Design Analysis of a Novel All-Fiber Mach-Zehnder Interferometer Interleaver

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Keywords: fiber coupler, dense wavelength division multiplexing (DWDM), Mach-Zehnder interferometer(MZI), interleaver, fiber ring resonator.

Abstract: In order to improve the output spectrum flatness and bandwidth characteristics of conventional Mach-Zehnder interferometer(MZI) filter, a novel two-stage cascaded MZI interleaver is constructed by adding one 8-shaped fiber ring resonator to the interference arms of a conventional single stage MZI filter. Based on a comprehensive analysis, the output spectrum expression is established and simulated numerically. The results of numerical simulation indicates that when the length difference of interference arms and the coupling coefficient of the couplers are some certain values, it will obtain a uniform flat-top passband and similarity to rectangular output spectrum. The improved interleaver has a wider 0.5dB passband bandwidth and 25dB stopband bandwidth, and the rejection in stopband and the roll-off in transition band are improved remarkably. The device has a certain ability to resist the deviation, which reduces the difficulty degree of making it. The design and analysis should be useful in the realization of flattop all-fiber interleaver for development in dense wavelength division multiplexing (DWDM) networks of high spectral efficiency.

1 INTRODUCTION

The demand for communication capacity is increasing with the rapid development of information technology and network, increasing the number of channels in dense wavelength division multiplexing(DWDM) networks becomes an effective and economical way to accommodate the progressive bandwidths requirements. Since the introduction of the novel filter-interleaver at the Optical Fiber Communication Conference in 2000 (OFC2000), and various technical solutions have been proposed about it. The interleaver can de-multiplex a channel-dense multiplexed optical signal into odd-even two signals. The interleaver can not only increase the DWDM system multiplexing channel number, but also has solved the problem of device manufacturing technology. In DWDM system, it is obvious that interleaver plays a critical role.

The all-fiber Mach-Zehnder interferometer (MZI) is a widely used solution for making all-fiber interleaver. The all-fiber interleaver has many advantages, such as simple structure, low insertion loss, good uniform channel passband, small channel crosstalk, low polarization dependent loss. So there has been some important application for the all-fiber interleaver in fiber-optical communication and fiber-sensing system. However, the conventional single-stage MZI interleaver of output spectrum is almost cosine, and the transmission efficiency is sensitive to the signal wavelength shift. Their peak characteristics and the passband bandwidth cannot satisfy the actual needs, and it is easy to generate large insertion loss and crosstalk when used. In order to reduce interleaver's requirements on the wavelength stability of the optical source, avoid unnecessary crosstalk, and realize the basic requirements of wide flat top, sharp cutoff and approximate rectangular wave of the output spectrum. After years of research and development, all-fiber MZI interleaver has two main types of structures: one is cascading many MZI stages, such as the interleaver using three cascaded 2 × 2 fiber couplers(Shaw Wei Kok, 2003), the interleaver cascading three 3 × 3 fiber couplers(H.W. Lu, 2015), the interleaver consisting of three cascaded 3 × 3 and one 2 × 2 fiber couplers(B.G. Zhang, 2016). And the other is a ring resonator into one of the MZI interference arms to form an asymmetry MZI

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interleaver, such as the interleaver is proposed that by adding one fiber loop to a fused-fiber nonsymmetrical MZI(G. Zhou, 2002), the interleaver based on MZI with a double-coupler and single mode fiber resonator in one arm is presented(W.B. Li, 2008), the interleaver combining ring resonator with MZI is proposed(X.W. Dong, 2008). The analysis results show that the two improved schemes can improve the flatness of the response passband. But the former scheme output performance is still not ideal(Shaw Wei Kok, 2003). The latter scheme needs active compensation transmission loss when it is actually applied(X.W. Dong, 2008). In this paper, a novel two-stage cascaded all-fiber MZI interleaver is constructed by adding one 8-shaped fiber ring resonator to the interference arms of a conventional single stage MZI filter. Further improve the interleaver response performance by using the phase adjustment effect introduced by the resonant loop feedback loop. The analysis results show that the output spectrum of the device is similar to the rectangular wave, the side mode suppression is higher, and the channel crosstalk is lower.

2 STRUCTURAL PRINCIPLE

The 8-shaped fiber ring resonator with self-feedback loop is shown by the dashed box in Figure 1, which is consists of two 2 × 2 fiber couplers DC1 and DC2, which are linked together by fiber arm l_1 and l_2. There is no cross connection point between fiber l_1 and l_2, and the optical signals through l_1 and l_2 are transmitted independently of each other. The lower-left input port of DC1 and the upper-right output port of DC2 are connected by l_2, and the lower-right output port of DC1 and the upper-left input port of DC2 are connected by l_1. In this paper, a novel all-fiber MZI interleaver based on the 8-shape fiber resonator is shown in Figure 1. It consists of two 2 × 2 fiber couplers (DC0, DC3) and an 8-shaped fiber ring resonator. The coupler DC0 and the 8-shaped fiber ring resonator are connected by optical fiber l_3 and l_4, the 8-shaped fiber ring resonator and the coupler DC3 are connected by optical fiber l_5 and l_6, and they form a two-stage cascaded MZI interleaver.

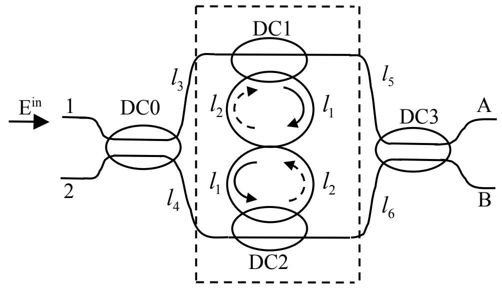


Figure 1: Structure of interleaver based on 8-shaped fiber ring resonator.

The 8-shaped fiber ring resonator shown in the dashed line of Figure 1 has two input ports and two output ports. Set input light fields be $\left[E_1^{in} \quad E_2^{in}\right]$, and output light fields be $\left[E_1^{out} \quad E_2^{out}\right]$. By using the principle of fiber transmission and matrix transfer theory, the relationship between the input light fields and the output light fields can be derived as follows in Equation 1.

$$\begin{bmatrix} E_1^{out} \\ E_2^{out} \end{bmatrix} = \begin{bmatrix} F_1 & F_2 \\ F_3 & F_4 \end{bmatrix} \begin{bmatrix} E_1^{in} \\ E_2^{in} \end{bmatrix} \tag{1}$$

Where

$M = 1 - \tau_1\tau_2 \cos k_1 \cos k_2 \exp(-j\beta(l_1 + l_2))$;

$F_1 = M^{-1}(\cos k_1 - \tau_1\tau_2 \cos k_2 \exp(-j\beta(l_1 + l_2)))$;

$F_2 = -M^{-1}\tau_2 \sin k_1 \sin k_2 \exp(-j\beta l_2)$;

$F_3 = -M^{-1}\tau_1 \sin k_1 \sin k_2 \exp(-j\beta l_1)$;

$F_4 = M^{-1}(\cos k_2 - \tau_1\tau_2 \cos k_1 \exp(-j\beta(l_1 + l_2)))$.

k_1 and k_2 represent the coupling coefficient of DC1 and DC2. β is the propagation constant in the fiber, and $\beta = 2\pi n_{eff} / \lambda$, n_{eff} is the refractive index of the fiber, λ is the wavelength. $\tau_1 = \exp(-\alpha l_1)$ and $\tau_2 = \exp(-\alpha l_2)$ (α is the transmission loss coefficient) are the normalized losses of light signals through fibers l_1 and l_2 respectively.

Figure 1 shows that the input light field E^{in} is only through port 1 of the coupler DC0, and the optical signal is transmitted to the 8-shaped fiber ring resonator via the interference arms l_3 and l_4, and then transmitted to the coupler DC3 via the interference arms l_5 and l_6. Finally, the output light fields from the A and B ports of the coupler DC3.

Set k_0 and k_3 represent the coupling coefficient of DC0 and DC3, neglecting the transmission loss of fiber couplers, and the expression of the output light fields E_A and E_B can be derived as Equation 2.

$$\begin{bmatrix} E_A \\ E_B \end{bmatrix} = S_3 \cdot \begin{bmatrix} \exp(-j\beta l_5) & 0 \\ 0 & \exp(-j\beta l_6) \end{bmatrix} \cdot \begin{bmatrix} F_1 & F_2 \\ F_3 & F_4 \end{bmatrix} \cdot \begin{bmatrix} \exp(-j\beta l_3) & 0 \\ 0 & \exp(-j\beta l_4) \end{bmatrix} \cdot S_0 \cdot \begin{bmatrix} E^{in} \\ 0 \end{bmatrix} \quad (2)$$

Where

$$S_i = \begin{bmatrix} \cos k_i & -j\sin k_i \\ -j\sin k_i & \cos k_i \end{bmatrix} (i = 0,3)$$

By the light intensity formula $P = EE^*$, set the device interference arms $l_1 = l_4$, $l_2 = 3l_1$, $l_3 = 2l_4$, $l_5 = 2l_4$, $l_6 = l_4$, $l_4 - l_3 = \Delta l$, $\theta = \beta\Delta l$ (transmission phase delay of interference arm), if the transmission loss of 8-shaped fiber ring resonator is ignored, P_A and P_B are normalized output intensity which are shown in Equation 3.

$$\begin{cases} P_A = D^{-1}(a_0 + a_1\cos 2\theta + a_2\cos 4\theta + a_3\cos 6\theta + a_4\sin 2\theta + a_5\sin 4\theta) \\ P_B = D^{-1}(b_0 + b_1\cos 2\theta + b_2\cos 4\theta + b_3\cos 6\theta + b_4\sin 2\theta + b_5\sin 4\theta) \end{cases} \quad (3)$$

Where

$A = \cos^2 k_0 \cos^2 k_3 + \sin^2 k_0 \sin^2 k_3$;

$B = \sin^2 k_0 \cos^2 k_3 + \cos^2 k_0 \sin^2 k_3$;

$C = \sin k_0 \cos k_0 \sin k_3 \cos k_3$;

$D = 1 + \cos^2 k_1 \cos^2 k_2 - 2\cos k_1 \cos k_2 \cos 4\theta$;

$a_0 = A(\cos^2 k_1 + \cos^2 k_2) + B\sin^2 k_1 \sin^2 k_2$;

$a_1 = 2C(\sin^2 k_1 \sin^2 k_2 + \cos^2 k_1 - 2\cos k_1 \sin k_2)$;

$a_2 = -2A\cos k_1 \cos k_2$;

$a_3 = 2C\cos^2 k_2$;

$a_4 = 2\sin k_1 \sin k_2 \sin k_0 \cos k_0 (\cos^2 k_3 - \sin^2 k_3)(\sin k_1 + \sin k_2)$;

$a_5 = 2\sin k_1 \sin k_2 \cos k_2 \sin k_3 \cos k_3 (\cos^2 k_0 - \sin^2 k_0)$;

$b_0 = B(\cos^2 k_1 + \cos^2 k_2) + A\sin^2 k_1 \sin^2 k_2$;

$b_1 = -a_1$; $b_2 = -2B\cos k_1 \cos k_2$;

$b_3 = -a_3$; $b_4 = -a_4$; $b_5 = -a_5$.

For all-fiber MZI interleaver, the basic requirement is that the two output channels should have the same output waveform. That is, the requirement is satisfied Equation 4.

$$P_B(\theta + \pi/2) = P_A(\theta) \quad (4)$$

Analysis Equation 3 can be found that the basic condition for satisfying Equation 4 is that the coefficients in $P_A(\theta)$ and $P_B(\theta)$ satisfy $a_0 = b_0$ and $a_2 = b_2$, from which can determine $k_0 = k_3 = \pi/4$. That is, DC0 and DC3 are designed as 3dB couplers. When $k_0 = k_3 = \pi/4$, the Equation 3 will be simplified to Equation 5.

$$\begin{cases} P_A = \dfrac{1}{2} - \dfrac{P\cos 2\theta - \cos^2 k_2 \cos 6\theta}{2Q} \\ P_B = \dfrac{1}{2} + \dfrac{P\cos 2\theta - \cos^2 k_2 \cos 6\theta}{2Q} \end{cases} \quad (5)$$

Where

$P = 2\cos k_1 \cos k_2 - \cos^2 k_1 - \sin^2 k_1 \sin^2 k_2$;

$Q = 1 + \cos^2 k_1 \cos^2 k_2 - 2\cos k_1 \cos k_2 \cos 4\theta$.

Obviously, Equation 5 satisfies both Equation 4 and $P_A(\theta) + P_B(\theta) = 1$. In addition, it can be seen from Equation 3 that P_A and P_B contain coupling coefficients of the fiber couplers and transmission phase delay of the interference arm. The former determines waveform of the output spectrum, and the latter decides cycle of the output spectrum. When the coupling coefficients and the fiber interference arm length select appropriate values, the device can realize comb and equivalent bandwidth of output spectrum. When the input light field E^{in} is through port 1 or port 2 of DC0, because the optical paths of the interfering optical signals are not much different, and the output spectrum of the device is the same.

3 NUMERICAL SIMULATION

In numerical simulation analysis, application optimization algorithm, selecting the parameters $k_1 = \pi/40$, $k_2 = \pi/2.8$, $k_0 = k_3 = \pi/4$, $\Delta l = 1mm$, $\lambda_0 = 1550nm$, $n_{eff} = 1.457$, the simulation result is shown in Figure 2(In the following figure, P_A is the solid line, P_B is the dotted line.). It can be seen from Figure 2 that interleaver output spectrum of the port A and port B are the same two groups of equal bandwidth periodic spectral lines, and each odd (even) group frequency interval is 100GHz, and calculated 0.5dB passband bandwidth is 43.2GHz, the 25dB stopband bandwidth is 32.3GHz. The flat-top appears in the output spectrum, which can offset the negative influence of channel wavelength drift. Figure 2 shows, through the phase adjustment of the fiber ring resonator, the output spectrum produces a steep edge, and forming a similar to a rectangle wave, which is greatly improved compared to the cosine output spectrum of the conventional MZI interleaver.

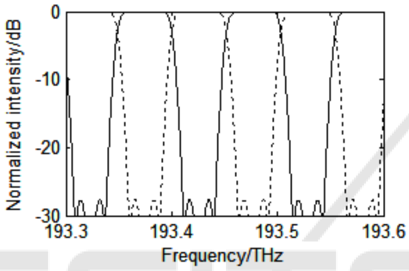


Figure 2: Normalized intensity of all-fiber MZI interleaver with $k_1 = \pi/40, k_2 = \pi/2.8, k_0 = k_3 = \pi/4$

Figure 3 is a comparison of the 0.5dB passband bandwidth and the 25dB stopband bandwidth between conventional MZI interleaver and improved MZI interleaver based on fiber ring resonator. The dashed lines and solid lines represent the output spectrum of conventional interleaver and improved interleaver. By calculation, the 0.5dB passband bandwidths respectively are 21.3GHz and 43.2GHz. The 0.5dB passband bandwidth of improved interleaver accounts for 86.4% of the 50GHz frequency interval, and the 0.5dB passband bandwidth of conventional interleaver accounts for 42.6% of the 50GHz frequency interval, the 0.5dB passband bandwidth of improved interleaver is significantly improved. The 25dB stopband bandwidths of the two interleavers respectively are 3.6GHz and 32.3GHz. The 25dB stopband bandwidth of improved interleaver accounts for 64.6% of the 50GHz frequency interval, and the 25dB stopband bandwidth of conventional interleaver accounts for 7.2% of the 50GHz frequency interval, the 25dB stopband bandwidth of improved interleaver is significantly broadened. These indicate that the output spectrum of the MZI interleaver based on the 8-shaped fiber ring resonator has good rectangle wave characteristics. In addition, the 25dB stopband bandwidth of the two-stage cascade MZI interleaver designed in paper (Shaw Wei Kok, 2003) is about 15.8GHz, accounting for 31.6% of 50GHz frequency interval; The 25dB stopband bandwidth of MZI interleaver designed in paper(H.W. Lu, 2012) is about 18.4GHz, accounting for 36.8% of 50GHz frequency interval; The 25dB stopband bandwidth of MZI interleaver designed in paper(H.W. Lu, 2006) is about 24GHz, accounting for 48% of 50GHz frequency interval; Compared with three interleavers above, the output spectrum of the novel MZI interleaver designed in this paper is more close to rectangle wave, and the 0.5dB passband and 25dB stopband are wider than others.

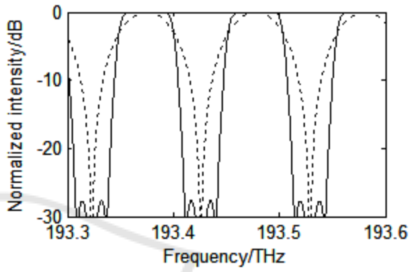


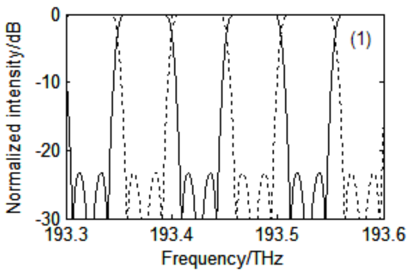
Figure 3: The comparison between conventional MZI interleaver and improved MZI interleaver

4 ANALYSIS DISCUSSION

4.1 Influence of Coupler Coefficient on the Interleaver Response

It can be seen from Equation 5 that when the couplers DC0 and DC3 are 3dB couplers, the length differences of interference arms are constant, and the output spectrum mainly depends on coupling coefficients of DC1 and DC2. The coupling coefficients k_1 and k_2 will determine the size of the channel segregation and the shape of the output spectrum. In addition, the influence of the experimental environment and the manufacturing process, the coupling coefficient of the couplers are deviated from the ideal values, and the deviation of k_1 and k_2 directly affect the split ratio of the couplers. Therefore, it is necessary to discuss the influence of the deviation of the coupling coefficient on the interleaver output spectrum.

Set $\Delta k_1 = k_1 \times 15\%$ and $\Delta k_2 = k_2 \times 5\%$ as the deviations of the coupling coefficients, other parameters remain unchanged, the numerical simulation results show the deviation in range. If only changes k_1 or k_2, the 0.5dB passband bandwidth and the 25dB stopband bandwidth of the output spectrum do not change much, and the output spectrum shape remains basically unchanged. If the coupling coefficients of DC1 and DC2 reduce simultaneously, the 0.5dB passband bandwidth will change the range of 43.2~44.7GHz, and the 25dB stopband bandwidth will change the range of 32.3~35.7GHz. Figure 4(1) is the output spectrum of interleaver with $k_1 = k_1 - \Delta k_1$ and $k_2 = k_2 - \Delta k_2$, its passband bandwidth and stopband bandwidth compared with best value increase slightly, but the side-lobe level also increase(In the following figure, P_A is the solid line; P_B is the dotted line.). If the coupling coefficients of DC1 and DC2 increase simultaneously, the 0.5dB passband bandwidth will change the range of 41.7~43.2 GHz, and the 25dB stopband bandwidth will change the range of 28.0~32.3GHz. Figure 4(2) is the output spectrum of interleaver with $k_1 = k_1 + \Delta k_1$ and $k_2 = k_2 + \Delta k_2$, its passband bandwidth and stopband bandwidth compared with best value decrease slightly, and its side-lobe level decrease. If the coupling coefficients of DC1 increases and the coupling coefficients of DC2 reduces, the 0.5dB passband bandwidth will change the range of 43.2~44.3GHz, and the 25dB stopband bandwidth will change the range of 32.3~35.1GHz. Figure 4(3) is the output spectrum of interleaver with $k_1 = k_1 + \Delta k_1$ and $k_2 = k_2 - \Delta k_2$, its passband bandwidth and stopband bandwidth compared with best value increase slightly, but the side-lobe level also increase. If the coupling coefficients of DC1 reduces and the coupling coefficients of DC2 increases, the 0.5dB passband bandwidth will change the range of 41.8~43.2GHz, and the 25dB stopband bandwidth will change the range of 28.4~32.3GHz. Figure 4(4) is the output spectrum of interleaver with $k_1 = k_1 - \Delta k_1$ and $k_2 = k_2 + \Delta k_2$, its passband bandwidth and stopband bandwidth compared with best value decrease slightly, and its side-lobe level decrease.



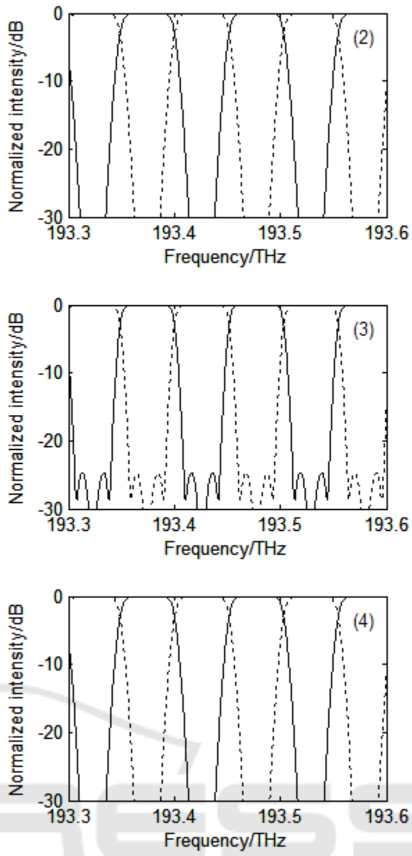


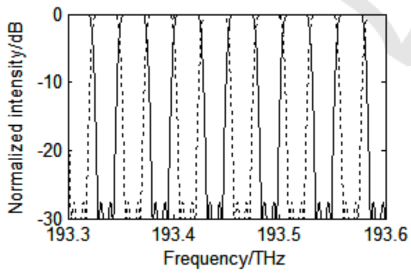
Figure 4: Normalized intensity of all-fiber MZI Interleaver with $k_0 = k_3 = \pi/4$, (1)$k_1 = k_1 - \Delta k_1, k_2 = k_2 - \Delta k_2$, (2)$k_1 = k_1 + \Delta k_1, k_2 = k_2 + \Delta k_2$, (3)$k_1 = k_1 + \Delta k_1$, $k_2 = k_2 - \Delta k_2$, (4)$k_1 = k_1 - \Delta k_1, k_2 = k_2 + \Delta k_2$

It can be known from the calculation that if the segregation of the adjacent channel is to be above 25dB, the deviation of k_1 is kept at $\pm 20\%$, and the deviation of k_2 is maintained at $\pm 8\%$. Moreover, the analysis found that increasing the coupling coefficient of DC2, the coupling coefficient of DC1 increases or reduces, the 0.5dB passband bandwidth and the 25dB stopband bandwidth decreases, and the side-lobe level decreases. Reducing the coupling coefficient of DC2, the coupling coefficient of DC1 increases or reduces, and the 0.5dB passband bandwidth and the 25dB stopband bandwidth increases, and the side-lobe level increases. It can be seen that the shape of the output spectrum mainly depends on coupling coefficient of DC2, and try to keep k_2 within the deviation range.

By analyzing the interleaver output spectrum performance, it can be concluded that the couplers DC0 and DC3 are 3dB couplers, the length differences of interference arms are constant, when slightly deviation of the coupling coefficients of DC1 and DC2 exists, the 0.5dB passband and the 25dB stopband will show deviation, but the change is not obvious, and the channel segregation can be above 25dB, which can satisfy the actual needs. The device has a certain ability to resist the deviation, which will reduce the difficulties in fabricating it.

4.2 Influence of Fiber Interference Arm the Interleaver Response

In the process of numerical simulation, when the ratio of the length difference of the three pairs of interference arms is kept constant, and the length difference is adjusted, the frequency interval of the output spectrum is adjusted accordingly. That is, if the length difference relationship of each interference arm is constant, the length difference increases, the frequency interval of the output spectrum will be narrowed, the length difference reduces, and the frequency interval will be widened. When the coupling coefficients of the couplers are constant, the length difference of fiber interference arm is $\Delta l = 2mm$, the output spectrum is shown in Figure 5, and each odd (even) group frequency interval is changed from 100GHz to 50GHz, the wavelength interval is 0.4nm. By changing the length difference, the frequency interval is changed, which has certain reference value in the practical application of the device.



Figue 5: Normalized intensity of all-fiber MZI Interleaver with $\Delta l = 2mm$

The derivation process found that within a given wavelength range, the periodicity of the output spectrum is determined by the transmission phase delay of interference arm ($\theta = \beta\Delta l$). The range of spectrum ($\Delta\lambda$) can be derived as follows in Equation 6.

$$\Delta\lambda = \lambda_2 - \lambda_1 = \lambda_2\lambda_1 / (n_{eff}\Delta l) \approx \lambda^2 / (n_{eff}\Delta l) \qquad (6)$$

5 CONCLUSIONS

A novel structure of all-fiber interleaver is proposed in this paper. Using an 8-shaped fiber ring resonator feedback loop to introduce phase adjustment into the optical signal, the interleaver has a wider 0.5dB passband bandwidth and 25dB stopband bandwidth, and the rejection in stopband and the roll-off in transition band are improved remarkably. Through theoretical analysis and numerical simulation, the structural parameters of the output spectrum with flat top and approximate rectangular wave are obtained. The output spectrum is not sensitive to the deviation of the coupling coefficient of the fiber coupler, and the device has a certain ability to resist the deviation and reduces the difficulty of its fabrication. Keep the ratio of the length difference of the interference arm unchanged, by changing the length difference, the frequency interval is changed, which has certain reference value in the practical application of the device. The study may provide a new idea and method for all-fiber passive components.

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