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Adjustable dispersion compensating in one dimensional coupled resonator planar optical waveguides

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ABSTRACT

In this paper, the optical properties in finite size one dimensional coupled resonator optical waveguide are investigated. The large dependence of the group velocity, dispersion parameter and its higher order slope such as transmission group delay, third order dispersion and intrinsic waveguide induced loss have been studied. By engineering the optical contrast ratio of the medium by using some accessible and compatible materials, according to the equivalent layers theory, the above mentioned parameters can either be adjusted or enhanced dramatically, according to the configuration of the optical networks and users' requirements. Also, by setting proper choice of the optical contrast ratio, super flattening of the transmittance group delay, third order dispersion spectrum and reduced intrinsic waveguide induced loss can be realized. Our results show the potential applications of the device for preventing the satellite pulse creating and transmitting pulse information distortion in multichannel lightwave systems.

1. Introduction

Optical waveguides have attracted considerable theoretical and experimental attention due to their intense applications in telecommunication systems [1]. During recent years, a new type of waveguiding, coupled resonator optical waveguides (CROW), based on the evanescent coupling between individual optical resonators, has been proposed [2]. Basically CROWs are waveguides based on periodic structure as photonic crystals, which consists of high Q cavities that are coupled to each of the nearest neighbor in multiple spatial dimensions. Due to the existence of these cavities, as a result of the overlapping of the evanescent fields, the light can be propagated through the structure in multiple spatial dimensions. Actually, it was investigated theoretically and demonstrated experimentally that CROW exhibit some advantages over conventional waveguides [3–5]. One of the most important advantages is that due to strong optical confinements in defect layer, CROW allows low group velocity (v_g) at the edge of the photonic band gap zone [2,6]. Low v_g near the photonic band edge is not only effective for a delay line and optical buffering [7] but also for the enhancement of various effects, such as optical amplification/absorption, electro and magneto optic effects and nonlinear effects [8]. Based on this prominent property, such a waveguide can serve as a new device for controlling the group velocity of optical pulses and thus potentially help to find application in storing and buffering optical pulses [9,10]. In the special case which the high Q cavities arise in the one dimensional perpendicular to the direction of light propagation which is called one dimensional CROW (1D-CROW), the light can be confined in one the same dimension as the direction of incident light [11] and as a consequence of evanescent fields overlapping in one dimension, the light can be propagated through the medium. Because of easy fabrication process, polarization independent and compact size, 1D-CROW has attracted more attention in optical communication systems.

On the other hand, from system viewpoints, in modern fiber optic communication systems, dispersion becomes a serious problem as the bit rates and transmission distances increase simultaneously. Therefore, in the high bit rate long haul optical communication systems, dispersion compensation enables the achievement of significant results such as increasing the number of optical transmission single channel.

Also in high bit rate wavelength division multiplexing (WDM) multichannel systems [13], impressive results have been demonstrated that the performance of the system has been severely affected by the higher order of dispersion, like group velocity dispersion (GVD) and third order dispersion (TOD). The dispersion length and bit rate associated with cubic and inverse of TOD, respectively [12]. Thus, an increase in bit rate from 10 Gb/s to 100 Gb/s reduces the dispersion length by a factor of 100.

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On the other hand, in the data transmission based on dark solitons it has been demonstrated that under the destructive action of TOD, the generation and growing tails and soliton decay has been occurred [14]. Therefore, not only dispersion but also dispersion slope compensation is becoming crucial bottleneck in high speed WDM lightwave systems. In future high speed WDM reconfigurable network, adjustable GVD and TOD compensation device, because of several potential impairment such as variation in optical power and imperfect gain flattening which can modify the optimal dispersion map of the systems, is very important. Consequently, both highly dispersion compensator single channel optical communication and adjustable dispersion compensator (DC) and its higher order in WDM systems are an important and crucial bottleneck.

In the current system, the dispersion compensation fiber (DCF) is most used [15]. However, since the absolute value of dispersion of a dispersion compensator fiber is as small as few tens of pico seconds/nanometer kilometers, a few kilometers long fiber is necessary to compensate completely, which make compensator large and expensive.

Also, several widely tunable dispersion compensator devices have been demonstrated at lower bit rates such as cascading of ring resonators. In these structures, each of ring resonators used for a specific channel and coupled to the one arm of an interferometer to give wide desired group delay characteristics. But there exist many limitations in the real application such as the necessity of the existence of external electric power and high sensitivity of the device working range of frequency to the environmental conditions. Another option is tunable dispersion compensation, using chirped fiber Bragg gratings (CFBGs), which provides wavelength dependent group delay (GD) when operated in reflection [16]. These devices can provide high dispersion, over bandwidths required for high bit rate applications, and provide significant tunability by altering the chirp on the fiber grating with an externally applied perturbation [17,18]. They are, however, typically single channel devices that require an optical circulator to retrieve the reflected signal, with the incurred expense and optical loss.

As mentioned above, a compact, low cost, less sensitivity to the environmental condition and highly adjustable dispersion is required by the market place. Therefore, according to the easy fabrication process and high environmental stability, 1D-CROW whose specification satisfies the requirements for its use in high bit rate WDM systems, make them as an effective and applicable component that can be used as the best candidate for optical buffering and dispersion compensators.

However, planar photonic crystals (PC) waveguides, or PC strip waveguides, have been extensively investigated in view of realization of integrated optical interconnects. In this paper, we propose a new structure of one dimensional coupled resonator planar optical waveguide (1D-CRPOW). In our proposed structure, the photonic bandgap effect is used to confine light in the in plane direction, meanwhile, index guiding [19,20] confines the light propagation in the vertical direction.

In this structure, we have investigated the strong dependency of the important parameters of 1D-CRPOW, such as group velocity, dispersion and group delay and third order dispersion on the coupling coefficient between each resonators and consequently, the optical contrast ratio of the used materials. But from the practical point of view, in any spectral region, the choice of materials with a specific and adjustable optical contrast ratio is impossible. This limitation can be overcome by using the equivalent layers theory [21]. In this approach, any desired optical contrast ratio can be engineered by using some accessible and compatible materials. Also by engineering the optical contrast ratio, a wide range of group velocity and highly negative dispersion can be achieved according to the users' requirements. Which this change, caused to overcome the distance limitation of per channel in optical communication systems.

However, perfect 1D-CRPOW without any disorder suffers from intrinsic radiation loss, in which the 1D-CRPOW mode leaks vertically out of the main propagation direction, consequently lossless waveguides is a crucial bottleneck in real applications. In final section, we have investigated that by proper choice of the optical contrast ratio, high Q cavity can be realized in such a way that the small portion of the incident energy leakage in the vertical direction can be confined.

2. 1D-CRPOW structures

1D-CRPOW is formed by placing optical resonators in a linear array, to guide light from one end of the chain to the other by photon hopping between adjacent resonators [2,8]. By using direct implications of the tight binding (TB) approximation, a novel propagation mechanism for photons along localized coupled cavity modes in photonic crystals was proposed and demonstrated [2]. In these structures, each resonator consist of high and low refractive index layers such as H and L, respectively, photons can hop from one tightly confined mode to the neighboring one due to the weak interaction between them (Fig. 1b) and therefore the electromagnetic waves propagate through coupled cavities.

Fig. 1b shows the in plane dielectric distribution of a waveguide. The structure has a periodically changing refractive index region in only x direction and light can be confined in this direction due to the periodic structure. According to the plane wave expansion (PWE) method, the propagation direction vector is not conservative inside the medium, as a result, part of the incident energy leak vertically in the planar waveguide. In our proposed structure, by using cladding region with refractive index n_c ($n_c < n_H$) surrounding the coupled resonators (Fig. 1a), vertical confinement can be realized through the index guiding (however, because of the existence of the cladding light line, which is defined as $\omega = cK/n_c$ (where ω is the frequency and K is the wave vector), there is an upper frequency limit on the guided modes [20]).

In 1D-CRPOW, according to tight binding approximation, the central frequency of each resonator, Ω, will be split up to two eigen-frequencies ω_1 and ω_2 due to coupling of the individual cavity modes as follows [22]:

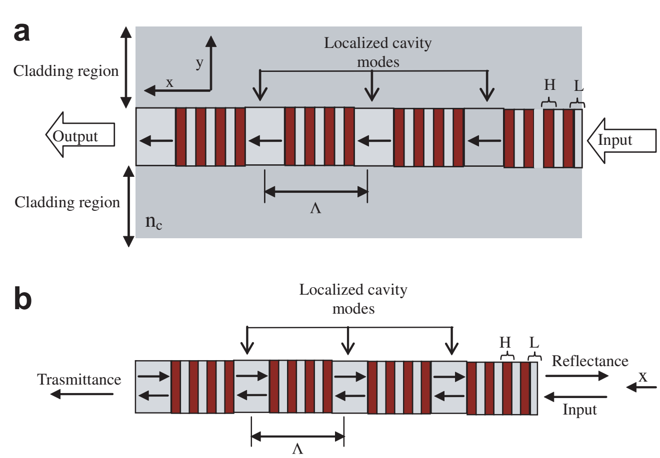

Fig. 1. (a) Schematic drawing of a 1D-CRPOW structure, (b) schematic drawing of in plane 1D-CRPOW structure. H, L, Λ and n_c depicts the high and low refractive index layers and the spacing between individual resonators and refractive index of cladding region, respectively.

$$\frac{\Omega^2}{c^2}(1 \pm \beta) = \frac{\omega^2}{c^2}(1 \pm \alpha + \Delta\alpha), \tag{1}$$

where c is the velocity of light in vacuum and α, β, $\Delta\alpha$ are TB parameters as following:

$$\begin{aligned}\alpha &= \int \varepsilon(r) E_\Omega(r) \,.\, E_\Omega(r - \Lambda\hat{x}) \mathrm{d}r,\\ \beta &= \int \varepsilon_0(r - \Lambda\hat{x}) E_\Omega(r) \,.\, E_\Omega(r - \Lambda\hat{x}) \mathrm{d}r,\\ \Delta\alpha &= \int (\varepsilon(r) - \varepsilon_0(r)) E_\Omega(r) \,.\, E_\Omega(r) \mathrm{d}r\end{aligned} \tag{2}$$

In these equations, $E_\Omega(r)$ is an individual localized mode of a single cavity that satisfies a simplified version of the Maxwell equations and $\varepsilon_0(r)$, $\varepsilon(r)$ and Λ are dielectric constant of the single cavity, dielectric constant of system and the spacing between individual resonators, respectively.

The self coupling parameter, $\Delta\alpha$, is sufficiently weak, because the signal is only non zero in the region of the perturbation $\Delta\varepsilon = \varepsilon(r) - \varepsilon_0(r)$, which lies in the evanescent region where the electric field is itself small. Consequently, we ignore $\Delta\alpha$ in Eq. (1) and we can obtain,

$$\omega_{1,2} = \Omega\sqrt{\frac{1 \pm \beta}{1 \pm \alpha}}. \tag{3}$$

From the splitting up of eigenmodes of two coupled cavities, we can obtained the coupling coefficient, k, of this structure as $k = \beta - \alpha$.

We assumed that the 1D-CRPOW consists of two kinds of dielectric films as quarter wave ($\lambda_0/4$) Bragg stack, one with a higher refractive index of $n_H = 2.25$ (TiO_2), and the other with a lower refractive index of $n_L = 1.44$ (SiO_2). The central wavelength of the first stop band of the photonic crystal is $\lambda_0 = 1550$ nm. Defects are introduced into the medium by periodically inserting SiO_2 layers, L_{in}, into the multilayer stack. The unit cell of the structure is $LHLHLHLHL_{in}$. The index profile of the structure, glass/ $(LHLHLHLHL_{in})^N$/air (here, $N = 3$), shown in Fig. 2.

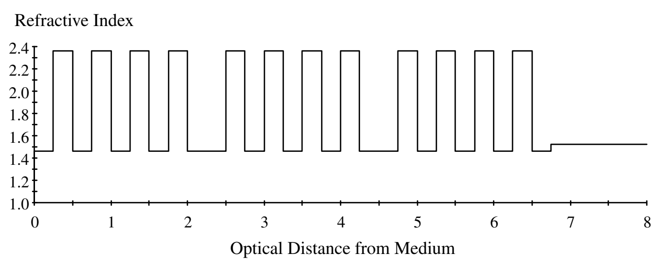

Fig. 2. Index profile of 1D-CRPOW with the glass/$(LHLHLHLHL_{in})^3$/air structure.

We know that all physical quantities including dispersion relation and group velocity depend on only a single TB parameter k [2], and this parameter can be controlled by changing the properties of cavities and the intercavity distance. Because of the importance of this parameter in 1D-CRPOW structure, k, we have determined this quantity from TB simulation results and this parameter is compared with the value extracted from impurity pass band.

Subsequently, the transmission properties of our structure in one dimensional photonic band gap materials have been investigated by transfer matrix method (TMM). Fig. 3a shows the transmission spectrum of the distributed Bragg reflector structure glass/(LHLHLHLHL)/air. As shown in this figure, the forbidden gap is extending from 1300 nm to 1900 nm.

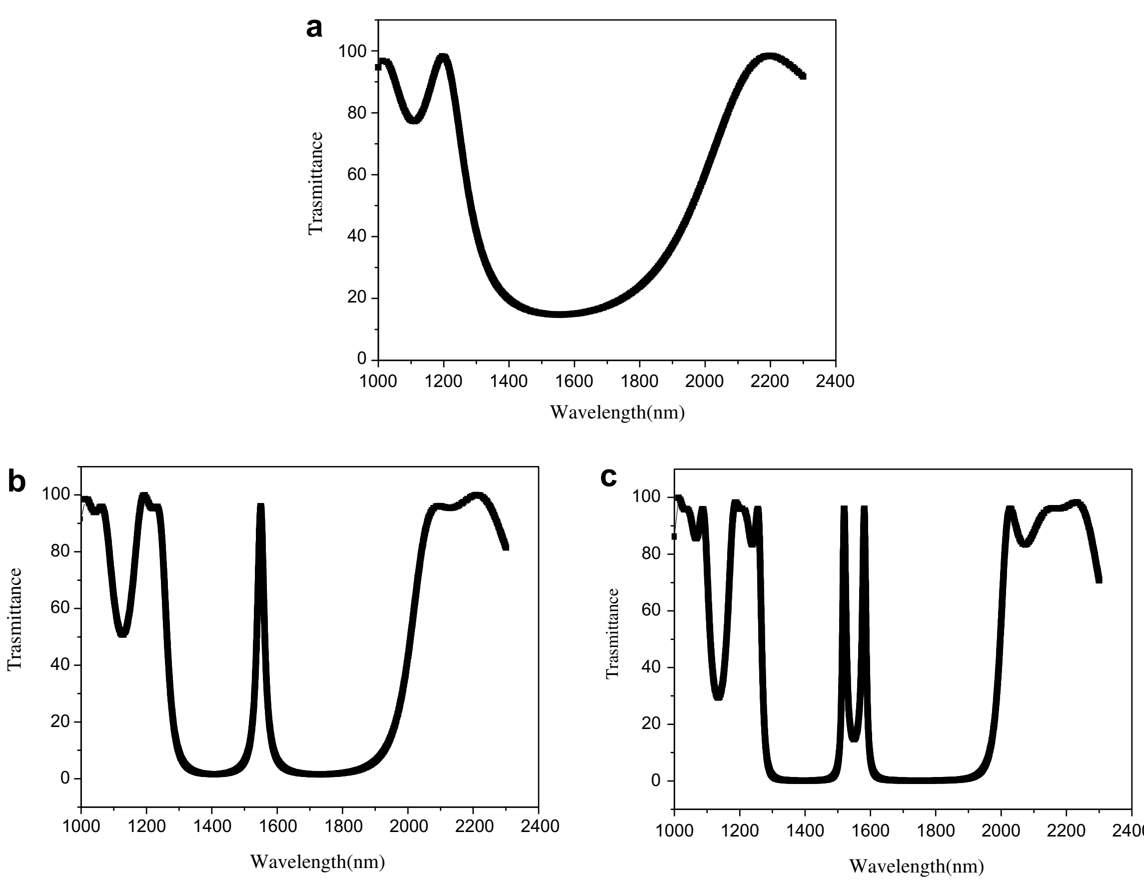

Fig. 3. Calculated transmission spectrum for (a) DBR and (b) single-cavity and (c) two coupled cavity structures.

The transmission spectrum of 1D-CRPOW structures that contains one cavity, glass/$(LHLHLHLHL_{\rm in})^2$/air, is shown in Fig. 3b. In the presence of a single cavity, a highly localized cavity mode is observed within the PBG. The simulated cavity wavelength appears at $\lambda_0 = 1550.2$ nm ($\Omega_0 = 2\pi\ c/\lambda_0 = 387\pi$ THz). Also for two coupled cavities, the transmission characteristics as a function of wavelength are calculated. As shown in Fig. 3c, we observe that the resonance mode is split up into two distinct symmetric and antisymmetric modes.

From the values of eigen-frequencies ω_1 (379.4π THz) and ω_2 (394.8π THz), and Eq. (3), TB parameters, α and β, can be determined as 0.0229 and -0.0169 correspondingly. The magnitude of the coupling coefficient $|k| = |\beta - \alpha|$, from TB approximation, will be derived as 0.039.

On the other hand, according to impurity pass band theory, the amplitude of parameter k can also be determined from the wave guiding bandwidth as $|k| = \frac{\Delta\omega}{2\Omega}$. Therefore, by using Thelen's theory [23,24], this bandwidth can be determined as a function of the optical contrast ratio of the used materials in the basic structure as:

$$|k| = \left|-\frac{2}{\pi}x^m(1-x^{\rm m})\right|, \tag{4}$$

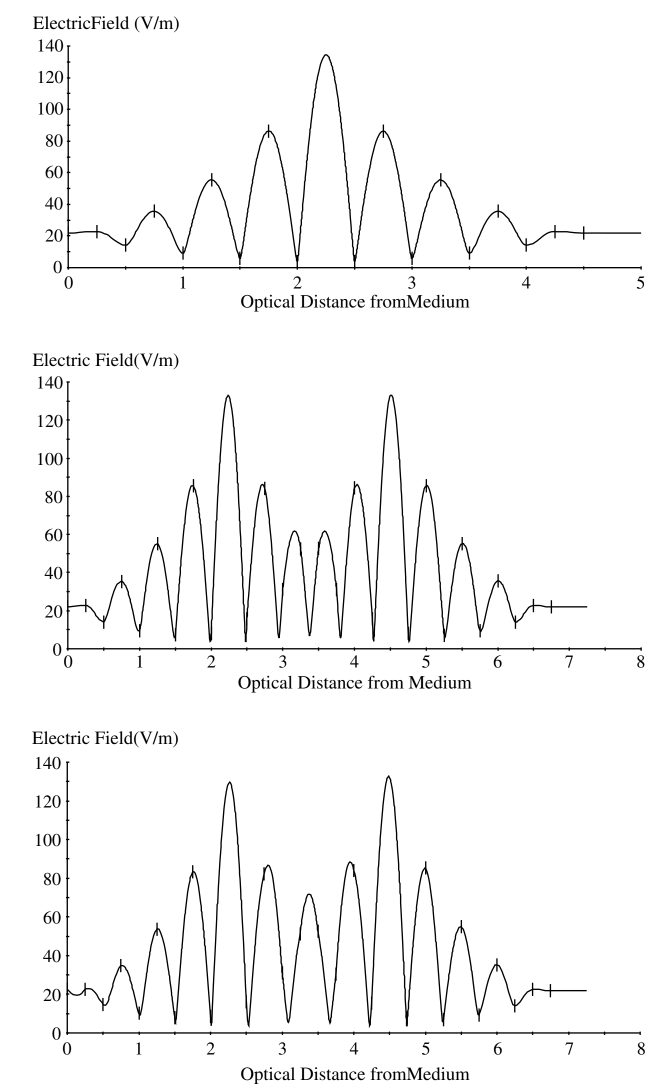

Fig. 4. Calculated field patterns of a single cavity and two coupled cavities as a function of the optical distance from medium. (a) The field intensity corresponding to the single cavity (b) the field intensity for two coupled cavities for $\lambda_1 = 1519.96$ nm and (c) the field intensity for two coupled cavities for $\lambda_2 = 1581.17$ nm .

Where $x = \frac{n_{\rm L}}{n_{\rm H}}$ the optical contrast ratio and m is the periods of the HL stacked layers. In this case, the amplitude of the coupling coefficient can be determined as 0.038 with a good agreement with TB approximation.

Also, the localized cavity field, $E_\Omega(r)$ is shown in Fig. 4. The electric field, exhibits an oscillatory behavior and most of the field is concentrated around the cavity region.

The calculated field patterns corresponding to modes of waveguide are plotted in Fig. 4b and c. It is observed that although both field patterns show two peaks around the cavity regions, they also exhibit different properties between the cavities. The field intensity corresponding to the higher-frequency mode, ω_1 (antisymmetric) has a node between the cavities. This result is along this expectation that as the localized photon modes should overlap when two isolated cavities are brought together and a new peak appears between two defect modes.

3. Controllable group velocity

By using the dispersion relation, the group velocity of photons along the localized coupled cavity modes is given by [2]:

$$v_{\rm g}(K) = \nabla_K\omega_K = -k\Lambda\Omega\sin(K\Lambda). \tag{5}$$

Where K is the wave vector along the propagation direction, which spans the region of $[0, \pi/\Lambda]$.

Substituting Eq. (4) in Eq. (5), the group velocity changes as follows:

$$v_{\rm g} = \frac{c\Lambda}{\lambda_0}\left[4\left(\frac{n_{\rm L}}{n_{\rm H}}\right)^m\frac{n_{\rm H}-n_{\rm L}}{n_{\rm H}}\right]\sin(K\Lambda). \tag{6}$$

From Eq. (6), it can be seen that the group velocity in 1D-CRPOW depends on the optical contrast ratio $(n_{\rm H}/n_{\rm L})$. Therefore, by changing the optical contrast ratio, one may tune and adjust the group velocity in a certain value. But the choice of materials with refractive indices intermediate to those of the highest and lowest values is impossible in any spectral region. Also, the selection of materials is further limited by a number of other practical considerations. This limitation can be solved by using the equivalent layers theory. According to equivalent layer theory, a basic multilayer that is symmetric with respect to a plane passing through its center of symmetry can be represented mathematically by a single equivalent layer which has associated also an equivalent characteristics matrix M($n_{\rm e}$, $\delta_{\rm e}$), with a given equivalent phase thickness, $\delta_{\rm e}$, and refractive index $n_{\rm e}$, or vise versa. According to the equivalent layers theory, for a plane wave propagating perpendicular to the surface of each thin layer, the equivalent functions $\delta_{\rm e}$ and n_e are given by the following relationships [21,23]:

$$n_{\rm e} = n_{\rm L}\left(\frac{\sin 2\delta_{\rm L}\cos\delta_{\rm H} + \rho^+\cos 2\delta_{\rm L}\sin\delta_{\rm H} + \rho^-\sin\delta_{\rm H}}{\sin 2\delta_{\rm L}\cos\delta_{\rm H} + \rho^+\cos 2\delta_{\rm L}\sin\delta_{\rm H} - \rho^-\sin\delta_{\rm H}}\right)^{\frac{1}{2}}, \tag{7}$$

$$\cos\delta_{\rm e} = \cos 2\delta_{\rm L}\cos\delta_{\rm H} - \rho^+\sin 2\delta_{\rm L}\sin\delta_{\rm H}, \tag{8}$$

where $\rho^\pm = \frac{1}{2}(x \pm \frac{1}{x})$ and x is the optical contrast ratio. The expressions (7) and (8) show a wavelength or frequency related refractive index $n_{\rm e}$ and phase thickness $\delta_{\rm e}$, as a result, this equivalent layer acts somewhat differently from normal layers, which comprise single material. If we assume the equivalent phase thickness $\delta_{\rm e} = \pi/2$ at λ_0, here we have:

$$\cos 2\delta_{\rm L} = \frac{(n_{\rm L}^2 + n_{\rm H}^2)(n_{\rm e}^2 - n_{\rm L}^2)}{(n_{\rm H}^2 - n_{\rm L}^2)(n_{\rm e}^2 + n_{\rm L}^2)}, \tag{9}$$

and

$$\tan\delta_{\rm H} = \frac{2n_{\rm L}n_{\rm H}}{(n_{\rm L}^2 + n_{\rm H}^2)}\frac{1}{\tan 2\delta_{\rm L}}. \tag{10}$$

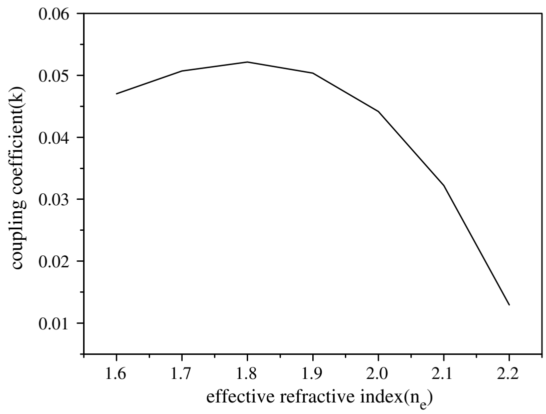

Fig. 5. Absolute value of coupling coefficient with respect of effective refractive index.

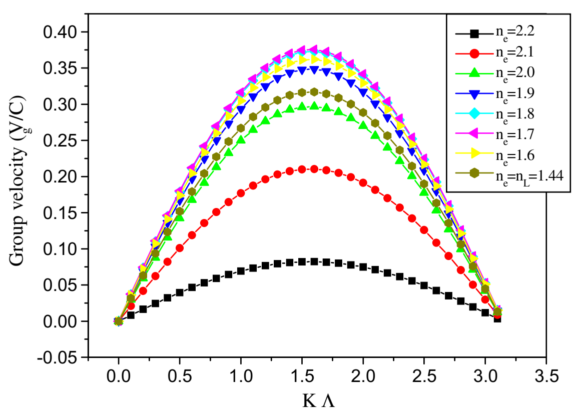

Fig. 6. Change of group velocity by different values of effective refractive indices.

Now, we can obtain the corresponding phase thicknesses of the high and low index fractional layers (δ_H, δ_L) at λ_0, from Eqs. (9) and (10) by setting the equivalent refractive index to any desired values between n_L and n_H. Consequently, the physical thicknesses d_H and d_L can be obtained [21]. Therefore, replacing each of the low refractive index layers by a combination of symmetric three layers, (aL)(bH)(aL), with proper thicknesses by (9) and (10), in basic 1D-CRPOW structure and using (4), the coupling coefficient of the resonators can be tuned to any desired value. Fig. 5 shows the absolute value of the coupling coefficient k with respect to effective refractive index n_e. It can be seen that when the effective refractive index, n_e, is changed from 1.6 to 2.2, the magnitude of coupling coefficient changes from 0.047 to 0.013.

Consequently, the group velocity from Eq. (6) can be changed as shown in Fig. 6.

According to Fig. 6, the group velocity has its maximum value at the coupled-cavity band center, and vanishes at the band edges. Also at one amount of $K\Lambda$, for example for $K\Lambda = 1.6$ at the center of band edge, the group velocity changed from 0.3169 c at 1D-CRPOW structure without any equivalent layer to 0.2103 at $n_e = 2.1$ and finally produces value 0.0822 c at $n_e = 2.2$.

4. Controllable dispersion compensation in WDM high bit rate data stream

In this section, we focus on the dispersion enhancement and its flexibility property of the 1D-CRPOW by employing the concept of equivalent layers and its effect on increasing the bit rate data stream (BRDS) in a desired window of optical communication spectrum. According to TB formalism and using dispersion relation, the group velocity of a monochromatic wave propagating through the waveguide can be derived as [25]

$$V_g = -2\pi c\Lambda \frac{[(k\lambda)^2 - (\lambda - \lambda_0)^2]^{1/2}}{\lambda\lambda_0}. \quad (11)$$

Consequently, the dispersion parameter in 1D-CRPOW can be written as:

$$D_{\text{1D-CRPOW}}(\lambda) = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right) = -\frac{\lambda_0^2(\lambda - \lambda_0)}{2\pi c\Lambda[(k\lambda)^2 - (\lambda - \lambda_0)^2]^{3/2}}, \quad (12)$$

where $\lambda_0 = 2\pi c/\Omega$ and Ω is the eigenfrequency of each resonator. This equation shows the dependence of the dispersion of 1D-CRPOW on the coupling coefficient k of each resonator in the structure or, strictly speaking, the optical contrast ratio of the basic materials in the 1D-CRPOW structure.

Fig. 7 shows the dispersion parameter as a function of wavelength for an ordinary 1D-CRPOW with optical contrast ratio n_H/n_L and $\lambda_0 = 1550$ nm.

According to Fig. 7, it can be seen that at the center of the 1D-CRPOW band the dispersion curve passes through zero. Furthermore, D increases sharply at the band edges, but toward positive values at one edge and negative values at the other. In Fig. 7b, it can be seen that there exists a large transition around 1612 nm between -3.99 ps/nm μm and 17 ps/nm μm. If we have to use this structure as dispersion compensator, we must pay attention to the dispersion parameter in fiber optic. As we know, the dispersion parameter in fiber optic transmission lines can be obtained as [15]

$$D_{\text{Fiber}}(\lambda) = S_0\frac{\lambda}{4}\left(1 - \left(\frac{\lambda_z}{\lambda}\right)^4\right). \quad (13)$$

In this equation, S_0 is the zero-dispersion slope (ps/nm^2 km), λ_z is the zero-dispersion wavelength and λ is the operating wavelength. As an example, for a communication fiber (SMT-A1310B) with $S_0 = 0.092$ ps/nm^2-km and $\lambda_z = 1311$ nm, the dispersion far from λ_z, for example $\lambda = 1611.9$ nm, in L band of OCS which lies from 1560 nm to 1620 nm, is as high as 20.85 ps/nm km.

Therefore, it seems that by cascading a large amount of an ordinary 1D-CRPOW the dispersion at 1611.9 nm can be compensated (as an example, with 200 μm of an ordinary 1D-CRPOW with -3.99 ps/nm μm at 1611.9 nm, the induced dispersion by 38.27 km of standard single mode fiber can be compensated).

On the other hand, in WDM systems, it is necessary for dispersion compensation at a particular wavelength. As an example, in L band of OCS, the above ordinary 1D-CRPOW cannot work properly; this arises from two important reasons as follows: firstly, at the left hand side, the amount of negative dispersion is not sufficiently high, so it is necessary to cascade too many ordinary 1D-CRPOW which caused many adverse effects such as loss, scattering and cracking. Secondly, at the right hand side, there is not negative dispersion, as an example at 1620 nm the amount of dispersion is 0.043 ps/nm μm. It is important to mention that by changing the central wavelength of 1D-CRPOW with normal optical contrast ratio, the dispersion curve can be shifted to any desired wavelength but its magnitude still is not sufficient. For overcoming this problem, we suppose that, each of the low index layers with $n_L = 1.45$ in the basic structure is replaced by the three symmetric equivalent layer with equivalent refractive index n_e, as discussed in the preceding section. Fig. 8 shows the dispersion of 1D-CRPOW, when the optical contrast ratio is changed from 1.41 to 1.02.

Evidently, if we choose optical contrast ratio 1.13 ($n_e = 2.0$), the corresponding negative value of dispersion can be increased to -39.95 ps/nm μm around 1620 nm. This structure with $n_e = 2.0$ and 200 μm length, can be used to compensate for the dispersion

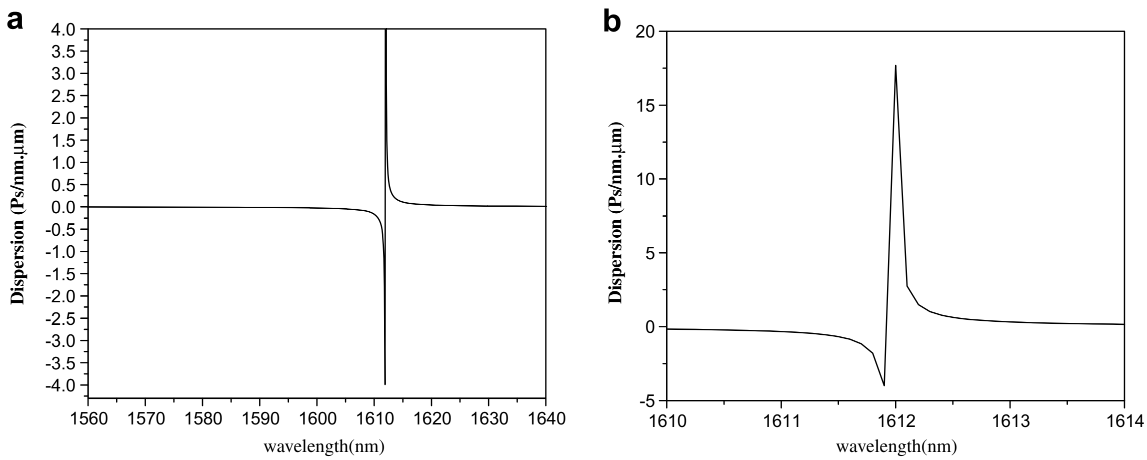

Fig. 7. (a) Dispersion parameter D in a 1D-CRPOW with $n_H/n_L = 1.56$ (without equivalent layer) as a function of the wavelength in L band of OCS, (b) detailed view of the highly negative dispersion zone.

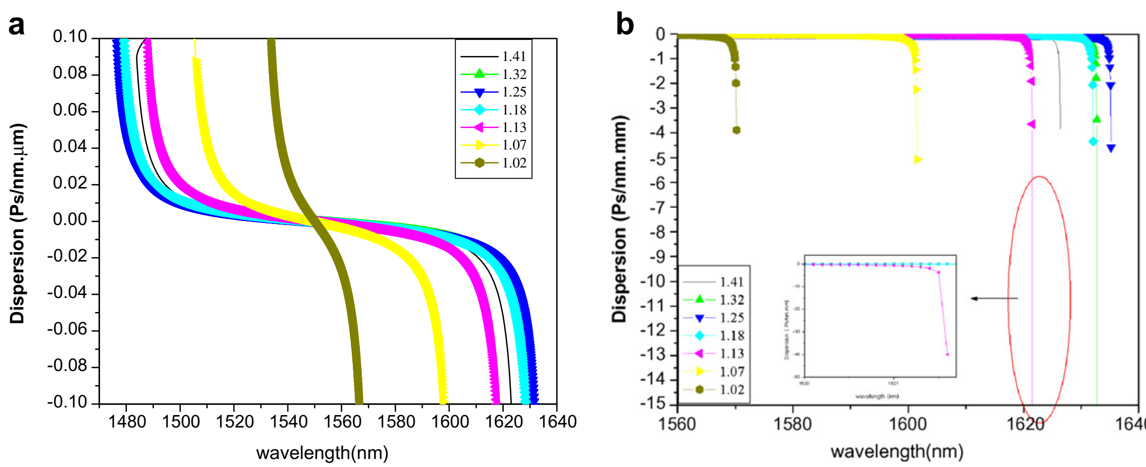

Fig. 8. (a) Dispersion parameter D in a 1D-CRPOW with different value of optical contrast ratio, as a function of the wavelength, (b) enlarged view of the highly negative dispersion zone in L band.

induced by a 374 km standard single mode fiber span. This amount is one order of magnitude larger than the amount in ordinary structure. Consequently, for a standard communication fiber (SMT-A1310B) span with a specific length, in a wide range of optical communication spectrum (second, third, fourth or even fifth window), by proper choice of optical contrast ratio in 1D-CRPOW the total dispersion can be compensated.

Now lets consider the dispersion compensation from the system standpoint and its effect on the BRDS. As we know in modern fiber optic communications systems, dispersion without loss is the bottleneck limiting factor. The maximum length of a fiber link which is mainly limited by the chromatic dispersion is derived as the following:

$$L_{\max} = [4BR|D_{\mathrm{tot}}(\lambda)|\Delta\lambda]^{-1}, \tag{14}$$

Where BR is the bit rate of system and D_{tot} is the dispersion parameter of the transmission line. It can be seen that bit rate (BR)-dispersion product is a very important factor for increasing the $L_{\max}$. Therefore, for achieving the maximum bit rate in a specific bandwidth, the length of optical communication and the dispersion parameter of the transmission line should be as low as possible. This task can be achieved by using 1D-CRPOW with proper optical contrast ratio.

By paying attention to the above discussion, in (SMT-A1310B) fiber at L band ($\lambda = 1620$ nm) and $\Delta\lambda = 0.2$ nm we have $D(\lambda) = 21.28$ ps/nm km and so for BR = 2.5 Gb/s, one finds that $L_{\max} = 23.6\,km$, and for high bit rate around 40 Gb/s this length decreases to 1.5 km. By using 1D-CRPOW as discussed above (with optical contrast ratio 1.13), to induce desirable high negative dispersion (-39.95 ps/nm μm) the total amount of dispersion in Eq. (14) can be as low as possible and consequently, the bit rate of data stream in a specific length of fiber span can be increased even to 40 Gb/s.

5. The reduction of the intrinsic waveguide induced loss in 1D-CRPOW

In 1D-CRPOW structure with ordinary optical contrast ratio, increasing the number of resonators and also defects increased the amount of the transmission coefficient sufficiently [26] and as a result, the intrinsic waveguide induced loss by pulse propagation from the 1D-CRPOW input to output can be decreased finitely. However, increasing the number of coupled resonators in 1D-CROW is limited by many practical limitations. Since, we studied the change in waveguide induced loss by the aid of ultrashort pulse propagation at 1550 nm through the 1D-CRPOW structure. In order to calculate this parameter, we assume that the complex transmission coefficient of the input pulse can be expressed as [7]:

$$t(\omega) = [T(\omega)]^{1/2}\exp[i\varphi(\omega)], \tag{15}$$

where $T(\omega)$ and $\phi(\omega)$ can be derived by using TMM simulation method. For simplicity, we examine only the spectral shape of the output pulse and neglect the relative position (group delay) between the input and output pulses. The spectral shape of the output pulse is obtained in several steps. First, we get the spectrum of the input pulse by a Fourier transformation, including the amplitude and phase. Then, the amplitude of the output pulse is given by multiplying the amplitude of the transmission coefficient while the phase is given by summing the phase of the transmission coefficient. Finally, the temporal shape of the output pulse is derived by an inverse Fourier transformation.

By engineering the optical contrast ratio of the medium via using equivalent layer approach as discussed in the Section 3 1D-CRPOW can be designed with transmission near 100% and the ripples in transmission zone can be suppressed sufficiently. Consequently, the waveguide inducing loss in the 1D-CRPOW structure can be reduced effectively. Fig. 9a and b shows the transmittance of 1D-CRPOW in the case, where $N = 10$ with ordinary optical contrast ratio and effective optical contrast ratio equal to 1.13. As shown in this figure, the ripple suppressed sufficiently in the structure with effective optical contrast ratio, 1.13, as compared with the ordinary structure (without equivalent layer). Also, in this figure (c, d), we can see the output ultrashort pulses in two structure.

The areas of the pulses in Fig. 9c and d give us the intensity of ultrashort pulse. As we see in this figure, the intensity of input pulse is 3.5445, which has been changed to 0.6866 in 1D-CRPOW without equivalent layers and increased to 1.4153 in the 1D-CRPOW with optical contrast ratio =1.13. This means that the loss which was resulted from waveguiding structure became smaller if we used equivalent layers in our structure Also, this can be resulted from the fact that by engineering the optical contrast ratio, the Q factor of the resonators per modal area can be enhanced which has a great advantages for increasing the nonlinear function of the device [27].

6. Ripple suppression in transmittance group delay and third order dispersion

In the preceding section, we discuss the unwanted dispersion effect in single channel optical communication systems. But the performance of the multichannel WDM systems has been severely affected by the slope of dispersion such as group delay and TOD and ripples in their spectrum characteristics that caused to create undesirable pulse tails and amplitude fluctuation, which caused signal distortion. Thus, it is necessary to suppress ripples in transmitted group delay and also in third order dispersion for keeping the initial shape of the pulse.

It has been shown that by increasing the number of resonators in a 1D-CRPOW structure with ordinary optical contrast ratio (as an example 1.56), the transmission coefficient can be enhanced effectively, Fig. 10a shows the group delay spectrum in a 1D-CRPOW structure with an ordinary optical contrast ratio. According

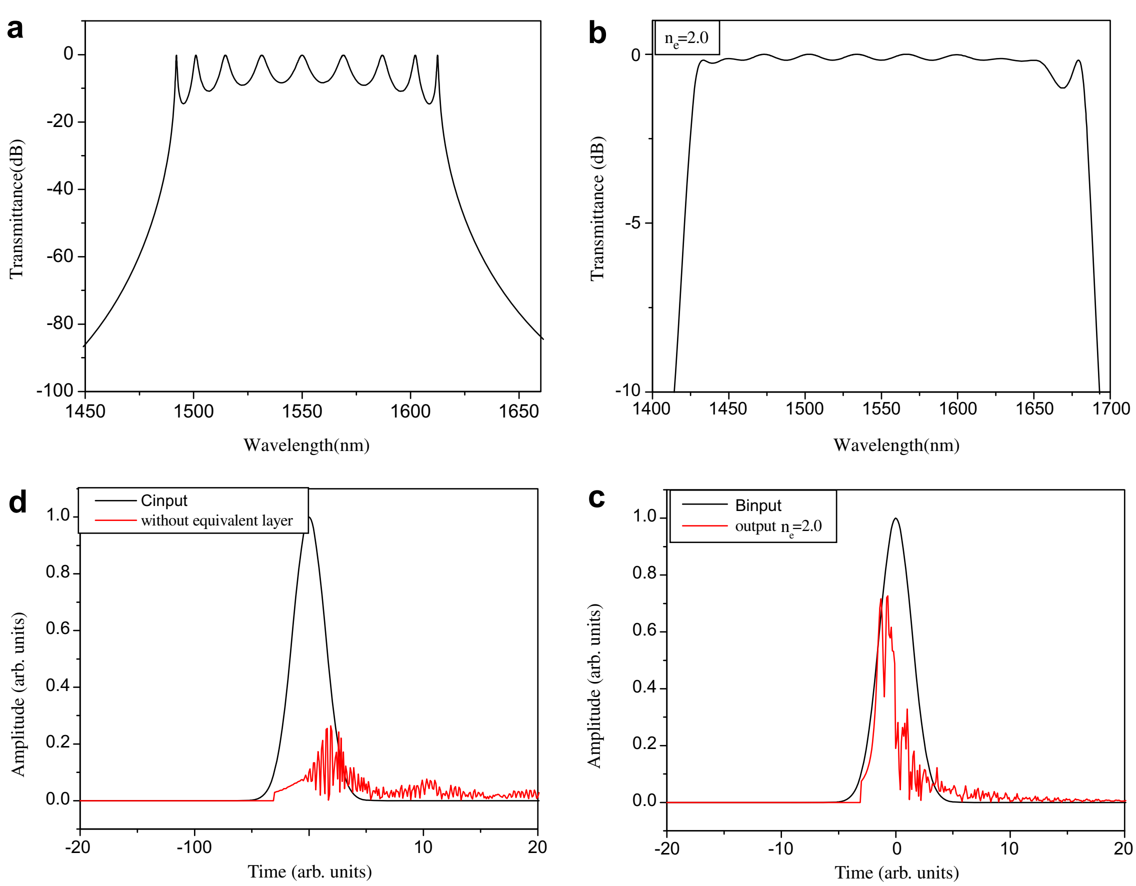

Fig. 9. Wavelength dependence of transmittance for 1D-CRPOW structure and transmitted pulses from 1D-CRPOW (a), (c) without any effective refractive index, $(LHLHLHLHL)^{10}$, and (b), (d) engineered with effective optical contrast ratio equals to 1.13 and the input pulse is also provided for comparison.

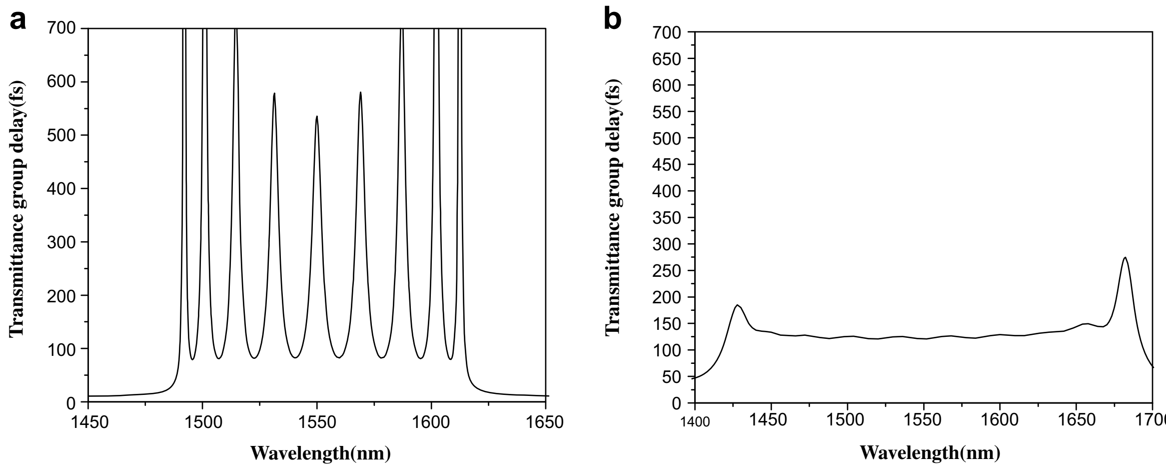

Fig. 10. The transmittance group delay of the 1D-CRPOW structure, $(LHLHLHLHL_{in})^{10}$, (a) without equivalent layer (b) engineered with optical contrast ratio = 1.13.

to this figure, the maximum transmitted group delay fluctuation is about 4.3 ps in 170 THz range of frequency. We observed that the group delay bandwidth product has the amount as 23.8. In this case, by employing the equivalent layers theory, and setting the effective optical contrast ratio on 1.13, the maximum transmittance GD can be decreased to 0.1 ps in the same range of frequency, as shown in Fig. 10b.

Also, there must be a trade-off between the ripple suppression in transmitted GD and transmittance. But as shown in Fig. 9b, we see that the transmittance in this engineered structure is nearly 100%. Which this property makes this structure suitable for dispersion compensator in WDM systems.

On the other hand, in WDM systems, the dispersion length and bit rate are associated with cubic and inverse of TOD parameter, respectively [12]. For this reason, the TOD property of the 1D-CRPOW is important from practical point of view. Fig. 11 shows the comparison between the TOD parameter of 1D-CRPOW with ordinary and engineered optical contrast ratio, 1.56, and 1.13, respectively. It is obvious that the amount of the TOD ripples decreased from 0.3 ps^3 to 0.08 ps^3 in the 50 THz range of frequency. This caused to increase the dispersion of less fiber length and bit rate to 0.000512 and 12.5 respectively.

As shown in this figure, in the structure with $n_e = 2.0$, we have fewer ripples and the amount of third order dispersion is increased one order of magnitude.

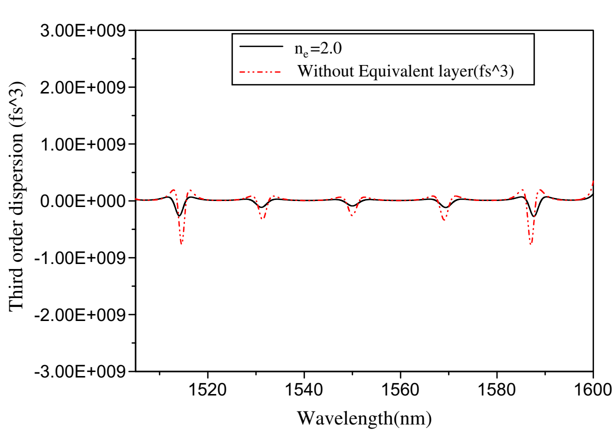

Fig. 11. Wavelength dependence of third order dispersion for 1D-CRPOW structure that in it effective refractive index equals to 2.0 as compared with the structure without equivalent layers.

7. Conclusion

In sum, in order to calculate the coupling coefficient in 1D-CRPOW structure, the splitting up of the eigenmodes due to interaction between the evanescent fields near each essential resonator is observed and the coupling coefficient of this structure has been calculated by using TB approximation and TMM approach and compared with each other.

Strong dependence of the group velocity and dispersion parameter in 1D-CRPOW on the optical contrast ratio has been investigated. In this structure, by using the symmetric periodic multilayer for engineering the optical contrast ratio of the medium, the group velocity can be tuned in a wide range of magnitude between 0.08 C and 0.32 C. Also, the negative value of the dispersion parameter, *D*, can be enhanced dramatically in any desirable wavelength of the OCS windows. As an example, in the L band of the OCS, by choosing the proper design of equivalent refractive index in 1D-CRPOW, the dispersion effect which raised by the fiber optic transmission line can be compensated. This caused to dramatically enhance the transmission line length without signal distortion and BRDS in WDM systems simultaneously. The results show that in the case which the optical contrast ratio is set to 1.13, the dispersion compensated fiber optic span length and BRDS can be increased greatly to hundred of kilometers and even 40 Gb/s correspondingly.

Finally, the effect of the optical contrast ratio on the waveguide induced loss, transmittance GD and TOD spectrum in finite size 1D-CRPOW have been studied. As a consequence of proper choice of the optical contrast ratio, the intrinsic waveguide induced loss can be decreased via Q factor enhancement of the cavity; therefore, super flattening in transmittance GD and TOD spectrum and a record high delay-bandwidth product for slow light in a long CRPOW can be achieved. As an example in the case which TiO_2 and SiO_2 are used as the basic materials and setting the optical contrast ration on 2.0, the ripples in transmittance GD and TOD spectrum can be decreased to 0.1 ps and 0.08 ps^3, respectively. Consequently, by properly engineering the optical contrast ratio, signal distortion in long haul and high bit rate WDM system can be eliminated.

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