Research Article

Investigation of Dispersion and Performance Based on Ring Cavity by Birefringent Interleaver for DWDM Transmission Systems

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We theoretically investigate a 25 GHz multichannel filter based on ring cavity birefringent optical interleaver for dense wavelength division multiplexing (DWDM) transmission systems. The simulation tool used in this work is the Advanced System Analysis Program (ASAP) optical modeling software. We improve the dispersion performance by employing $\lambda/6$ and $\lambda/4$ wave plates as birefringent compensators for interleavers. The new structure exhibits a high performance with nearly zero ripple, a channel isolation greater than 102 dB, and a passband utilization of 86% within the C-band. The research results illustrate that our modified scheme can improve the dispersion of more than 76.6% in comparison with the previous studies of optical interleaver with birefringent crystal and ring cavity structures.

1. Introduction

In the recent years, with the rapid growth of internet and the maturity of multimedia conferencing, dense wavelength division multiplexing (DWDM) [1, 2] has emerged as a vital component for optical fiber networks. And how to increase the number of channels is an important issue [3]. One way to increase the channels number is to widen the usable wavelength bandwidth in low-loss region of the used single-mode fiber [4, 5]. Another way to increase the channels number is to narrow the channel spacing. Several techniques have been engaged in DWDM systems with channel spacing of less than 0.8 nm [6, 7]. A spectral interleaver is capable of separating a set of channels into two sets at twice the channel spacing [8, 9]. An optical interleaver has been verified as an effective technique in increasing channel counts by doubling or quadrupling the number of optical channels when the channel spacing is in the range of 0.2 nm (25 GHz). Nevertheless, the greatest shortcoming of conventional interleavers is an inferior dispersion.

In this paper, we improve the dispersion performance by employing $\lambda/6$ and $\lambda/4$ wave plates as birefringent compensators for Sagnac-interferometer-based flat-top birefringent

optical interleaver employing a ring cavity as a phase-shift element, which was proposed by Lee et al. [10]. The simulation tool used in this work is the Advanced System Analysis Program (ASAP) optical modeling software [11]. And the interleaver design model is configured based on the actual component parameters.

2. Configuration of the Proposed Birefringent Interleaver

Figure 1 depicts the configuration of ring cavity birefringent interleaver. For this scheme, an optical circulator, a polarization beam splitter (PBS), two birefringent crystals (YVO_4 has the length of 30 mm), a triangular-shape prism (transmission 91.4%; refraction index 1.6), and four highly reflective mirrors (reflectivity 99.8%) are used. In this structure, we proposed two $\lambda/4$ wave plates and two $\lambda/6$ wave plates as dispersion compensators employed in the ring cavity to ensure excellent flat-top spectral passband. The YVO_4 birefringent crystal is used for appropriate retardance of interference. The $\lambda/6$ and $\lambda/4$ wave plates are engaged to rotate the beam polarization state by 30 and 45 degrees, respectively.

FIGURE 1: Configuration of the proposed ring cavity birefringent interleaver.

The input signal of unpolarized light in the 1530–1565 nm wavelength range (C-band) with a channel spacing of 0.2 nm is considered. When the input signal was transmitted through the PBS, the s-component propagates along the loop in the clockwise direction and the p-component propagates along the loop in the counterclockwise direction. As a result, the beams inside the birefringent crystals consist of both the ordinary wave and the extraordinary wave with equal amplitudes. As the beams propagate inside the birefringent crystals, a phase retardation exists between these two waves at the end of the crystals. These beams, consisting of both ordinary wave (o-ray) and extraordinary wave (e-ray), are then directed toward the ring cavity which is configured by a prism and two mirrors (M_3 and M_4).

In the two birefringent crystals, the ordinary wave corresponds to s-wave, while the extraordinary wave corresponds to p-wave. The prism interface of the ring cavity exhibits different Fresnel reflectivities for these two polarization components (s and p) of the beam. Due to the different reflectivities, these two polarization components experience different phase shifts upon transmitting (or reflecting) through the ring cavity. Through the ring cavity, these two components of the beam incur further phase retardation from the birefringent crystal before they are mixed and recombined by the PBS.

3. Computer Simulation

The air-prism interface is aligned perpendicularwise to the light beams, as shown in Figure 1. And the prism is cut into a triangular shape to provide an appropriate angle of incidence so that the desired Fresnel reflectivities, R_o and R_e , are obtained. R_e and R_o are the reflectivities of the air-prism interface for the e-ray and the o-ray. In this work, the optimum incident angle is near 34.5° , and, at this angle of incidence, the reflectivities are $R_o = 17.01\%$ and $R_e = 8.39\%$. The normalized intensity of one of the output ports can be expressed as follows [12, 13]:

$$I = \frac{I_0}{2} \left[I_0 + \cos \left(\frac{2\pi}{\lambda} (n_e - n_o) L + (\phi_e - \phi_o) \right) \right], \quad (1)$$

where I_0 is the intensity of the unpolarized incident beam, L is the length of the two birefringent crystals, ϕ_e and ϕ_o are the phase shifts of the beam for the e-ray and the o-ray, respectively, upon reflection from the ring cavity, and $\Delta n (=n_e - n_o)$ is the refractive index difference of n_e and n_o . Chromatic dispersion compensation [14] is the most deserving in our study because the dispersion is the parameter which restricts the transmission distance of DWDM systems. The polarization azimuth angle of the birefringent crystal [15, 16] is obtained by $\lambda/4$ wave plates ($\lambda/4$ at 45°) and $\lambda/6$ wave plates ($\lambda/6$ at 30°). Then, the output group delay after compensation can be viewed as the average group delay from two modes, $\tau(\omega) = [\tau_e(\omega) + \tau_o(\omega)]/2$, and can be shown as in (2), where $\omega = 2\pi c/\lambda$ is the optical angular frequency, $T = L_R/c$ is the round-trip time in the ring cavity, L_R is the round-trip optical path of the ring cavity, and d_1 and d_2 are the round-trip phase shifts of $\lambda/4$ wave plates and $\lambda/6$ wave plates, respectively. The group velocity dispersion (GVD) is given by $D(\lambda) = d\tau/d\lambda$ (ps/nm) and can be obtained as in (3). Consider the following:

$$\begin{aligned} \tau(\omega) &= \frac{T}{2} \left\{ (1 - R_o) \times \left(1 + R_o - 2\sqrt{R_o} \cos \left(\left(\frac{2\pi}{\lambda} \right) L_R \right) \right)^{-1} \right. \\ &\quad \left. + \left(1 - \left(\frac{R_e}{(d_1^2 + d_2^2)} \right) \right) \right. \\ &\quad \left. \times \left(1 + \left(\frac{R_e}{(d_1^2 + d_2^2)} \right) - 2 \left(\frac{R_e}{(d_1^2 + d_2^2)} \right)^{1/2} \right. \right. \\ &\quad \left. \left. \times \cos \left(\left(\frac{2\pi}{\lambda} \right) L_R \right) \right)^{-1} \right\}, \end{aligned} \quad (2)$$

$$\begin{aligned} D(\lambda) &= \frac{2\pi L_R T \sin \left(\left(\frac{2\pi}{\lambda} \right) L_R \right)}{\lambda^2} \end{aligned}$$

FIGURE 2: The optical spectral (a) signal intensity of one of the output ports and (b) chromatic dispersion characteristics of partial C-band, with and without compensation.

$$\times \left\{ (R_o)^{1/2} (1 - R_o) \times \left(\left[1 + R_o - 2(R_o)^{1/2} \times \cos \left(\left(\frac{2\pi}{\lambda} \right) L_R \right) \right]^2 \right)^{-1} + \left(\frac{(R_e)}{(d_1^2 + d_2^2)} \right)^{1/2} \left(1 - \left(\frac{R_e}{(d_1^2 + d_2^2)} \right) \right) \times \left(\left[1 + \left(\frac{(R_e)}{(d_1^2 + d_2^2)} \right) - \frac{2(R_e)}{(d_1^2 + d_2^2)^{1/2}} \times \cos \left(\left(\frac{2\pi}{\lambda} \right) L_R \right) \right]^2 \right)^{-1} \right\}.$$

(3)

FIGURE 3: The relative transmission power of partial C-band: (a) output port 1 (odd channels) and (b) output port 2 (even channels).

According to (1) and (3), calculated by the simulation software ASAP, we can get normalized intensity of the output channels and their chromatic dispersion. Figure 2(a) shows the calculated spectral output power of one channel. The optical intensities of with- and without-compensation schemes are 0.91 a.u. and 0.553 a.u., respectively. Figure 2(b) shows the chromatic dispersion of partial C-band comparison between with- and without-compensation schemes of 25 GHz channel spacing. The research results illustrate that our modified scheme can improve the dispersion of more than 76.6% $(= (1632.67 - 381.12) / 1632.67)$ in comparison. The channel isolation of the interleaver with compensators is greater than 102 dB, and the calculated results of the stop-band and channel isolation of a 25 GHz channel spacing application are shown in Figure 3. The 25 dB stopband was found to be 0.10018 nm, the 0.5 dB wide passband was found

FIGURE 4: The eye diagrams by PRBS $2^{31}-1$ for 10 Gb/s application: (a) with compensation and (b) without compensation.

to be 0.08605 nm, and the passband utilization was 86% ($=0.08605 \text{ nm} / 0.10018 \text{ nm}$) within the C-band. Figure 4 shows the eye diagrams for 10 Gb/s application of with- and without-compensation schemes by pseudorandom binary sequence (PRBS) ($2^{31}-1$).

4. Conclusions

We have investigated the characteristics of a flat-top 25 GHz optical interleaver based on ring cavity architecture with

and without dispersion compensation elements. We found that the ring cavity birefringent interleaver with two $\lambda/4$ wave plates and two $\lambda/6$ wave plates as birefringent compensators exhibited a 0.5 dB passband larger than 10.75 GHz (0.08605 nm), a 25 dB stopband greater than 12.52 GHz (0.10018 nm), and a channel isolation higher than 102 dB. The benefit of this interleaver is that it utilizes the Fresnel principle to achieve precise reflectivities. Unlike dielectric mirrors with thin-film coatings, the reflectivities of the Fresnel reflection are insensitive to wavelength variations in the transmission band. The uniform reflectivities are essential to ensure the same performance over the entire C-band. In particular, the novel interleaver can simultaneously produce the excellent performance of chromatic dispersion that achieved an improvement of 76.6% when compared to the currently available interleaver without wave plates as birefringent compensators, which was proposed by Lee et al. [10]. This modified interleaver may find important applications in DWDM systems and transmission networks.

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