Low-Loss Planar Lightwave Circuit OADM with High Isolation and No Polarization Dependence

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***Abstract*—A passive optical add–drop multiplexer with 1 dB of insertion loss and 36 dB of isolation is fabricated by writing Bragg gratings in a waveguide Mach–Zehnder interferometer using ArF excimer laser light. The spectral properties and bit-error-rate performance of the device are fully characterized using polarized light.**

***Index Terms*—Bragg gratings, Mach–Zehnder interferometer, optical add–drop module, optical waveguides, polarized light, wavelength division multiplexing.**

I. Introduction

PASSIVE optical add–drop filters are needed in various optical fiber network configurations involving wavelength-division multiplexing (WDM). One of the device options for an add–drop filter is the Mach–Zehnder interferometer (MZI) with wavelength selective Bragg gratings in the two arms of the interferometer [1]. Such devices have been realized using both all-fiber [2] and integrated optical MZI [3]–[7]. In the following, we limit the discussion to passive MZI in glass waveguides where Bragg gratings are formed by the photosensitive process. While all-fiber MZI have excellent optical performance and polarization independence, waveguide-based MZI have the advantage in terms of potential mass production, compactness, mechanical integrity, cascadability, and eventual hybrid integration with other devices on the same substrate [8].

There is however one obstacle to the widespread use of planar-waveguide-based devices in interferometers such as MZI: the polarization dependence of the effective index of the waveguides [9]. Because of this dependence, light polarized in the plane of the waveguide (TE) or out of the plane (TM) will have different optical path lengths in the device. As a result, the light output to the different ports of the device varies when the state of polarization of the incoming light signal fluctuates. The birefringence of planar optical waveguides come from the fact that the substrate and deposited thin-film layers do not have the same thermal expansion coefficients. In particular, the commercially available germanium-doped silica-on-silicon planar lightwave circuits (PLC's)[1] used here have a birefringence of about 2×10^{-4}. We have shown a solution to this problem in a previous paper and written strong Bragg gratings in PLC's in such a way as to compensate for the birefringence [10]. The final spectral response of these gratings is indistinguishable (within less than 0.05 nm) when measured in TE or TM light. The purpose of this letter is to show that using the same techniques, a PLC-based MZI add–drop module for narrow-band WDM can be fabricated with high channel isolation and low polarization sensitivity.

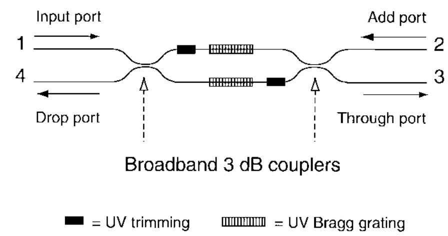

Fig. 1. Schematic layout of the planar waveguide balanced Mach–Zehnder interferometer (not to scale). The device length is 25 mm and the spacing between the two branches is 250 μm. The Bragg gratings are 3.8 mm long.

II. Device Design and Fabrication

The add–drop function of the MZI shown in Fig. 1 is described in [1]. In the drop mode, all the light entering Port 1 exits at Port 3, except for the light resonant with the Bragg wavelength which exits at Port 4. Since the device is symmetric, light at the Bragg wavelength can be added to the light going out of Port 3 by injecting it in Port 2. The actual device used is 25 mm long and the spacing between the two arms of the interferometer is 250 μm. The core index difference of the channel waveguides is 0.3%.

Two identical Bragg gratings of 3.8 mm in length are written one after the other in the two arms of the device in conditions similar to those described in [10]. In this case, a 10-min irradiation with 193-nm light from an ArF excimer laser at 100 pps and 200 mJ/cm^2/pulse through a phase mask is used to form the gratings. In these conditions, no hydrogen loading is needed to enhance the photosensitivity. In order to monitor the device performance during the fabrication of the gratings, a polarization-maintaining fiber pigtail connects a broad-band light source with a waveplate polarization controller to the input of the device while the output of the drop and through ports are connected to two optical spectrum analyzers with 0.1-nm resolution. This allows the writing of identical and polarization independent gratings as shown in [10]. However,

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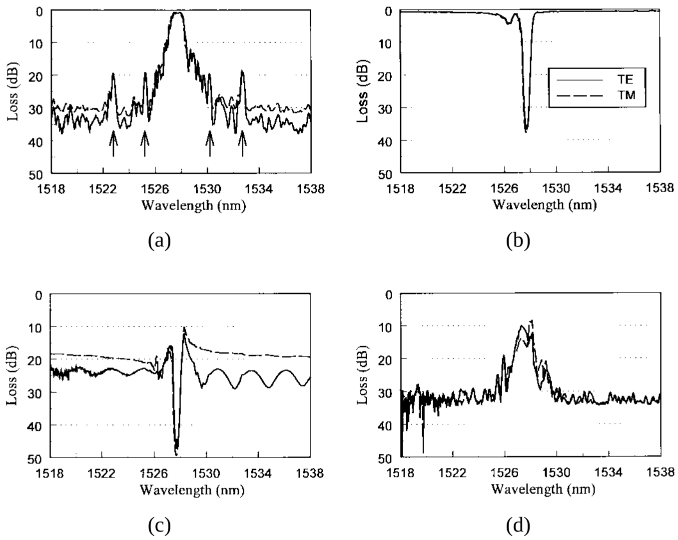

Fig. 2. Fiber-to-fiber broad-band spectral loss of the device obtained using a polarization-controlled tunable laser source emitted into Port 1. TE (solid line) and TM (dashed line) curves are plotted in all cases.

even the slightest imbalance in the two gratings will noticeably disrupt the optical path length equilibrium. Trimming the path length by uniform UV exposure of the interferometer arms away from the gratings is used to compensate for this as shown in Fig. 1. Since no hydrogen loading is involved, the trimming may be monitored in real time and does not pose a particular problem, in contrast to the case where the presence of hydrogen or deuterium used to sensitize the waveguides makes real time adjustement of the path length difficult [7].

III. Measurements and Discussion

The fiber-to-fiber loss spectra of the device were measured with a tunable laser source, waveplate polarization controllers and a power meter. Before the Bragg gratings were put in, the insertion loss for 1550-nm-wavelength light going from Ports 1–3 was 0.14 dB for TE and TM polarizations, while the crosstalk (Ports 1–2) was 26 and 24.9 dB for TE and TM light, respectively.

The loss spectra measured out of all the ports following the inscription of the Bragg gratings are shown in Fig. 2 for both polarization states. The first observation to make is that the plots for TE and TM measurements are so identical that they are difficult to distinguish on the figures. The drop port spectra [Fig. 2(a)] indicate a loss of 1 dB for TE light and 0.7 dB for TM light at the Bragg wavelength and losses of the order of 30 dB at other wavelengths. The 3-dB bandwidth of the dropped light is 1.1 nm. The strong evenly spaced peaks marked by the arrows in the drop spectra peaks are due to stitching errors in the electron beam written phase mask that was available at the time of the experiment. This problem can be removed with a better phase mask. Also, apodization techniques [2], [6] are available to improve the sharpness of the wavelength filtering. The through Port spectra [Fig. 2(b)] show that the insertion loss has increased to 1 dB for nonresonant light while the extinction due to the Bragg gratings at 1527.7 nm is 36 dB. The polarization dependent loss at the Bragg wavelength is

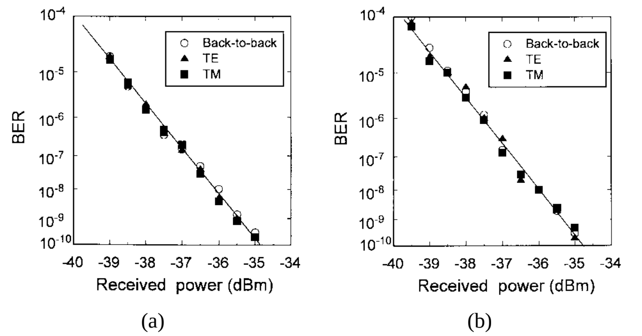

Fig. 3. Polarization dependence of the bit error rates of the Add and Drop signals at 2.5 Gb/s in the presence of seven other channels spaced by 200 GHz. All channels have an optical power of -3 dBm.

0.07 dB. Unfortunately, a small loss peak located 1.2 nm away on the short wavelength side of the Bragg wavelength appears, similar to the cladding mode coupling loss observed in fiber Bragg gratings. This size of this unwanted loss increases with the extinction of the gratings and reaches $\sim$3 dB for the 36-dB extinction gratings. Our experiments indicate that the size of this loss depends on the core index difference of the channel guides, but is unavoidable for the particular composition used in this work, which is a standard PLC composition for best overall performance.

Fig. 2(c) shows the spectra of the light going out of Port 2 and Fig. 2(d) the spectra of the light returned toward the input. In spite of UV trimming, it was impossible to increase the losses across the measured spectrum to higher values. In both cases the final spectra represent a compromise to achieve the highest losses at all wavelengths for both polarizations. This is partly due to the fact that UV-induced path length changes are birefringent [10] and to the fact that the Bragg gratings are not perfectly identical. Both of these spectra include losses as low as 10 dB, clearly insufficient protection for signal sources used in WDM systems. It is likely that isolators would be required for Ports 1 and 2 of these devices or equivalently in front of all the signal sources.

The final measurement to be reported here is a preliminary system study in which the bit-error-rate (BER) penalty for the drop (Port 4) and add (Port 3) operations was determined for each polarization state. Eight 2.5-Gb/s channels at wavelengths ranging from $\lambda_1 = 1526.1$ to $\lambda_8 = 1537.2$ nm (200-GHz spacing) were used. Channel 2 at 1527.7 nm was resonant with the Bragg wavelength of the device. The BER of the dropped and of the added channels were measured as follows. For the drop operation, eight channels were simultaneously coupled to Port 1 with the TE or TM polarization with an optical power of -3 dBm/channel and the add signal at λ_2 was coupled to Port 2 with a circular polarization, also at -3 dBm. For the add operation, the eight channels were coupled to Port 1 with a circular polarization and the add signal at λ_2 was coupled to Port 2 with either the TE or TM polarization and the same optical power. The received power in the two measurements (add and drop) was changed by an attenuator in front of the BER measurement receiver. Fig. 3 shows that no power penalty was observed for the add and drop signals compared to the back-to-back measurement for both polarization states.

IV. SUMMARY

We have presented detailed measurement results on a compact, polarization-insensitive MZI-based planar optical add–drop module with 36 dB of isolation between the dropped and added channels and insertion losses of only 1 dB. BER measurements using eight 2.5-Gb/s channels spaced by 200 GHz confirm that there is no measurable coherent crosstalk between the added and dropped channels in both TE and TM light at the power levels used. The add–drop filter can be used in a backbone of an economical optical LAN which does not employ optical amplifiers [11].

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