Dispersion compensation based on the combination of coupled ring resonator and photonic crystal structures

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An optical delay line of coupled resonator optical waveguide (CROW) compensated by photonic crystal waveguide (PhCW) is proposed. In the structure, etching the periodic holes around the waveguide of the ring resonator waveguide does not increase the size of the CROW. Theoretical studies and numerical models indicate that through careful design, CROW and PhCW exhibit different group velocity dispersion (GVD) properties at a certain frequency range. Optical signal can not only be compensated in terms of GVD, but can also be delayed with longer time period. Due to the propagation mode mismatch of the two structures, optical loss becomes inevitable.

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Optical delay lines have potential applications in future optical communication systems, such as data buffering and synchronization[1]. Slow light can be achieved using atomic vapors based on coherent effects called electromagnetically induced transparency (EIT)[2,3], optical fibers based on stimulated Brillouin scattering[4], or ruby crystals based on coherent population oscillations[5]. There are other methods of storing optical data pulses, such as converting them into long-lived acoustic excitations[6], among others.

In terms of integration, silicon-on-insulator (SOI) devices are more flexible. Although based on SOI, slow light has also been demonstrated using stimulated Raman scattering[7]. In comparison, coupled resonator optical waveguide (CROW) and photonic crystal waveguide (PhCW) are more compact[8−10] because they are smaller in size. Moreover, CROW and PhCW slow lights are achieved based on the structures of material; thus, their wavelengths are independent. They can be adjusted to any frequency range as long as the material is transparent, and both are considered good candidates for optical delay line designs. However, CROW structures always have a dispersive $\omega - k$ curve (ω is angular frequency, k is wave vector), which may cause significant distortion of the output signal, and a high bit error rate (BER). In a linear time-invariant medium, CROWs and PhCWs are limited by a delay in the bandwidth product constraint. Group delay from an optical resonance is inversely proportional to the bandwidth within which the delay occurs. PhCWs can be fabricated with low dispersion and high group index[11], as well as with limited corresponding frequency bandwidth. The maximal rate for pulses is limited. In addition, high dispersion becomes inevitable if a sufficiently wide bandwidth is required.

In this letter, a dispersion compensation device is designed, which is a combination of CROW and PhCW. Part of the ring resonator waveguide is designed to form part of the PhCW. Unlike other dispersion compensators[12] in which they are considered separate devices, the two structures are integrated together. However, this does not increase the size of the structure and also leads to higher delay time.

We first consider the structure of a typical CROW with one chain of infinite periodic rings, in which light propagates by direct coupling between the adjacent resonators (Fig. 1(a)). The structure can be regarded as a waveguide, and the group dispersion relation can be obtained using the following equation[13]:

$$\omega_{\rm K} = \omega_0 \left[1 - \frac{\Delta\alpha}{2} + \kappa\cos(ka)\right], \tag{1}$$

where ω_0 is the resonant frequency of an individual resonator and a is the lattice constant. $\Delta\alpha$ and κ are defined as

$$\Delta\alpha = \int {\rm d}^3\mathbf{r}\,[\varepsilon(\mathbf{r}) - \varepsilon_0(\mathbf{r})]\,{\rm E}_{\omega0}(\mathbf{r})\cdot{\rm E}_{\omega0}(\mathbf{r}) \tag{2}$$

and

$$\kappa = \int {\rm d}^3\ \mathbf{r}\,[\varepsilon(\mathbf{r} - a\mathbf{z}) - \varepsilon_{\rm o}(\mathbf{r} - a\mathbf{z})]\,\mathbf{E}_{\omega0}(\mathbf{r})\cdot\mathbf{E}_{\omega0}(\mathbf{r} - a\mathbf{z}), \tag{3}$$

where $\varepsilon(\mathbf{r})$ is the dielectric coefficient of the CROW and $\varepsilon_0(\mathbf{r})$ is the dielectric coefficient of an individual resonator.

Based on the above, the following holds true:

$$\frac{\partial v_{\rm g}}{\partial\omega} < 0, \tag{4}$$

where $v_{\rm g}$ is group velocity. We now consider a typical

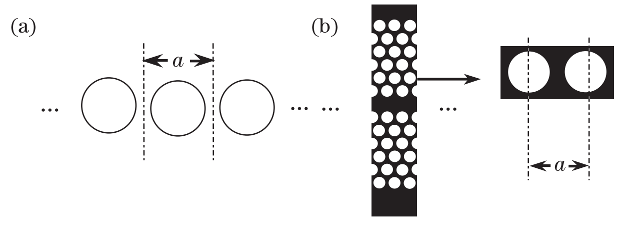

Fig. 1. Schematic diagrams of (a) CROW and (b) PhCW.

PhCW as shown in Fig. 1(b). The structure consists of a periodic triangular lattice of air holes forming a photonic band gap (PBG) for transverse electric (TE) modes. A single line of missing holes form a W1 waveguide, which induces a W1 mode in PBG (Fig. 2(b)). The band diagram can be obtained from finite-difference time-domain (FDTD) method[14]. At the Q area near the lower band edge, the dispersion curve satisfies the following equation:

$$\frac{\partial v_{\mathrm{g}}}{\partial \omega} > 0. \qquad (5)$$

Equation (4) shows that the group velocity decreases with the increased frequency. Meanwhile, Eq. (5) shows that the group velocity increases with increased frequency. Thus, variations in the group velocities of CROW and PhCW have opposite signs, which can be used to compensate for the dispersion, if the P and Q areas are in the same frequency range.

To observe the response of the input optical pulse of CROWs in time domain, we consider the structure in which seven coupled rings are used and two line waveguides are placed at the two sides of the coupled rings as input and output ports ($\mathrm{P_{in}}$ and $\mathrm{P_{out}}$), respectively (Fig. 3). This is a realistic CROW structure, which consists of finite rings. Although the structure is not infinitely periodic, transmission peaks arise from the resonance and are considered as Fabry-Perot (FP) fringes. We use numerical simulations to study the GVD of the structure. Signal comes in from one port of the structure and goes out from the other port of the structure, where a monitor is set to record the optical response of the input signal. The FDTD method is used to simulate the numerical response of the signal. In the numerical simulation, the normalized inner radius of the ring is 8, the thickness is 0.8,

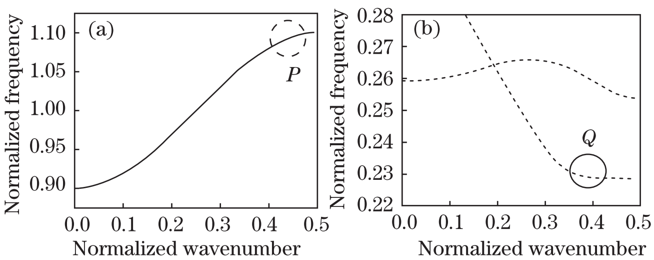

Fig. 2. Dispersion relations of (a) CROW and (b) PhCW.

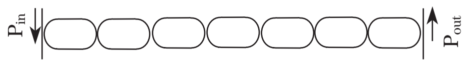

Fig. 3. Schematic of seven coupled micro-ring resonators with two coupled line waveguides as input and output ports.

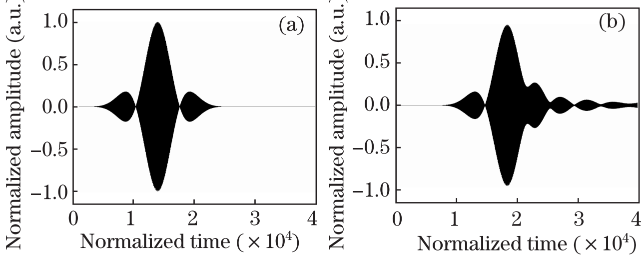

Fig. 4. Temporal evolution of the pulse. (a) Input signal and (b) output signal.

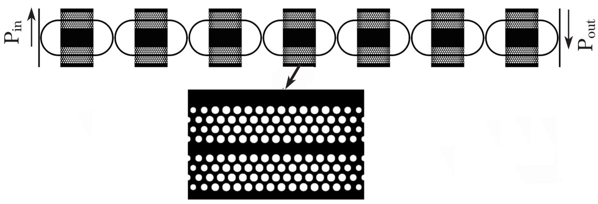

Fig. 5. Combination of CROW and PhCW.

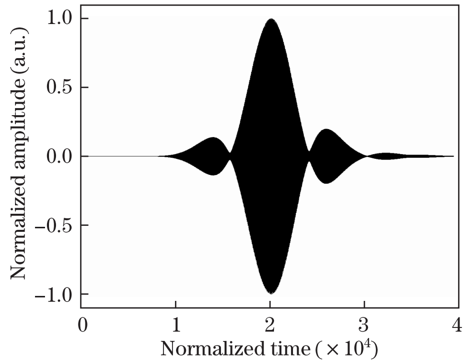

Fig. 6. Temporal evolution of the output pulse.

the space between the rings is 0.3, the distance between the line waveguide and ring waveguide is 0.15, and the normalized center frequency of the input pulse is 0.2299, which served as the center of the transmission peak of the FP fringe. The normalized full-width at half-maximum (FWHM) of the pulse is 0.0005. The refraction index of the waveguide is assumed to be 3.4, and TE-polarized light is used. Amplitude variations in the magnetic field perpendicular to the plane are recorded to characterize the output signal, which is shown in Fig. 4(b). The delay time is normalized with tc/a, where c represents the velocity of light in vacuum and a represents the normalized lattice constant of PhCW. Distortion and multiple tails can be observed from the figure, which proves GVD in time domain.

As shown in Eqs. (4) and (5), the differentials in group velocities show opposite signs with an increase in frequency. This property can be used to compensate for the separate dispersion of CROW and PhCW. The structure, which combines PhCW and the coupled rings, is shown in Fig. 5. To achieve dispersion compensation, the frequency ranging in the P and Q areas are made to coincide with each other. To achieve this, the parameters of CROW are kept invariant, as described above, while the normalized lattice constant a of PhCW is set to 1. In this structure, if the radius of the rings and the width of the ring waveguide are kept invariant, the dispersion properties can be tuned by adjusting the periods of hole numbers. In all, 11 rows of air holes with a normalized radius of $r = 0.35$ are set. To realize mode matching in the ring waveguide and to allow PhCW to enhance the transmittivity, 6 additional rows of air holes with reduced radius are set symmetrically at both sides of the PhCW boundary, with the corresponding values set at $r_1 = 0.25$, $r_2 = 0.29$, and $r_3 = 0.33$, where r_1, r_2, and r_3 are the radii of each of the three rows of air holes arranged from side to inner PhCW. The input optical pulse is set at the same parameters, as shown in Fig. 4(a), except that the center frequency is changed to 0.2292, which is the center of the transmission peak of the FP fringe of this structure. The amplitude of magnetic field variation at the output port is shown in Fig. 6. By comparing the output signal shown in Fig. 4(b) with that in Fig. 6, we find that the signal distortion and the multiple tail effect (Fig. 4(b)) are eliminated and that the output signal shape slightly expands in the time domain. This indicates that the GVD of the coupled ring resonators is compensated by the PhCW. Another advantage of the combined structure is its longer delay time. The peaks of the input and the output signals are centered at about 14 000 and 20 000, respectively. The normalized delay time is about 6 000, and the delay bandwidth product (DBP) is about 3 with little signal distortion. Furthermore, the corresponding group index is about 30. On the other hand, for the CROW structure, the peak centers of the input and the output signals are at about 14 000 and 18 500, respectively. The normalized delay time is about 4 500. The delay time of the combined structure is approximately 1.3 times longer than that of a CROW. At an optical telecommunication wavelength of 1.55 μm, the corresponding size of the structure is about 82 μm, and the delay time is 7.1 ps.

In conclusion, without increasing the size of a structure, PhCW has been introduced directly on a CROW. Compensation is achieved using this combined structure. In addition, compensation has been tuned mainly in the ratio of the different lattice constants of the CROW and the PhCW, and then tuned precisely by the number of rows of air holes of the PhCW. Signals transmitted in this structure have longer delay time period and broader bandwidth, both of which help enhance the value of DBP. The limitation, however, is optical loss. For a certain CROW and a certain frequency range f of a signal, the length of the PhCW needed is shorter when f is near the band edge, thus leading to propagation mode mismatch. The waveguide appears to be very lossy. To resolve this problem, a compromise method has been used by choosing f to be at a short distance from the band edge, thus increasing the number of rows of air holes and changing the size of the holes near the edge of the waveguide. In spite of this, optical loss has remained inevitable. The optical loss is about 8 dB in the combined structure, which is larger than that of a simple CROW and a PhCW structure. Optical losses in CROW and PhCW, in the same length as the structure analyzed, are about 3 and 2 dB, respectively, in the numerical simulation.

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