

Time Domain Modeling of All-Optical Switch based on PT-Symmetric Bragg Grating

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Abstract: In this paper, the transient behavior of an all-optical switch based on a Parity-Time (PT) Bragg grating structure is analyzed using the time domain Transmission Line Modeling (TLM) method. The accuracy of the TLM model is analyzed and time and frequency responses of the PT all-optical switch are discussed.

Keywords: ALL-OPTICAL SWITCHING, PT-SYMMERTIC GRATING, TIME-DOMAIN SIMULATION, TRANSMISSION LINE MODELING METHOD

1. Introduction

In the last couple of decades, a considerable amount of research has been focused on improving the quality of optical telecommunication in terms of increasing the signal speed and bandwidth. Many new photonic technologies and solutions have been investigated and proposed including photonic crystals, micro-resonators, plasmonics, optical metamaterials [1] and most recently Parity and Time (PT) material structures [2].

In optics, PT-symmetric materials are artificial structures that combine gain and loss in an optical waveguide so that it mimics the complex Parity-Time (PT) symmetric potential in quantum physics [2,3]. The main characteristic of the PT-symmetric structure is that below a certain threshold breaking point the system operates in a stable regime with average no net-loss or gain [4] whereas above the breaking point the system exhibits an energy growth (lasing-like behavior). PT-symmetric structures in the form of a grating [4,5], coupled waveguides [6,7] and lattices [2,8] have been investigated and functionalities such as all-optical switching [9], unidirectional invisibility [5], double refraction and power oscillation [2], lasing and absorber cavity [10] have been reported. Experimentally, PT couplers have been demonstrated on a LiNbO₃ platform with one waveguide providing gain and the other an equal amount of loss [9]. In terms of modeling, PT-symmetric structures have thus far been studied exclusively in the frequency domain using coupled mode theory [4,11], Floquet-Bloch theory [2] and modal analysis [12].

In this paper we report on the time-domain modeling of a PT-symmetric Bragg grating using the Transmission Line Modeling (TLM) method and investigate transient behavior in an all-optical switch application.

The paper is organized as follows: in the next section a brief overview of the PT-Bragg grating structure and the TLM model are given, and frequency domain results are compared with the analytical method. In section 3 a time-domain response of an all-optical switch is obtained and discussed. Section 4 outlines the conclusion of the paper.

2. The TLM Model of the PT Bragg Grating

A. PT-Symmetric Bragg Grating

A schematic presentation of a PT Bragg grating having N periods of length Λ and surrounded in a medium of refractive index n_0 is shown in Fig.1(a). Periodic layers of the PT structure are comprised of a dielectric material possessing gain and loss such that refractive index of the material satisfies the condition $n(x) = n^*(-x)$, i.e the real part of refractive index is a symmetric function whereas the imaginary part is an odd function of the position x as shown for one period of the grating Λ in Fig.1(b). It is noted that one period of the grating consists of four piecewise constant layers of complex refractive index. The complex refractive index $\hat{n}(x) = n_R \pm \Delta n_R(x) \pm jn_I(x)$ consists of the average refractive index n_R , real index modulation Δn_R and gain/loss n_I . A positive n_I defines gain whereas negative n_I defines loss. The length of each period Λ is defined by the Bragg frequency f_B and the average index n_R as $\Lambda = c/(2n_R f_B)$, where c is the speed of light in free space.

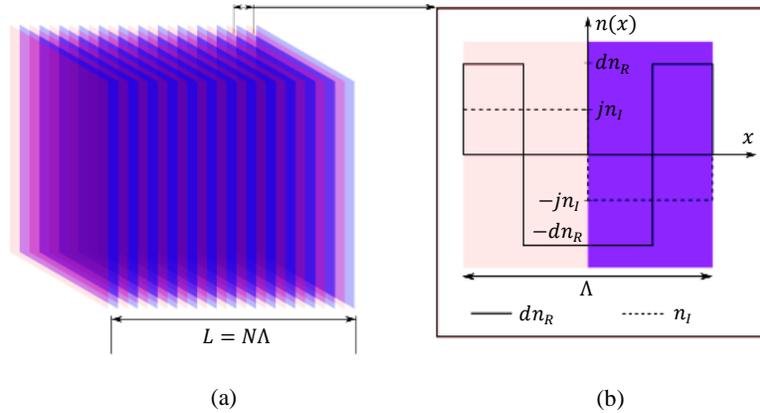


Fig. 1. Schematic illustration of PT-symmetric Bragg grating; (a) PT-symmetric Bragg grating of length L and N periods ; (b) Refractive index distribution for a single period Λ .

B. The TLM model

The TLM method uses equivalences between the fields and the transmission line theory to model propagation of the electromagnetic field. In its simplest one-dimensional form the whole structure is discretized into small sections of transmission lines of length $dx < \lambda/10$ where λ is the operating wavelength. The circuit equivalent of one transmission line section is given in Fig. 2 where L_0 , C_0 , G are inductance, capacitance, and conductance per unit length in vacuum. Voltage impulses scatter at each section according to network theory and subsequently propagate to the neighboring sections. Successive repetitions of this scatter-propagate procedure provides an explicit and stable time stepping algorithm that mimics electromagnetic field behavior to second order accuracy in both time and space. Implementation of material properties, gain and loss in the TLM method is straightforward and as such the method is ideally suited to modeling nonlinear and time-varying behavior. In order to model material properties in the TLM method the following equivalences are valid [13]:

$$\epsilon \leftrightarrow \frac{C}{\Delta x} \quad , \quad \mu \leftrightarrow \frac{L}{\Delta x} \quad , \quad \sigma \leftrightarrow \frac{G}{\Delta x} \quad (1)$$

where ϵ , μ and σ denote dielectric permeability, magnetic permeability and conductivity.

The real part of index is directly modeled through its extra capacitance ΔC as,

$$\Delta C = \epsilon_0 \operatorname{Re}(\hat{n}^2 - 1) \Delta x. \quad (2)$$

Gain and loss in the TLM model are modeled using the conductivity G as,

$$G = -2 \omega \operatorname{Re}(\hat{n}) \operatorname{Im}(\hat{n}) \Delta x, \quad (3)$$

where $\operatorname{Re}(\hat{n})$ and $\operatorname{Im}(\hat{n})$ are the total real (average and the modulation) and the imaginary part of the index at the corresponding TLM segment and Δx is the spatial discretization of the TLM. It is important to note that when n_I is negative the conductivity G is positive thus acting as a conductive (lossy) node. In addition, conductivity G is frequency dependent and is approximated to be at the center (Bragg) frequency f_B . It is worth mentioning that the model as presented does not include gain saturation so that transmitted and reflected signals can increase without limit whilst in practice this is not the case.

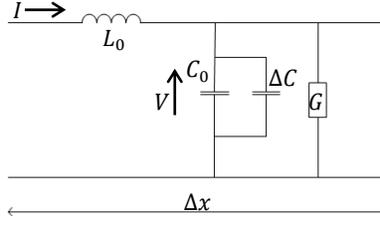


Fig. 2. A single segment of one dimensional TLM meshing.

As an illustration, a 100 periods PT Bragg grating surrounded by air ($n_0 = 1$) and having a Bragg frequency $f_B = 667$ THz, average refractive index $n_R = 1.5$, real index modulation $\Delta n_R = 0.05$ and gain/loss index $n_I = 0.03$ is considered. The excitation signal is centered at a Bragg frequency of f_B and modulated by a Gaussian function having a normalized maximum value of 1 V and a width of 0.03 ps between the 0.1% truncation points. In order to assess the accuracy of the model the frequency domain of the transmitted signal for various spatial discretizations Δx is shown in Fig. 3(a) and compared against the analytical model based on a transmission matrix approach [5]. For clarity Fig. 3(b) shows the transmittance over the frequency range $651 - 656$ THz. It can be seen that accuracy strongly depends on the mesh discretization, and that for good agreement a fine spatial discretization of $\Delta x < \lambda/48$ is required, where λ is the wavelength inside the material of average index n_R . The fact that the frequency response is not symmetric with respect to the Bragg frequency is due to the fact that the grating is embedded in air rather than in a material with the average refractive index n_R .

It is known that a PT-Bragg grating is not a reciprocal structure and therefore the responses will depend on the direction of the input signal, i.e., whether the grating is excited from the left or from the right of the grating [4]. Fig. 4 depicts the transmitted power, the reflected power for the left incidence (Γ_L) and the reflected power for the right incidence (Γ_R) as a function of frequency for different values of gain/loss, i.e. $n_I = 0, 0.003$ and 0.04 . The input signal is the same as that used to obtain Fig. 3, with a spatial sampling rate $\Delta x = \lambda/96$. As shown in Fig. 4, when the structure is not having any gain/loss ($n_I = 0$), the frequency responses correspond to the conventional Bragg stack with a band-gap centered at the Bragg frequency (f_B). Fig. 4 shows that the transmitted power is the same, whilst the reflected powers for the left and right incidence differ. In addition to the non-reciprocal behavior, as gain/loss increases, the band gap disappears with the most dramatic changes occurring on the band-edge. This specific

property of the PT-Bragg structure can be exploited for all-optical switching applications and this is demonstrated in the next section.

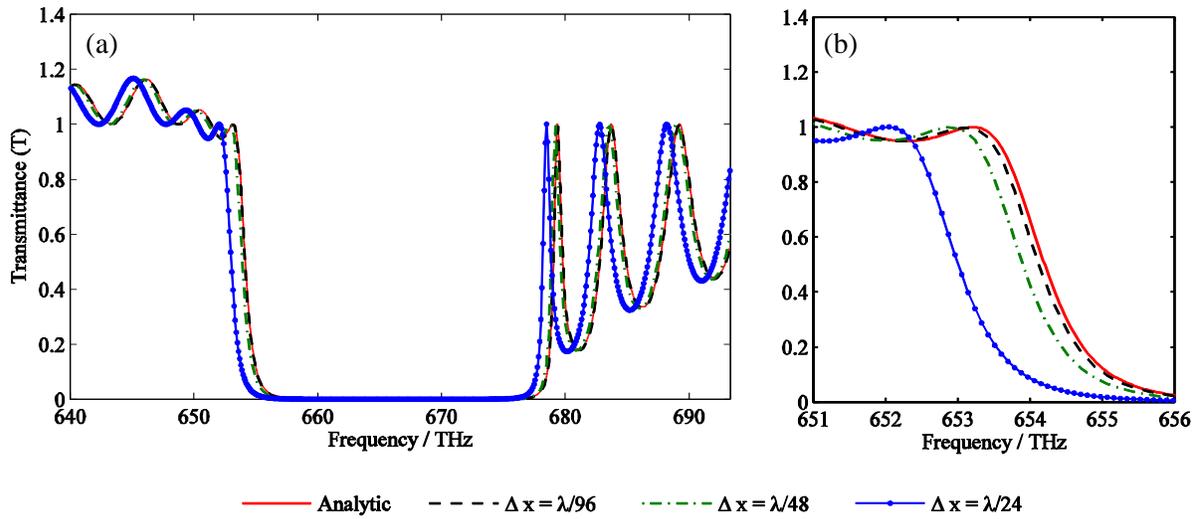


Fig. 3. Transmitted power (T) of PT-symmetric Bragg grating as a function of frequency generated by analytic model and the TLM method for a various number of spatial discretizations $\lambda/24$, $\lambda/48$ and $\lambda/96$.

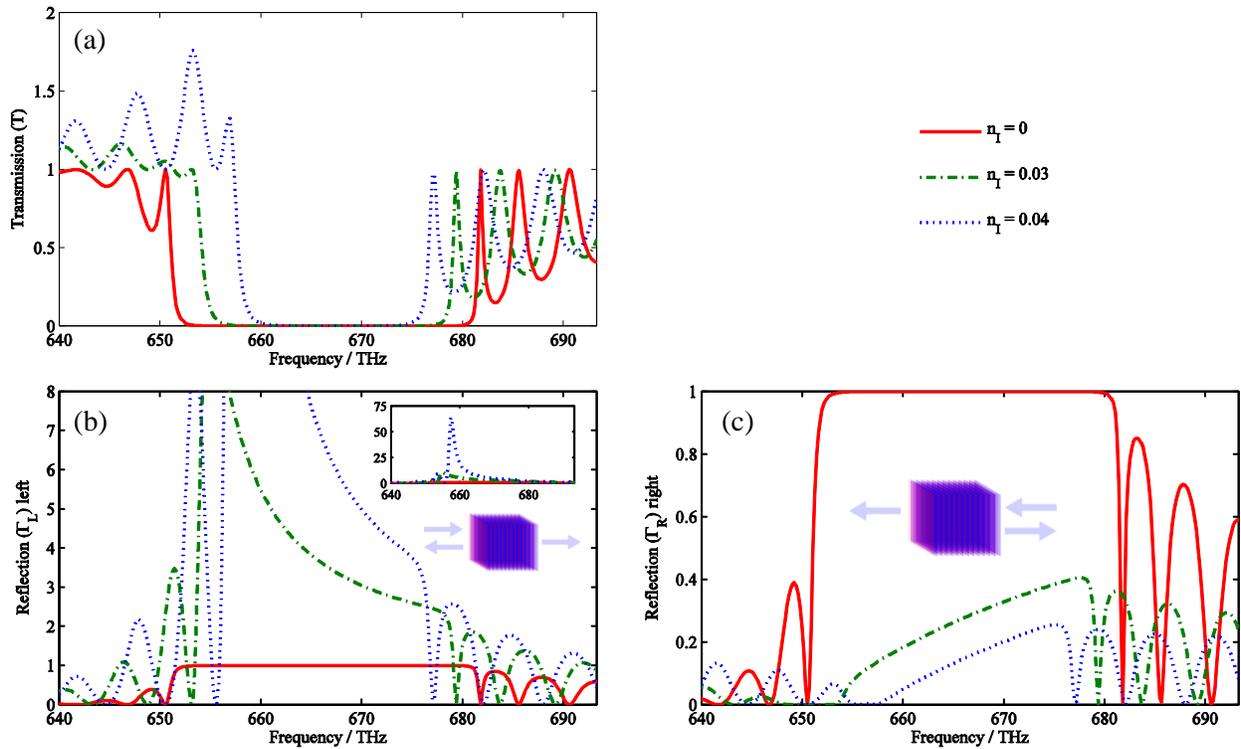


Fig. 4. (a) Transmitted T , (b) reflected power for left Γ_L and (c) reflected power for the right Γ_R incident of PT-symmetric Bragg grating for various values of gain/loss as a function of frequency.

3. PT-Symmetric Bragg Grating All Optical Switching Application

In this section the application of the PT Bragg grating as an all-optical switch is investigated. The model used is the same as for Fig.4 with the only difference that the gain/loss (n_I) value is switched at the time $t = 2.73 \text{ ps}$ from $n_I = 0$ to $n_I = 0.0375$. The plane wave is launched with the frequency at the band-edge of the Bragg grating $f = 655 \text{ THz}$. The spatial step of $\Delta x = \lambda/96$ is used and the problem is run for 5.46 ps . Figs. 5 shows the envelope of (a) the transmitted, (b) reflected power for the left incidence and (c) reflected power for the right incidence before and after switching at $t = 2.73 \text{ ps}$. Fig.5(a) shows that the total transmitted power before switching is very low, less than 0.01% corresponding to the conventional Bragg grating, and that after switching transmitted power sharply increases. The transient state in the transmitted signal is noticeable and is less than 1 ps long. Reflected power for the incidence from the left (Γ_L) of the structure is shown in Fig.5(b) showing that after the strong transient lasting less than 0.5 ps there is almost no reflection. Similar behavior is observed for the reflection for the incidence from the right of the structure in Fig.5(c) but with much smaller transient time ($< 0.2 \text{ ps}$).

It is interesting to also analyze the frequency content of signals in Figs. 5(a,b,c). Figs. 5(d,e,f) compares the frequency of the transmitted and reflected signals with (solid line) and without switching of the gain/loss (dashed line). Fig.5(d) shows that transmitted signal has much wider spectrum compared with the one in the case of no switching (inset picture); this is caused by the presence of the strong transient. Similar behavior is noticeable for the reflected signals in Fig. 5(e,f) but the intensity is reduced due to reduced reflection.

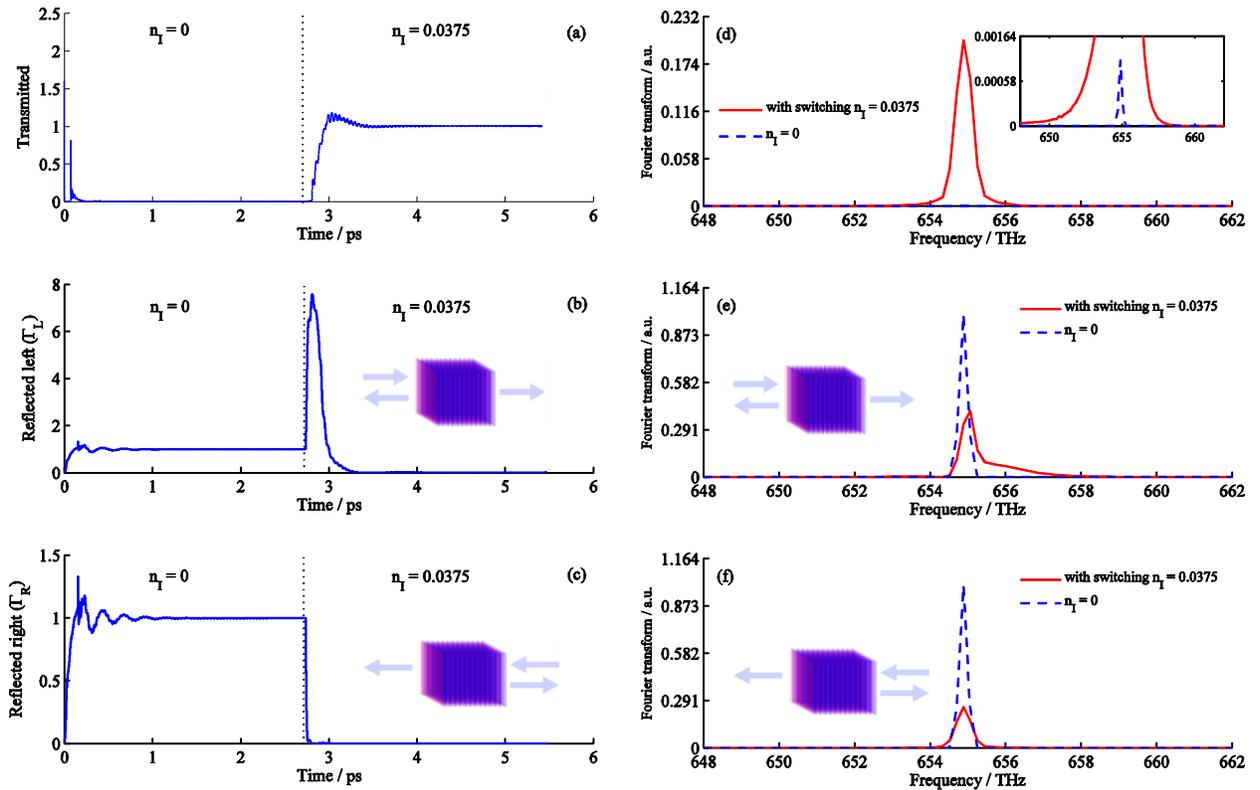


Fig. 5. The envelope of transmitted and reflected signals when the switching from $n_I = 0$ to $n_I = 0.0375$ occurs at $t = 2.73 \text{ ps}$ for: (a) the transmitted signal intensity; (b) reflected signal for the left incidence and (c) reflected signal for the right incidence. Fig.5(d-f) compares the frequency content of the transmitted and reflected signals in the case of gain and loss switching in the grating and no switching.

4. Conclusion

The paper reports on the time-domain modeling of PT-symmetric Bragg gratings. The material parameters are modeled by adding extra capacitance to deal with material parameters and conductance to deal with the gain and loss in the model. The paper shows that the accuracy of the time domain model strongly depends on the mesh size and that discretization of $\Delta x < \lambda/48$ is required for good accuracy. The TLM model is used to engineer the application of the PT Bragg grating as an all-optical switch by choosing the operating frequency to be on the band edge of the transmission spectrum. The simulation shows that the switching of the gain and loss in the system introduces strong transients in transmitted and reflected signals which then consequently increase the frequency content of these signals.

References

- [1] R. Soref, "The past, present, and future of silicon photonics," *IEEE Journal of selected topics in quantum electronics*, vol. 12, no. 6, Part 2, pp. 1678-1687, 2006.
- [2] K. G. Makris, R. El-Ganainy, and D. N. Christodoulides, "Beam dynamics in PT symmetric optical lattices," *Phys. Rev. Lett.*, vol. 100, no. 103904, pp. 1-4, March 2008.
- [3] C. M. Bender, S. Boettcher, and P. N. Meisinger, "PT-symmetric quantum mechanics," *Journal of Mathematical Physics*, vol. 40, pp. 2201-2229, 1999.
- [4] M. Kulishov, J. M. Laniel, N. Belanger, J. Azana, and D. V. Plant, "Nonreciprocal waveguide Bragg gratings," *Optics Express*, vol. 13, no. 8, pp. 3068-3078, April 2005.
- [5] Z. Lin, H. Ramezani, T. Eichelkraut, T. Kottos, H. Cao, and D. N. Christodoulides, "Unidirectional invisibility induced by PT-symmetric periodic structures," *Phys. Rev. Lett.*, vol. 106, no. 213901, pp. 1-4, May 2011.
- [6] T. Kottos, "Broken symmetry makes light works," *Nature Physics*, vol. 6, pp. 166-167, March 2010.
- [7] R. El-Ganainy, K. G. Makris, D. N. Christodoulides, and Z. H. Musslimani, "Theory of coupled optical PT-symmetric structures," *Opt. Lett.*, vol. 32, pp. 2632-2634, 2007.
- [8] S. Nixon, L. Ge, and J. Yang, "Stability analysis for soliton in PT-symmetric optical lattices," *Phys. Rev. A*, vol. 85, no. 023822, pp. 1-10, 2012.
- [9] C. E. Rüter, K. G. Makris, R. El-Ganainy, D. N. Christodoulides, M. Segev, and D. Kip, "Observation of parity-time symmetry in optics," *Nature Physics*, vol. 6, pp. 192-195, March 2010.
- [10] Y. D. Chong, L. Ge, and A. D. Stone, "PT-symmetry breaking and laser-absorber modes in optical scattering systems," *Phys. Rev. Lett.*, vol. 106, no. 093902, pp. 1-4, March 2011.
- [11] D. Kip and E. Kratzig, "Anisotropic four-wave mixing in planar LiNbO₃ optical waveguides," *Phys. Rev. Lett.*, vol. 17, pp. 1563-1565, 1992.
- [12] J. Čtyroký, V. Kuzmiak, and S. Eyderman, "Waveguide structures with antisymmetric gain/loss profile," *Optics Express*, vol. 18, no. 21, pp. 1-9, October 2010.
- [13] C. Christopoulos, *The Transmission Line Modeling Method: TLM*. Piscataway, NJ: IEEE Press, 1995.