Design and Analysis of an all-fiber MZI Interleaver Based on Fiber Ring Resonator

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ABSTRACT: An all-fiber Mach-Zehnder interferometer (MZI) interleaver using one planar 3×3 fiber coupler, one 2×2 fiber coupler and one 8-shaped fiber ring resonator is developed by the new configuration. Based on its structure, the output spectrum expression is established and described by using the principle of fiber transmission and the matrix transfer function. The results of numerical simulation indicate that when the length difference of interference arms and the coupling coefficients of the couplers are some certain values, it obtains a uniform flat-top passband and similar to rectangular output spectrum. Compared with the traditional MZI interleaver, the isolation in stopband and the rolloff in transition band are strengthened, the 25dB stopband bandwidth and 0.5dB passband bandwidth are simultaneously remarkably improved. Compared with the asymmetrical ring resonator MZI interleaver, the influence of transmission loss on extinction ratio can be effectively reduced. The device has a certain ability to resist the deviation, which reduces the difficulties in fabricating it. The experiment results agree with the theoretical analysis well. The interleaver designed by the proposed approach has favorable performance, which has the potential application value in optical fiber communication system.

Keywords: interleaver; fiber ring resonator; fiber coupler; Mach-Zehnder interferometer(MZI); equivalent bandwidth

1 INTRODUCTION

In optical fiber communication system, with the demand of communication capacity increasingly growing, using optical fiber bandwidth efficiently is becoming more and more important. As the key device of dense wavelength division multiplexing (DWDM) system multiplexer/de-multiplexer is not only faced with the improvement of technical difficulty, device cost also increases accordingly. The optical interlever has been proven to be an effective way to increase the capacity by doubling the number of channels. The interleaver can not only increase the DWDM system multiplexing channel number, but also has solved the problem of device manufacturing technology.

Much study has been done about equivalent bandwidth and different bandwidth of interleavers. The main types of interleavers include methods of all-fiber Mach-Zehnder interferometer(MZI), Gires-Tournoise interferometer, Fabry-Perot interference filter, photonic crystal and so on. Among the abovementioned interleavers, all-fiber MZI interleaver based on fused fiber interferometer exhibits special qualities with even channel, simple structure and low insertion loss. However, the conventional single-stage MZI interleaver of output spectrum is almost cosine, and their passband width and peak cannot satisfy the actual needs, therefore, the interleaver designed by cascading many MZI stages and a ring resonator with MZI(RRMZI) are presented. Theoretical analysis shows that the two plans may improve the transmission performance of MZI interleavers. But the cascaded MZI transmission performance is still not ideal. The upper and the lower interference arms of RRMZI are asymmetrical because the ring resonator is coupled to one arm of an MZI, and according to the interference theory, compensating for the transmission loss is needed in practice.

In this paper, a novel all-fiber MZI interleaver is designed with one planar 3×3 fiber coupler, one 2×2 fiber coupler and an 8-shaped fiber ring resonator. Theoretical analysis and experimental verification indicate that designing structure parameters of the device reasonably can realize equivalent bandwidth transmission. The device of output spectrum is almost rectangular, common-mode rejection being high, crosstalk being low, the 25dB stopband and 0.5dB passband are increased remarkably. In addition, the influence of transmission loss on extinction ratio can also be effectively reduced. The device has a certain ability to resist the deviation, which reduces the difficulties in fabricating it.
2 DEVICE STRUCTURE AND THEORETICAL ANALYSIS

2.1 Structure of an 8-shaped fiber ring resonator

The 8-shaped fiber ring resonator is shown in Figure 1, which is composed of two 2×2 fiber couplers DC1 and DC2, which are linked together by fiber arm $l_1$ and $l_2$. The upper-left input port of DC2 and the lower-right output port of DC1 are connected by $l_1$, and the upper-right output port of DC2 and the lower-left input port of DC1 are connected by $l_2$. 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.

![Figure 1. Structure of an 8-shaped fiber ring resonator](image)

In the structure of 8-shaped fiber ring resonator, there are two input ports and two output ports, $k_1$ and $k_2$, representing the coupling coefficient of DC1 and DC2, $\beta$ is the propagation constant in the fiber, and $\beta = 2 n_{eff}/\lambda$. $n_{eff}$ is the refractive index of the fiber, $\lambda$ is the wavelength. $r_i = \exp(-\alpha l_i)$ ($i=1,2$) ($\alpha$ is the transmission loss coefficient) is the normalized loss of light signals through the transmission distance being $l_1$ and $l_2$. In Figure 1, $\left[E_{in}^1, E_{in}^2\right]$ are input light fields, and $\left[E_{out}^1, E_{out}^2\right]$ are output light fields, whereas the rest fields $E_{1}^{*}, E_{2}^{*}, E_{1}''$ and $E_{2}''$ are the circulated fields inside the fiber ring. By using the principle of fiber transmission and matrix transfer function DC1, DC2 and 8-shaped fiber ring resonator of output can be derived as follows in Eq.(1)–Eq.(3):

$$\begin{bmatrix} E_{out}^1 \\ E_{out}^2 \end{bmatrix} = \begin{bmatrix} 
\cos k_1 - j \sin k_1 & 0 \\
- j \sin k_1 & \cos k_1
\end{bmatrix} \begin{bmatrix} E_{in}^1 \\ E_{in}^2 \end{bmatrix}$$  \hspace{1cm} (1)

$$\begin{bmatrix} E_{out}^1 \\ E_{out}^2 \end{bmatrix} = \begin{bmatrix} 
\cos k_2 - j \sin k_2 & 0 \\
- j \sin k_2 & \cos k_2
\end{bmatrix} \begin{bmatrix} E_{in}'' \\ E_{in}''' \end{bmatrix}$$  \hspace{1cm} (2)

$$\begin{bmatrix} E_{out}^1 \\ E_{out}^2 \end{bmatrix} = \begin{bmatrix} 
\cos k_3 & 0 \\
0 & \cos k_4
\end{bmatrix} \begin{bmatrix} E_{in}^4 \\ E_{in}^5 \\ E_{in}^6 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$ \hspace{1cm} (3)

Where,

\[
E_1^* = r_1 E_1^1 \exp(-j \beta l_1), E_2^* = r_2 E_2^1 \exp(-j \beta l_2);
\]

\[
C_1 = A^{-1} \left( r_1 \tau_1 \cos k_1 \sin k_1 \exp(-j \beta l_1) - \cos k_1 \right);
\]

\[
C_2 = A^{-1} \left( r_2 \tau_2 \sin k_1 \sin k_2 \exp(-j \beta l_2) \right);
\]

\[
C_3 = A^{-1} \left( r_1 \tau_1 \cos k_1 \sin k_2 \exp(-j \beta l_1) \right);
\]

\[
C_4 = A^{-1} \left( r_2 \tau_2 \sin k_2 \sin k_2 \exp(-j \beta l_2) \right);
\]

\[
A = \tau_2 \tau_3 \cos k_1 \cos k_2 \exp(-j \beta l_2 l_1) - 1.
\]

2.2 Structure of interleaver based on 8-shaped fiber ring resonator

A novel all-fiber MZI interleaver based on 8-shaped fiber ring resonator is shown in Figure 2, which consists of one planar 3×3 fiber coupler DC0, one 2×2 fiber coupler DC3 and an 8-shaped fiber ring resonator, among which the DC0 is the fused planar 3×3 single mode fiber coupler in which three fibers in the same planar are weakly coupled, and it is used as input device where the function is distribution of the input light. When the coupling coefficient of DC0 is equal to $\pi/2$ 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. Fiber couplers DC0 and DC3, DC3 and 8-shaped fiber ring resonator are connected in series by optical fiber $l_1$ and $l_4$, $l_5$ and $l_6$ respectively.

![Figure 2. Structure of interleaver based on 8-shaped fiber ring resonator](image)

Figure 2 shows the input light field $E_{in}$ through middle port of DC0 and output light fields from A and B ports of 8-shaped fiber ring resonator. Set $M_1$ and $M_2$ as the transmission matrix of fiber coupler DC0 and DC3 ($k_0$ and $k_1$ represent their coupling coefficients), neglecting the transmission loss of fiber coupler, and we can obtain the output light fields $E_{out}$ and $E_{out}''$ expressions for Eq.(5).

\[
M = \begin{bmatrix} M_1 & 0 \\ 0 & E_{in} \end{bmatrix}
\]  \hspace{1cm} (4)
The wavelength response at both output ports. When Eq. (6) shows that when the power coupling ratio of the interference arm, if the transmission loss of 8-shaped fiber ring resonator is ignored, Eq. (6) will be simplified to Eq. (7).

\[
\begin{align*}
&\frac{P_a}{P_b} = \frac{1}{2} \frac{(\sin^4 k - \cos^2 k - 2 \cos^2 k \sin 4\theta)}{2(\sin^4 k + \cos^2 k - 2 \cos^2 k \cos 4\theta)} \\
&P_b = \frac{1}{2} \frac{(\sin^4 k - \cos^2 k - 2 \cos^2 k \sin 4\theta)}{2(\sin^4 k + \cos^2 k - 2 \cos^2 k \cos 4\theta)}
\end{align*}
\]

It can be seen from Eq. (6) that \( P_a \) and \( P_b \) contain transmission phase delay of interference arm and coupling coefficients of fiber couplers. The former decides cycle of the output spectrum, and the latter determines waveform of the output spectrum. When the interference arm length and the coupling coefficients select appropriate values, the device can realize comb and equivalent bandwidth of output spectrum. In addition, through numerical calculation Eq. (7), extreme value point and maximum channel segregation can determine \( k = \pi / 2.25 \).

3 NUMERICAL SIMULATION AND DISCUSSION

3.1 Numerical Simulation

Application of optimization algorithm, without regard to transmission loss \( r = 1 \) ), the simulation result is shown in Figure 3 (In the following figure, \( P_a \) is the solid line, \( P_b \) is dotted line, ) which is calculated with the parameters \( k_0 = \pi / 2 \), \( k_1 = \pi / 4 \), \( k_2 = k_3 = \pi / 2.25 \), \( \lambda_0 = 1550 \) nm, \( \Delta l = 2 \) mm and \( n_{df} = 1.457 \). Figure 3 shows, interleaver output spectrum of the port A and B are the same two groups of bandwidth periodic spectral lines, and their frequency interval is 100 GHz. Flat-top can offset the negative influence of channel wavelength drift.

![Normalized intensity of all-fiber MZI interleaver](image)

Figure 3. Normalized intensity of all-fiber MZI interleaver with \( k_0 = \pi / 2 \), \( k_1 = k_2 = k_3 = \pi / 2.25 \), \( k_3 = \pi / 4 \)

It is clear in Figure 3 that the proposed interleaver is attractive in flat stopband/passband and big isolation, and the 25dB stopband and 0.5dB passband are 26.2GHz and 38.4GHz. In Ref.[14], conventional MZI interleaver’s output spectrum is similar to cosine wave,
and the 25dB stopband and 0.5dB passband are 3.6GHz and 21.3GHz. In Ref.[11], MZI interleaver is cascaded, and the 25dB stopband and 0.5dB passband are 15.8GHz and 30.2GHz. By comparison, the novel interleaver through 8-shaped fiber ring resonator phase adjustment and the output spectrum produces curve steep edge and is more close to the rectangular wave, and the 25dB stopband and 0.5dB passband are wider than others.

3.2 Influence of Coupling Coefficient on the Interleaver Response

![Figure 4](image)

Figure 4. Normalized intensity of all-fiber MZI interleaver with $k_i = k_i + k + \Delta k$, its stopband and passband compared with the best value decrease slightly, and its side-lobe level decreases. If the coupling coefficients of DC1 and DC2 reduce simultaneously, the 25dB stopband will change the range of 26.2~32.4GHz, and the 0.5dB passband will change the range of 38.4~40.9GHz. Figure 4(2) is output spectrum of interleaver with $k_i = k_i - \Delta k$, and its stopband and passband compare with the best value increase slightly, but the side-lobe level also increases. If the coupling coefficient of DC1 reduces and the coupling coefficient of DC2 increases, the output spectrum will basically remain unchanged, while side-lobe will change slightly. Figure 4(3) is output spectrum of interleaver with $k_i = k_i + \Delta k$ and $k_i = k_i - \Delta k$, the 25dB stopband is 26.24GHz, and the 0.5dB passband is 38.27GHz. Because of the structure symmetry, when the coupling coefficient of DC1 increases and the coupling coefficient of DC2 reduce, the simulated results are consistent with Figure 4(3). By analyzing the interleaver output spectrum performance, it can be concluded that when slight deviation of the coupling coefficients of DC1 and DC2 exists, the 25dB stopband and 0.5dB passband will show deviation, but the change is not obvious, and the channel segregation can be above 30dB, which can satisfy the actual needs. It also indicates that the performance can be controlled in 5% deviations during the fabrication, which reduces the difficulties in fabricating the all-fiber MZI interleaver.

3.3 Influence of Transmission Loss on the Interleaver Response

In the discussion about transmission performance of interleaver, the transmission loss of optical signal in the 8-shaped fiber ring resonator is ignored. But the fiber must be curved by the fiber ring so that fiber transmission loss will certainly be introduced. In order to analyze influence of transmission loss on interleaver response, choose different normalized loss value $\tau = \sqrt{r} \times r$, to simulate calculation. In Fig5(1), the peak of output spectrum with $\tau = 0.9 \cdot k_i = k - 2\% \times k$ is descended by about 0.35dB, and that with $\tau = 0.8, k_i = k$ is descended by about 0.76dB in Figure 5(2). Compared with asymp-
metric optical fiber auxiliary ring structure in Ref.[13], the interleaver based on 8-shaped fiber ring resonator is proposed in this paper, and there are no amplitude differences about the two interference beams, and the influence of transmission loss on extinction ratio can be effectively reduced.

Figure 5. Normalized intensity of all-fiber MZI interleaver with
\[ k_1 = k_2 = k - 2\%_0 \times k, \tau = 0.9 \]
\[ k_1 = k_2 = k, \tau = 0.8 \]

4 EXPERIMENTAL APPARATUS

The basic principle of interleaver is the light interference. Because the optical fiber welding will introduce waveguide discontinuity, which will affect insertion loss and polarization of optical fiber, the continuous melting method should be used. In the process of melt control, the compute test system will monitor the change of couplers ratio and interference arm’s length. First, according to the conventional method to melt 3dB fiber coupler DC3, from one end of the DC3 insert another optical fiber continuous melting pull DC0, and then from the other end of the DC3 fusion DC1 of 8-shaped fiber ring resonator, to the two synthetic fibers drawn from the DC3 insert another optical fiber. Inserted fiber and DC3 draw one fiber to fuse coupler DC1, and the output port of inserted fiber and DC3 draws another optical fiber to fuse coupler DC2. When couplers coupling ratio and interference arm’s length meet the requirement, inserted fiber will weld in DC2 out end with DC1 insert end. The method of melting drawn by fiber interference arms and fiber couplers can refer to Ref. [15-16].

The output performance of the experimental interleaver is tested, light source is Santec company TSL2210 wavelength tunable laser, and wavelength range is 1520~1580nm. The linear polarized light is input through middle port of DC0, its power is 1mW, and port A and B of ring resonator measure the output power. Figure 6 is tested output of spectrum of the experimental sample. Compared with Figure 3, the influence of experimental environment makes micro variable exists in the experimental sample output spectrum, and the peak also declines slightly because of transmission loss. Overall experimental sample spectrum agrees with theoretical analysis well.

5 CONCLUSION

The all-fiber MZI interleaver based on 8-shaped fiber ring resonator is proposed in this paper, and its structure parameters are obtained and described by theoretical analysis and numerical simulation, which indicates that when the length difference of interference arms and the coupling coefficient of the couplers are some certain values, the 25dB stopband and 0.5 passband are improved remarkably, which can achieve almost rectangular spectrum response, and the influence of transmission loss on extinction ratio can reduce remarkably. The experimental results agree with the theoretical analysis. The interleaver designed by the proposed approach has favorable performance, which has the potential application value in optical fiber communication system. The study may provide reference for the facture of the apparatus later.

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REFERENCES

[1] X. H. Ye, M. Zhang & P. D. Ye. 2006. Flat-top interleavers with chromatic dispersion compensator based on phase dispersive free space Mach-Zehnder interferometer. Opt. Commun. 2: 255.

[2] Naveen Kumar, M. R. Shenoy & B. P. Pal. 2008. Flattop all-fiber wavelength interleaver for DWDM transmission: design analysis, parameter optimization, fabrication and characterization recipe. Opt. Commun. 20: 5156.

[3] H. W. Lu, K. J. Wu, Y. Wei, B. G. Zhang & G. W. Luo. 2012. Study of all-fiber asymmetric interleaver based on two stage cascaded Mach-Zehnder Interferometer. Opt. Commun. 6: 1118.

[4] H. W. Lu. 2013. Study of a Novel All-fiber 3x3 Interleaver with a Dual-eight-shaped Ring Resonator. IEEE Photo. Tech. Lett. 9: 806.

[5] H. W. Lu, Y. Wei, K. J. Wu, B. G. Zhang & G. W. Luo. 2011. Design of all-fiber Asymmetric Interleaver with 2x2 and 3x3 Fiber Couplers. Acta Optica Sinica, 11,1106002-1.

[6] H. L. Pu & H. W. Lu. 2014. Design of a New Type of All-fiber MZI Interleaver with Different Bandwidth. Journal of Lanzhou Jiaotong University, 3: 120

[7] X. L. Wang, W. C. Huang, Y. Zhang & Z. P. Cai. 2009. Design and analysis on a Gires-Tournois resonator based interleaver. Opt. Lett. 1, 51.

[8] L. Wei & J. W. Y. Lit. 2007. Design optimization of flattop interleaver and its dispersion. Opt. Express. 10: 6439.

[9] Q. Ye, R. H. Qu & Z. J. Fang. 2007. Generation of millimeter-wave sub-carrier optical pulse by using a Fabry-Perot interferometer. Chin. Opt. Lett., 1: 8.

[10] X. X. Pan, F. G. Luo & L. Deng. 2011. Structure design of interleaver based on birefringent-crystals. Asia Commun. Photonics Conf. Exhib., ACP.

[11] S. W. Kok, Y. Zhang, C. Y. Wen & Y. C. Soh. 2003. Design of all-fiber optical interleavers with a given specification on passband ripples. Opt. Commun. 225: 241.

[12] Y. Yu, J. J. Dong, X. Li & X. L. Zhang. 2011. Ultra-wideband generation based on cascaded mach-zehnder modulators. IEEE Photo. Tech. Lett. 23: 1754.

[13] X. W. Dong, L. Pei, O. Xu, S. H. Lu, S. C. Feng, R. F. Zhao & Z. W. Tan. 2008. Study of Interleaver Based on Ring Resonator Assisted Mach-Zehnder Interferometer. Acta Optica Sinica, 4: 638.

[14] W. B. Li & J. Q. Sun. 2008. Analysis of Characteristics of the Interleaver Based on a Double-Coupler Resonator. Chinese J. Laser, 8: 1191.

[15] W. M. Sun, S. Shi & Q. Dai. 2009. Fabrication and measurement of tapered fibers. Journal of Optoelectronics: Laser, 11: 1474.

[16] S. W. Harum, K. S. Lim, A. A. Jasim & H. Ahmad. 2010. Fabrication of tapered fiber based ring resonator. Laser Phys. 7: 1629.