STUDY ON Z-SCAN CHARACTERISTICS FOR LIGHT-TUNNELING HETEROSTRUCTURES COMPOSED OF ONE-DIMENSIONAL PHOTONIC BAND GAP MATERIAL AND METALLIC FILM

S.-Q. Chen
The Key Laboratory of Weak Light Nonlinear Photonics, Ministry of Education, Teda Applied Physics School, Nankai University Tianjin 300457, China

W.-Y. Zhou
School of Physics, Nankai University Tianjin 300071, China

Z.-B. Li and Z.-B. Liu
The Key Laboratory of Weak Light Nonlinear Photonics, Ministry of Education, Teda Applied Physics School, Nankai University Tianjin 300457, China

J.-G. Tian †
School of Physics, Nankai University Tianjin 300071, China

Abstract—The transmitted and reflected Z-scan characteristics for light-tunneling heterostructures composed of one-dimensional photonic bandgap material and metallic film are theoretically investigated. An apparent Z-scan signal will appear around the light-tunneling even if the incident peak intensity is very low. Both of the transmitted and reflected Z-scan signals from left incidence are much larger than those from right incidence, demonstrating the nonreciprocal for two incident directions. The variation of the reflected Z-scan curve shape is opposite to that of transmitted Z-scan curve shape as light wavelength increases. Moreover, the reflected Z-scan signals from left incidence will appear a very sharp peak around the light-tunneling.

† Corresponding author: J.-G. Tian (jjtian@nankai.edu.cn).
1. INTRODUCTION

One-dimensional (1D) photonic band gap (PBG) materials are periodic dielectric structures that enable engineering of the most fundamental properties of electromagnetic waves through selective trapping or "localization of light" [1]. These include the laws of refraction, diffraction, and spontaneous emission of light. This simple and traditional system can also illustrate most of the physical features of the more complex two- and three-dimensional PBG materials, and can even exhibit omnidirectional reflection [2-4]. In recent years, 1D PBG has been widely studied as their numerous potential applications in high quality filter [5-7], tunable polarizer [8], nonlinear optical diode [9], and optical switch [10], as well. If the 1D PBG structures exist of the nonlinear optical material, their nonlinearity can be substantially enhanced around the band edge or the defect mode by the presence of the localized electric field [11].

The third-order nonlinear susceptibility of the typical noble metals is nearly $10^6$ times larger than those of typical dielectrics. However, when the thickness is much larger than skin depth, the metal is nearly opaque because of high reflectance. In recent years, in order to adequately utilize the large nonlinearity of the metals, researchers have investigated two types of composite structures. One is metal-dielectric PBG materials based multiple Bragg reflections [12-14], and another is 1D PBG-metal heterostructures based on light tunneling of evanescent wave [15-17]. The small electric field at each metal layer of metal-dielectric PBG structure still limits the enhancement of the nonlinear effect. However, the electric field in the thick metal film of PBG-metal heterostructure can be greatly enhanced due to the light tunneling effect.

The nonlinear optical properties of the 1D PBG materials are widely studied by the Z-scan technique because of its simplicity and high accuracy [18-21]. However, most of the previous works on 1D PBG materials are simulated by the standard Z-scan theory [22, 23]. This neglects the fact that both open- and closed-aperture Z-scan curves of 1D PBG materials are quite different from those of uniform materials. Recently, we proposed a Z-scan theory for 1D PBG material and analyzed its Z-scan characteristics [24]. Results show that the Z-scan curves for PBG materials are similar to those of uniform materials with both nonlinear refraction and nonlinear absorption simultaneously.

In this paper, we simulated the transmitted and reflected Z-scan characteristics of PBG-metal heterostructure from two incident directions. Results show that there are distinct Z-scan signals around the light tunneling. The Z-scan signals are nonreciprocal for two
Study on Z-scan characteristics for light-tunneling heterostructures composed of one-dimensional photonic band gap materials in incident directions, and both of the transmitted and reflected Z-scan signals from left incidence are much larger than those from right incidence. The transmitted Z-scan curves change its shape from a valley to a peak as laser wavelength increases. In contrast, the shape of reflected Z-scan curve is opposite to that of transmitted Z-scan curve. Moreover, the reflected Z-scan signals from left incidence will appear a very sharp peak around the light-tunneling.

2. 1D PBG-METAL HETEROSTRUCTURE

![Diagram of 1D PBG-Metal Heterostructure](image)

**Figure 1.** (a) Schematic of the considered configuration with 1D PBG-metal heterostructure. (b) Linear transmission (red) and reflection from left (blue) and right (green) incidence of the 1D PBG-metal heterostructure. Inset: Zoom in the Linear transmission and reflection spectra. Marked are the wavelengths: A=381.4 nm, B=540.3 nm, C=620.4 nm, D=538.5 nm and E=542.3 nm.
We consider a 1D PBG-metal heterostructure composed of a 1D SiO$_2$/TiO$_2$ PBG material with 7 periods and a thick silver layer, which is shown in Fig. 1(a). The thicknesses of the layers are $d_{SiO_2} = 80$nm, and $d_{TiO_2} = 50$nm, respectively. The total thickness of the heterostructure $L$ is 967 nm. The refractive indices of the SiO$_2$ and TiO$_2$ are $n_{SiO_2} = 1.443$ and $n_{TiO_2} = 2.327$, respectively. The nonlinear susceptibility of TiO$_2$ is $\chi^{(3)}_{TiO_2} = 2.10 \times 10^{-12}$ esu [25]. The nonlinearity of SiO$_2$ can be neglected. The linear permittivity of silver is expressed by the Drude model [26]

$$\varepsilon_{Ag}^{L} = 1.0 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega},$$

where the plasma frequency $\omega_p$ is 10.939 fs$^{-1}$, and the collision frequency $\gamma$ is 0.076 fs$^{-1}$. The nonlinear susceptibility of silver is $\chi^{(3)}_{Ag} = 2.49 \times 10^{-8} + i7.16 \times 10^{-9}$ esu [27], which has a real part notably larger than the imaginary part. Figure 1(b) gives the linear transmission and reflection of the 1D PBG-metal heterostructure from two normal incident directions. It can be seen that the linear transmission is independent of the direction of propagation of the light. This applies regardless of whether or not the layers are absorbing. However, the linear reflection is nonreciprocal as absorption exists in the silver layer, which doesn’t matter with the symmetric or asymmetric of the structure [28]. There is almost zero reflection from left incidence, but apparent reflection from right incidence at tunneling mode B, which can be clearly seen from the inset of the Fig. 1(b).

3. Z-SCAN THEORY FOR 1D PBG-METAL HETEROSTRUCTURES

We consider a plane wave that is propagating in z direction and normally incident on the 1D PBG-metal heterostructure (Fig. 1(a)). The electric field polarized in the y direction is chosen, so that $E(z) \hat{y}$ and $H(z) \hat{x}$ hold. As the plasmonic resonance occurs for metal-dielectric surfaces perpendicular to the polarization, this arrangement can avoid the plasmonic resonance. Then, the Maxwell’s equations (in Gaussian cgs units) for the 1D PBG-metal heterostructure are [29]

$$dE/dz = ikH,$$  \hspace{1cm} (2)

$$dH/dz = ik \left[ \varepsilon_{lin}(z) + 12\pi \chi^{(3)}_{1111} |E|^2 \right] E,$$ \hspace{1cm} (3)
Study on Z-scan characteristics for light-tunneling heterostructures composed of one-dimensional photonic band gap material and metallic film

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

The transmitted electric field $E(L)$ at the exit surface of the 1D PBG-metal heterostructure can be assumed as $Et = E_t \exp(i\varphi_t)$, where $E_t$ and $\varphi_t$ are the amplitude and the phase of the transmitted light. Then, the magnetic field at the exit surface of the sample can be written as $H(L) = n_0 Et$, where $n_0$ is the linear refractive index of the surrounding medium. Treating $E(L)$ and $H(L)$ as the initial conditions, the electric field $E(0) \exp(i\varphi_t)$ and the magnetic field $H(0) \exp(i\varphi_t)$ at the incident surface of the sample can be obtained by solving Eqs. (2) and (3). According to the external boundary condition, the incident and reflected fields can be expressed as follows [24]:

$$E_i = \frac{1}{2} [E(0) \exp(i\varphi_t) + H(0) \exp(i\varphi_t)/n_0], \quad (4)$$

$$E_r = \frac{1}{2} [E(0) \exp(i\varphi_t) - H(0) \exp(i\varphi_t)/n_0]. \quad (5)$$

The incident and reflected fields can also be written as

$$E_i = E_i \exp(i\varphi_i), \quad (6)$$

$$E_r = E_r \exp(i\varphi_r), \quad (7)$$

where $E_i$, $E_r$ and $\varphi_i$, $\varphi_r$ are the amplitude and the phase of the incident light and reflected light, respectively. Therefore, the phase relation between transmitted (or reflected) and incident fields can be obtained by solving Eqs. (4)-(7), which can be written as

$$\varphi_t = \varphi_i - \arg[E(0) + H(0)/n_0], \quad (8)$$

$$\varphi_r = \varphi_i - \arg[E(0) + H(0)/n_0] + \arg[E(0) - H(0)/n_0], \quad (9)$$

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

Curves for the amplitude and phase relations between the transmitted (or reflected) and the incident fields can be obtained by integrating Eqs. (2) and (3) backward from $z = L$ to $z = 0$. Assuming a fundamental TEM$_{00}$ Gaussian beam traveling in the $+z$ direction, we can write $E$ as [23].
\[ E(z, r, t) = \frac{E_0(t)}{w_0(z)} \exp \left[ -\frac{r^2}{w^2(z)} - \frac{ikr^2}{2R(z)} \right] \exp [-i\phi(z, t)], \]

where \( w^2(z) = w_0^2 \left( 1 + \frac{z^2}{z_0^2} \right) \) is the beam radius, \( w_0 \) is beam waist radius, \( R(z) = z \left( 1 + \frac{z^2}{z_0^2} \right) \) 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 \( \exp [-i\phi(z, t)] \) contains all the radially uniform phase variations. Considering Eq. (10) as the incident field, we can calculate the distribution of the amplitude and phase of the electric field at the exit and reflection surfaces of the sample.

**Figure 2.** The transmitted open- (OA) and closed-aperture (CA) Z-scan curves from left incidence at three modes. (a) mode A; (b) mode B; (c) mode C. (d) The distribution of the electric field intensity for the three modes A (orange), B (red) and C (green).
Study on Z-scan characteristics for light-tunneling heterostructures composed of one-dimensional photonic band gap material and metallic film by the interpolation method. Finally, the open- and closed-aperture Z-scan curves can be successively obtained by analyzing the electric field distribution between the 1D PBG-metal heterostructure and the aperture.

4. RESULTS AND DISCUSSIONS

4.1. Transmitted Z-scan for 1D PBG-metal heterostructures

There are pronounced Z-scan signals near the band edges of the 1D PBG materials as the electric field is predominantly localized in the high or low refractive index layers [24]. The beam waist radius $w_0$ and

\[
\chi^{(3)}_{\text{TiO}_2} = 2.10 \times 10^{-12} \text{ esu}
\]

for red and blue solid line and \( \chi^{(3)}_{\text{TiO}_2} = 0 \) for red circle and blue diamond, respectively.

Figure 3. The transmitted open- (OA) and closed-aperture (CA) Z-scan signals from left incidence at (a) modes B and (b) C for two cases.
the on-axis peak intensity at the focus are 30 $\mu$m and 0.049 GW/cm$^2$ in the whole paper. We check the Z-scan signals from left incidence at three modes A, B and C, which correspond to Fig. 2(a), (b) and (c), respectively. Results show that the deviations from unity of the open- and closed-aperture Z-scan signals at mode B are about 16 and 5 times larger than those at modes A and C, respectively. Figure 2(d) gives the distribution of the electric field intensity for the three modes A, B and C. The electric field distribution of the silver layer is set to be same at the three modes. It is clearly seen that the incident electric field intensity at mode B is far less than those at modes A and C. The amplitude of Z-scan signals depends on the nonlinear distribution in the high or low refractive index layers. However, only silver layer has large third-order nonlinearity in the presented PBG-metal heterostructure, which is about four orders larger than that of TiO$_2$. To test the nonlinear contribution of TiO$_2$, we give the Z-scan signals from left incidence at modes B and C for two cases in Fig. 3. One is considering the third-order nonlinearity of TiO$_2$. The other is neglecting the third-order nonlinearity of TiO$_2$. The

Figure 4. The transmitted Z-scan curves from left incidence for different wavelengths from 530.0 nm to 550.0 nm. (a), (c) Open-aperture Z-scan; (b), (d) close-aperture Z-scan.
Figure 5. The amplitude of the transmitted (a) open- and (b) closed-aperture Z-scan signals from left (red circle) and right (blue diamond) incidence for different wavelengths.

electric field is localized in the layers of TiO$_2$ for modes B and C, which can be seen from Fig. 2(d). Results show that the nonlinear contribution of TiO$_2$ to Z-scan signals can be neglected in the current PBG-metal heterostructure. Therefore, the localization of the electric field is not the main contribution to increase the amplitude of Z-scan signals. The relative electric field intensity in the silver layer $|E|^2_{Ag} = \int_{0}^{dAg} |E|^2 dz / |E_i|^2$ is the key factor. The relative electric field intensity of the silver layer $|E|^2_{Ag}$ at mode B is about 30 times larger than those at modes A and C. That is the main reason why the Z-scan signals are distinct at mode B. Certainly, the other factors will also affect on the amplitude of Z-scan signals, such as the modulation of the PBG structure to the electric field, the peak shape of the transmission curve, and so on.
In the following, we present more details of the Z-scan characteristics around the light-tunneling B. The Z-scan curves from left incidence for different wavelengths from 530.0 nm to 550.0 nm are shown in Fig. 4. The Z-scan curves (Fig. 4(a) and (b)) change its shape from a valley to a peak as wavelength increases. The maximum valley and peak of the open-aperture Z-scan correspond to the wavelengths of D and E. In addition, the amplitude of the peak is much larger than that of the valley, which indicates that the transmitted signal of the heterostructure is more suitable to be a laser cavity than an optical switching. For the closed-aperture Z-scan, the peak and valley can coexist around 540.0 nm, however, they can not coexist for open-aperture Z-scan, as shown in Fig. 4(c) and (d).

To further compare the Z-scan signals from left incidence with those from right incidence, we define an easily measurable quantity $\Delta T_{p-v}$ as the absolute value of the difference between the normalized peak and valley transmittance: $|T_p - T_v|$. Apparently, the normalized peak or valley transmittance will be abbreviated to unit in the open-aperture Z-scan signals. Figure 5 gives the variation of $\Delta T_{p-v}$ for the

**Figure 6.** The reflected Z-scan curves from right incidence for different wavelengths from 530.0 nm to 550.0 nm. (a), (c) Open-aperture Z-scan; (b), (d) close-aperture Z-scan.
Z-scan signals from two incident directions as a function of wavelength. Results show that the Z-scan characteristics of the heterostructure from right incidence are similar to those from left incidence, but the $\Delta T_{p-v}$ of Z-scan signals from left incidence are larger than that from right incidence. Meanwhile, the maximum valley and peak of the Z-scan signals are located at the same spectral position for both of incident directions.

4.2. Reflected Z-scan for 1D PBG-metal heterostructures

It is well known that the reflection of the 1D PBG material can not be ignored. Therefore, the reflected Z-scan signal should also be considered in the current 1D PGB-metal heterostructure. Figure 6 gives the reflected Z-scan curves from right incidence for wavelength ranging from 530.0 nm to 550.0 nm. The reflected Z-scan curves change its shape from a peak to a valley as wavelength increases, whose shape is opposite to that of transmitted Z-scan curves. The valley of the reflected Z-scan curves is deeper that of the transmitted Z-scan curves.

Figure 7. The reflected Z-scan curves from left incidence for different wavelengths from 540.0 nm to 541.0 nm. (a), (c) Open-aperture Z-scan; (b), (d) close-aperture Z-scan.
Figure 8. The reflected open- (OA) and closed-aperture (CA) Z-scan curves from left ((a) and (c)) and right ((b) and (d)) incidence for spectra position $\lambda_1=540.0$ nm ((a) and (b)) and $\lambda_2=541.6$ nm ((c) and (d)).

There is a light-tunneling in the 1D PBG-metal heterostructure from the left incidence, where the reflection is about zero. The light-tunneling will shift dynamically since the nonlinear dielectric constant of silver varies with the field, which is very sensitive to the input light intensity. Therefore, the reflected Z-scan signals of the heterostructure from the left incidence are very intense close to the light-tunneling, as shown in Fig. 7. A very sharp peak appears in both of the reflected open- and closed-aperture Z-scan signals for the wavelength from 540.0 nm to 541.0 nm. The reflected Z-scan characteristics from left incidence are similar to those from right incidence away from the light-tunneling.

The reflected Z-scan curves from two incident directions at 540.0 nm and 541.6 nm are given in Fig. 8, which correspond to the
maximum peak and valley of the reflected open-aperture Z-scan signal from right incidence. It can be seen that the reflected Z-scan signals from left incidence are much larger than those from right incidence for the two cases. Then, we can conclude that the reflected signal of the 1D PBG-metal heterostructure from left incidence is a good candidate for optical switching according to the results of Fig. 6 and 8. As the nonreciprocity of the transmitted or reflected Z-scan signals, the 1D PBG-metal heterostructure can also be used as optical diode.

5. CONCLUSION

In conclusion, we simulated the transmitted and reflected Z-scan characteristics of the PBG-metal heterostructure from left and right incidence. An apparent Z-scan signal will appear around the light-tunneling. The variations of the transmitted and reflected Z-scan shape are discussed. The transmitted and reflected Z-scan amplitude in two incident cases are also analyzed. Results show that the Z-scan signals are nonreciprocal for two incident directions, and both of the transmitted and reflected Z-scan signals from left incidence are much larger than those from right incidence. Applying our results enable to optimize the PBG-metal heterostructure designs and operation wavelengths for particular applications such as laser cavity, optical diode and optical switching.

ACKNOWLEDGMENTS

This research was supported by the Chinese National Key Basic Research Special Fund (grant 2011CB922003), National Natural Science Foundation of China (NNSFC) (grant 10974103, 60708020 and 61008002), 111 project (B07013), and the Fundamental Research Funds for the Central Universities.

REFERENCES

3. Rahimi H., A. Namdar, S. Roshan Entezar, and H. Tajalli, “Photonic transmission spectra in one-dimensional fibonacci
multilayer structures containing single-negative metamaterials,” 


