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Design analysis of flattop all-fiber asymmetric interleaver

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ABSTRACT

A novel all-fiber interleaver consisting of a three-stage cascaded Mach–Zehnder interferometer (MZI) is presented. Based on a comprehensive analysis, a mathematical description is provided. To achieve a flattop wavelength response, a design process is adopted to determine the optimum coupling-coefficient-angle values according to finite impulse response (FIR) digital filter theory. A set of coupling-coefficient-angles of fiber couplers were obtained. Furthermore, these optimum coupling-coefficient-angle values were exploited to fabricate an interleaver with flattop response within the passband in the experimental, so these optimum values are validated. The theoretic analysis and the experimental results indicate that the flattop passband in odd channels and even channels could be obtained. 3 dB passband in odd channels and in even channels are asymmetric, and the 3 dB passband is more than the 60 GHz passband and 30 GHz passband, for transmission speed of 40 Gb/s and 10 Gb/s, respectively. The channel isolation of the interleaver is more than 35 dB. The tolerance characteristics of the splitting ratios are favorable. Our design and analysis should be useful in the realization of flattop all-fiber asymmetric interleaver for deployment in dense wavelength division multiplexing (DWDM) networks of high spectral efficiency.

1. Introduction

With the increasing demand for more and more bandwidth brought about by the Internet revolution, increasing the number of channels in dense wavelength division multiplexing (DWDM) networks becomes an effective and economical way to accommodate the progressive bandwidths requirements. The optical interleaver was firstly reported in the Optical Fiber Communication Conference in 2000 year, because interleaver technology can achieve narrower channel spacing in the currently used bands, today's DWDM systems with interleavers can be upgraded with much narrower channel spacing and more channel counts for very large capacity applications, moreover, from the perspective of cost effectiveness, the existing optical components designed for wide channel spacing can still be used. Hence it is obvious that interleaver technology plays a critical role [1,2].

Several techniques have already been proposed for implementing optical interleaver. Among these techniques, some are for symmetrical interleaver, and others are for asymmetric interleaver. For symmetrical interleaver, the 3 dB passband in odd channels and in even channels are equal, and the interleaver is only used for optical signal transmission with one sort of speed. For asymmetric interleaver, the 3 dB passband in odd channels and in even channels are unequal, and the interleaver can be used for optical signal transmission with two sorts of speed. So, the flexibility and utilization of asymmetric interleaver are higher [3,4]. Nowadays, the researches about asymmetrical interleaver focus on two channels. There are some reports on the application and study in the asymmetric interleaver. First kind of asymmetric interleaver takes advantage of two Gires–Tournois and multi Gires–Tournois, whose wavelength response within the passband is flattop state, but the technology could lead to high cost in practical application [5]. Second kind of asymmetric interleaver using thirty-three cascaded fiber couplers by fusion technology is achieved, which also has flattop response within the passband, but there exist high complexity and manufacturing difficulty in practical application [6]. Third kind of asymmetric interleaver based on only three cascaded fiber couplers by fusion technology is also achieved, but the wavelength response within one passband is sine state which leads to worse optical signal transmission [7,8]. To third kind of asymmetric interleaver, the sine response within the passband should be improved into the flattop response within the passband by certain theory to make optical signal transmission well [9].

In application of the interleaver, with the rapid development of the fused biconical taper technology, the fused fiber cascade Mach–Zehnder interferometer (MZI) is highly concerned. In this paper, a novel all-fiber asymmetric interleaver is proposed, which

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is based on a three-stage cascaded MZI. Theoretical analysis and experimental results show that the wavelength responses within the passband are flattop, and one bandwidth of the outports at 3 dB is greater than 60 GHz, and the other is greater than 30 GHz. Its asymmetric interleaving feature provides an ideal solution for this unbalanced DWDM system. Comparing to the interleaver in [4,5], the proposed interleaver has lower insertion loss, lower manufacturing cost, simpler structure, better polarization correlation and better dispersion characteristics. And comparing to the interleaver in [7,8], the wavelength response within the passband of the proposed interleaver is improved into flattop response within the passband, and the proposed interleaver has better characteristics when the same lateral deviation of the coupling-coefficient-angle is introduced.

2. Structure and principle

The proposed interleaver is based on a three-stage cascaded MZI as shown in Fig. 1. It consists of four cascaded 2×2 single mode fiber couplers C_j (j=1, 2, 3, 4) linked by three differential delays.

Denote the phase delay as $\Delta\varphi_i=2\pi n\Delta l_i/\lambda$ that corresponds to Δl_i (i=1, 2, 3), where Δl_i is the physical length of the differential delay, λ is the wavelength of the wave propagating through free space, and n is the refractive index of the optical fiber. The interleaver is a scalable device, by this we mean that its spectral properties are periodic and this periodicity, the so-called free spectral range (FSR), is determined solely by the phase difference $\Delta\varphi_i$. In order to achieve an all-fiber interleaver with unequal passband, Δl_i is chosen to be $\Delta l_i=m_i\Delta l$ (m_i=1, 2, −2) corresponding differential phase delays $\Delta\varphi_i$ of the three stages, Δl is the basic value of the differential delay. Because the light transmission distance of the optical fiber in the device is quite short, the transmission loss and chromatic dispersion can be neglected. It is assumed that the input optical signal is inputted from the port^1, the intensity transfer function of the normalized electric field from the port^1 to the port^3 and the port^4 can be expressed by the matrix transfer function [10], so the transmission spectra function are obtained as follows, respectively:

$$P_3^{\text{out}}=a_0+a_1\cos\Delta\varphi+a_2\cos2\Delta\varphi+a_3\cos3\Delta\varphi+a_4\cos4\Delta\varphi+a_5\cos5\Delta\varphi \tag{1}$$

$$P_4^{\text{out}}=b_0+b_1\cos\Delta\varphi+b_2\cos2\Delta\varphi+b_3\cos3\Delta\varphi+b_4\cos4\Delta\varphi+b_5\cos5\Delta\varphi \tag{2}$$

where $\Delta\varphi$ is a phase difference corresponding the basic value of the length difference Δl, the coefficients a_i and b_i are the functions associated with k_i (i=0, 1, 2, 3), respectively, k_i (i=0, 1, 2, 3) are the coupling-coefficient-angle of the simple directional couplers, which is equal to the multiplier of the coupling coefficient and the equivalent coupling length of the coupler in the coupling region. At the same time, splitting ratio represents the power coupling ratio of the coupler C_j. (The mathematical descriptions of a_i and b_i are rather complicated, which are all too inconvenient to be provided).

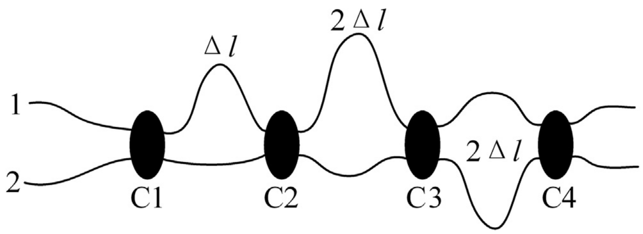

Fig. 1. Schematic diagram of the flattop all-fiber asymmetric interleaver.

According to Fourier series theory, it can be seen that Eqs. (1) and (2) are all periodical with respect to $\Delta\varphi$, and two equations are characterized by a sum of simple sinusoidal components corresponding to Fourier relations. These determine the output waveforms of Eqs. (1) and (2), the interleaver design can be described to obtain k_i, such that Eqs. (1) and (2) have an asymmetric identical spectrum [11]. Therefore, in order to achieve a uniform flattop response, it is necessary to choose optimum coupling-coefficient-angles for the couplers C1, C2, C3, and C4.

According to the matrix transfer function [10], the normalized electric field transfer function from the port^1 to the port^3 and the port^4 can be expressed as follows, respectively:

$$E_3^{\text{out}}=\exp(j2\Delta\varphi)\sum_{i=0}^{5}c_i\exp(-ji\Delta\varphi) \tag{3}$$

$$E_4^{\text{out}}=\exp(j2\Delta\varphi)\sum_{i=0}^{5}d_i\exp(-ji\Delta\varphi) \tag{4}$$

Substituting $Z=\exp(j\Delta\varphi_i)$ into Eqs. (3) and (4), Eqs. (3) and (4) are rewritten as

$$E_3^{\text{out}}=Z^2\sum_{i=0}^{5}c_iZ^{-i} \tag{5}$$

$$E_4^{\text{out}}=Z^2\sum_{i=0}^{5}d_iZ^{-i} \tag{6}$$

where the coefficients c_i and d_i (i=0, 1, 2, 3, 4, 5) are the functions associated with k_i (i=0, 1, 2, 3), respectively.

Here Eq. (6) is optimized as the specific calculation, to achieve a uniform flattop response, and the functions d_i associated with k_i are listed as follows:

$$d_0=-\cos k_0\cos k_1\cos k_3\cos k_2 \tag{7.1}$$

$$d_1=-\sin k_1\sin k_2\sin k_0\cos k_3 \tag{7.2}$$

$$d_2=-\sin k_3\cos k_2\cos k_0\cos k_1-\cos k_2\cos k_0\cos k_3\sin k_1 \tag{7.3}$$

$$d_3=\sin k_3\cos k_2\sin k_0\sin k_1-\cos k_2\cos k_1\cos k_3\sin k_0 \tag{7.4}$$

$$d_4=\sin k_3\sin k_1\sin k_2\cos k_0 \tag{7.5}$$

$$d_5=-\sin k_3\sin k_0\sin k_2\cos k_1 \tag{7.6}$$

It is quite obvious that Eq. (6) is a complex function in a complex z-plane, and this technique called z-transform is commonly used in the field of digital filter synthesis. So it should be noted that the transfer function expressed by Eq. (6) agrees with that of usual finite impulse response (FIR) digital filters with complex expansion coefficients [5]. This fact is successfully used to calculate the expansion coefficients for the desired filter characteristics in our method. By using methods developed for FIR digital filters, the complex expansion coefficients d_i can be obtained. Here, wavelength interval is 0.8 nm (f_0=100 GHz), the effective index of the fiber is 1.57, the range 0–$f_0/2$ is taken as the normalized frequency, and the corresponding wavelength range is 1551.7–1552.1 nm. Judging from Eq. (6), the order number of FIR digital filters is five, and unit delay is $\Delta\tau$=10 ps, then Δl=1.91 mm, so the ideal expansion coefficients can be obtained: p=[−0.2551; 0.0545; −0.7051; −0.2080; 0.0678; 0.0545]. Furthermore, the optimal coupling-coefficient-angle k_i can be obtained by the genetic algorithm [12], the math function is as