A research on the characteristics of an interleaver with a symmetrical resonator*

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In order to improve the transmission performance of the conventional Mach-Zehnder interferometer (MZI), a novel interleaver combining an "8" form ring resonator with a planar 3×3 single fiber coupler is proposed. Based on the phase modulation provided by the ring resonator, a flat filtering response is obtained by optimizing the coupling angle of resonator. The output expression is derived and numerical simulation is performed. The simulation indicates that the 0.5 dB passband and 25 dB stopband of the proposed interleaver are simultaneously improved remarkably, which are much wider than those of the single-stage MZI and the two-stage MZI interleavers, and the filtering performance of the proposed interleaver, which achieves a nearly square spectrum response, is also much better. Compared with the interleaver based on an asymmetrical MZI with a resonator in one arm, there is no difference between the intensities of two coherent beams in the condition of considering the influence of the propagation loss. Theoretical analysis shows that the influence of the propagation loss on extinction ratio can be effectively reduced.

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When the Mach-Zehnder interferometer (MZI) is used for an interleaver, the bandwidth of passband/stopband of the single-stage MZI is limited[1-4]. In order to obtain a flat-top passband, an interleaver with a good flat passband response designed by cascading many MZIs and ring resonator MZIs (RRMZIs) is presented[5-10]. Theoretical analysis shows that RRMZI and cascaded MZI have quite good passband flatness, large isolation, and a wide passband/ stopband, which is very close to the ideal rectangular spectrum and quite suitable for dense wavelength division multiplexing (DWDM) systems[11,12]. But the more MZI stages are cascaded, the longer delay lengths are needed, and the more complicated the control is. RRMZI is a promising device because of its simple structure, compact size, and good performance. However, considering the influence of the propagation loss, there is significant difference between the intensities of two coherent beams in the lower and the upper interference arms of RRMZI. The study results in Ref.[11] show that RRMZI can not meet the actual requirements of application unless a technology of active power compensation is adopted to compensate for the transmission loss. In this paper, a novel interleaver with a symmetric structure is designed with an 8-shaped ring resonator. The results of the study show that the extinction ratio can be improved obviously.

The 8-shaped ring resonator is shown in Fig.1, which has two input ports and two output ports. The lower-right output port of DC_1 and the upper-left input port of DC_2 are connected by l_1. The lower-left input port of DC_1 and the upper-right output port of DC_2 are connected by l_2. The optical signals through l_1 and l_2 are transmitted independently of each other and utilize separated communication channels. For the sake of clearness, the interleaver is referred simply as SRR-MZI throughout this paper.

The relationship between input light field $[E^1_{in}, E^2_{in}]$ and output light field $[E^1_{out}, E^2_{out}]$ can be expressed as

$$\begin{bmatrix} E^1_{out} \\ E^2_{out} \end{bmatrix} = \begin{bmatrix} M_1 & M_2 \\ M_3 & M_4 \end{bmatrix} \begin{bmatrix} E^1_{in} \\ E^2_{in} \end{bmatrix}, \quad (1)$$

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where

M_1=-A^{-1}[cos(k_1)-τcos(k_2)exp(-iβ(l_1+l_2))] ,

M_2=A^{-1}[$\tau_2$sin(k_1)sin(k_2)exp(-iβl_2)] ,

M_3=A^{-1}[$\tau_1$sin(k_1)sin(k_2)exp(-iβl_1)] ,

M_4=-A^{-1}[cos(k_2)-$\tau_1\tau_2$cos(k_1)exp(-iβ(l_1+l_2))] ,

A=$\tau_1\tau_2$cos(k_1)cos(k_2)exp(-iβ(l_1+l_2))-1 ,   (2)

â (=2ðn_{eff}/ë, n_{eff} is the effective index of the fiber, and ë is the wavelength) is the propagation constant in the fiber. k_j represents the coupling-coefficient of DC_j (j=1, 2, 3). $ô_1$= exp(-ál_1) and $ô_2$=exp(-ál_2) (á is the transmission loss coefficient) are the normalized losses of light signals through fibers l_1 and l_2, respectively.

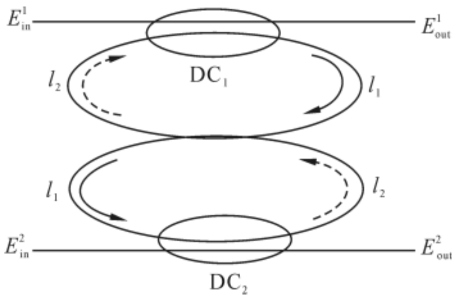

Fig.1 Schematic diagram of an 8-shaped ring resonator

The fibers l_3 and l_4 are used to connect the ring resonator and coupler DC_3 together to form an SRRMZI as shown in Fig.2. The DC_3 is the fused planar 3 ×3 single mode fiber coupler in which three fibers in the same plane are weakly coupled. The DC_3 is used as input device where the function is distribution of the input light. When the coupling coefficient of DC_3 is equal to ð/2 and the signal is input from the middle input port, the power coupling ratio is 0.5:0.0:0.5 at the three output ports. In other words, when the input optical matrix is adopted as [0 E_{in} 0], the output optical matrix will be [$E_{in}/2^{1/2}$ 0 $E_{in}/2^{1/2}$][12,13]. In this situation, the overall transmission of the proposed interleaver can be obtained by

$$\begin{bmatrix} E^1_{out} \\ E^2_{out} \end{bmatrix} = \begin{bmatrix} M_1 & M_2 \\ M_3 & M_4 \end{bmatrix} \begin{bmatrix} \dfrac{\mathrm{i}\sqrt{2}E_{in}}{2}\mathrm{e}^{-\mathrm{i}\beta l_3} \\ \dfrac{\mathrm{i}\sqrt{2}E_{in}}{2}\mathrm{e}^{\mathrm{i}\beta l_4} \end{bmatrix} . \quad (3)$$

An ideal all-fiber interleaver should have symmetric and complementary wavelength response at the both outputs. For this purpose, DC_1 and DC_2 should have the same coupling coefficient. The relations of k_1, k_2, l_1, l_2, l_3 and l_4 are adjusted to satisfy k_1=k_2=k, l_3-l_4=Äl, l_1=3l_4 and l_2=l_4, respectively. In order to have the simpler results, we can choose ô=$ô_1ô_2$=exp (-á(l_1+l_2)) and $ô_1$=$ô_2$=$ô^{1/2}$. These choices are reasonable because fibers l_1 and l_2 can be provided with approximately equal length and similar shape. By straightforward calculations, the normalized output intensities P_1(è) and P_2 (è) are obtained as follows:

$$\begin{cases} P_1(\theta) = \left|\dfrac{E^1_{out}}{E^1_{in}}\right|^2 = \dfrac{1}{2}[1 + B((\tau^2 - 1)\cos(k) + 2(\tau + 1)\sin(\theta))] \\ P_2(\theta) = \left|\dfrac{E^2_{out}}{E^1_{in}}\right|^2 = \dfrac{1}{2}[1 + B((\tau^2 - 1)\cos(k) - 2(\tau + 1)\sin(\theta))] \\ \theta = \beta\Delta l = \beta(l_3 - l_4) \\ B = \dfrac{\sin^2(k)\cos(k)}{[(\tau\cos^2(k) - 1)^2 + 4\tau\cos^2(k)\sin^2(\theta)]} \end{cases} . \quad (4)$$

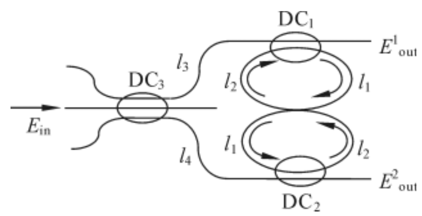

Fig.2 Schematic diagram of a symmetrical interleaver based on ring resonator assisted MZI

It can be seen from Eq.(4) that P_1(è) and P_2 (è) have the same transmission spectrum and it is sufficient just to examine the derivatives of P_1(è). Moreover, high adjacent channel isolation and uniform flat-top spectral response are the basic requirements for the interleaver. First, the derivatives of P_1(è) with respect to è are examined. Forcing dP_1(è)/dè equal to zero, it is derived that dP_1(è)/dè has extreme points when è=$è_1$=ð/2 and è = $è_{2,3}$= ð/2 ± Äè =è=ð/2 ±arcsin[sin^2 (k)/ (2cos(k))]. After simple analysis and calculation, P_1(è) at $è_1$ and $è_{2,3}$ is as follows:

$$\begin{cases} P_1(\theta_1) = \dfrac{1}{2} + \dfrac{2\sin^2(k)\cos(k)}{\sin^4(k) + 4\cos^2(k)} \\ P_1(\theta_{2,3}) = 1 \end{cases} . \quad (5)$$

It is obvious that P_1($è_2$)=1 and P_1($è_3$)=1, which means P_1(è) reaches its maximum at è=$è_2$ and è=$è_3$. It is concluded in turn that P_1(è) has a minimum at è=$è_2$, otherwise P_1(è) will be flat over [$è_2$,$è_3$] because P_1(è) has only three stationary points in [$è_2$,$è_3$]. It can be obtained from the above analysis that the bigger the Äè is, the wider the passband bandwidth is.

For optical communication purposes, crosstalk is one of the most important factors which limit the wide use of an optical interleaver. Therefore, the channel isolation of optical interleaver should also be discussed. The higher the sidelobe peak value is, the more intense the channel crosstalk is. The sidelobes will introduce an undesirable crosstalk to an adjacent wavelength channel. In order to minimize the crosstalk isolation of an optical interleaver, it is necessary to reduce the sidelobe level as much as possible. It is also highly desired that $P_1(\theta)$ is isolated as much as possible to achieve lower sidelobe peak. The interleaver design problem is reduced to finding k to minimize the channel crosstalk. This is equivalent to maximizing $\{|P_1(\pi/2)-P_1(\pi/2+\pi)|\}$, that is,

$$\left|P_1(\frac{\pi}{2})-P_1(\frac{3\pi}{2})\right|=\frac{4\sin^2(k)\cos(k)}{\sin^4(k)+4\cos^2(k)} \quad . \tag{6}$$

Through numerical calculation, Eq.(6) will be equivalent to the maximum when k=1.131($\approx\pi/2.8$).

To verify the theoretical analysis, simulation studies are carried out for the design of an optical interleaver which is capable of separating two sets of interleaving 50 GHz signals. In the design, the differential delay Δl is tuned for 50 GHz. At first, without regard to transmission loss (τ=1), the simulation result is shown in Fig.3, which is calculated utilizing Eq.(4) with the parameters $k_1=k_2=k=\pi/2.8$, n_{eff}=1.457 and λ_0=1550 nm. It is clear from Fig.3 that the proposed interleaver is attractive in flat passbands/stopbands and big isolation. In Fig.3, the 0.5 dB passband (larger than 15 GHz for MZI, and 5 GHz for the TSMZI) and the 25 dB stopband (larger than 15 GHz for MZI, and 2.6 GHz for the TSMZI[6]) are 35.56 GHz and 18.4 GHz, respectively. The channel isolation is far greater than 30 dB. Obviously, the obtained interleaver designed by the proposed approach demonstrates superior performance to the MZI and the TSMZI.

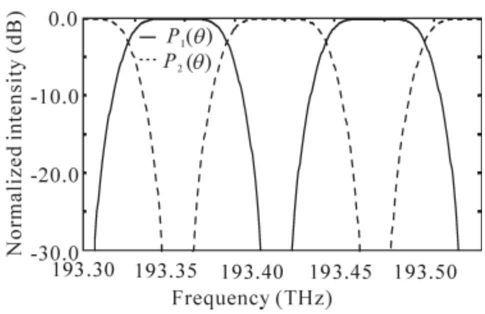

Fig.3 Calculated transmission spectra of the proposed interleaver with $k_1=k_2=k=\pi/2.8$

In the simulation, 10% tolerant fabrication errors are considered for the design parameters k_1 and k_2. The simulation results of the transmission spectra of SRRMZI with $k_1=k\pm\Delta k$ and $k_2=k\pm\Delta k$ are shown in Fig.4.

The 0.5 dB passband and the 25 dB stopband in Fig.4(a) are declined significantly with $k_1=k+\Delta k$ and $k_2=k+\Delta k$. Therefore, it should be controlled that k_1 and k_2 are more than $k=\pi/2.8$ simultaneously.

Fig.4(b) shows clearly that interleavers with $k_1=k-\Delta k$ and $k_2=k-\Delta k$ can provide a wider passband (0.5 dB) and a more smoothing flat-top. But the channel isolation has declined

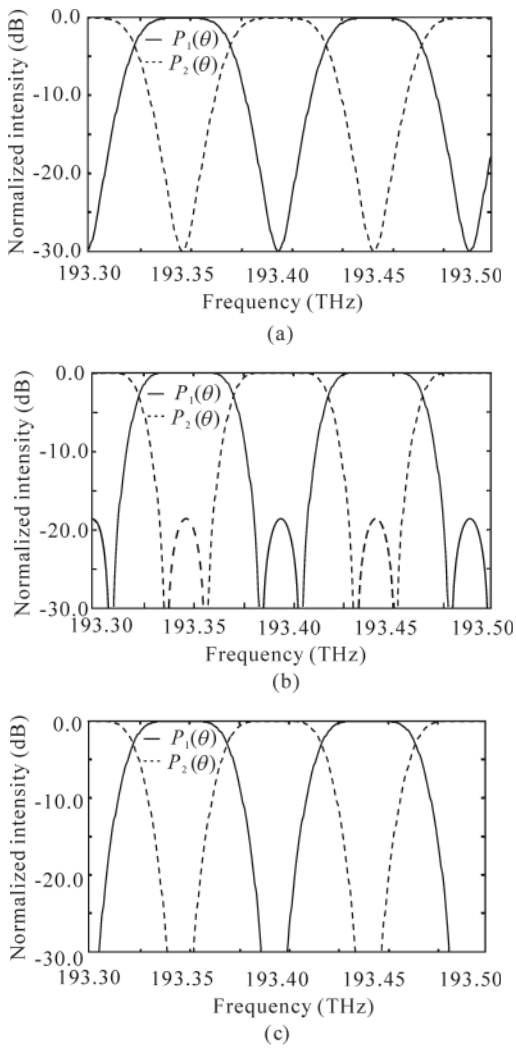

Fig.4 Spectra of the proposed interleaver with (a) $k_1=k+\Delta k$ and $k_2=k+\Delta k$; (b)$k_1=k-\Delta k$ and $k_2=k-\Delta k$; (c)$k_1=k+\Delta k$ and $k_2=k-\Delta k$

significantly. Further calculation shows that the channel isolation can be above 25 dB when $\Delta k=k\times2\%$. In that case, 0.5 dB passband and 25 dB stopband are 35.3 GHz and 21.3 GHz, respectively.

The 0.5 dB passband and 25 dB stopband in Fig.4(c) both decrease to 34.1dB and 17.5 dB, respectively. It also indicates that the performance of the interleaver is acceptable when the design parameters can be controlled within 10% deviations during the fabrication. This feature is very favorable to avoid the crosstalk interference and reduce the difficulties in fabricating the all-fiber interleaver.

According to Ref.[11], the 0.5 dB passband and 25 dB stopband of RRMZI can reach 41.9 GHz and 32.2 GHz, respectively. But these results are calculated in the conditions of not considering the influence of transmission loss. It can be seen from Fig.5 that the interference arms of RRMZI are not symmetrical in which a ring resonator is coupled to the upper arm of the MZI[14]. The extra delay line can be introduced into the upper arm by fiber ring. With the continuous increase of cycle times of the optical signal in upper arm through the ring, the length of the delay line is accumulated continuously. However, the length of the delay line determines the free spectral range (FSR)[15]. For this reason, the fiber length of the ring must be strictly limited[15].

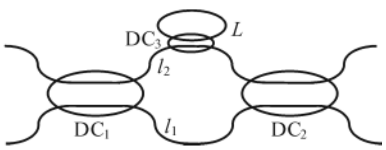

Fig.5 Schematic diagram of RRMZI-interleaver

Moreover, the fiber must be curved by the fiber ring so that fiber bending loss can be certainly introduced. Precisely because of the fiber bending loss and the cumulative optical paths, there will be a large difference between the amplitudes of both two coherent transmitted signals in the lower and the upper interference arms of RRMZI. By interference theory, the difference causes the extinction ratio of the output spectrum of interleaver to decline, and further reduces the channel isolation of interleaver. The lower the extinction ratio of the output spectrum is, the more serious the crosstalk between the channels is.

Fig.6 shows the comparison between RRMZI and SRRMZI considering the transmission losses. In Fig.6(a), the peaks of RRMZI and SRRMZI with τ=0.6 are descended by about 1 dB and 0.4 dB, respectively, and those with τ=0.8 are descended by about 0.5 dB and 0.2 dB in Fig.6(b), respectively. It is clear from Fig.6 that the peak descending

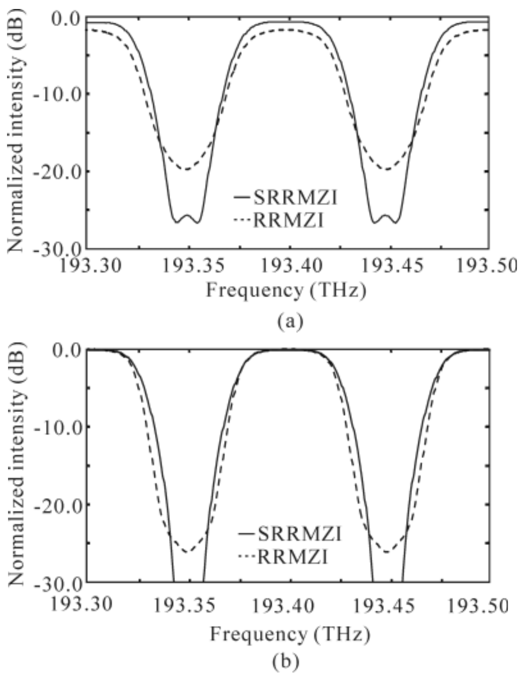

Fig.6 Influence of loss on extinction ratios of RRMZI and SRRMZI with (a) τ=0 .6 and (b) τ=0 .8

values of RRMZI are much more than those of SRRMZI. When $\hat{o}$=0.8, the 0.5 dB passband and 25 dB stopband of RRMZI no longer exist, but those of SRRMZI can still reach 29.2 dB and 18.2 dB, respectively. Fig.6(a) also shows that the stopband rejection of RRMZI is significantly below 20 dB, and that of the proposed interleaver is still above 25 dB when normalized loss $\hat{o} \approx 0.6$.

A novel structure of all-fiber interleaver and the associated design method are presented. It attempts to obtain a wider bandwidth of passband/stopband without cascading more stages of MZIs so as to reduce the insertion loss of the optical interleaver. The simulation indicates that the 0.5 dB passband and 25 dB stopband of the proposed interleaver are improved remarkably, which can achieve a nearly square spectrum response. It shows that the interleaver designed by the proposed approach has favorable performance, which is superior to the RRMZI and the TSMZI.

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