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MZI wavelength interleaving filter based on double microring structure

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Abstract: To improve the output characteristics of all-fiber Mach-Zehnder interferometer (MZI)-interleaver, a dual microring-assisted MZI interleaver is designed. According to its structure, the output expression of the device is derived from the signal flow diagram. After simulation analysis, the optimal structural parameters during the transmission process are obtained. In addition, the coupling coefficient and transmission loss of the coupler are analyzed. The results show that the improved interleaver output line wave is closer to the square wave, and its 25 dB cutoff band bandwidth and 0. 5 dB passband bandwidth are significantly improved, with the values of 41. 2 GHz and 18. 9 GHz, respectively. The device has a certain resistantability to deviation, and the transmission loss has less influence on the extinction characteristics of the filter.

Key words: optical fiber communication; Mach-Zehnder interferometer (MZI); interleaver; dual microring resonator

0 Introduction

With the increase of dense wavelength division multiplexing (DWDM) transmission rate and the reduction of channel spacing, more stringent requirements are imposed on the performance of wavelength selective devices in the system, resulting in a significant increase in manufacturing costs. Liu et al. [1] designed an interleaver that used the interference effect of light to form a periodic, center-wave-interleaved and complementary comb-like spectrum to separate the multiplexed channels in a parity-interleaved manner. Since the channel spacing after separation is doubled, the design pressure of the demultiplexer or the upper and lower speech wavelength interleaving filters in the system will be greatly reduced. In recent years, microring resonators have attracted the attention of researchers because of their simple structure, stable performance and high integration[1]. Based on a two-channel single microring filter proposed by Chen et al., we have designed promising opticed devices such as filters, optical switches, wavelength division multiplexers, lasers and fiber optic sensors[2-8]. These devices have great application value in the fields of new generation all-optical communication networks and integrated optics. The Mach-Zehnder interferometer (MZI) is the most widely used solution to wavelength interleaving filters. However, the transmission spectrum of a single-stage MZI is of cosine shape, and its transmission efficiency is very sensitive to the signal wavelength shift. Multi-stage MZI tandem-type comb filters can improve the passband flatness and the asymmetric fiber resonant ring assisted MZI type[9-10], which largely relieved the laser wavelength accuracy requirements while increased the total arm length of the MZI and affected the simplicity of device structure and the stability of performance[9]. Asymmetric fiber-resonant ring-assisted MZI comb filters also can improve the passband flatness[11-13], but this solution requires active compensation transmission loss in practical applications[12]. In order to address the above problems, we combine the microring resonator with the MZI[14], and use the phase adjustment effect introduced from the resonator feedback loop to further improve response performance of the filter while enhance design flexibility of the wavelength interleaving filter.

1 Device structure and theoretical analysis

The structure of the dual microring-assisted MZI

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interleaver is shown in Fig. 1, and the microring is coupled to the MZI interference arm by a 2×2 coupler. Using k_i to represent the coupling coefficient of the ith coupler, and γ to denote the insertion loss of the coupler, the transmission path gain of the ith coupler can be expressed as

$$C_i=(1-\gamma)(1-k_i), \tag{1}$$

and the coupling path gain can be expressed as

$$Y_i=-\mathrm{j}(1-\gamma)k_i. \tag{2}$$

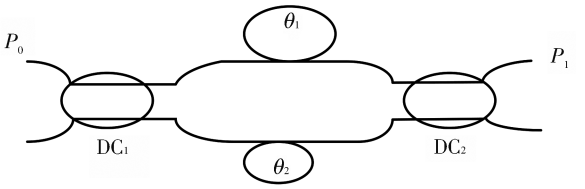


Fig. 1 Structure of dual microring-assisted MZI interleaver

The effective refractive index of the microring waveguide and the MZI interference arm waveguide is represented by n_{eff}, and the gain transmitted by the light along the annular cavity is

$$\theta_i=\exp(-\alpha l_i-\mathrm{j}\beta l_i), \tag{3}$$

where α is the intrinsic loss of the waveguide; l_i is the microring; the length, $\beta=Kn_{\mathrm{eff}}$; and $K=2\pi/\lambda$ is the wave number in vacuum. The gain transmitted on the interference arm of the MZI is

$$L_i=\exp(-\alpha d_i-\mathrm{j}\beta d_i), \tag{4}$$

where d_i is the arm length of the interference arm. Fig. 2 shows the signal flow diagram of the microring resonator, the MZI upper, lower arm phase-coupled filter. The signal transfer theory is used to deduce the filter transfer function[1].

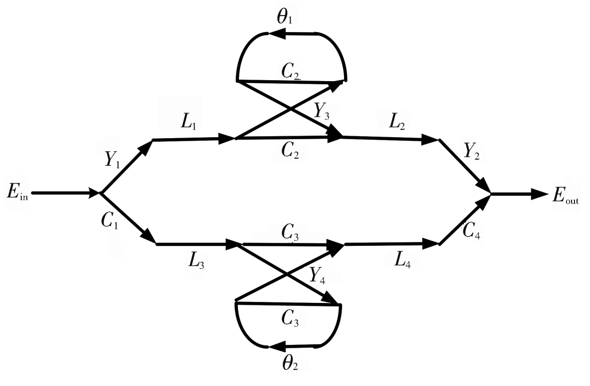


Fig. 2 Signal flow diagram of microring resonator, MZI upper, lower arm phase-coupled filter

It can be seen that the structure contains two closed loops denoted as $S_1=C_2\theta_1$ and $S_2=C_3\theta_2$, respectively. Since the two closed loops are not contacted with each other, the characteristic determinant of the structure is

$$\Delta=1-(S_1+S_2)+S_1S_2. \tag{5}$$

There are four forward paths from E_{in} to E_{out}. The characteristic determinants are $P_1=C_1C_4C_3L_3L_4$, $\Delta_1=\Delta$; $P_2=C_2Y_1Y_2L_1L_2$, $\Delta_2=\Delta$; $P_3=C_2\theta_1Y_1Y_2Y_3^2L_1L_2$, $\Delta_3=1-S_2$; and $P_4=C_1C_3C_4\theta_2Y_4^2L_3L_4$, $\Delta_4=1-S_1$. According to the Mason formula, the transfer function from E_{in} to E_{out} can be expressed as

$$\frac{E_{\mathrm{out}}}{E_{\mathrm{in}}}=\frac{P_1\Delta_1+P_2\Delta_2+P_3\Delta_3+P_4\Delta_4}{\Delta}. \tag{6}$$

In numerical simulation analysis, the optimization algorithm is applied. The coupling coefficients of DC_1 and DC_4 are $k_1=k_4=\pi/4$; the coupling coefficients of the two microrings are $\theta_1=\pi/2.67$ and $\theta_2=\pi/0.3$, respectively; and the length of the fiber interference arm is long. The difference $\Delta_1=4$ mm, the center wavelength $\lambda_0=1\ 550$ nm, the effective core refractive index $n_{\mathrm{eff}}=1.454$, the transmission spectra obtained by simulation 3 are shown in Fig. 3, where the output light intensity of port 1 is indicated by a solid black line, and the output intensity of port 2 is indicated by a dotted line. Fig. 3 shows that the output spectra of port 1 and port 2 of the comb filter are periodic spectra with equal bandwidth and flat top in output line, which can offset the adverse effect of channel wavelength drift.

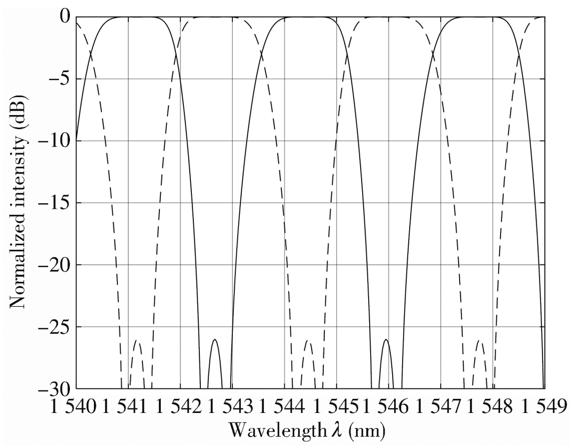


Fig. 3 Calculated transmission spectra of proposed interleaver in cases of $k_1=\pi/4$ and $k_4=\pi/4$

It is calculated that the 25 dB cutoff band bandwidth of the output spectrum of the comb filter is about 39. 4 GHz, and the 0. 5 dB passband bandwidth is about 19. 2 GHz. In Ref. [10], the passband shape of the conventional MZI comb filter is similar to the cosine wave. Its 25 dB cutoff band bandwidth is about 3. 6 GHz, and the 0. 5 dB passband bandwidth is about 21. 3 GHz. The symmetrical structure based "8" shaped cavity MZI interleaver designed in Ref. [13] has a 25 dB cutoff bandwidth of approximate 18.4 GHz. In Ref. [9], the cascaded MZI comb filter has a 25 dB cutoff bandwidth of 15.8 GHz and a 0.5 dB passband bandwidth of 30.2 GHz. Compared with the designs in Refs. [9,10,13], our designed dual microring-assisted MZI interleaver adjusts phase with the fiber resonant ring. Its output spectrum curve produces a steep edge with a 25 dB cutoff band bandwidth and a 0.5 dB passband bandwidth and the output spectrum is closer to square wave.

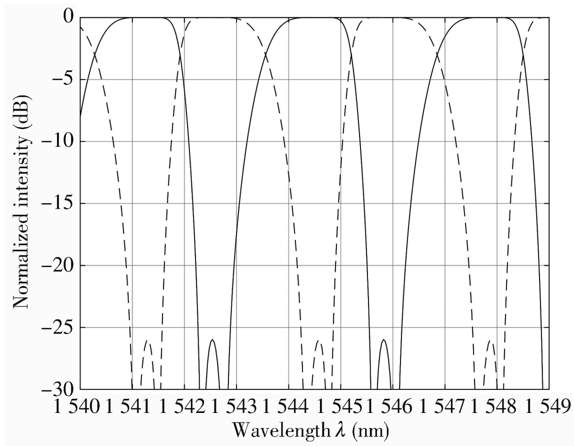
2 Numerical simulation

2.1 Effect of coupling ratio on output spectrum

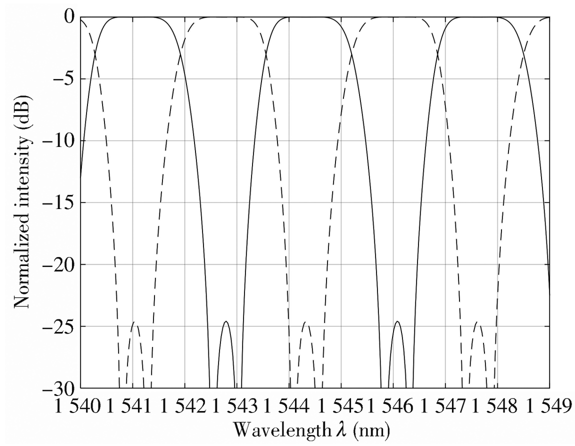
The coupling coefficient and the splitting ratio of the coupler directly determine the shape of the output spectrum of the device and the channel isolation. Due to the limitations of the manufacturing process and experimental conditions, there is a certain deviation between the actual value and the expected value of the fiber coupler splitting ratio. Therefore, it is necessary to discuss the influence of the coupling coefficient deviation of the coupler on the output spectrum of the interleaver. As can be seen from Fig. 2, both the coupler DC_1 and the coupler DC_4 are 3 dB couplers, and the output spectral characteristics of the device are the coupling coefficients k_2 and k_3 of the coupler DC_2 and the coupler DC_3, respectively; Δk is the deviation of the coupling coefficient, and $\Delta k = k \times 10\%$. Fig. 4 is the output spectrum of interleaver when $k_2 = k_2 \pm \Delta k_2$, and $k_3 = k_3 \pm \Delta k_3$, respectively.

It can be seen from Fig. 4 that although the 0.5 dB passband width, the 25 dB stopband width, the channel isolation, etc. are not significantly reduced compared with those in Fig. 3, the flatness of the output wave in Fig. 4(a) is better than those of Fig. 2 and Fig. 4(b). In Fig. 4(c), although the 0.5 dB passband width and the 25 dB stopband width are significantly increased compared with those in Fig. 3, the channel isolation is significantly reduced and the channel-to-channel isolation is less than 20 dB.

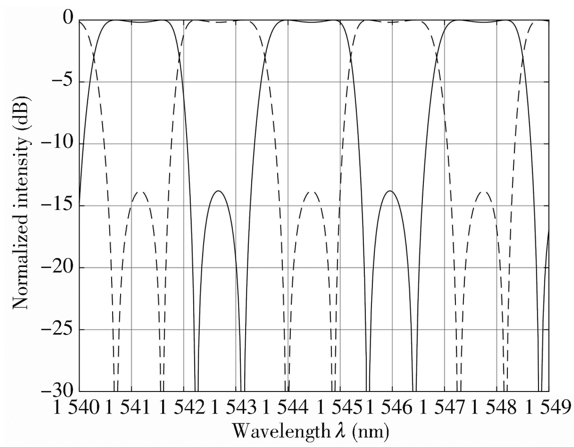
In summary, under the premise of the splitting ratio of the input coupler DC_1 and the output coupler DC_4 is 1∶1, the coupling coefficients k_2 and k_3 of the fiber coupler DC_2 and the coupler DC_3 are greater or smaller than the best as long as they are not different at the same time. The coupling angle, within the error range of $\Delta k_i (i=2,3)$, the interleaver with the designed structure can obtain the ideal output spectrum and bandwidth. This shows that the all-fiber interleaver of this structure has strong anti-deviation ability, which reduces the difficulty of actual production to some extent.



(a)



(b)



(c)

Fig. 4 Output spectrum of interleaver when (a) $k_2 = k_2 + \Delta k_2$, $k_3 = k_3 - \Delta k_3$, (b) $k_2 = k_2 - \Delta k_2$, $k_3 = k_3 + \Delta k_3$ and (c) $k_2 = k_2 - \Delta k_2$, $k_3 = k_3 - \Delta k_3$, respectively

2.2 Influence of transmission loss and length of microring on output spectrum

The transmission loss of the optical signal in the double micro-resonant ring is neglected in the discussion of the output spectrum of the comb filter. However, due to the existence of the fiber resonant ring, the fiber used for the fiber resonant ring inevitably bends, which will increase the transmission loss. In order to analyze the influence of transmission loss on the output spectrum of the comb filter designed, different normalized loss values $\tau_1=\tau_2=\sqrt{\tau}$ are used for simulation. Keeping the values of the coupler DC_1 and DC_4 and the length difference of the fiber arm unchanged. Fig. 5(a) shows the output spectra of the comb filter when $\tau=0.9$, $k_2=k_2-10\%\times k_2$, and $k_3=k_3+k_3\times1\%$.

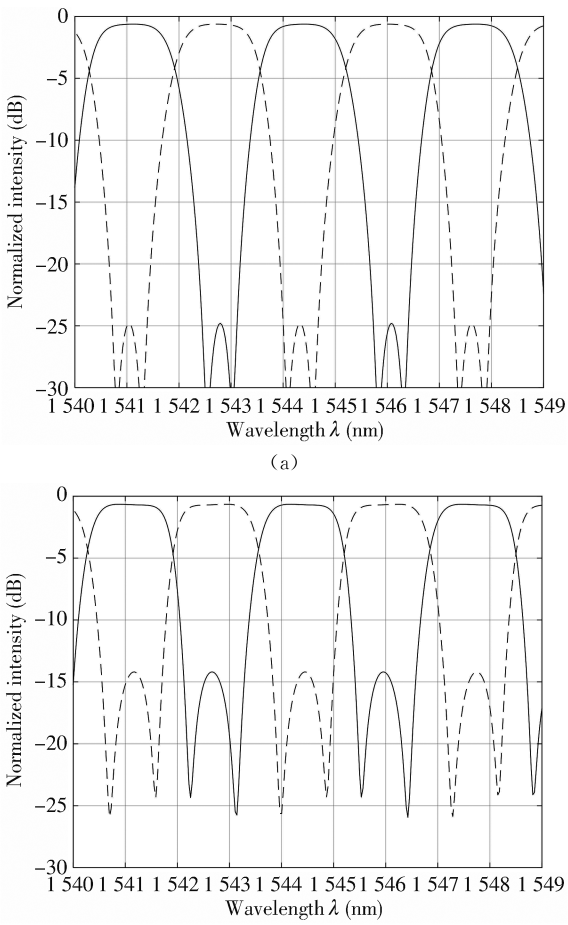


Fig. 5 Output spectrum of all-fiber MZI comb filter: (a) $\tau=0.9$ and $k_2=k_2-10\%\times k_2$, $k_3=k_3+k_3\times1\%$ and (b) $\tau=0.9$ and $k_2=k_2-k_2\times10\%$, $k_3=k_3-k_3\times1\%$

It can be seen from Fig. 5(a) that the peak value of the spectra drops by 0.36 dB, and the isolation between channels is greater than 25 dB. However, the output waveform still has square wave characteristics. Fig. 5(b) is the output spectrum of the comb filter when $\tau=0.9$, $k_2=k_2-k_2\times10\%$, and $k_3=k_3+k_3\times1\%$. It can be seen from Fig. 5(b) that the peak value is decreased by 1.5 dB, however, the channel isolation is greater than 20 dB. Compared with the asymmetric fiber-assisted ring structure in Ref. [10], the two microring fiber resonator ring MZI comb filters interfere with the two optical signals without amplitude difference, which reduces the influence of transmission loss on the extinction characteristics of the device.

3 Conclusions

After adding the double coupler resonant ring, the filtering characteristics of the unbalanced MZI filter are theoretically analyzed. The simulation results show that the improved filter has better filtering effect. Under reasonable parameters, a square-wave comb filter with flat top and low valley can be obtained. At the same time, the filter has a wider 0.5 dB transmission bandwidth and a 25 dB cutoff bandwidth, reducing the need for incident signal light. In addition, the influence of the coupling ratio of the coupler on the filtering performance is analyzed, and the coupling ratio range that satisfies the practical requirements of communication is given. Finally, when considering the transmission loss of the signal, there is no significant difference in the amplitude between the two mutually interfering signals, which effectively reduces the influence of transmission loss on the extinction characteristics of the comb filter, and makes it important in the DWDM system in the future.

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基于双微环结构的 MZI 型波长交错滤波器

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摘　要： 为了改善全光纤马赫-曾德尔干涉仪（Mach-Zehnder interferometer，MZI）的传输特性，提出了一种基于双微环辅助型的 MZI 交叉复用器。根据其结构，利用信号流图推导出了该器件的输出表达式，并进行了数值模拟分析，得到了传输过程中的最佳结构参数。此外，还分析了耦合器耦合系数及传输损耗对该器件的影响。结果表明，改进后的 MZI 交叉复用器输出谱线更加接近方波，其 25 dB 截止带带宽和 0.5 dB 通透带带宽明显改善，其值分别为 41.2 GHz 和 18.9 GHz。器件具有一定的抗偏差能力且传输损耗对滤波器消光特性的影响较小。

关键词： 光纤通信；马赫-曾德尔干涉仪；交叉复用器；双微环谐振腔

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