Arrayed Waveguide Gratings Based on Perfluorocyclobutane Polymers for CWDM Applications

Jia Jiang, Claire L. Callender, Chantal Blanchetière, Julian P. Noad, Shengrong Chen, John Ballato, and Dennis W. Smith, Jr.

***Abstract*—Compact wavelength-division multiplexers based on arrayed waveguide grating structures have been designed and fabricated for short-haul communication network applications using low-loss perfluorocyclobutane-containing polymers. The devices exhibit high thermal stability and low on-chip losses. The average on-chip loss was <6 dB, including the fiber-to-chip coupling loss. The output uniformity across five channels was typically ±0.5 dB, and the thermal sensitivity of the central wavelength was 0.045 nm/°C. Optimization of devices through material properties and fabrication process parameters is discussed.**

***Index Terms*—Arrayed waveguide grating (AWG), compact wavelength-division multiplexers (CWDM), optical loss, perfluorocyclobutane (PFCB) polymer, waveguide.**

I. INTRODUCTION

POLYMER materials for photonic applications have evolved rapidly over the past few years, enabling the design and fabrication of a variety of planar photonic components [1], [2]. However, despite the availability of some polymers with excellent optical and mechanical properties, it is still very challenging to meet the rigorous specifications of devices with high channel counts and closely spaced wavelengths, such as those typically employed in long-haul dense wavelength-division multiplexing (DWDM) networks. In particular, polarization and/or temperature independence are not easy to achieve, due to optical birefringence or thermal instability of the polymer materials. However, the cost effectiveness and flexibility of design of polymer photonic devices are enabling them to gain increasing attention in broad-band environments such as coarse wavelength-division multiplexing (CWDM) in network access and fiber-to-the-home (FTTH) applications. The device specifications for CWDM devices, based on the ITU standard of 20-nm channel spacing, are much less stringent than those in DWDM systems, thus offering more opportunities to match material properties with device performance. In CWDM systems, relaxed tolerances for thermal management, polarization sensitivity, and optical loss allow a range of polymer materials to be considered as candidates for planar devices, with potential advantages in size, cost, and integratability over thin film or fiber Bragg grating solutions.

PFCB is a perfluorocyclobutane aromatic polyether polymer based on thermal cyclopolymerization of aromatic trifluorovinyl ether monomers. A few photonic devices employing PFCB materials as either core or cladding layers have been demonstrated in the past few years [3]. Recently, a range of easily processible PFCB optical polymers with highly tailorable properties including low optical loss, tunable refractive index, and superior thermal stability have been developed at Tetramer Technologies and Clemson University [4]. In this letter, specifically designed waveguide core and cladding materials from this range were used to fabricate compact wide-band wavelength division multiplexers, based on arrayed waveguide grating (AWG) structures, for CWDM applications. With their low-optical absorption and high-thermal stability these PFCB-based devices are expected to show low optical loss and have transmission characteristics that are relatively insensitive to temperature change. Data on the AWG design, fabrication, and characterization are reported. Optimization of devices through material properties and fabrication process parameters is discussed.

II. MATERIALS AND EXPERIMENTS

The new PFCB-containing polymer is based on the thermally induced cyclopolymerization of bi- or tri-functional aryl trifluorovinyl ethers to form perfluorocyclobutyl-containing structures [3], [4]. These polymers exhibit excellent thermal stability; the Tg of the waveguide core material used in this letter is up to 260 °C. The refractive indexes were adjusted by copolymerization of commercial monomers, allowing specific refractive indexes to be produced for the core and cladding layers in the waveguide structures. The refractive indexes of fully crosslinked polymer thin films were measured with the prism coupler technique to be 1.478 and 1.464 at 1537 nm for the core and cladding materials, respectively. The birefringence of the films on silicon substrates is around 0.002–0.003 for the core material and 0.002 for the cladding polymer.

The waveguides have been fabricated with a dry etch process. A lower refractive index PFCB-containing polymer was spin coated on an oxidized silicon wafer as a lower cladding layer.

Manuscript received September 28, 2005; revised October 28, 2005.

J. Jiang, C. L. Callender, C. Blanchetière, and J. P. Noad are with the Communications Research Centre, Ottawa, ON K2H 8S2, Canada (e-mail: jia.jiang@crc.ca).

S. Chen is with Tetramer Technologies, L.L.C., Pendelton, SC 29670 USA (e-mail: www.tetramertechnologies.com).

J. Ballato and D. W. Smith, Jr., are with the Center for Optical Materials Science and Engineering Technologies (COMSET), Clemson University, Clemson, SC 29634 USA.

Digital Object Identifier 10.1109/LPT.2005.862364

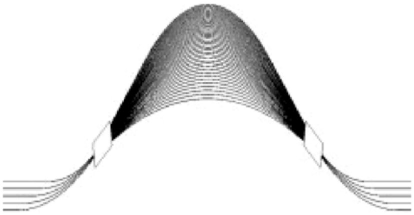

Fig. 1. Typical layout of 5 × 5 AWG.

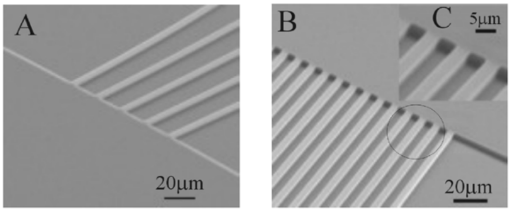

Fig. 2. SEM photographs of 5 × 5 AWG: (A) input/output waveguides and (B) and (C) array waveguides at dense side near slab region.

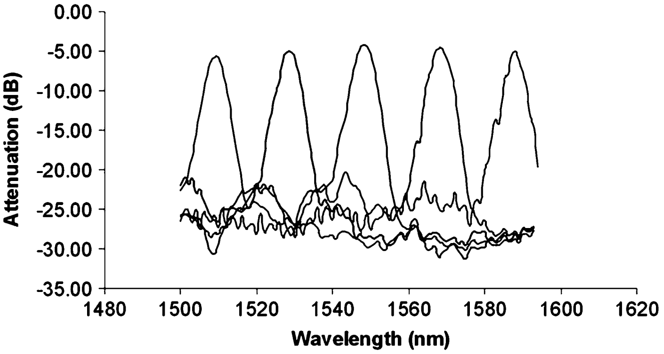

Fig. 3. Transmission spectra of five-channel AWG with 20-nm spacing.

After complete thermal crosslinking of this layer in a vacuum oven, the waveguide core polymer film was then made on top and thermally cured. Next, a thin film of silicon dioxide was deposited onto the core polymer surface by rf sputtering or e-beam evaporation and patterned by photolithography to serve as a mask for subsequent reactive-ion etching (RIE). The waveguide ridges were then formed using an O_2/CHF_3 RIE process. Three etching steps with different ratios of CHF_3 and O_2 were used to pattern the SiO_2, etch the polymer layer, and finally remove the residual SiO_2 layer. A top cladding layer of a polymer with a refractive index matching that of the lower cladding was then deposited by spin coating and thermally crosslinked to complete the AWG structure. The waveguide profile was evaluated using a scanning electron microscope (SEM), and the ridge waveguide loss was estimated with the cut-back method, that is measuring the transmitted optical power in successively shorter lengths of a straight ridge waveguide.

AWG characterization was completed using a tunable laser (1500 to 1600 nm). The light was butt coupled from a fiber into one channel at the cleaved edge of the device, and the transmitted light was monitored by a photodetector for each output channel as a function of input wavelength.

III. AWG DESIGN, FABRICATION, AND CHARACTERIZATION

A. Device Design

The refractive indexes of 1.478 and 1.464 for the polymer core and cladding layers were used to design the AWG structure on the silicon wafer. Relatively high refractive index contrast of $\Delta n = 0.014$ between the core makes it possible to obtain compact devices. The core waveguide size was selected to be $4 \times 3\ \mu\text{m}^2$ to ensure single-mode propagation. The loss of a straight waveguide with the same cross section was measured to be typically ~0.6–0.7 dB/cm.

5 × 5 AWGs with channel spacing of 20 nm have been designed with a central wavelength at 1550.1 nm. The device size is around $25 \times 5.0\ \text{mm}^2$. This small chip dimension allows a relatively large number of devices from one wafer. The path length difference between adjacent waveguides in the AWGs was chosen to be typically 12 integer multiples of wavelength to accommodate a free-spectral range (FSR) of 130 nm. The minimum bending radius is 5700 μm, and there are typically 59 waveguides in the array section of the device. Fig. 1 is the schematic structure of a typical AWG.

B. Device Fabrication

Fig. 2 shows SEM pictures of the AWG fabricated with a PFCB core polymer before deposition of the top cladding layer. Fig. 2(A) shows the area of input/output waveguides, and Fig. 2(B) and (C) focus on the dense side of the array waveguide gratings nearing the slab region where the distance between ridges is only 4 μm apart. It can be seen that excellent waveguide shape and very smooth sidewalls were obtained. A top cladding of PFCB-containing polymer, with refractive index 1.464 and a typical thickness of ~10 μm, was finally deposited over the waveguide ridges by spin coating and then thermally cured for 4 h typically.

C. AWG Characterization

The transmission spectra for the 5 × 5 channel AWGs with channel spacing of 20 nm are shown in Fig. 3. The measured channel spacing was 20 nm, and the channel width is 7 nm at −3 dB. The average on-chip loss, including coupling loss between fiber to waveguide, was 5–6 dB, with a uniformity of ±0.5 dB across the channels. The losses in these devices can be attributed to several sources. The fiber-to-chip coupling loss is typically around 1.5–2.0 dB in our measurement when refractive index-matching oil is used between the fiber and waveguide edge. In addition, there is diffraction loss (calculated to be 1.8 dB at center guide of the AWG) and waveguide propagation loss, which causes about 1.8–2.1 dB of loss for the chip, based on 0.6–0.7 dB/cm of straight waveguide attenuation and roughly a 30-mm-long path. The total loss from all those contributions is around 5.1–5.9 dB. The remaining loss may come from the scattering at the sidewall of the waveguides, especially at the curved sections. The adjacent channel crosstalk was ≤ -20 dB. This value is relatively high and is likely due to phase errors that are probably related to the geometric deviations of ridge waveguide shape created during the fabrication process. These waveguide geometric deviations could be caused by lower cladding layer roughness or lithography variations. Fabrication of devices with improved surface flatness of the lower cladding layer and

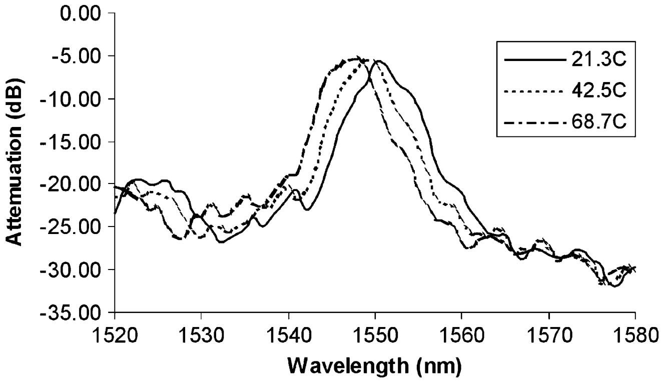

Fig. 4. Central channel wavelength shift with temperature change.

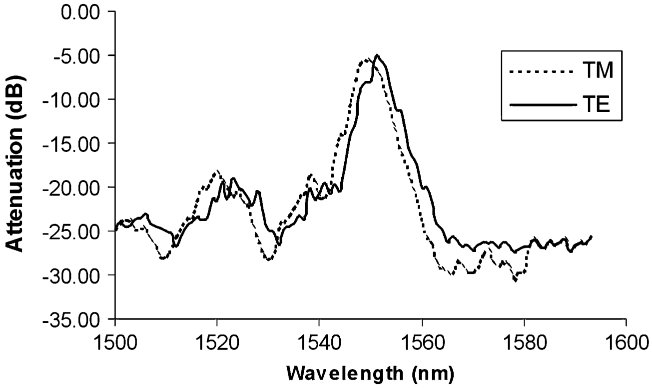

Fig. 5. Polarization-dependent wavelength shift of central channel.

more careful lithography control is currently underway in order to further ameliorate the channel-to-channel crosstalk.

The device thermal stability was evaluated by recording the spectral response at different temperatures. Fig. 4 shows the transmission spectrum of the central channel as a function of the device temperature. PFCB is a highly thermally stable polymer with a Tg higher than 260 °C. Compared with the devices fabricated using a lower Tg polymer in which the thermal shift of the spectral response can be typically − 0.25 nm/°C [2], the PFCB-based device shows significantly less temperature dependence. Within the temperature range of 21 °C to 69 °C, the temperature-dependent wavelength shift of the PFCB device is only − 0.045 nm/°C. Over this temperature range, the on-chip loss reduced slightly with increasing temperature, while the channel uniformity, crosstalk, and spacing remained unchanged. While this temperature-dependent shift is larger than other device technologies, the material properties are such that operation of the device in a range typically required for CWDM devices (−5 °C to 65 °C) would result in a maximum temperature-dependent shift of around 3 nm. With some improvements to the design to flatten the passband [5], these devices could be used in a CWDM system without the need for stringent temperature control, thus avoiding the higher costs, power consumption, and increased device size associated with packaging a temperature controller into the devices.

The polarization-dependent wavelength shift of each channel was measured to be 2–3 nm (Fig. 5) at room temperature, which is due to the PFCB film birefringence $(n_{\mathrm{TE}} - n_{\mathrm{TM}})$ of 0.002–0.003 on the silicon substrate. This value tended to decrease slightly as the temperature was increased. This may suggest that the residual stress within the waveguide is partially reduced, and hence the stress-induced birefringence is decreased when the device is at a higher temperature. Increasing the final bake time up to 28 h at 220 °C was found to minimize the polarization-dependent wavelength shift to 1.5–1.8 nm without deteriorating other aspects of the performance of the devices. This demonstrates once again the superior thermal stability of the materials. Similarly to the temperature dependence, this could also be improved by flattening the passband of the device. This polarization-dependent wavelength shift should not be a major obstacle for its application in a CWDM system. According to Telcordia standard GR-1209, the maximum acceptable variation of the central wavelength could be 20% of the channel spacing [6].

IV. CONCLUSION

Compact broad-band WDMs with channel spacing of 20 nm based on an AWG structure have been demonstrated using new highly thermal stable PFCB-containing copolymers with optical property tailorability. The devices exhibit low on-chip losses of < 6 dB, which includes the fiber-to-chip coupling loss, crosstalk of around −20 dB, and output channel uniformity of ± 0.5 dB. This device shows low thermal sensitivity, with a central wavelength shift of −0.045 nm/°C. These devices offer excellent potential as low-cost solutions for short-haul communications in a variety of applications.

REFERENCES

[1] M. Zhou, "Low-loss polymeric materials for passive waveguide components in fiber optical telecommunication," *Opt. Eng.*, vol. 41, no. 7, pp. 1631–1643, 2002.

[2] J.-F. Viens, C. L. Callender, J. P. Noad, and L. Eldada, "Compact wide-band polymer wavelength-division multiplexers," *IEEE Photon. Technol. Lett.*, vol. 12, no. 8, pp. 1010–1012, Aug. 2000.

[3] J. Ballato, S. Foulger, and D. W. Smith, "Optical properties of perfluorocyclobutyl polymers," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 20, no. 9, pp. 1838–1843, 2003.

[4] B. Spraul, S. Suresh, S. Glassar, S. Perahia, and D. W. Smith Jr., "Perfluorocyclobutyl linked hexabenzocoronene networks," *J. Amer. Chem. Soc.*, vol. 126, pp. 12772–12773, 2004.

[5] D. Dai, S. Liu, S. He, and Q. Zhou, "Optimal design of an MMI coupler for broadening the spectral response of an AWG demultiplexer," *J. Lightw. Technol.*, vol. 20, no. 11, pp. 1957–1961, Nov. 2002.

[6] *Generic Requirements for FIBER Optic Branching Components Performance Criteria*, 1998. Telecordia standard (Bellcore) GR1209-Core, 4–12.