Characteristics of an add-drop filter composed of a Mach-Zehnder interferometer and double ring resonators

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A planar lightwave circuit (PLC) add-drop filter is proposed and analyzed, which consists of a symmetric Mach-Zehnder interferometer (MZI) combined with double microring resonators. A critical coupling condition is derived for a better box-like drop spectrum. Comparisons of its characteristics with other schemes, such as a MZI with a single ring resonator, are presented, and some of the issues about device design and fabrication are also discussed.

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The optical add-drop multiplexer (OADM) is a key device in wavelength division multiplex (WDM) communication systems. Integrated OADMs, such as the arrayed waveguide grating (AWG), have been widely used in practical applications. Recently planar lightwave circuits (PLCs) incorporated with microring resonators (MRRs) are developing rapidly and showing potential advantages in performance, size, and cost. MRRs with radii less than 10 μm have been proposed and demonstrated using different high index contrast waveguide materials including compound glass[1], Si/SiO_2[2], and semiconductors[3], which result in a large free spectral range (FSR) of 20 nm. PLC OADMs with vertical coupled MRRs were reported[4]. In this letter a novel add-drop filter is proposed, which consists of a Mach-Zehnder interferometer and double ring resonators (MZDRR). The MZDRR has some advantages, such as larger FSR, better flat top, and sharper roll-off band edges, compared to the filter consisting of a MZI and a single MRR.

A MZI incorporated with a single MRR coupled to one of its beams can be operated as an OADM with a drop output

$$I_{\rm d} = \frac{(1-T)(1+\cos\beta l)}{2(1-T\cos\beta l)}. \qquad (1)$$

The device, denoted here as the Mach-Zehnder interferometer and single ring resonators (MZSRR), has a narrower width at half maximum and a sharper peak for a higher coupling coefficient $T = 2t/(1+t^2)$. Here t is the field transmission index for the "bar" port. It is not possible for a MZSRR to form a good "box-like" spectral shape by only one adjustable parameter T.

The proposed MZDRR add-drop filter consists of a symmetric MZI and two MRRs, as shown in Fig. 1. The lengths of the two rings are l_1 and l_2, and the coupling coefficients between the rings and MZI arms are supposed to be the same and lossless for simplicity. It was shown in Ref. [5] that at resonance, the ring resonator introduces a phase shift of π to the lightwave propagating on the MZI arm coupled with the ring. If the waveglength of an input optical signal is coincident with the resonance peak of the MZDRR, it is dropped at the drop port, whereas other signals goes to the through port. Simultaneously a signal with the resonance wavelength injected at the add port is multiplexed to the through port. Since there is a slight length difference between the two rings, the resonance occurs at two slight shifted wavelengths, and the transmission spectrum is shaped somewhat box-like.

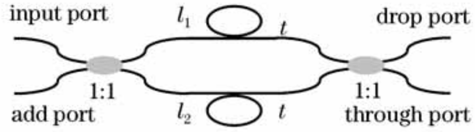

Fig. 1. A schematic diagram of the proposed MZDRR add-drop filter.

The output intensity from the drop port can be derived as

$$I_{\rm d} = \frac{(1-T^2)\sin^2\beta d}{[1-T\cos\beta(l+d)][1-T\cos\beta(l-d)]}, \qquad (2)$$

where $l = (l_1+l_2)/2$, $d = (l_1-l_2)/2$, $\beta = 2\pi n_{\rm eff}/\lambda$, and the output intensity is normalized.

From Eq. (2), the transmission peak of $I_{\rm d} = 1$ occurs under the following condition

$$\cos\beta d = T\cos\beta l. \qquad (3)$$

Therefore, the resonance peaks occur with period which is determined by the ring lengths and their difference, and the coupling coefficient. The spectral characteristics of transmitted light signal near the peak can be obtained by unfolding Eq. (2) in the Taylor series

$$I_{\rm d} \approx 1 + D_2\delta^2 + D_4\delta^4 + D_6\delta^6 + \cdots, \qquad (4)$$

where $\delta = \beta - \beta_0$, and β_0 is the wave vector at the peak which satisfies condition Eq. (3). In the series, the second coefficient is

$$D_2 = -(d\sin\beta_0 d - Tl\sin\beta_0 l)^2/(1-T^2)\sin^2\beta_0 d. \qquad (5)$$

In a critical case, when the parameters are adjusted to meet the condition

$$d\sin\beta_0 d = Tl\sin\beta_0 l, \qquad (6)$$

then $D_2 = 0$ and the resonance peak is flattened somewhat. This condition coincides with the critical case of Eq. (3), that is, the curves of $\cos\beta d$ and $T\cos\beta l$ varying with β get tangent contact, and Eq. (3) has one solution at near the resonance. Apart from the critical case, there are two solutions or no solution for Eq. (3). At the critical case, from Eqs. (3) and (5), one has

$$\cos^2\beta l = \frac{T^2 l^2 - d^2}{T^2(l^2 - d^2)}. \tag{7}$$

And Eq. (4) can be rewritten as

$$I_{\mathrm{d}} = 1 - \frac{(l^2 - d^2)^2(T^2l^2 - d^2)}{4(1 - T^2)^2 l^2}\delta^4 + D_6\delta^6 + \cdots. \tag{8}$$

From Eq. (2) the half maxima are located at points with the following condition

$$\cos\beta_\pm d \pm \sqrt{1 - T^2}\sin\beta_\pm d = T\cos\beta_\pm l, \tag{9}$$

where $\beta_\pm = 2\pi n_{\mathrm{eff}} f_\pm / c$ represents the optical frequencies at the half maximum.

It is noticed that for the MZDRR, there are at least two parameters to be used to adjust the spectrum shape, one is coupling coefficient t, and another is the length difference of the two rings, which make the device with better performance and make the design more flexible. Compared with the multiple ring MZI[6], the MZDRR is simpler in device fabrication.

To describe the characteristics of the MZDRR filter, its transmission spectra are calculated for different parameters. The parameters used in the calculation are as follows: core refractive index of 1.65, cladding index of 1.45; the waveguide height and width both of 1.5 μm. The effective index of the waveguide is calculated to be 1.57 by using effective index method. Figure 2 shows a typical spectrum over its FSR with $l_1 \approx 62.34$ μm, $l_2 \approx 62.33$ μm, and $t^2 = 0.935$. The spacing between two resonant peaks is 3.06 THz, equivalent to about 30 channels with 100 GHz channel spacing. Figure 3 shows the spectra of one peak with different parameters, in which the thin solid line is for the MZSRR, the bald solid line is for the critical coupling defined above, with the same parameters as in Fig. 2. The dash line is for $t^2 = 0.905$, in this case Eq. (3) has no solution, and the peak amplitude is lower than 1. The dot line is for $t^2 = 0.965$, in this case Eq. (3) has two solutions, and there are two peaks near the center and a dip at the center. It can be noticed that the suppression ratio for 100 GHz side channel is 25 dB for the MZDRR filter, while it is 15 dB for the MZSRR filter. And the 1-dB bandwidth of the MZDRR is about 3 times wider than that of MZSRR. It means that the transmission spectrum of the critical coupling has more flattened top and narrower bottom width than the MZSRR, but the parameters of the coupling coefficient and the ring length difference should be well adjusted to get the spectral line shape better.

Although the bandwidth can be calculated by using Eq. (2), in order to give an explicit view, an approximate expression can be derived for the $1/\eta$ bandwidth as

$$B_\eta \approx 2\left\{\frac{2\pi n_{\mathrm{eff}} l}{\cos^{-1}[1 - \sqrt{\eta - 1}(1 - T^2)/T]} - \lambda_0\right\}. \tag{10}$$

The formula has been verified by simulations, as shown in Fig. 4. By using Eq. (8), the 3-dB bandwidth and side channel isolation can be calculated as functions of the coupling coefficient t, as shown in Fig. 5. It can be read that as the coupling coefficient increases, the bandwidth decreases, and side channel isolation increases.

Since the ring length difference is a critical parameter in adjusting MZDRR's characteristics, its precise control is necessary. In a typical glass planar waveguide ring with a 10 μm radius, a deviation of 50 nm in the radius shifts the resonant wavelength by 8 nm[7]. It is not easy to get such high precision for the proposed MZDRR structure in lithographic fabrication processing. Fortunately some more precise control technologies have already been

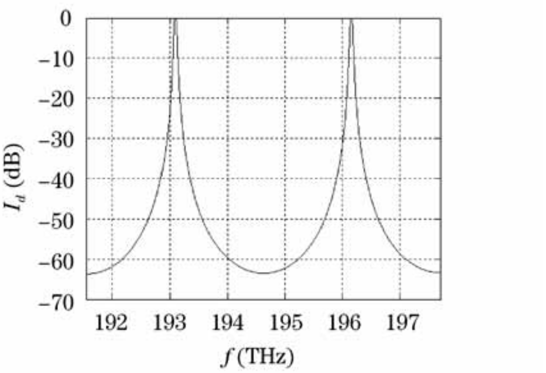

Fig. 2. A typical spectrum of the MZDRR over a FSR.

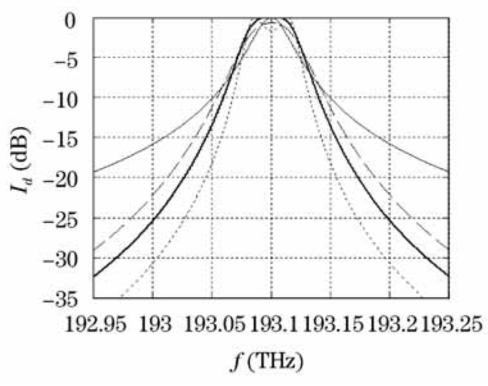

Fig. 3. Typical spectra of the MZDRR at different coupling states.

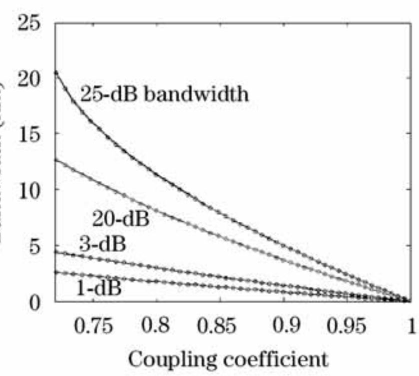

Fig. 4. Bandwidth variation with the coupling coefficient of the MZDRR. Dot: calculated by Eq. (8); line: by Eq. (2).

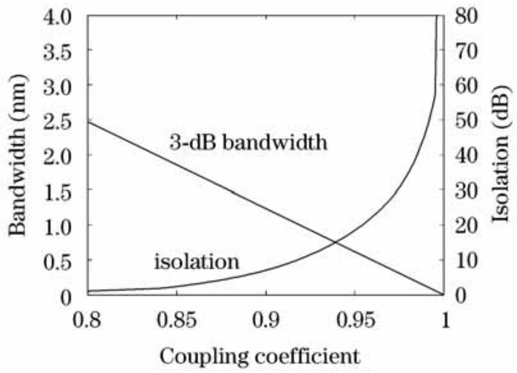

Fig. 5. 3-dB bandwidth and side channel isolation of the MZ-DRR as functions of coupling coefficient.

developed, or in developing. One is post-fabrication wavelength trimming by UV exposure, for example. Another widely used method is by using thermo-optic effect. The thermo-optic phase shifter can be applied to the rings waveguide by a metal coating. The optical path length change is $\Delta l = l(\mathrm{d}n/\mathrm{d}t)\Delta T$, where $\mathrm{d}n/\mathrm{d}t$ is the thermo-optical constant of glass, l is the heater length, and ΔT is the temperature increase. According to the typical datum[8] of glass waveguide, $\mathrm{d}n/\mathrm{d}t = 1.1\times10^{-5}$, to get an optical path control of $\Delta l = 10$ nm, the heater temperature change of about 14.5 °C is needed, which should be in a practical available range.

In conclusion, an add-drop filter composed of a Mach-Zehnder interferometer and a pair of ring resonators is proposed. Its transmission spectrum is discussed, and a critical coupling condition is presented. Its characteristics, such as the FSR, bandwidth, top flatness, and side channel isolation, are simulated. The proposed MZDRR filter has better spectral line-shape than the MZSRR, which has only one ring resonator incorporated, and has some advantages of simpler fabrication process compared with multiple ring filters.

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