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Controlling ultrashort pulses shape using one-dimensional graded index photonic crystals

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ABSTRACT

In this study, we analyze the characteristics of a one dimensional coupled cavity-waveguide composed of SiO_2/TiO_2 layers in which three defects are located symmetrically in structure, using finite-time domain-method and transfer matrix method. Then we introduced a new structure based on mentioned one-dimensional structure in which the higher refractive index material is maintained constant, while lower refractive index slightly increases with a constant step value from the beginning to the end of the structure. Simulation results reveal that the graded structure represents unique features in comparison with the conventional structure.

1. Introduction

In the past three decades, photonic crystals (PCs) which are periodic structures in one or more spatial direction, have inspired great interest because of their potential applications in various optoelectronic devices, e.g., lasers, light emitting diodes and waveguides [1–4]. Specifically, PC waveguides have attracted considerable theoretical and experimental applications in telecommunications systems [4,5]. Generally, conventional PC waveguides are formed by removing a series of elements from the PCs. However, another type of waveguides, which is now referred to as coupled cavity waveguides (CCWs), was proposed and demonstrated during past years [6–8]. CCWs are constructed by introducing localized defect modes along the structures. In fact the defects play a crucial effect to localize the electromagnetic (EM) waves between defects and make CCWs as one of the best candidates to transmit ultrashort pulses. CCWs have exhibited some advantages over conventional waveguides due to their applications in integrated delay lines, because of their specific low group velocity [9] and nonlinear optical devices, because these waveguides can confine light strongly, in the small cavity regions and enhance nonlinear optical effects [10]. Moreover CCWs are attractive for their applications for dispersion compensators, due to the potentially rich tunability of dispersion characteristics [11].

The PCs are classified mainly into three categories, that is, one dimensional (1D), two dimensional (2D) and three dimensional (3D) crystals, according to the dimensionality of periodicity. 1D PCs are made of stacked thin layers which have several advantages in comparison with 2D and three dimensions 3D structures. For instant, in 1D PCs the thickness of each layer is rather easy to control and it is possible to fabricate CCWs precisely as we design. In addition, a 1D structure shows no polarization dependence, which is required in practical usage in optical communication systems [12,13]. Hence, 1D PCs have attracted much attention from researchers.

In most cases, 1D CCWs are composed of two kind of dielectric films, one with higher refractive index (n_H) and the other one with a lower refractive index of (n_L) in which defect layers are located in the structure and separated with each other by a fixed length [14]. Corresponding to the number of defects in CCWs structures, the same number of defect modes can be seen in the band gap area of transmission spectrum. Thus, the transmittance spectrum has a multi-peak structure within the band and low-transmittance region existing between the peaks similar to a normal pass band of PCs [15]. So in such structures the loss of light propagating through the CCWs can be seen and especially it would severely affect the ultrashort pulses transmitting the CCWs, either in intensity or in shape.

Researchers for overcoming this problem have increased the size of the CCWs structure and number of defects [16]. In the structures that the coupled-cavity system is composed of n defects, n discrete levels are formed. When the numbers of defect increases, the oscillations of CCW bandwidth, reduced and finally the discrete levels become a continuous band structure under the condition in which the number of defects is infinite, whereas fabricating such structures with lots of layers is complicated, from the manufacturing point of view.

In this paper, we investigate the properties of a 1D CCWs with finite size, made of dielectric films, one with high and the other with low refractive index in which 3 defect layers are created symmetrically in structure. Then the low refractive index slightly increases with a constant step value from the beginning to the end of the structure

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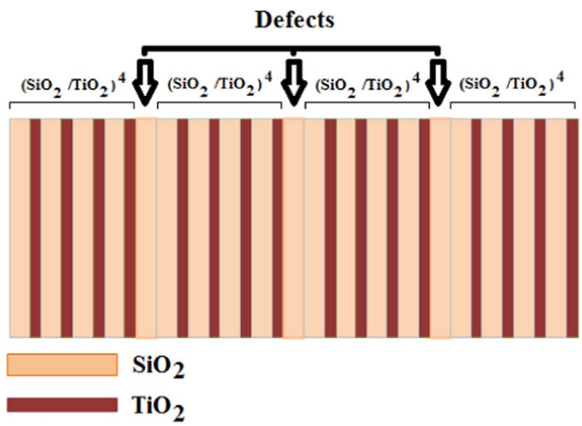

Fig. 1. Schematic diagram of 1D CCW structure.

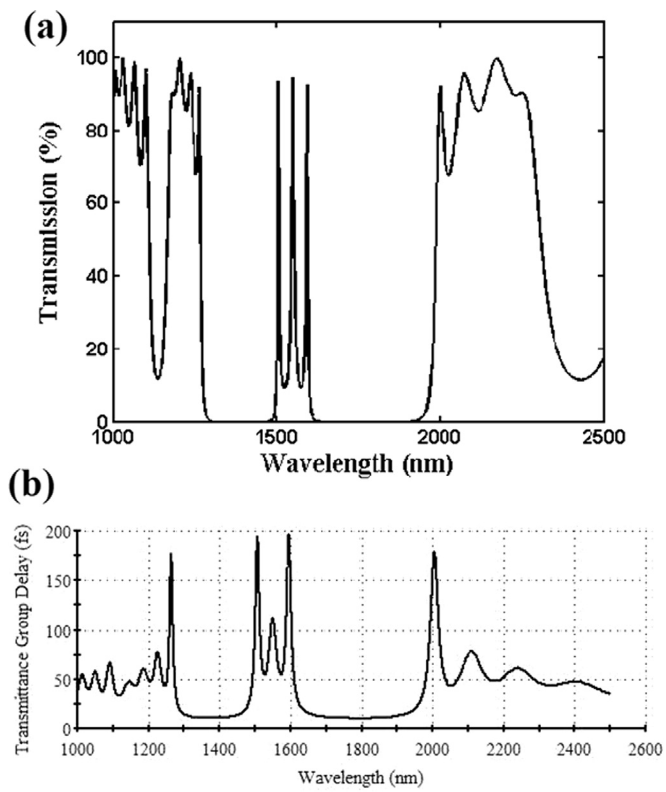

Fig. 2. (a) Transmission and (b) group delay spectrum of the 1D CCWs consist of two kinds of dielecteric thin films with refractive index of $n_H = 2.25$ (TiO_2) and $n_L = 1.444$ (SiO_2) in which three defects layer located periodically in structure.

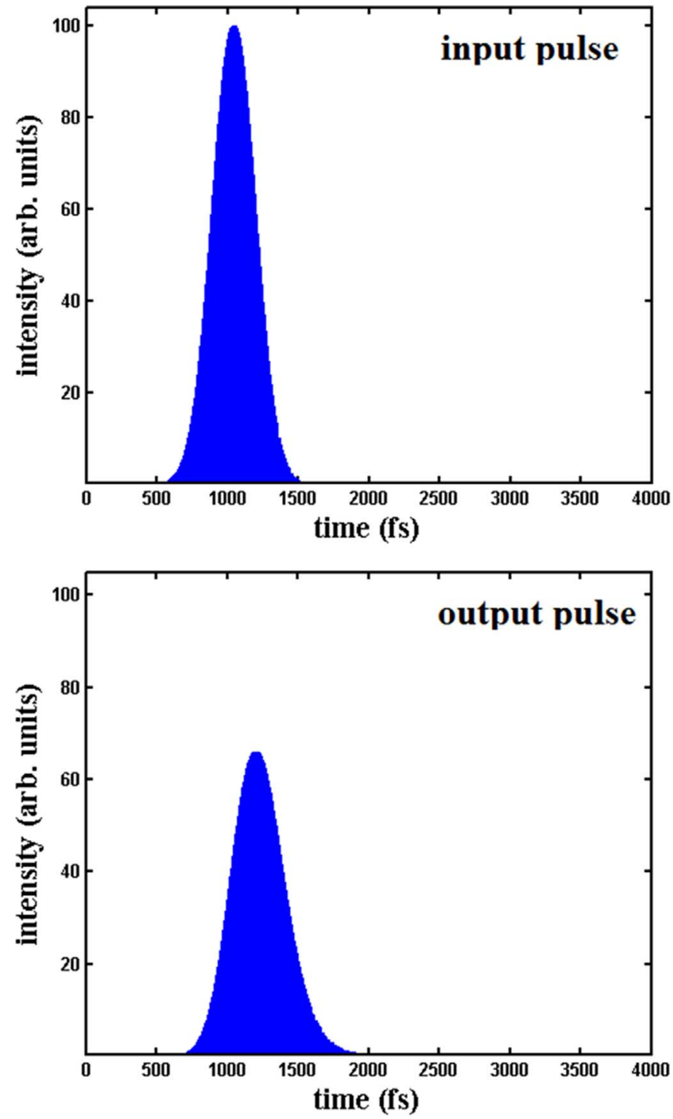

Fig. 3. Input and output shape of a 1000 fs pulse regarding the 1D CCWs consist of two kinds of dielecteric thin films with refractive index of $n_H = 2.25$ (TiO_2) and $n_L = 1.444$ (SiO_2) in which three defects layer located periodically in structure.

while the higher refractive index is maintained constant. The proposed structure are able to transmit ultrashort pulses with retaining all original features of the pulses which can be employed to construct very good and efficient delay lines for ultrashort optical pulses.

2. Structures and computational methods

In the present study, at first we study a 1D CCW consist of dielectric films one with higher refractive index of $n_H = 2.25$ and the other with lower refractive index of $n_L = 1.444$ corresponding to TiO_2 and SiO_2 materials, respectively. Defects are introduced into the medium by periodically inserting SiO_2 layers into the multilayer stack. Briefly, this CCW presents in notation form as: $air|\,(LH)^4L\,(LH)^4L\,(LH)^4L\,(LH)^4|air$. The optical thickness of high and low index materials and also defect layers are equal to a quarter-wavelength ($n_L d_L = n_H d_H = n_D d_D = \lambda_0/4$) where $\lambda_0 = 1.55$ µm. The structure under consideration is shown schematically in Fig. 1. At the next step we consider the case in which the low refractive index (n_L), slightly increase with a constant step value from the beginning to the end of the structure; it should be noted that the high refractive index is fixed. In this structure, we investigate the strong dependency of the important parameters of the graded structure, such as transmission, group delay spectrum and waveform of transmitted pulse, to step function.

One of the most common computational tools in classical electromagnetism is the finite-difference time-domain (FDTD) algorithm, which divides space and time into a regular grid and simulates the time evolution of Maxwell's equations. This method is implemented perfectly in MIT Electromagnetic Equation Propagation (Meep) pack-