Optik 127 (2016) 4839–4843

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Physical origin of twice threshold phenomena in the transmission of the nonlinear photonic crystal molecules☆,☆☆

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ARTICLE INFO

Article history:
Received 11 January 2016
Accepted 12 February 2016

Keywords:
Photonic crystal
Transmission jump
FDTD

OCIS codes:
160.0160
190.0190
230.0230

ABSTRACT

We investigate the dynamics response of photonic crystal (PC) molecules with Kerr nonlinearity to the input continuous wave (CW) and focus on the jump action of the transmission on the input power density with the theoretical analyses and the simulation which is based on the finite-difference time-domain technique. It is found that the twice transmission jump behaviors exist when the frequency of input CW source be reasonable chosen and the photonic crystal (PC) atoms have the nearly same resonant frequency and different size. Therefore, these kinds of PC molecules can be employed to build new type optical diodes.

Photonic crystals (PCs) [1] have been widely used and various functional devices based on PCs have been proposed and demonstrated, such as waveguides [2–4], power splitters [5], wavelength multiplexers, optical delay lines, and optical switches [6]. As compared to perfect PCs, PCs with defect are more interesting and useful. It has been recognized that photons can be strongly localized into a point defect in a similar way by which electrons are confined into an atom [7,8]. Due to this reason, a PC defect is sometimes referred to as a PC atom. Naturally, a structure consisting of two coupled PC defects is generally termed as a PC molecule. Indeed, there exist many similarities between the coupling of real or artificial atoms and that of PC atoms [9]. In the past several years, PC defects have been extensively studied and explored for various applications [10,11]. In particular, it can be used to build all-optical switches, optical diodes [12,13], a key component for ultrafast all-optical communication and optical computation in the future, when Kerr nonlinearity is introduced [14].

The dynamical behaviors of nonlinear PCs have been studying recent years, some people focus on the PC atoms respond to the excitation of ultrashort pulse and present an analytical description for the pump-probe simulation which used to characterize the dynamical response of nonlinear PC structures [15]. But the analysis cannot describes how the defect mode of nonlinear PC defect pairs shifts under the different pump CW frequencies when the two defect mode similar to each other. Besides, there have no one analysis the continuous jump behavior of PC molecules composed of defect pairs, for the sake of this phenomenon can be observed only when the resonant frequencies of the constitutional PC atoms properly misaligning. As we know, if there exist continuous jump behavior of transmission when launch CW from one side, it implies that the PC defect pairs can be use to design a new type of optical diode.

Previously, we investigate the unidirectional transmission behavior of photonic crystal (PC) molecules consisting of defect pairs with Kerr nonlinearity [16], it is found that by intentionally and properly misaligning the resonant frequencies of the constitutional PC atoms, the transmission contrast as well as the maximum transmission of the nonlinear PC molecules can be significantly improved. In addition, there exist twice jump behaviors of the transmission when launch from right sides. In this paper we

☆ Foundation item: Supported by the Foundation of Key Laboratory of Opto-electronic Information Acquisition and Manipulation of Ministry of Education (OEIAM201413).
☆☆ The Natural Science Foundation of the Education Department of Anhui Province (KJHS2015B07).
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http://dx.doi.org/10.1016/j.ijleo.2016.02.038
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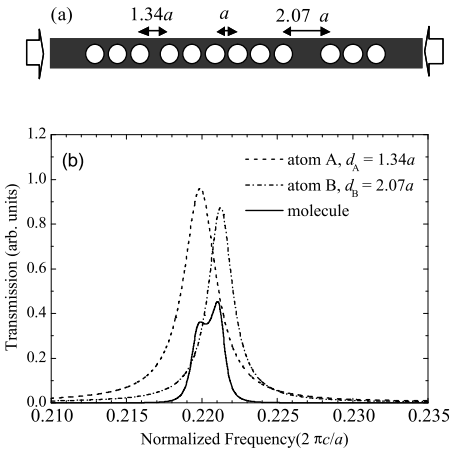

Fig. 1. (a) Basic structure of the nonlinear PC molecules studied in this paper. (b) Linear transmission spectrum of the nonlinear PC molecule in which $d_A = 1.34a$ and $d_B = 2.07a$ (solid curve). The spectra of the two constitutional atoms (atoms A: dashed curve and atom B: dotted curve) are also provided for.

investigate the continuous transmission jump behavior of PC molecules composed of defect pairs to the different pump CW frequencies then we change the power density and analyses the phenomena observed in the simulations.

The basic structure of the nonlinear PC molecules to be studied in the paper is schematically shown in Fig. 1(a). Twelve identical air holes are drilled in a slab waveguide made of a material with Kerr nonlinearity (e.g. GaAs). This kind of structure can be easily obtained with the present fabrication technologies [17–20]. The linear refractive index and the nonlinear coefficient for the Kerr material are assumed to be $n_0 = 3.37$ and $n_2 = 0.01\ \mu m^2/W$. The radius of the air holes is 0.12 μm and the width of the waveguide is 0.6 μm. The distance between the neighboring air holes is kept to be $a = 0.4$ μm except that between the third and fourth air holes and that between the ninth and tenth air holes. Two defects are introduced by increasing the separation between the third and fourth air holes to 1.34*a* and that between the ninth and tenth air holes to 2.07*a*. In the following, the two defects are denoted as defects A and B and their sizes are represented by d_A and d_B for the sake of convenience. Thus, we have $d_A = 1.34a$ and $d_B = 2.07a$ in this case and this choice makes the frequency of defect mode B little higher than the frequency of defect mode A, it can be seen from Fig. 1(b), it shown the Linear transmission spectrum of the nonlinear PC molecule. The spectra of the two constitutional atoms are also provided for reference. Misaligning the resonant frequencies can improve the transmission contrast as well as the maximum transmission, what important, we intentionally misalign the two defect modes in order to observe the phenomena of continuous jump behavior in transmission when the CW intensity reaches thresholds. In theory, when the defect mode A is easier to be shifted than defect mode B under the input CW. We launch the wave from the right side, the defect mode B will shift first toward low frequency. As a result, the separation between the two defect modes is narrowed and the overall transmission is enhanced. With increasing the power density, defect mode B will eventually coincide with defect mode A. Further increase in the power density leads to an increase in the separation. However, defect mode A may catch up with defect mode B if the power density is further raised because it is more sensitive to the external excitation. Consequently, there may exist twice threshold in the transmission when the input wave frequency is reasonable chosen.

Previously, Lan has studied the interaction of nonlinear PC atoms [22], he provide a physical insight into the dynamics of nonlinear PC atoms under the excitation of pump pulses. Basically, it is assumed that the transmission we observed in the simulation is the time-averaged transmission of the transient values within an oscillation period between its initial position and a final position. In this case, the time-averaged transmission spectrum of the nonlinear PC atom is given by the integration of the transient spectrum, which has been weighted by the corresponding staying time, within an oscillation period. Based on this model, the time-averaged transmission spectrum of a nonlinear PC atom with a Lorentz spectral shape has been derived to be

$$\bar{T}(\omega) = \frac{2}{\pi}\int_0^{\pi/2} \frac{\gamma^2}{\gamma^2 + \left(\omega_0 - \Delta\omega\cos^2\varphi\right)^2}\mathrm{d}\varphi \tag{1}$$

where ω_0 is the resonant frequency of the PC atom, γ is the linewidth of the spectrum, $\Delta\omega$ is the total shift of the defect mode, and φ represents the phase of the oscillation. The transmission spectrum given by Eq. (1) can be numerically calculated. However, it only discusses the dynamics of PC atoms under the excitation of pump pulse. For device applications, e.g., in all-optical switches, it is necessary to find out major features of the transmission under the input of continuous wave which act as both control and signal wave with different frequency and different power density. So the validity of the physical model needs to be verified by numerical simulations and/or practical experiments and the driven of CW source should to be taken into account. Besides, it is necessary to study the transmission under different pump frequency which act as probe wave also and analysis the pump frequency and the power density which is the decisive factor to the dynamics of the PC structure.

Our study start from analyses the transmission trend of different CW sources with the same power density, then discusses the feature of defect mode in the nonlinear PC atoms. We proposed a numerical simulation based on the nonlinear finite-difference time-domain (FDTD) technique. The grid size used in the simulation is *a*/20 for both PC atoms. The size of the nonlinear PC atom is 1.34*a*, the dependencies of the transmission on the different pump CW frequencies are presented in Fig. 2, the power density of the pump waves choused to be 1 W/μm, 20 W/μm, 40 W/μm, 60 W/μm, and 80 W/μm. In all cases, it can be seen that the time-average transmission increases slowly when gradually enhance the pump frequency of CW source while the power density remain unchanged. However, a sharp increase in transmission is observed as the frequency reaches a certain level. When we keep on increase the frequency of CW source, the transmission starts to decrease gradually. It proves that the final position of defect mode of PC structure change slightly under different pump frequencies when keep the power density unchanged. However, when the pump frequency close to the defect

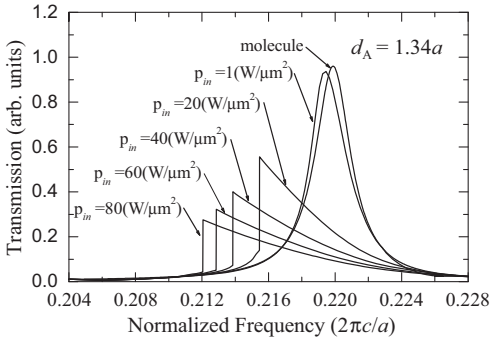

Fig. 2. Dependence of the transmission of a CW source launched into nonlinear PC atom in which $d_A = 1.34a$ on the frequency of the CW source. The power density of the CW source chosen to be 1 W/μm, 20 W/μm, 40 W/μm, 60 W/μm, and 80 W/μm, respectively.