Effect of an imperfect antireflection coating on a birefringent interleaver in an optical communications system

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Abstract. The effect of an imperfect antireflection (AR) coating on a birefringent interleaver (an important optical communication component) and on an optical communications system containing such a birefringent interleaver is investigated. We demonstrate how the imperfect AR coating on the rhomb surfaces affects the birefringent interleaver's intensity spectrum and generates undesirable chromatic dispersion (CD) ripples for an interleaver that should be dispersion-free by design. Our results show that a rhomb with a close-to-perfect AR surface coating ($T=99.8\%$) can still generate a ±30-ps/nm CD ripple, causing a nonnegligible power penalty in an optical communications system. We also demonstrate a simple and practical approach to reduce the CD ripple caused by the imperfect AR coating. [DOI: 10.1117/1.2783389]

Subject terms: chromatic dispersion; interleaver; optical filter.

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1 Introduction

Optical multiplexers and demultiplexers are fundamental building blocks for wavelength separation and combination within wavelength-division multiplexing (WDM) networks. Among the possible technical approaches, the combination of less expensive optical filters, such as thin-film filters (TFFs) or fiber Bragg gratings, and the interleaver provides a cost-effective method of separating or combining wavelengths to effectively increase the capacity of an existing fiber. Figure 1 demonstrates the concept of demultiplexing by using the combination of an interleaver and TFFs. The incoming WDM multiple-wavelength signal is separated into two 100-GHz channel-spacing ports by using a 50-GHz channel-spacing interleaver. The output channels contained in the two ports are further separated into individual channels by using one 100-GHz TFF module on each port. The first filter in the TFF module allows one wavelength to pass and rejects another wavelength. The rejected wavelength is then input into the second filter, which is designed to pass this wavelength. Combined with the time-division multiplexing technique, the WDM systems provide new opportunities for high-bit-rate transmission systems with terabit capacities.

Among the different types of interleavers,[1] the one based on a birefringent crystal may have been the first one ever proposed and manufactured.[2] The birefringent-crystal-based interleaver is a special type of Mach-Zehnder interferometer (MZI).[3] A simplified birefringent-crystal-based interleaver structure and its corresponding mathematical model are illustrated in Figs. 2(a) and 2(b), respectively. It is worthy of note that the *polarization diversity* scheme is used in the interleaver structure illustrated in Fig. 2(a) to reduce polarization-dependent loss (PDL) and polarization mode dispersion (PMD).[2] In the structure illustrated in Fig. 2(a), a polarization beam displacer is used to separate input signals with orthogonal polarizations aligned with laboratory x and y axes, and a half-wave plate is used to guarantee that the signal entering the birefringent materials has the same polarization. As a result, one input port of the corresponding MZI model illustrated in Fig. 2(b) is blocked. Each birefringent crystal has a different angle ψ_i between its optical axis and the laboratory axis. Each birefringent crystal has the same thickness, so the delay differences between the two orthogonal polarizations aligned with fast and slow axes are the same in each stage. By changing the angles ψ_i, the coupling ratio between successive stages of the MZI can be changed to achieve the desired filtering function. At the receiver side, half-wave plates and polarization beam displacers are used to manipulate the signal polarization and direct output signals to two output ports. Because input signals with orthogonal polarizations aligned with laboratory axes are converted to the same polarization before subsequent processing, device polarization-dependent effects like PDL and PMD can be minimized.

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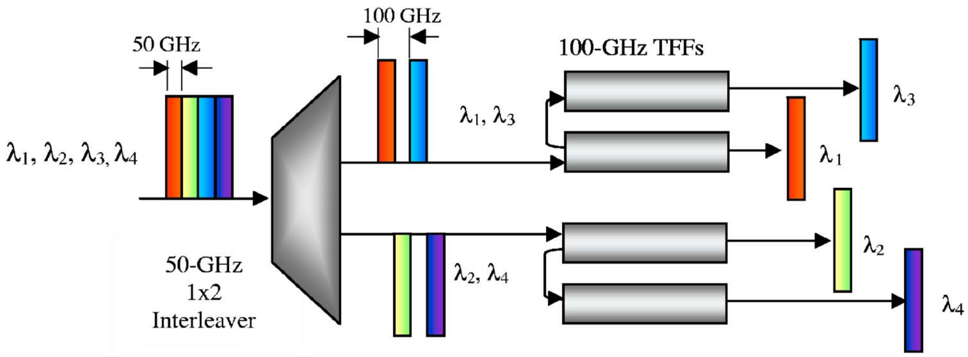

Fig. 1 Schematic of the combined interleaver and the TFFs to separate the incoming WDM signal into individual channels.

The birefringent-crystal-based interleaver is a finite impulse response (FIR) filter whose output for an impulse input has finite duration.[3] It is well known that we can design two FIR filters with the same magnitude spectra but opposite phase spectra.[3,4] By cascading two such FIR filters together, we can build a dispersion-free FIR filter, also referred to as a linear-phase filter. Because the chromatic dispersion (CD) is one of the major restricting factors in high-speed optical communication systems,[5] the fact that a birefringent-crystal-based interleaver can be designed as a dispersion-free device makes the interleaver very attractive. However, if any element within such a dispersion-free interleaver produces CD due to, for example, an imperfect manufacturing process, the resulting dispersion could be significant. In this article, we report on the CD ripples caused by imperfect AR coating on rhomb surfaces within a dispersion-free birefringent crystal-based interleaver. We demonstrate how a near-perfect AR coating can still generate significant CD ripples, consequently causing a power penalty in an optical communication system. We also demonstrate a practical approach to reduce CD ripples caused by the imperfect AR coating.

AR coatings are widely used to reduce backreflection and enhance transmission from optical surfaces; therefore, the study of CD ripples presented in this article is applicable not only to interleavers, but also to general transmission components that contain such elements as beam displacers and retroreflectors with AR coatings on their surfaces.

2 CD Caused by the Etalon Effect of a Rhomb AR Coating

The polarization beamsplitter (PBS), which physically separates two perpendicularly polarized components of incident light, is the crucial element of most interferometers. When separated components need to travel in the same direction, a rhomb is often used, as shown in Fig. 3(a). The dimensions of the rhomb determine the beam separation. For example, a 5-mm by 12-mm rhomb separates two perpendicularly polarized components by 7 mm. To reduce the backreflection, an AR coating on the rhomb surfaces is necessary. However, it is almost impossible to have zero reflectance, even if sophisticated coating techniques are used. When light passes through the rhomb, part of the light is bounced back and forth by the coating surfaces. This bouncing results in an etalon effect as shown in Fig. 3(b). Because p polarization and s polarization take different paths, as shown in Fig. 3(a), the equivalent etalon thicknesses are different for them. For a 5-mm by 12-mm rhomb, the etalon thickness l is 5 mm for p polarization and 12 mm for s polarization. It has been shown that the etalon effect causes CD ripples and that the amplitude of the CD ripples is proportional to the square of the etalon thickness, which can be expressed as follows:[6]

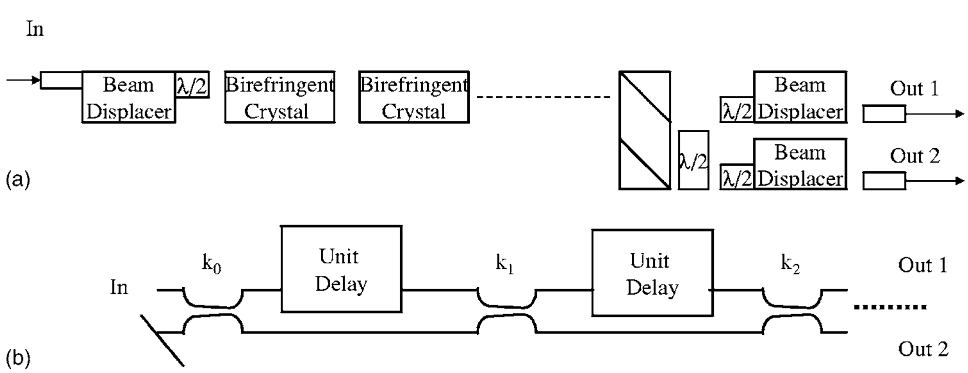

Fig. 2 (a) Simplified diagram of a birefringent-crystal-based MZI-type interleaver. (b) Mathematical model of the interleaver illustrated in (a).

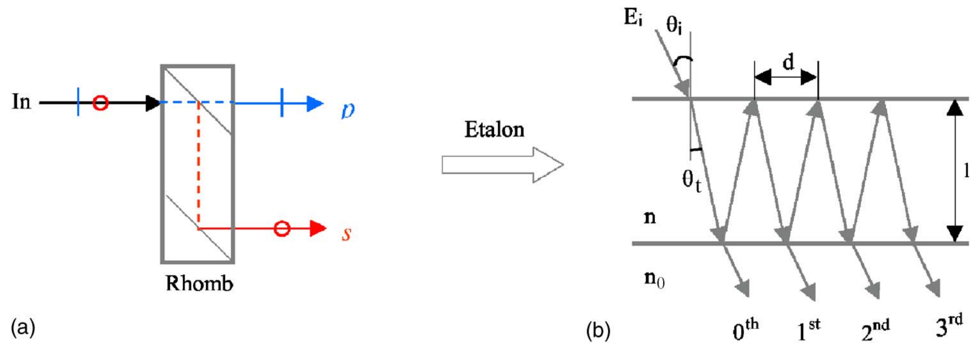

Fig. 3 (a) A rhomb is used to separate two perpendicularly polarized components *p* and *s*. (b) The imperfect AR coating on rhomb surfaces induces the etalon effect.

$$\mathrm{CD} = \delta \frac{2nl}{c} \frac{rr'[1-(rr')^2]\sin\delta}{\lambda[1+(rr')^2-2rr'\cos\delta]^2}, \tag{1}$$

where $\delta = (4\pi nl\cos\theta_t)/\lambda$ is the phase arising from an optical-path-length difference between adjacent rays, r and r' are the amplitude reflection coefficients for the two surfaces, n is the index of refraction of the rhomb material, λ is the incident light wavelength, c is the speed of light in a vacuum, and θ_t is the transmission angle, which is related to the incident angle by $\theta_t = \sin^{-1}[(\sin\theta_i/n)]$.

Figure 4 depicts simulated magnitude (solid line) and CD (dashed line) spectra of an interleaver that is designed as a dispersion-free device yet consists of a rhomb with 99.8% surface transmittance (T). This rhomb behaves like an etalon with 12-mm thickness. As a result, the interleaver has a CD ripple whose amplitude is about 30 ps/nm within the theoretically dispersion-free interleaver passband. The presence of magnitude ripples in the stop band means that passband ripples are also present, since for the interleaver the passband and the stop-band power are complementary. The passband ripples are so small that they are not noticeable in Fig. 4.

In the next section, we demonstrate how to reduce the CD ripple caused by an imperfect AR coating as well as the performance improvement of the optical communication system as a result of the proposed approach.

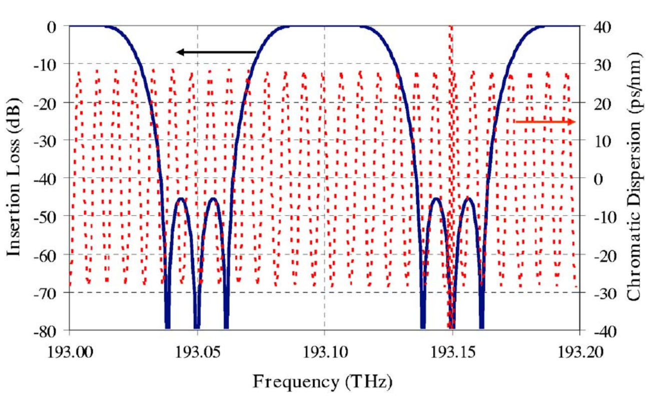

Fig. 4 Insertion-loss spectrum of a theoretically dispersion-free interleaver (solid line) and its CD ripples caused by the 99.8% transmittance AR coating of a rhomb with an equivalent etalon thickness of 12 mm (dashed line).

3 CD Reduction and Resulting System Performance Improvement

Equation (1), the formula for the CD ripple caused by the rhomb etalon effect, presented in Sec. 2, assumes that light falls normal to the incident surface. This etalon effect can be totally removed or significantly reduced by tilting the rhomb slightly so that multiple reflected beams will not be coupled into the interleaver's output ports. The interleaver's insertion loss will be increased because of the signal loss caused by rhomb tilting. In this section, we verify the resulting insertion-loss penalty. A simulation of the optical system is also carried out to illustrate the performance improvement achieved with this CD ripple reduction technique.

Figures 5(a) and 5(b) show the magnitude spectra and CD spectra, respectively, of two birefringent-crystal-based interleavers with the same design and the same rhomb surface AR coating ($T=99.8\%$). The rhomb has an equivalent etalon thickness of 12 mm. The difference between the two interleavers lies at the output ports. One interleaver collects all of the reflected beams generated by rhomb etalon effects at the output, and the other interleaver rejects multiply reflected beams except for one by means of a tilted rhomb. From Fig. 5(a), it is clear that the interleaver with rhomb etalon effects has less insertion loss (solid line) than the one without rhomb etalon effects (dashed line). Notice that the magnitude spectrum has been zoomed in on to display the slight insertion-loss difference between these two interleavers. The small insertion-loss ripples related to the stop-band ripples mentioned in the previous section are noticeable now. The etalon effects caused by the imperfect coating also contribute extra insertion loss ripple; thus, the dashed-line and solid-line spectra have different insertion-loss ripples. Figure 5(b) shows that the interleaver with rhomb etalon effects has a CD ripple within the passband (solid line), and the interleaver without rhomb etalon effects has virtually no CD within the passband (dashed line). The large dispersion variation at the center of the interleaver stop band (edges of the plot) is due to the fact that all of the input signals at the stop-band center frequency are blocked. Although the filter output should have zero energy at this frequency, our software generates a very small filter output signal (output signal magnitude $\approx 10^{-27} \times$ input signal magnitude) at the stop-band center frequency, because of a numerical error, and calculates the filter phase response based

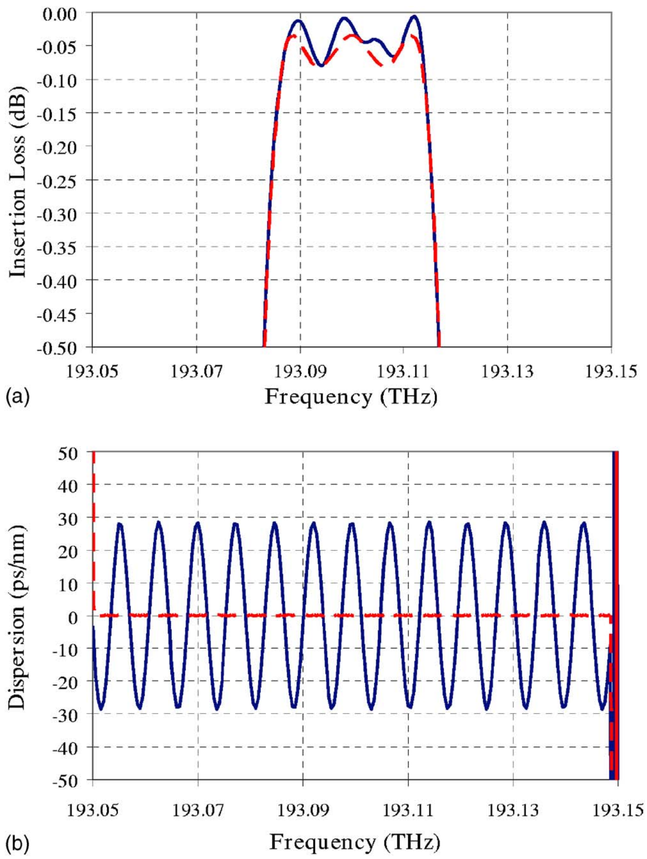

Fig. 5 (a) Zoomed-in simulated insertion-loss spectra of two theoretically dispersion-free interleavers (solid line: the interleaver with rhomb etalon effect; dashed line: the interleaver with tilted rhomb). (b) Simulated CD spectra of the same interleavers (solid line: the interleaver with rhomb etalon effect; dashed line: the interleaver with tilted rhomb).

on this small number. As the result, the group delay has a large variation at the center of the stop band.

To compare the performance of the two interleavers whose spectra are illustrated in Fig. 5, we use a simple simulation model for a 10-Gbit/s optical communication system, illustrated in Fig. 6. One interleaver module is placed on the transmitter side to represent the interleaver used in the multiplexer, and one interleaver module is placed on the receiver side to represent the interleaver used in the demultiplexer. Each transmission loop consists of an 80-km transmission fiber and a 16-km chromatic dispersion compensation fiber (DCF) to compensate the transmission fiber's CD. Two ideal amplifiers are used to compensate the loss caused by the transmission fiber and the CD compensation fiber. The number of loops is 5, so this model simulates a 400-km transmission for a single 10-Gbit/s optical channel. Commercial software (OptiSystem) is used to conduct the simulation task. The longer the bit sequence, the more accurate the simulation result should be. Both 8192 bits and 16,384 bits were simulated, and similar results were obtained. We present simulation results generated by the 16,384-bit test sequence. When conducting the simulation, we changed the input signal power and calculated the corresponding bit error rate (BER) for two optical communication systems, one consisting of the interleaver with rhomb etalon effects and the other consisting of the interleaver with the rhomb etalon effects removed by tilting the rhomb. The resulting simulation results are presented in Fig. 7.

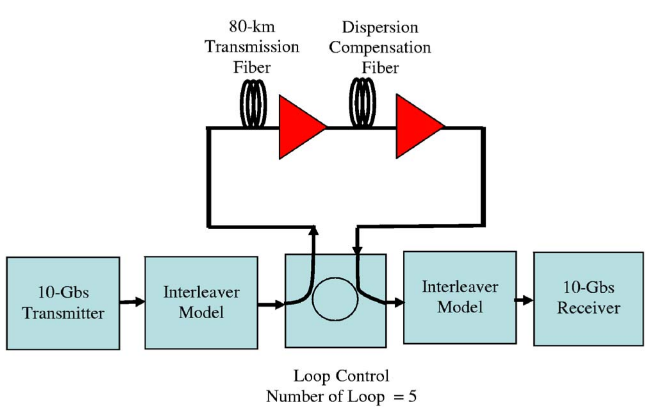

Fig. 6 Simulation model of optical communication system for comparison of interleaver performance.

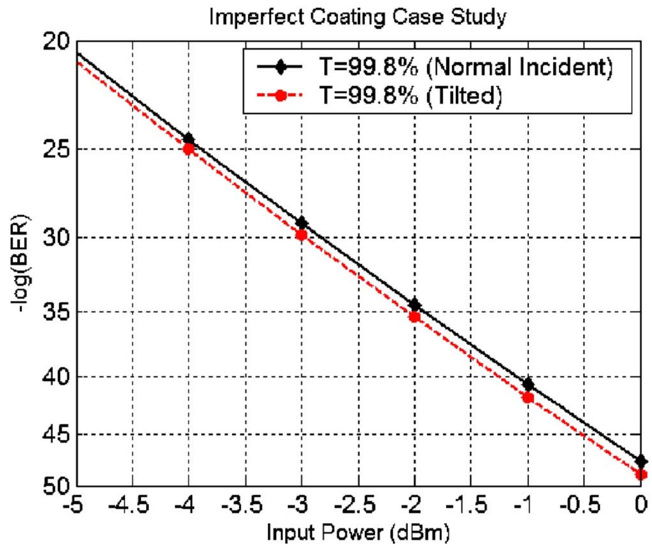

Fig. 7 Simulated relations of BER versus input power for an optical communication system consisting of interleavers with rhomb etalon effect (solid line) and one consisting of interleavers with tilted rhomb (dashed line).

The simulation data presented in Fig. 7 show that the system consisting of the interleaver with rhomb etalon effects needs more power ($\approx$0.2 dBm) to achieve the same BER than the system consisting of the interleaver with a tilted rhomb. In other words, the power penalty reduction achieved by the tilted rhomb is only about 0.2 dBm. The extra insertion loss brought about by the tilted etalon can thus be justified.

The measured CD data on interleavers with a nontilted rhomb and with a tilted rhomb are presented in the next section to demonstrate the feasibility of the proposed dispersion reduction method.

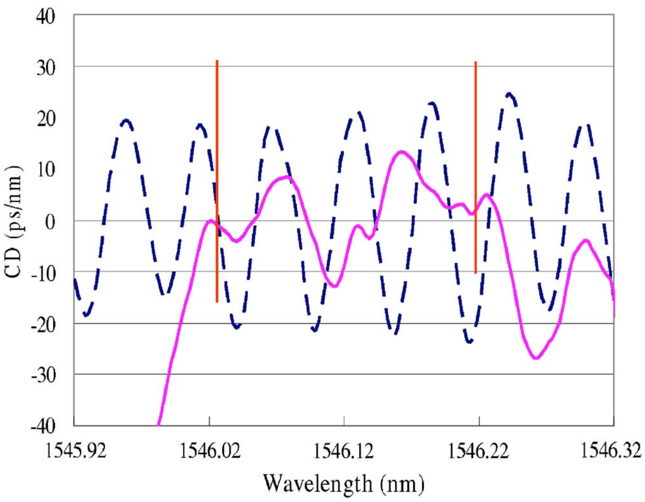

Fig. 8 Comparison of CDs before and after tilting the rhomb for a 50-GHz channel-spacing interleaver.

4 Experiment and Discussion

As described previously, the rhombs (5 by 12 mm) are used in the interleavers to separate two output ports that are perpendicularly polarized with respect to each other. The rhomb causes CD ripple because of its imperfect AR coating. Figure 8 depicts the typical measured CD within a 50-GHz channel-spacing interleaver passband. The CD ripples (indicated by the dashed line) are in agreement with the simulation. They have the same frequency as the simulation results, and their amplitudes are slightly smaller than the simulation. We believe that the smaller amplitude is due to the slight rhomb tilt relative to the incident beam. Thereby, different orders of the transmitted light through the etalon effect are separated, and not all of them are coupled into the interleaver output collimator; as a result, the smaller amplitudes are observed. The solid line represents the measured CD for the same interleaver after the rhomb is tilted by 3.5 deg; no noticeable periodic ripples are observed. The CD within the 25-GHz passband (between the two vertical lines) is controlled below ±15 ps/nm. We observe large measured CD ripples outside the passband, because our CD measurement equipment, which is based on the phase-shift method, cannot generate accurate results when the signal intensity changes significantly.[7] In this case, the signal energy level is reduced significantly outside the interleaver passband; therefore, the CD result outside the passband is not reliable.

The experiment results clearly demonstrate that by tilting the rhomb with an imperfect AR coating within a birefringent-crystal-based interleaver, we can significantly reduce the device CD ripples. When the rhomb is tilted 3.5 deg relative to the incident beam, the separation between the zeroth and the first order will be approximately 840 μm. Based on the calculation of coupling loss due to the collimator's misalignment, first- and higher-order transmitted light through the etalon effect will not be coupled into the output collimator.

5 Conclusions

We have investigated an important and universal, yet seldom discussed, issue in optical communication system design, viz. the effect of imperfect AR coating on optical system performance. Our simulation data shows that a birefringent-crystal-based interleaver can have significant CD ripples if it consists of rhombs with imperfect surface AR coating ($T=99.8\%$). The resulting CD ripple brings about a significant power penalty for an optical communication system. We have demonstrated how the imperfect-coating effects can be reduced by tilting the rhomb. Simulation and experimental data were presented to support our arguments.

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Biographies and photographs of the authors not available.