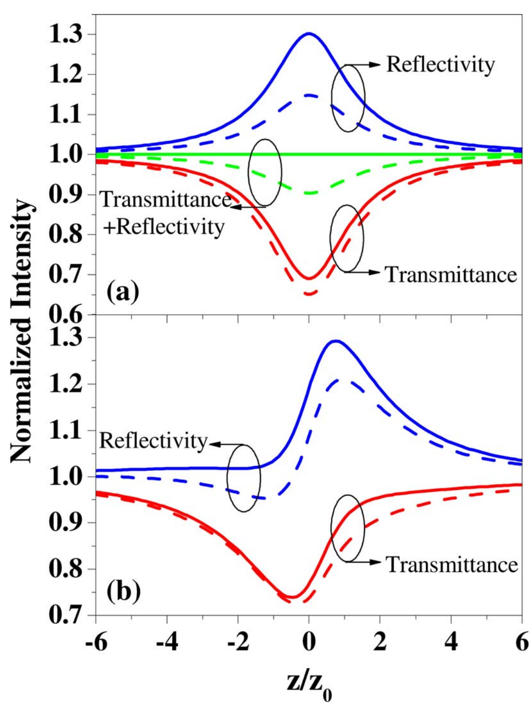

Fig. 3. (Color online) (a) Open-aperture Z scan and (b) closed-aperture Z scan including the reflected and transmitted signal for different nonlinear absorption coefficients [solid curves, $\mathrm{Im}(\chi^{(3)})=0$; dashed curves, $\mathrm{Im}(\chi^{(3)})=-3\times10^{-13}$ (esu)] at spectral position $\mathrm{E}=0.872\omega_0$.

In conclusion, we presented a Z-scan theory for 1D nonlinear PBG materials, which enables a direct calculation of both open- and closed-aperture Z-scan curves. We analyzed the Z-scan characteristics for a 1D PBG material, which are quite different from those of uniform materials. The effects of nonlinear absorption on reflected and transmitted Z-scan curves are also discussed. Our results can be used to simulate the experimental Z-scan results and obtain the nonlinear material response. Optimizing 1D PBG structure designs and operation wavelengths can be applied to engineer nonlinear PBG materials and tailor their properties for various applications.

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