An All-Fiber Dense-Wavelength-Division Multiplexer/Demultiplexer Using Photoimprinted Bragg Gratings

F. Bilodeau, D. C. Johnson, S. Thériault, B. Malo, J. Albert, and K. O. Hill

Abstract— **A wavelength multiplexing/demultiplexing device is fabricated and used to drop/insert a single wavelength channel from/into a multiple wavelength transmission link with 100 GHz channel-spacing at 1550 nm. The device consists of an all-fiber Mach–Zehnder interferometer with photoinduced Bragg gratings. The following performances were measured: extraction/coupling efficiency = 99.4%, excess loss <0.5 dB, adjacent channel isolation > 20 dB, and return loss > 23 dB.**

I. INTRODUCTION

DENSE wavelength division multiplexing (WDM) lightwave systems will require devices for accessing the individual wavelength channels of multiwavelength optical fiber links. The process of photoimprinting Bragg gratings in optical fibers and silica-on-silicon waveguides using glass photosensitivity [1] is a proven flexible means for fabricating narrowband reflectors. Recently several fiber-based components fabricated using photosensitivity were demonstrated for demultiplexing narrowband channels [2]–[4]. In this paper, we describe and characterize a high performance wavelength multiplexing/demultiplexing (mux/demux) device based on a fiber Mach–Zehnder interferometer with photoinduced Bragg gratings in the interferometer arms. When spliced into a multiwavelength transmission line, the mux/demux device can be used to extract wavelength channel(s) from the transmission line and/or add wavelength channel(s) to the transmission line. In particular, the device is capable of multiplexing and demultiplexing optical channels spaced 100 GHz apart (0.8 nm spacing at 1550 nm).

II. DEVICE OPERATION

The concept for the mux/demux device was originally described in [5]. The device consists of an all-fiber Mach–Zehnder interferometer with identical Bragg gratings in the interferometer arms. The device can operate as a demultiplexer (shown in Fig. 1) and as a multiplexer (shown in Fig. 2). Fig. 1 shows the demultiplexing of a single wavelength channel from a multiwavelength transmission line. A stream of several wavelengths $(\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_7)$ is launched into the input port (port 1) of the mux/demux device. Assuming the grating resonant wavelength is λ_4, light at λ_4 emerges from port 2 and the remaining light emerges from the output port (port 4). Ideally in a properly balanced interferometer, no light emerges from port 3. Because of the inherent symmetry of the interferometer it is possible to use the device as a multiplexer as shown in Fig. 2. In that case, assuming again that the grating resonant wavelength is λ_4, light at λ_4 launched in port 3 comes out of port 4 multiplexed with the other wavelengths that are launched in port 1. The placing of additional matched pair gratings with different resonant wavelengths would permit the mux/demux device to extract or insert several different wavelengths channels at once.

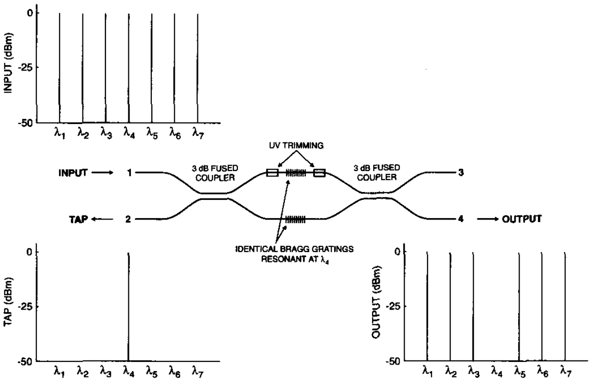

Fig. 1. Schematic of mux/demux device showing extraction of wavelength channel λ_4 from a WDM transmission stream.

Because of the symmetry of the device multiplexing and demultiplexing can take place at the same time in the same device. In this case crosstalk between the multiplexed and demultiplexed signals occurs unless the reflectivity of the Bragg gratings is infinitely high. In practice, to minimize crosstalk, reflectivities above 99% will be required. This type of crosstalk could also be avoided by placing in the interferometer arms additional grating-pairs with different resonant frequencies; then crosstalk within a wavelength channel is eliminated if the wavelength of the extracted channel is kept different from the wavelength of the inserted channel.

III. EXPERIMENTAL

The mux/demux is fabricated using techniques similar to that described in [2] for the fabrication of a narrowband

Manuscript received November 23, 1994.

The authors are with the Communications Research Centre, Ottawa, ON K2H 8S2 Canada.

IEEE Log Number 9409034.

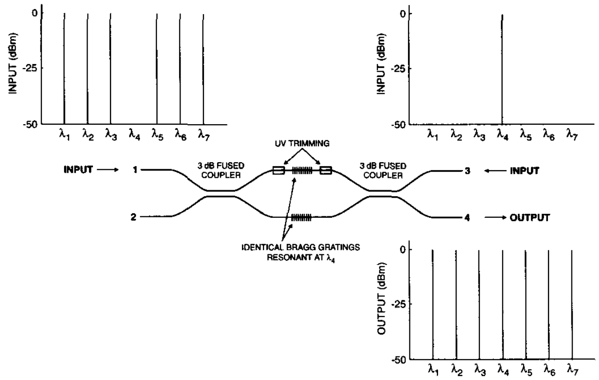

Fig. 2. Schematic of mux/demux device showing insertion of wavelength channel λ_4 into a WDM transmission stream.

transmission filter using an all-fiber Michelson interferometer. In this work, a balanced Mach–Zehnder interferometer of monolithic construction and consisting of two identical 3 dB fused couplers is made from two continuous strands of Corning SMF-28 fiber without the use of splicing. The optical fibers are laid parallel and in contact on a fused-taper-coupler fabrication jig [6]. Then the two couplers are made in succession without moving the fibers off the jig. The couplers are kept short by stopping the elongation at the first 3 dB splitting point (50% splitting ratio at 1549 nm) which corresponds to an elongation of about 10 mm. This produces couplers that exhibit a splitting ratio that varies slowly with wavelength. Also the coupling coefficients of such compact couplers exhibit extremely low sensitivity to light polarization.

Although the fabrication of the two identical 3-dB fused-taper-couplers is accomplished easily, there is typically a small path length difference between the two interferometer's arms that needs to be nulled in order to balance the Mach–Zehnder interferometer. This is accomplished by exposing one arm of the interferometer to uniform UV light to photoinduce an average index change in the fiber core (see UV trimming in Fig. 1) on each side of one of the gratings.

Because the natural photosensitivity of Corning SMF-28 optical fiber is low the fibers are first photosensitized using either flame brushing [7] or hydrogen loading [8]. Following photosensitization the Bragg gratings are photoimprinted simultaneously using a KrF excimer laser and a zero-order-nulled phase mask [9]. The distance between the two couplers is chosen to accommodate the desired grating length and UV trimming. In this case the distance between the couplers is 4 cm and the Bragg gratings are 1 cm long. The length required to do UV trimming is 2 to 3 mm. The total length of the device is 8 cm, which is short enough to be compatible with fused taper coupler packaging techniques.

In order to characterize the grating-pair and the path length equalization, white light was launched into port 1 and the tap efficiency measured out of port 2. The result is shown in Fig. 3: the reflectivity = 99.4%, the full width at half maximum = 0.2 nm and the rejection 100 GHz away from the peak = 24 dB. The rejection can be increased further by modulating the coupling coefficient of the Bragg gratings with a raised cosine [10].

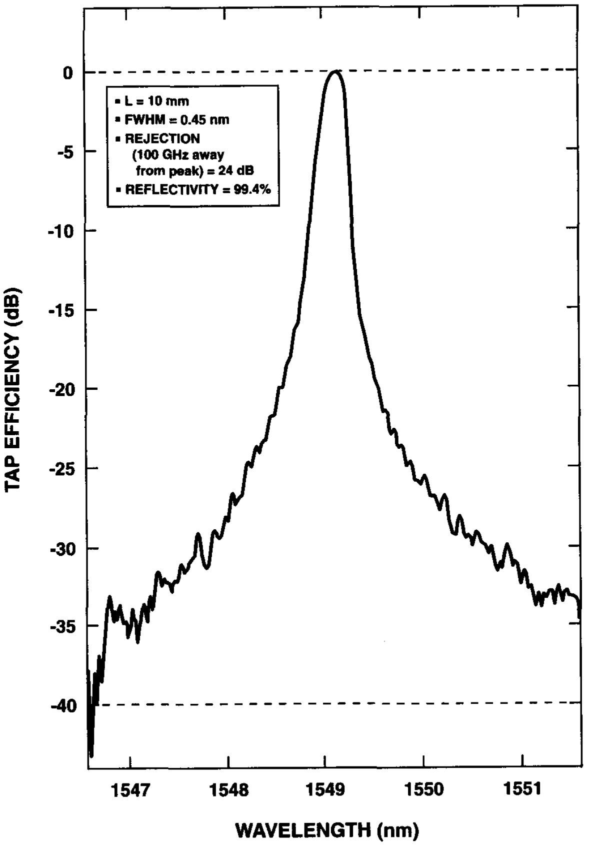

Fig. 3. Tap light coming out of port 2 normalized to the input power. The resolution of the optical spectrum analyzer was 0.1 nm.

To characterize fully the device a WDM demultiplexing experiment was simulated. The wavelength emitted from a tunable laser diode (Hewlett-Packard 8168A) is tuned through seven discrete wavelengths spaced 100 GHz apart and the light out of each of the four ports is monitored with an optical spectrum analyzer (resolution = 0.1 nm). Only one of the discrete wavelengths, $\lambda_4 = 1549.1$ nm, corresponds to the resonant wavelength of the grating-pair. The demultiplexing performance is shown in Fig. 4 where the measured input and output spectra at each port are shown in the insets. The key performance parameters are the efficiency = 99.4% with which light at λ_4 is extracted out of port 2 (shown in Fig. 4(b)); the rejection > 20 dB at port 2 of light in the adjacent channels (shown in Fig. 4(b)); and the excess loss < 0.5 dB for the unextracted light transmitted out of port 4 (shown in Fig. 4(d)). The light emerging from port 3, shown in Fig. 4(c), is loss that results from an imperfectly balanced interferometer. The spectrum of the back-reflected light into port 1 is shown as the shaded area in Fig. 4(a). The return loss is 23 dB for light at the extracted wavelength and is much higher at the other wavelengths. A high return loss is an indication of good path length equalization between the two couplers and of identical Bragg gratings. The measured performance of the

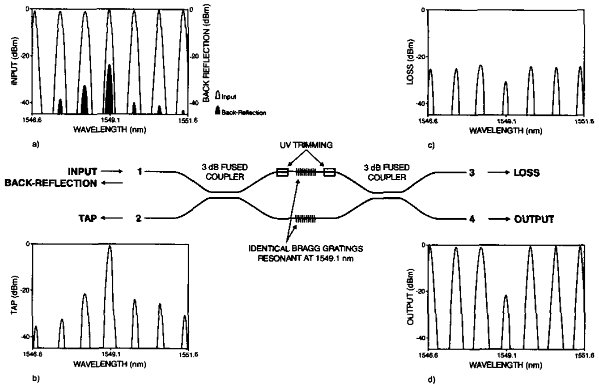

Fig. 4. Schematic of mux/demux device showing a seven-channel WDM simulation. At each port of the device the insets show the measured optical spectrum of the light with a resolution of 0.1 nm.

same device, but used for multiplexing (λ_4 launched into port 3 and transmitted out of port 4) is almost identical to that described above when the device is used for demultiplexing.

The device was found to be insensitive to the state of polarization of the input light. The insensitivity to light polarization results from using fused couplers with short taper lengths (elongation stopped at the first 3 dB splitting) and photoimprinting the Bragg gratings using unpolarized UV light. The balance of the interferometer is insensitive to the ambient temperature changes due to the interferometer's compact design configuration. Because the optical fibers inside the interferometer are parallel and in close contact both arms of the interferometer will follow identically changes in ambient temperature and balance of the interferometer will be maintained. However, a change in ambient temperature tunes the central wavelength of the Bragg reflectors at a rate of 0.015 nm/°C at 1550 nm.

IV. CONCLUSION

An all-fiber multiplexing/demultiplexing device designed for 100 GHz dense WDM at 1550 nm was fabricated and demonstrated. The mux/demux showed high performance and can be further improved by writing more than one grating-pair within the interferometer and by apodizing the gratings spectral response.

REFERENCES

[1] K. O. Hill, Y. Fujii, D. C. Johnson, and B. S. Kawasaki, "Photosensitivity in optical fiber waveguide: Application to reflection filter fabrication," *Appl. Phys. Lett.*, vol. 32, pp. 647–649, 1978.

[2] F. Bilodeau, K. O. Hill, B. Malo, D. C. Johnson, and J. Albert, "High-return-loss narrowband all-fiber bandpass Bragg transmission filter," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 80–82, 1994.

[3] V. Mizrahi, T. Erdogan, D. J. DiGiovanni, P. J. Lemaire, W. M. Macdonald, S. G. Kosinski, S. Cabot, and J. E. Sipe, "Four channel fiber grating demultiplexer," *Electron. Lett.*, vol. 30, pp. 780–781, 1994.

[4] J.-L. Archambault, P. St. J. Russel, S. Barcelos, P. Hua, and L. Reekie, "Grating-frustrated coupler: A novel channel-dropping filter in single-mode optical fiber," *Opt. Lett.*, vol. 19, pp. 180–182, 1994.

[5] D. C. Johnson, K. O. Hill, F. Bilodeau, and S. Faucher, "New design concept for a narrowband wavelength-selective optical tap and combiner," *Electron. Lett.*, vol. 23, pp. 668–669, 1987.

[6] F. Bilodeau, K. O. Hill, S. Faucher and D. C. Johnson, "Low-loss highly overcoupled fused couplers: Fabrication and sensitivity to external pressure," *J. Lightwave Technol.*, vol. 6, pp. 1476–1482, 1988.

[7] F. Bilodeau, B. Malo, J. Albert, D. C. Johnson, K. O. Hill, Y. Hibino, M. Abe, and M. Kawachi, "Photosensitization of optical fiber and silica-on-silicon/silica waveguides," *Opt. Lett.*, vol. 18, pp. 953–955, 1993.

[8] P. J. Lemaire, R. M. Atkins, V. Mizrahi, and W. A. Reed, "High pressure H_2 as a technique for achieving ultrahigh UV photosensitivity in GeO_2-doped optical fibers," *Electron. Lett.*, vol. 29, pp. 1191–1193, 1993.

[9] K. O. Hill, B. Malo, F. Bilodeau, D. C. Johnson, and J. Albert, "Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask," *Appl. Phys. Lett.*, vol. 62, pp. 1035–1037, 1993.

[10] M. Matsuhara and K. O. Hill, "Optical-waveguide band-rejection filters: Design," *Appl. Opt.*, vol. 13, pp. 2886–2888, 1974.