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Light delay and advancement by coupled double-ring resonators

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Through finding the derivatives of the group delay and transmittance of the coupled double-ring resonators (CDRRs) with respect to different structure parameters, the dispersion and filtering characteristics of CDRRs varying with different coupling and attenuation/gain coefficients are analyzed systematically. The parameter ranges in which slow and fast light can be achieved are given, and large light delay and advancement without serious attenuation and great distortion are obtained.

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Obvious slow and fast light, and even negative group velocity control have been implemented these years. Group velocity control is not only of great application potential, but also profound physics significance. Recently, the group velocity control of light in matter has been one of hot research areas in photonic domain. Group velocity control occurs mainly in dispersion media and dispersion structures. With the development of integrated optics, microring resonators as a kind of group delay lines such as optical delay lines[1,2], light storage[3,4], and laser gyroscopes[5,6], etc.

Using lossy microring resonators to realize fast or slow light often suffers serious attenuation and great distortion[7–9]. This usually poses a great difficulty to the application of group velocity control by microring resonators. Introducing gain to microring resonators can not only overcome severe attenuation and distortion, but also enrich filtering and dispersion characteristics of microring resonators[10–13].

Coupled double-ring resonators (CDRRs) are very useful in group velocity control due to their simple structure and high transmission capacity. Characteristics of CDRRs are influenced by coupling coefficients and attenuation/gain coefficients, and the influences of these parameters are different under different conditions. So it is very complicated to tell how dispersion and transmittance vary with these parameters.

In this letter, we show that the disciplinarians of dispersion and filtering characteristics of CDRRs varying with different parameters can be summarized under different conditions. The group velocity controls are optimized and large delay and advancement are achieved.

A CDRR consists of two coupled microring structures and an excitation waveguide, and its structure is shown in Fig. 1.

The transfer functions of the first ring and the whole system, $\tau_1(\phi_1)$ and $\tau_2(\phi_1, \phi_2)$ are

$$\tau_1(\phi_1) = \frac{t_1 - a_1 \exp(i\phi_1)}{1 - t_1 a_1 \exp(i\phi_1)} = |\tau_1| \exp[i\phi_{1\text{eff}}],$$

$$\tau_2(\phi_1, \phi_2) = \frac{t_2 - a_2 \tau_1 \exp(i\phi_2)}{1 - t_2 a_2 \tau_1 \exp(i\phi_2)} = |\tau_2| \exp[i\phi_{2\text{eff}}],$$

where $\phi_i$ and $a_i$ are the phase shifts and the amplitude transmission factors of the round-trip propagation respectively, $t_1$ are the coupler transmission coefficients, $\phi_{i\text{eff}}$ are the effective phase shifts, and $i = 1, 2$ specifies the first or second ring. In this letter, we only consider CDRRs whose two rings have identical perimeters and refractive indexes. So we can define $\phi_1 = \phi_2 = \phi$.

The first-order derivative of the effective phase shift of a waveguide structure corresponds to its group delay[14]. For a CDRR, at resonance wavelength when the first ring is under-coupled ($t_1 > a_1$), it can be written as[14]

$$\frac{d\phi_{2\text{eff}}}{d\phi_2}|_{\phi_1 = \phi_2 = 0} = \frac{a_2 |\tau_{1,0}| (t_2^2 - 1)}{(t_2 - a_2 |\tau_{1,0}|)(1 - t_2 a_2 |\tau_{1,0}|)(t_1 - a_1)(1 - a_1 t_1)} t_1 (1 + a_1^2) - 2a_1,$$

and when the first ring is over-coupled ($t_1 < a_1$), we have

$$\frac{d\phi_{2\text{eff}}}{d\phi_2}|_{\phi_1 = \phi_2 = 0} = \frac{a_2 |\tau_{1,0}| (1 - t_2^2)}{(t_2 + a_2 |\tau_{1,0}|)(1 + t_2 a_2 |\tau_{1,0}|)(t_1 - a_1)(1 - a_1 t_1)} t_1 (1 + a_1^2) - 2a_1.$$

Fig. 1. Structure of CDRR.
where \( \tau_{1,0} \equiv \tau_{1}(0) \). For the case of \( \partial \phi_2^{(\text{eff})}/\partial \phi_2 > 0 \), the CDRR has normal dispersion and gives out slow light, the larger \( \partial \phi_2^{(\text{eff})}/\partial \phi_2 \) is, the greater the delay. For \( \partial \phi_2^{(\text{eff})}/\partial \phi_2 < 0 \), anomalous dispersion results in fast light, the smaller \( \partial \phi_2^{(\text{eff})}/\partial \phi_2 \), the greater the advancement. Large positive or negative group delay can be achieved by microring resonators due to interaction between pulses and the resonators[7–9].

When the first ring is under-coupled \((t_1 > a_1)\), the first-order derivative of the group delay and transmittance with respect to \(a_2\) can be written as

\[
\frac{d}{da_2} \left( \frac{\partial \phi_2^{(\text{eff})}}{\partial \phi_2} \right) = \frac{t_2 |\tau_{1,0}| (t_2^2 - 1) \left( 1 - a_2^2 |\tau_{1,0}|^2 \right) [t_1 (1 + a_2^2) - 2a_1]}{(t_1 - a_1) (1 - t_1 a_1) [(t_2 - a_2 |\tau_{1,0}|) (1 - t_2 a_2 |\tau_{1,0}|)]^2},
\]

where \( \tau_{2,0} \equiv |\tau_2(0)|^2 \). The non-lasing condition of ring 1 and CDRR are \( t_1 < 1/a_1 \) and \( t_2 < 1/(a_2 \tau_{1,0}) \)[14], respectively. In addition, to realize significant mode splitting and large dispersion, we should choose \( t_1 < 2a_1/(1 + a_2^2) \). When \( a_2 |\tau_{1,0}| < 1 \), it can be seen from Eq. (5) that \( \partial \phi_2^{(\text{eff})}/\partial \phi_2 \) increases with \( a_2 \). From Eq. (6) we know that when \( t_2 > a_2 |\tau_{1,0}|, \tau_{2,0}^2 \) decreases with \( a_2 \), and when \( t_2 < a_2 |\tau_{1,0}|, \tau_{2,0}^2 \) increases with \( a_2 \). Whereas for the case of \( t_2 < 1 < a_2 |\tau_{1,0}|, \partial \phi_2^{(\text{eff})}/\partial \phi_2 \) decreases with \( a_2, \tau_{2,0}^2 \) increases with \( a_2 \). Similarly, disciplinarians of \( \partial \phi_2^{(\text{eff})}/\partial \phi_2 \) and \( \tau_{2,0}^2 \) varying with \( a_2 \) at other conditions, and varying with \( a_1, t_1 \) and \( t_2 \) at various conditions can be summarized also.

Detailed analysis indicates that when there is gain in the first ring, only slow light can be obtained. In addition, when \( a_2 < 1, a_2 |\tau_{1,0}| > 1 > a_1 a_2 \), and \( t_1 < t_1^{(\text{cr})} \), that large \( \partial \phi_2^{(\text{eff})}/\partial \phi_2 \) and \( \tau_{2,0}^2 \) is about 1 can be achieved. Here \( t_1^{(\text{cr})} \) is a parameter which can be used to distinguish between coupled-resonator-induced transparency (CRIT) and coupled-resonator-induced absorption (CRIA)[15], and it can be expressed as

\[
t_1^{(\text{cr})} = \frac{2t_2 \left( 1 - a_1^2 |a_2|^2 \right)}{2a_1 t_2 (1 - a_2^2) + a_2 (1 - a_1^2) (1 + t_2^2)}.
\]

We choose a series of parameters satisfying above condition as \( t_1=0.9995, a_1=1.0001, a_2=0.99, \) and \( t_2=0.78 \), and calculate pulse responses of a CDRR with these parameters. The ring radius is 300 \( \mu \)m, the length of the straight waveguide is 1 cm, and the effective refractive indexes of the ring and straight waveguide are both 3. The input pulse is Gaussian and can be expressed as

\[
A(t) = \exp \left( -\frac{t^2}{t_d^2} \right) \exp (i2\pi ct/\lambda_0),
\]

where \( \lambda_0 =1550.1275 \) nm is the resonance wavelength of the CDRRs, and \( t_d=9 \) ns is the pulse width. The calculated output pulses are shown in Fig. 2. A delay of 7.2042 ns is obtained.

According to Eq. (3), when the first ring is under-coupled \((t_1 > a_1)\), and the whole structure is over-coupled \((t_2 < a_2 |\tau_{1,0}|)\), fast light is obtain. In the case of \( a_2 > 1, a_2 |\tau_{1,0}| < 1 < a_1 a_2 \), and \( t_1 < t_1^{(\text{cr})} \), large \( \partial \phi_2^{(\text{eff})}/\partial \phi_2 \) and transmittance about 1 can be achieved. As shown in Fig. 3, \( \partial \phi_2^{(\text{eff})}/\partial \phi_2 \) increases with \( a_2 \) when \( a_2 |\tau_{1,0}| < 1 \), and decreases with \( a_2 \) when \( a_2 |\tau_{1,0}| > 1 \), and the transmittance at resonance always increases with \( a_2 \).

To realize large advancement and ideal transmittance \(( \tau_{2,0}^2 \approx 1) \) simultaneously, we select the CDRR parameters as \( t_1=0.9993, a_1=0.992, a_2=1.169, \) and \( t_2=0.8 \). Other parameters, including ring radius, waveguide length, and effective refractive index, are the same as the CDRR calculated in Fig. 2. An advancement of 2.3614 ns for above input pulse is obtained, as shown in Fig. 4.

In conclusion, categorizing the characteristics of CDRRs is considerably complicated due to the variety of their possible responses under different parameter conditions. By getting derivations of dispersion and transmittance with respect to each coupling coefficient and amplitude transmission coefficient respectively, we show that the disciplinarians of dispersion and filtering characteristics of CDRRs varying with different parameters can be summarized under different conditions. The group velocity controls are optimized. For CDRRs with
Pulse advancement by a CDRR. The solid and dashed curves indicate the pulses passing the straight waveguide only and output from the CDRR, respectively. $t_1 = 0.9993$, $a_1 = 0.992$, $a_2 = 1.169$, and $t_2 = 0.8$.

ring radius of 300 $\mu$m, delay of 7.2042 ns is obtained when there is gain in the first ring and loss in the second, and advancement of 2.3614 ns is obtained when there is loss in the first ring and gain in the second. In addition to these large advancement and delay the peak transmittances of the pulses are ideally about 1. It is shown that by introducing gain, obvious group velocity control with ideal transmittance can be realized by CDRRs.

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References