Analysis of Optical Reflector Based on Circular Coupled Microring Resonators

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ABSTRACT
In this paper, we analyzed the reflective properties of optical reflector based on circular coupled microring resonators using the transfer matrix method. The reflective spectrum changes greatly for different interresonator coupling due to constructive and destructive interference for different wavelength. Coupled resonator induced transparency occurred when all the resonators are weakly coupled with each other. When the ring-ring is symmetric coupling, single narrow reflection peak can be obtained while single/multiple-peaks box-like profiles would be produced for asymmetric coupling. Optimization of the ring-bus and ring-ring coupling coefficients to achieve different reflective spectrum has been done to provide a design guideline for this novel structure.
Keywords: Integrated optics, Microring resonator, Coupled resonator induced transparency, Optical reflector

1. INTRODUCTION

Optical microring resonator has recently become the subject of intense research in the area of integrated optics due to its unique features such as compactness, low cost, tunability and easy integration on a chip with other photonic devices, which find a variety of applications such as optical filter, optical switch, optical modulator, optical delay line, dispersion compensator, optical sensor and so on [1].

Previously, most of the researches are focused on the transmission characteristics of the microring resonators. Different ring configurations with all kinds of transmission spectrums have been proposed over the past years. Even high-order serial and parallel cascaded coupled microring resonators are employed to improve the transmission performance [2]. However, very few works have been done to design reflective devices based on microring resonators which may play an important role in future optical communication system, such as wavelength reflective filter, tunable laser end-mirror, etc.

A microring resonator based optical reflector can be obtained by simply introducing a notch in a single ring resonator side-coupled to a straight waveguide to generate the coupling between the forward and backward travelling-wave which may produce a box-like reflection response [3]. However, in practical fabrication, it is very difficult to realize because the notch should be controlled in the order of nanometer. Recently, three kinds of optical reflector based on microring resonators have been reported. In 2004, J.K.S. Poon proposed a wavelength selective reflector based on a circular array of coupled microring resonators [4]. This structure has been predicted to have the capability of producing a narrow-band reflection peak but no related experiment was reported until now. In 2005, G.T. Paloczi proposed and experimentally demonstrated another kind of compact wavelength selective in line reflector, which employed a microring resonator and Mach-Zehnder interferometer (MZI) to realize Bragg Grating reflection [5]. This structure can deliver the desired reflection band profile by employing many cascaded ring resonators. Later, a novel coupled double ring resonator based optical reflector was investigated in theory and experimentally demonstrated by several groups [6-8].

Here in this paper, we theoretically analyzed the reflective properties of optical reflector based on three circular coupled microring resonators in detail. We found the flat-top reflection spectrum will be splitting when the loss in the ring is rather small and coupled resonator induced transparency (CRIT) would be produced. We further investigated the reflection spectrum by considering more complicated interresonator coupling such as symmetric coupling and asymmetric coupling, and found this structure can exhibit versatile reflection responses, such as single or multiple narrow/wide-band peaks. The analysis and design guideline presented here allow one to fabricate practical optical reflector based on the circular coupled microring resonators.

2. THEORETICAL ANALYSIS

To analyze the reflection spectrum for a three circular coupled ring resonators (0, 1and 2) shown in Figure 1, we use the transfer matrix method proposed in [4] but made some corrections for the equations. The forward and backward propagating electrical field components for each coupler can be expressed as

$$x_{i'} = [a_{i'} \quad b_{i'} \quad c_{i'} \quad d_{i'}]^T \, (i' = in, 0, 1) \tag{1-a}$$

$$x_{i+1} = [a_{i+1} \quad b_{i+1} \quad c_{i+1} \quad d_{i+1}]^T \, (i+1 = in, 1, 2, 3) \tag{1-b}$$

The coupling between the electrical field components can be represented by

$$x_{i+1} = P_i x'_i \tag{2}$$

Where P_i is the coupling matrix for the coupler. Using the same method, we can get the relation

$$x'_i = Q_i x_i \tag{3}$$

Where Q_i is transfer matrix for the i_{th} ring. Combing the above equations, we can get

$$x_{i+1} = P_i Q_i x_i \tag{4}$$

For three circular coupled ring resonators, by cascading the transfer matrix, we can obtain

$$x_3 = P_2 Q_2 P_1 Q_1 P_0 x'_0 = A x'_0 \tag{5}$$

Moreover, there are six phase relations in the structure, from which we can get the following modified equations:

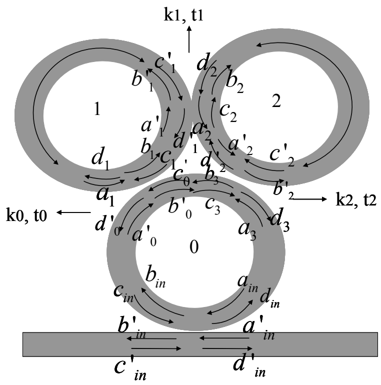


Figure.1 Scheme of circular coupled microring resonator

$$b_3 = \frac{d_{in} A_{21} e^{-i\beta R\theta/2} + a_{in} A_{22} A_{34} e^{i\beta R(2\pi-\theta/2)}}{1 - A_{22} A_{33}}, \quad c_3 = \frac{a_{in} A_{34} e^{i\beta R\theta/2} + d_{in} A_{21} A_{33} e^{-i\beta R(2\pi-\theta/2)}}{1 - A_{22} A_{33}} \tag{6}$$

Combining the six phase relations and equation (6), we can rewrite equation (5) as

$$x'_{in} = P_{in}^{-1} M^{-1} P_2 Q_2 P_1 Q_1 P_0 W P_{in} x'_{in} = B x'_{in} \tag{7}$$

We assume there is only one input ($c'_{in} = 1$), the eigenvector of equation (7) has the form

$$x'_{in} = [0 \quad b'_{in} \quad 1 \quad d'_{in}] \tag{8}$$

From equation (7) and (8), we can get the following modified matrix equation

$$\begin{bmatrix} \dfrac{B_{42}}{1-B_{44}} & -1 \\ 1 & -\dfrac{B_{24}}{1-B_{22}} \end{bmatrix} \begin{bmatrix} b'_{in} \\ d'_{in} \end{bmatrix} = \begin{bmatrix} -\dfrac{B_{43}}{1-B_{44}} \\ \dfrac{B_{23}}{1-B_{22}} \end{bmatrix} \tag{9}$$

The complex reflection coefficients b'_{in} can be calculated from the above matrix equation.

3. REFLECTION SPECTRUM

In this section, the reflection spectrum of the proposed structure is investigated in detail for various values of coupling coefficients based on the above theoretical method. The parameters used in our simulation and analyses are as follows: the three rings have the same radius of 50 μm and effective refractive index $n_0 = n_1 = n_2 = 3$, the ring-bus coupling coefficient is k_{in} and the ring-ring coupling coefficients between the ring 0, 1 and 2 are k_0, k_1 and k_2, respectively, the operating wavelength is in the range of 1550nm (C band).

Firstly, we analyzed the reflection spectrum when all the coupling coefficients are of the same value $k_{in}=k_0=k_1=k_2=0.1$, which is shown in Figure 2 (a). It can be seen that there are four narrow peaks in the reflection spectrum in this case. When the effective refractive index of the ring 1 or 2 is slightly changed such as $n_2=3.0001$, the reflection peaks increase to six, as is shown in Figure 2(b). Further increase of the n_1 or n_2 will change the resonant wavelength of the reflection peaks. Therefore, it is possible to design an optical reflector with several narrow reflection peaks that can be reflected simultaneously. By properly changing the effective refractive index of ring 1 or 2, the reflection peaks can be adjusted accordingly as our desire. This can be potentially used in the add-drop multiplexer and tunable multi-wavelength laser generation.

In the following simulation, we investigated the reflection and transmission behaviour for the structure with different ring-bus and ring-ring coupling coefficients. Figure 3 shows the reflection spectrum (a) and phase

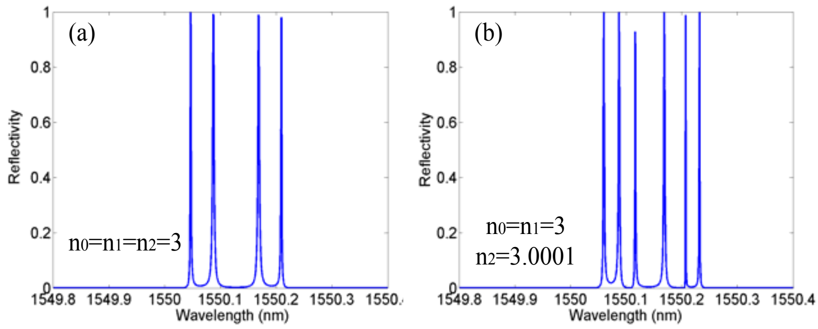


Figure.2 Reflection spectrum when $k_{in}=k_0=k_1=k_2=0.1$ for (a) $n_0=n_1=n_2=3$ and (b) $n_0=n_1=3$, $n_2=3.0001$

response (b) for a lossless structure with k_{in}=0.53, k_0=k_1=k_2=0.08, from which we can see the flat-top reflection spectrum has two narrow splitting resonances with reflectivity of zero when the ring-ring are weakly coupled with each other. The phase response is totally different for the two resonances, as it can be seen from the zoomed in Figure 3 (c) and (d). An input light with its wavelength falling into the two narrow splitting resonant windows will transmit through the structure without any reflection. This is very similar to the electromagnetic induced transparency (EIT) in the atomic system and has also been observed in a two coupled resonators system regarded as coupled resonator induced transparency (CRIT) [9].

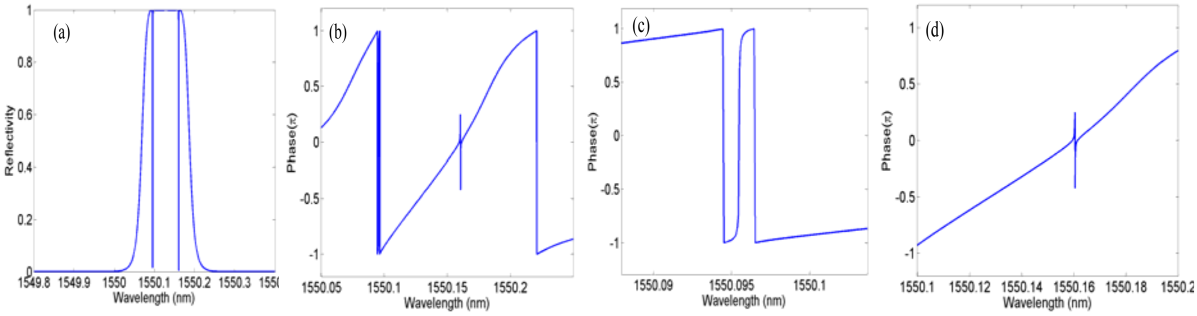
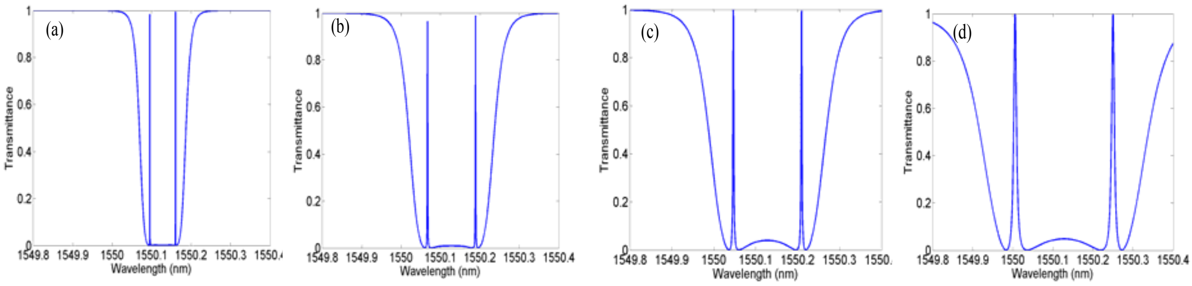


Figure.3 Reflection spectrum (a) and phase response (b)、(c) and (d) when k_{in}=0.53, k_0=k_1=k_2=0.08

The resonance splitting is strongly dependent on the coupling coefficients. When the ring-bus and ring-ring coupling is increased, the two splitting resonances will be widened with their resonant wavelength moving toward the opposite directions, which is shown in Figure 4. This capability of tuning the wavelength and linewidth of the splitting resonance is particularly important for application such as tunable bandwidth filter, optical switching, optical gyroscope [10], as well as other nonlinear on-chip optical components.



k_{in}=0.53, k_0=k_1=k_2=0.08 k_{in}=0.7, k_0=k_1=k_2=0.15 k_{in}=0.8, k_0=k_1=k_2=0.2 k_{in}=0.9, k_0=k_1=k_2=0.3

Figure.4 EIT-like transmission spectrum with different coupling coefficients

In general, the transmission loss inside the ring resonators can not be ignored. Figure 5(a) shows the reflective spectrum with different losses, from which we can see the two splitting resonances gradually disappear as the loss increases while the peak reflectivity is degraded. A wideband reflection spectrum without any splitting will be produced as a result of the loss though its peak reflectivity is no longer unity. For a fixed loss of 3dB/cm, the relationship between the peak reflectivity, 3dB bandwidth and the ring-ring coupling coefficients for k_{in}=0.7 is shown in Figure 5(b). It can be seen as the ring-ring coupling coefficients decrease from k_0=k_1=k_2=0.2, the peak reflectivity and 3dB bandwidth will also be decreased. Further increase of the ring-ring coupling will cause the resonance splitting and the CRIT will occur. By dynamically adjusting the loss in the ring, the two splitting resonances can be switched between "on" and "off" state.

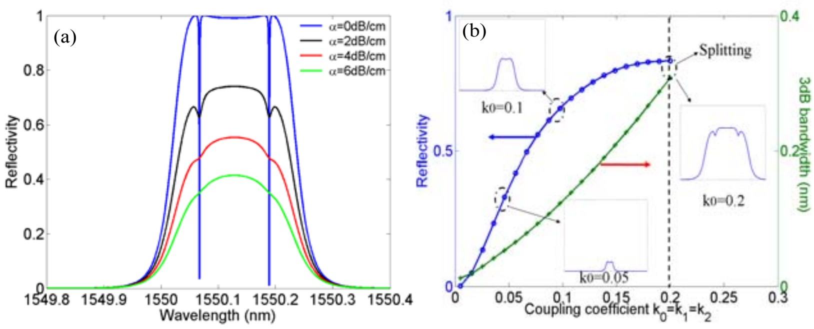


Figure.5 (a) Reflective spectrum for different loss and (b) reflectivity and 3dB bandwidth versus coupling coefficients k_0=k_1=k_2 for k_{in}=0.7 and α=3dB/cm

We also analyzed the reflection behaviour when the ring-ring coupling coefficients are different with each other, such as the symmetric coupling with k0=k2≠k1 and asymmetric coupling with k0≠k1=k2. For symmetric coupling, one can obtain an ultra-narrow linewidth reflection spectrum (0.01nm) when the ring 1 and 2 is weakly coupled ($k_1 \leq 0.02$), as is shown in Figure 6 (a). As the coupling coefficient k_1 decreases from 0.02, the peak reflectivity will be degraded and the 3dB bandwidth decreases. For the asymmetric coupling, the reflective spectrum exhibit several profiles as the coupling coefficients $k_1=k_2$ increase. When $k_1=k_2$ is small, a similar ultra-narrow reflection spectrum can be obtained, but when the coupling increases, the reflective spectrum becomes a wideband box-like profile and then split into three narrow flat-top spectrums, which can be seen from Figure 6 (b). This indicates us that the reflection profile can be designed by appropriately changing the coupling coefficients $k_1=k_2$ in this case which may be potentially used as different functional devices, such as single/multi-wavelength reflective filter.

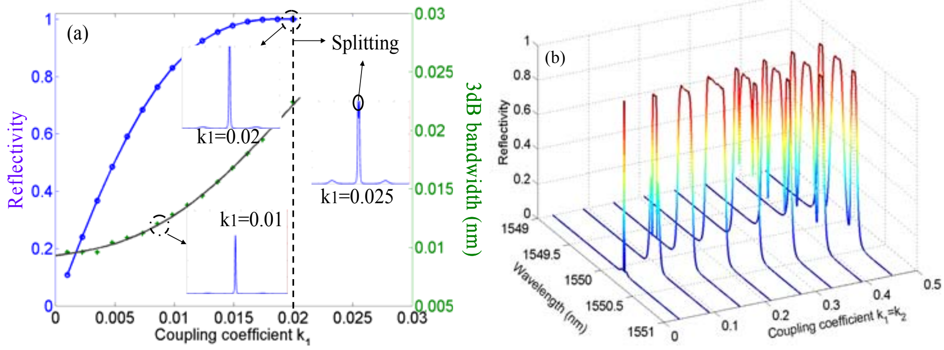


Figure.6 (a) Reflectivity and 3dB bandwidth versus k_1 for symmetric coupling $k_{in}=0.7$, $k_0=k_2=0.6$, and (b) reflective spectrum when $k_{in}=0.7$, $k_0=0.18$ for asymmetric coupling $k_1=k_2$

4. CONCLUSIONS

We analyzed the reflection behaviour of a novel optical reflector based on three circular coupled microring resonators in detail. Different combination of ring-bus and ring-ring coupling coefficients and the effect of loss which were neglected in former work have been studied. Coupled resonator induced transparency (CRIT) has been observed when all the rings are weakly coupled. As the loss in the structure increases, the CRIT will disappear and a wideband reflection spectrum without any splitting would be produced. We further extended this work by considering symmetric and asymmetric ring-ring coupling and found the reflection spectrum exhibit different profiles, including single or multiple narrow/wideband reflection peaks, which allows us to design various reflective optical components. The analysis presented in this paper can guide one in the fabrication of circular coupled microring resonator based optical reflector.

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