Dynamic All Optical Slow Light Tunability by Using Nonlinear One Dimensional Coupled Cavity Waveguides

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1. Introduction

Light propagation at slow speed, delaying light, has a tremendous role in a wide range of advanced technology from peta-bit optical networks to even laser fusion technology [1,2]. Recently, it was realized that delaying of an optical signal is useful for a number of applications such as optical buffering, signal processing, optical sensing and enhancement of optical nonlinearity in materials [3]. Also, as a consequence of important role of fiber lasers in laser fusion technology, coherent beam combining of several fiber lasers for achieving high power output is a crucial problem in future fusion technology. This task can be overcome by using proper engineered photonic components for achieving specific group delay time [2].

Generally, the speed of light is related to the refractive index of the propagation medium. From the basic definition of group velocity, $v_g = \frac{d\omega}{dk}$, It can be shown that group velocity of light in a medium can be derived as [4]:

$$v_g = \frac{d\omega}{dk} = \frac{c}{n + \omega(\frac{dn}{d\omega})}$$

Where, ω is the light frequency, *c* is the speed of light in vacuum, *n* is the refractive index of the medium and *k* is the propagation constant. Evidently, as a reason of limited optical materials and hence, limited refractive indices, it is not possible to slow down the speed of light sufficiently or adjust it to a specific desired value. However, it is obvious that by controlling the rate of refractive index changing, $\frac{dn}{d\omega}$, the speed of light can be controlled and in a special case when $\frac{dn}{d\omega} \gg 1$, slow down the speed of light can be obtained sufficiently.

During recent years different approaches have been done by scientists for generating of slow light. Electromagnetically induced transparency (EIT) is the first technique for achieving group delay and slow light in vapor mediums [5-9]. The group delay of incident pulses in an EIT system was studied first by Kasapi *etal* in lead vapor. Also, in 1999 Hau *etal* showed 7.05 μs delay in an EIT system which consists of condensed cloud of sodium atoms [10].

As a reason of complicated situation for slow light generation in EIT systems, it is important for real applications that these phenomena could be occurred in room temperature and in compact and solid materials.

Therefore, Spectral holes due to coherence population oscillation (CPO) in room temperature and in solids, can be considered as one of the interesting methods for slow light generation [11]. Slow light generation based on CPO has been studied in various material systems. So, ultraslow light, 57.5m/s, in ruby crystal has been studied by Boyd's group at Rochester [12].

On the other hand, during recent years a new kind of optical waveguides have been considerable attracted both theoretical and experimental attention due to their intense applications not only in data transferring but also in optical data processing [13]. Coupled cavity optical waveguides (CCWs) can be considered as the latest proposal mechanism for optical waveguiding which have been introduced by Yariv *etal* at Caltech [14]. This new kind of waveguides is based on the periodic dielectric structures as photonic crystals, which is separated by the high quality factor cavities that are coupled to each of the nearest neighbor in multiple spatial dimensions [15]. Due to existence of the cavities along the structure and as a result of the overlapping of the evanescent fields, light can be propagated through the CCWs [16]. Actually, it was investigated theoretically and experimentally that CCWs exhibit more advantages over conventional optical waveguides. One of the most important features of CCW is that due to strong optical confinement in defect medium, and high slope of transmission at resonance wavelengths, group velocity at the edge of each resonance modes can be reduced considerably [17]. Slow light generation in CCWs offers several practical advantageous like, design freedom, direct integration with other optoelectronics devices and ability to slow down light in a desired region of wavelengths at room temperature [18].

On the other hand, it should be noticed that the CCWs structures for stopping light suffer a fundamental trade off between the transmission and the optical delay bandwidth [19,20]. Therefore, in the field of slow light technology, delay-bandwidth product is an important parameter which should be considered greatly.

Furthermore, from system points of view, in future photonic circuits, adjustability of the optical properties of components is a great and important bottleneck which many scientists have been proposed special methods. In CCWs, the optical properties such as group velocity, dispersion and its higher order can be modulated through different mechanism such as electro optic effect, free-carrier injection and thermo optic effect [21]. As a consequence of necessity for all optical networks in future, dynamic all optical processing, controlling light by light, can be considered as one of the crucial bottlenecks for future all optical systems [22].

In the following chapter we will investigate the optical properties of the resonance modes such as, group delay, group velocity and bandwidth-delay product (BDP), in nonlinear one dimensional CCWs (1D-NCCWs) which defect mediums consist of intensity dependent-refractive index material. It can be seen by tuning the input optical intensity, the interested parameters such as, group velocity, delay time and specially delay-bandwidth product can be tuned to any desired values.

2. Theory

1D-NCCW is formed by placing optical resonator in a linear array, to guide light through whole of the structure by photon hopping between adjacent resonators. As a result of overlapping the evanescent field in the defect medium, cavity zone, electric field enhancement in this region can be obtained. Tight binding (TB) approximation (like using it in solid state physics) is used to describe the mechanism of waveguiding of the structure.

The basic structure for 1D-NCCW is as:

$$n_0 \left| (HL)^N HD(HL)^N HD(HL)^N H \right| \text{Glass}$$

Where, *H* and *L* denotes for high index (TiO_2) and low index (SiO_2) materials as n_H=2.33 and n_L=1.45, respectively for construction the basic resonators. Also, *N* is number of the repetition for the basic structure. It can be shown that by increasing *N*, light confinement in defect layer will be increased. Fig.1. Shows the basic structure of 1D-NCCW.

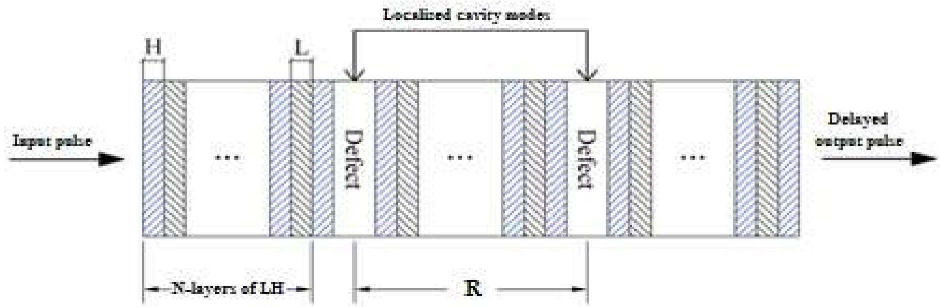

Fig. 1. Schematic illustration of 1D-NCCW with two defects.

As an example, defect layer, *D* is consist of CdSe which is an intensity dependent refractive index material.

The input pulse comes from left hand and during passing through whole of the 1D-NCCW, experiences delay time. This phenomenon is as a reason of reduction the speed of light propagation and confinement in the defect layer. It can be seen the enhancement of the electric field component of the incident light in the defect layer [21].

Nonlinear refraction is commonly defined either in terms of the optical field intensity *I* as [23]:

$$n_d = n_{d0} + \gamma I \tag{1}$$

Or in terms of average of the square of the optical electric field <E2> as:

$$n_d = n_{d0} + n_2 \langle E^2 \rangle \tag{2}$$

Where n_{d0} is the ordinary linear refractive index and γ is the nonlinear refractive index coefficient and n_2 is the nonlinear refractive index. The conversion between n_2 and γ can be written as [23]:

$$n_2[cm^3 / erg] = (cn_0 / 40\pi)\,\gamma[m^2 / W] = 238.7\ n_0\ \gamma[cm^2 / W] \tag{3}$$

For CdSe γ=-147cm²/W and n_{d0}=2.56. By choosing $\lambda_0 = 1.55\mu m$ as the practical optical communication wavelength, and choosing quarter-wavelength optical thickness for high index and low index materials ($n_H d_H = n_L d_L = \frac{\lambda_0}{4}$, where $\lambda_0 = 1.55\mu m$), TiO2 and SiO2 respectively (for constructing the basic resonators), it can be derived the central frequency for the basic resonator as $\Omega = 1.21 \times 10^{15}\,Hz$.

According to TB approximation, in the presence of defect layer between each resonators with initial half-wavelength optical thickness ($n_{d0} d_d = \frac{\lambda_0}{2}$), the central frequency of each resonator, will be split to two eigen frequency due to coupling of the individual cavity modes [15]. In the case which $I_{in}=0$, the transmission properties of the 1D-NCCW has been investigated by transfer matrix method (TMM) which is widely used for calculating the optical properties of alternative stack layers. TMM is based on solving the Maxwell's equations in each individual layer and considering the continuity conditions for the electric and magnetic components of the incident electromagnetic field yields to obtain the characteristics matrix of each individual layer as following:

$$M_q = \begin{pmatrix} \cos\delta_q & i\sin\delta_q / n_q \\ in_q \sin\delta_q & \cos\delta_q \end{pmatrix} \tag{4}$$

where n_q and δ_q denotes the refractive index and phase thickness ($\delta_q = 2\pi n_q d_q / \lambda_0$) of the qth layer respectively and λ_0 is the wavelength of the incoming light. By multiplication of the characteristics matrix of each layer, transfer matrix of the multilayered structure can be obtained. Therefore, by using the TMM method the electric and magnetic components of the input and output signal through the whole of structure can be obtained. Hence, optical properties such as transmission, phase characteristics and dispersion and its higher order such as group velocity and third order dispersion of the structure can be derived. Fig.2 shows the transmission spectrum of the structure in the case which $I_{input} = 0$.

For investigating the optical properties of the 1D-NCCW in the presence of input optical intensity signal, Eq.1 is used for determination of refractive index of the nonlinear defect layer. As an approximation method the transmission spectral characteristics of the 1D-NCCW can be obtained in the presence of nonlinear phenomena in the defect lyers. Painou *etal* and Johnson *etal*, have confirmed the convergence and correctness of this approximate approach [24]. Fig.3 shows the effect of increasing the input intensity on the position of the twin mini transmission frequencies band (resonance frequencies). It can be seen by increasing the input optical intensity, (form 0 to 6.4mW/cm²); the resonance modes shift toward right side in the frequency domain (blue shift in wavelength domain).

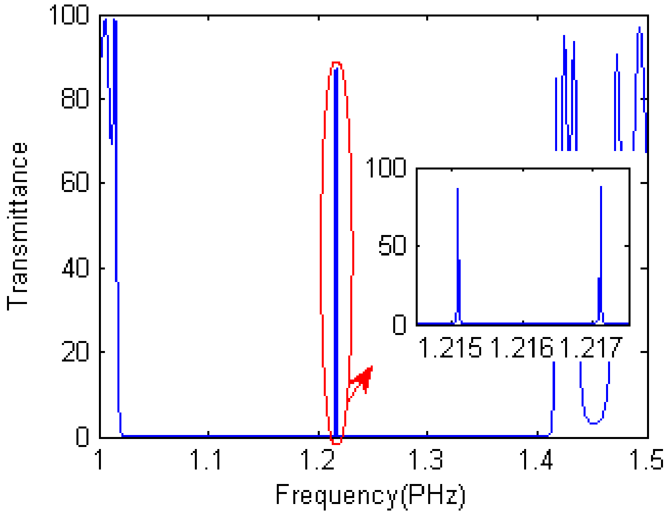

Fig. 2. Illustration of twin resonance bands in transmission spectrum of 1D-NCCW when $I_{input} = 0$.

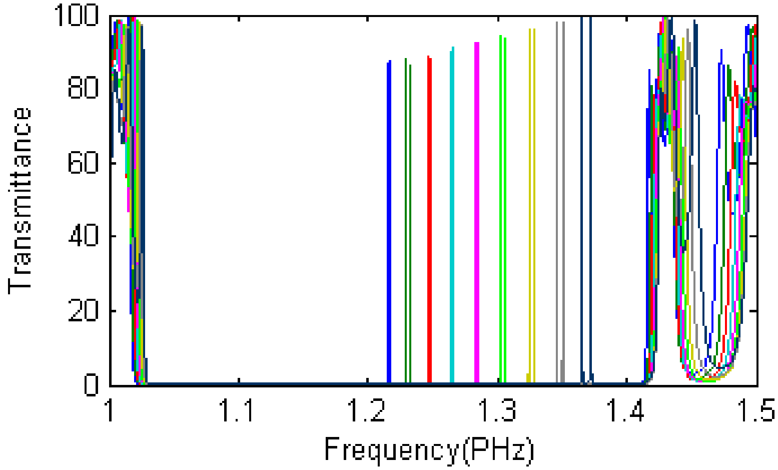

Fig. 3. Right side frequency shifting of the transmitted twin resonance modes when the input intensity changes from 0 to 6.4mW/cm² .

Under TB approximation, it can be shown that the group velocity at the resonance bands can be written as [25]:

$$V_g = -\kappa R \Omega \sin(kR) \quad (5)$$

where κ indicates coupling factor that is the value related to the overlapping of the electric field between the localized modes. $R = 4.8 \times 10^{-6}\,m$, is the separation between each of defect mediums and k is the wave vector of the light traveling in 1D-NCCW.

The coupling factor can be written as [25]:

$$\kappa = \frac{(\Delta\omega_{res})_{FWHM}}{2\Omega} \quad (6)$$

which indicates the inverse proportionality of the coupling factor to the quality factor (Q) of cavity modes ($\kappa \approx \frac{1}{2Q}$). Fig.4 indicates the variation of the Q for the resonance modes in the presence of input power.

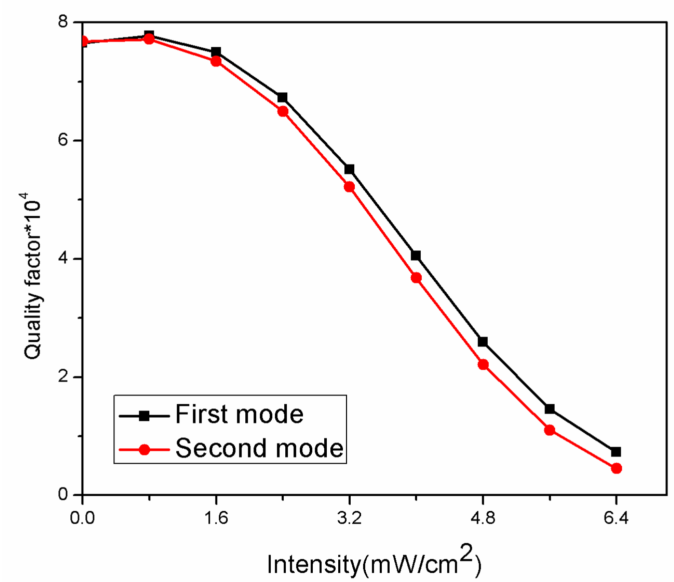

Fig. 4. variation the Q factor of the twin resonance modes versus optical input power.

As a result of increasing the input optical intensity, Q factor of each resonance modes of changes and hence, according to Eqs.5,6 coupling coefficient and group velocity at resonance modes alternate. Fig.5 shows the slow down factor, $S=V_g/C$, as a function of the input optical intensity, where C is the speed of light in vacuum.

It can be seen when the input optical intensity changes from 0 to 6.4mW/cm^2, the slow down factor can be tuned from 0.43×10^{-4} to 5.6×10^{-4} for the first resonance mode and 0.43×10^{-4} to 9.2×10^{-4} for the second mode. Group delay of resonance modes propagation through the 1D-NCCW, can be derived as following:

$$\tau_{group} = \frac{V_{group}}{L} \tag{7}$$

Where L is the length of the 1D-NCCW and equal to 1.42×10^{-5} m.

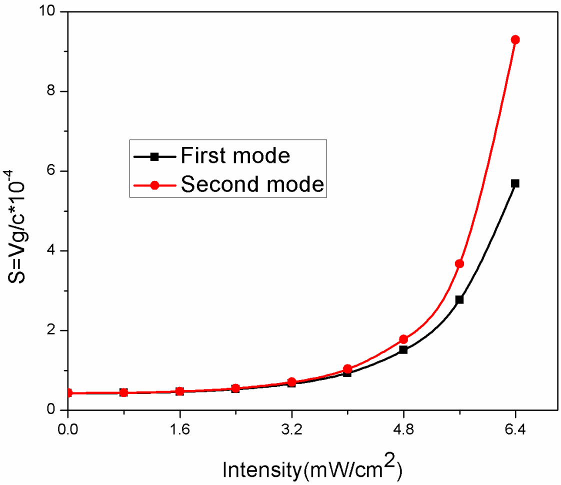

Fig. 5. Slow down factor increasing as a function of input intensity.

As a consequence of Eqs.5,7, the input intensity dependent of group delay of the resonance modes during propagation through the 1D-NCCW is obvious. Fig.6 shows group delay for the first and second resonance modes when the input intensity changes from 0 to 6,4 mW/cm². As an example, for the second mode, it can be seen by adjusting the input intensity between 0 to 6.4mW/cm², the group delay can be tuned from 1.1ns to 0.05ns.

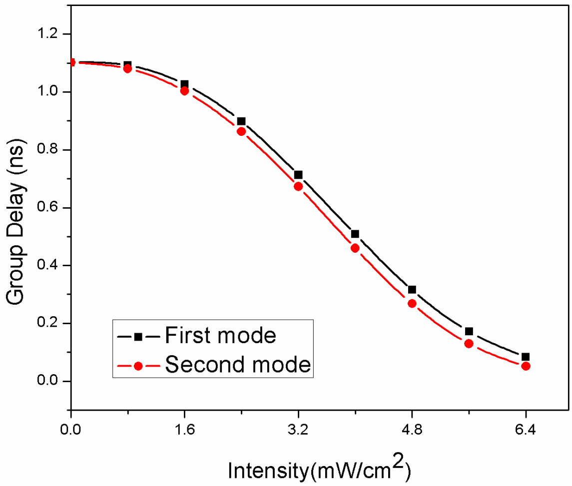

Fig. 6. Group delay versus of input intensity.

As mentioned before, photonic structures suffer from fundamental trade off between transmission bandwidth (FWHM of the transmitted resonance modes) and the optical delay, as delay bandwidth product (DBP).

The DBP variation in 1D-NCCW when the optical input intensity changes, is shown in Fig.7 As an example, for the second mode, it can be seen the DBP can be tuned from 17.4 to 15.6 by increasing the input optical intensity up to 6.4mW/cm^2.

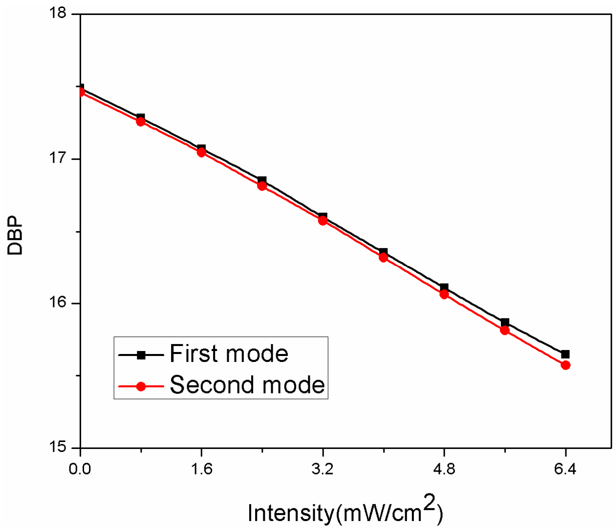

Fig. 7. DBP at the resonance modes versus input intensity.

3. Conclusion

The results of our theoretical study show that 1D-NCCWs can be considered as one of the best candidates for future all optical processing and high energy laser applications.

It can be seen that by introducing nonlinear defect medium in the one dimensional photonic crystals, three important tasks can be achieved. Firstly, in the presence of defect medium, a new mechanism for transferring optical data as coupled cavity waveguide can be achieved. It can be seen as a reason of intensity dependent of the refractive index in the defect medium, the resonance frequency (mini transmission band) can be tuned in the photonic bandgap zone of the basic one dimensional photonic crystal.

Secondly, as a reason of high slope of transmission at resonance bands, slow light in the order of 10^{-4} and group delay in nanosecond regime can be generated. It can be seen, as a reason of increasing the optical input intensity, not only the magnitude of the speed of light propagation and hence its group delay can be tuned, but also the propagation wavelength can be adjusted in wide range of photonic bandgap zone.

Thirdly, from practical system point's of view, as a consequence of importance of DBP parameter, and necessity to tune it for different users with various technical requirements, the DBP parameter can be dynamically tuned by adjusting the optical input intensity.

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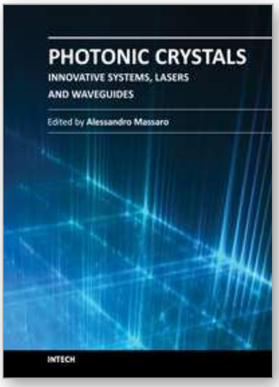

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The second volume of the book concerns the characterization approach of photonic crystals, photonic crystal lasers, photonic crystal waveguides and plasmonics including the introduction of innovative systems and materials. Photonic crystal materials promises to enable all-optical computer circuits and could also be used to make ultra low-power light sources. Researchers have studied lasers from microscopic cavities in photonic crystals that act as reflectors to intensify the collisions between photons and atoms that lead to lazing, but these lasers have been optically-pumped, meaning they are driven by other lasers. Moreover, the physical principles behind the phenomenon of slow light in photonic crystal waveguides, as well as their practical limitations, are discussed. This includes the nature of slow light propagation, its bandwidth limitation, coupling of modes and particular kind terminating photonic crystals with metal surfaces allowing to propagate in surface plasmon-polariton waves. The goal of the second volume is to provide an overview about the listed issues.

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