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Ultracompact AWG Using Air-Trench Bends With Perfluorocyclobutyl Polymer Waveguides

Yongbin Lin, Nazli Rahmanian, Seunghyun Kim, Gregory P. Nordin, *Member, IEEE*, Chris Topping, Dennis W. Smith, Jr., and John Ballato

Abstract—Using air-trench bends, an ultracompact 8×8 arrayed waveguide grating (AWG) demultiplexer (200-GHz channel spacing) for wavelength-division multiplexing (WDM) has been designed and fabricated with perfluorocyclobutyl (PFCB) core and clad co-polymers on a polyimide substrate. Compared to a conventional AWG in the same material system, the air-trench bend AWG shrinks the required chip area by a factor of 20. The decreased size is a factor in reducing the measured thermal shift to -0.012 nm/°C and decreasing the polarization-dependent wavelength shift to 1.3 nm.

Index Terms—Optical filters, optical planar waveguide components, waveguide arrays, waveguide bends.

I. INTRODUCTION

ARRAYED-WAVEGUIDE gratings (AWGs) [1] are key enabling components for high-capacity fiber communication systems based on wavelength-division multiplexing (WDM). Conventional AWGs implemented in low index and low index contrast (LILIC) waveguide material systems (core-clad refractive index contrast $\Delta n/n \leq 1.5\%$) rely on curved waveguide bends to achieve waveguide path length differences in the arrayed waveguides. The minimum radius of curvature for LILIC waveguides is at least several millimeters to achieve high optical throughput [2], which fundamentally limits how small such AWGs can be made. The relatively large size of conventional AWG devices not only increases the device manufacturing cost, but also affects AWG device performance. For example, the amount of phase error caused by refractive index fluctuations in the waveguides is directly related to the

length of the waveguides. Likewise, the amount of thermal wavelength shift and polarization-dependent shift also increase with larger optical path lengths. Hence, dramatic reduction in AWG size is not only beneficial from an economic point of view, but can also yield improvements in performance.

There are basically two approaches that have been reported to reduce AWG size in low refractive index material systems such as silica and various polymers. One is to increase the refractive index contrast from 0.75% to 1.5% or even higher. This leads to limited device dimension reduction while posing the challenge of higher loss for fiber-to-chip coupling. An example of this approach is a compact AWG based on silica-on-silicon (SOS) reported by Mizuno *et al.* [3]. In their work, a 16-channel AWG was fabricated with SOS waveguides having a refractive index contrast of 1.5% and with integrated spot-size converters to reduce the coupling loss from fiber to chip. The reported device measured 16×16 mm². The limitation of this approach is that it is based on curved waveguide bends, which make it difficult to further reduce device size because of limitations on how much the refractive index contrast can be increased. A second approach is to use abrupt waveguide bends such as corner mirrors or air-trench bends to reduce or eliminate the need for large radius bends. An example is the ultrasmall arrowhead silica AWG with V-shaped bends in the arrayed waveguides reported by Suzuki and Tsuda [4]. V-shaped bends are realized with an elliptic silver mirror along with curved waveguide bends. By using the v-shape waveguide bend, the authors greatly reduce the length of the curved waveguide bends in the arrayed waveguide region, thus dramatically reducing device dimensions. However, the input and output waveguide sections still rely on curved waveguide bends which limits the possible overall size reduction.

In this paper, we demonstrate an ultracompact AWG that totally avoids curved waveguide bends by using 45° air-trench bends in both the arrayed waveguide and input/output waveguide regions. We implement an 8×8 AWG in a perfluorocyclobutyl (PFCB) polymer (Tetramer Technologies, Pendleton, SC) waveguide material system [5]–[7] with a 1.3% refractive index contrast on polyimide substrates. The chip area for our air-trench bend PFCB AWG is 8.4 mm $\times$ 1.5 mm, which is only 1/20 the size of a comparable AWG using curved waveguides in the same material system. To the best of our knowledge, this is the smallest 8×8 AWG device that has been reported for LILIC material systems.

While the results reported in this paper are demonstrated in a PFCB waveguide material system, similar results should be obtainable in other LILIC materials such as silica. PFCB was

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Fig. 1. Three-dimensional schematic illustration of an air-trench 45° bend [17], [18].

chosen because of its unique combination of low loss in the near infrared and its processability, and because it has been shown to offer a wide range of optical functionalities including doping with rare earth [8], inorganic nanoparticle [9]–[11], organic chromophore [12], and quantum dot light emitters [13], nonlinear chromophores [14], and liquid crystalline moieties [15]. This diversity of optical functionalities in one host is useful for the development of other active and passive devices. Nonetheless, the success of our approach to reduce AWG size through use of air trench bends depends only on the ability to etch smooth, highly vertical interfaces that are precisely positioned with respect to each waveguide bend intersection. A key advantage of using air-trench bends is that the waveguide bend structure is independent of both the refractive index and the refractive index contrast between the core and clad materials since it is based on total internal reflection (TIR). Hence, it may be used even for very low refractive index contrast waveguides (such as 0.5% or 0.75%) in silica or other polymers as long as the requisite TIR interfaces can be etched and properly positioned.

II. WAVEGUIDE AIR-TRENCH BENDS AND AWG

A schematic diagram of an air-trench 45° waveguide bend is shown in Fig. 1. It consists of input and output single-mode waveguides embedded in a cladding, and an air-trench that has a vertical sidewall positioned near the intersection of the center lines of the input and output waveguides. For our PFCB waveguides the cross-sectional dimension of the core is $3.6\ \mu\text{m} \times 3.6\ \mu\text{m}$ to ensure single-mode propagation at a wavelength of 1550 nm. The core refractive index is 1.4836 for TE polarization (electric field in the plane of the substrate) and 1.4816 for TM polarization (electric field out of the plane of the substrate). The cladding refractive indexes for TE and TM polarization are 1.4644 and 1.4625, respectively. The core and clad are comprised of the same PFCB copolymers but in different proportions.

We have done extensive design, analysis and characterization of air-trench bends for low refractive index waveguide material systems [16] and have demonstrated high efficiency 45° air-trench bends in PFCB waveguides on silicon substrates [17], [18]. The measured bend optical efficiency for TE and TM po-

Fig. 2. Layouts for a conventional AWG and an air-trench bend AWG for PFCB waveguides with a refractive index contrast of 1.3%.

larization is 97.2% and 96.2% [bend loss of 0.124 (TE) and 0.166 (TM) dB/bend] [18], respectively. This compares favorably with three-dimensional finite-difference time-domain (3D-FDTD) simulation predictions of 98.5% (TE) and 98.0% (TM) when the Goos–Hanchen shift is properly accounted for [18]. The key factors in obtaining such high measured efficiencies are 1) properly designed bends (the bend angle must be selected to insure that all of the angular spectrum components of the waveguide mode undergo TIR as discussed in [16]), 2) vertical and smooth etched sidewalls, and 3) very accurate positioning (typically within 100 nm) of the etched interface. As discussed in [17] and [18], we have developed fabrication processes to achieve these criteria for PFCB waveguides based on inductively coupled plasma reactive ion etching (ICP RIE) and electron beam lithography (EBL) in a scanning electron microscope (SEM).

A schematic layout of our ultracompact AWG using air-trench bends is shown in Fig. 2 at the same scale with one for a conventional AWG designed for the same materials and design parameters. As illustrated in Fig. 3, the footprint of our ultracompact AWG is minimized by applying air-trench bends to the input and output waveguides as well as the arrayed waveguide region, thus totally avoiding large radius curved waveguide bends. The size of the air-trench bend AWG is $8.4\ \text{mm} \times 1.5\ \text{mm}$, which is 1/20 that of the conventional design.

Our 8×8 air-trench bend AWG is designed to have a channel spacing of 200 GHz (1.6 nm). The path length difference between adjacent waveguides in the arrayed waveguide region is $110\ \lambda$, which results in a free spectral range (FSR) of 1741.33 GHz (14 nm). The optical path length difference between neighboring waveguides (ΔL) is achieved by carefully adjusting the spacing of the waveguides and the positioning of the bends. The size of the air trenches in this experiment is $50\ \mu\text{m} \times 8\ \mu\text{m}$. Due to the size of the air trenches and the waveguide mode profile, the minimum waveguide spacing is set to $35\ \mu\text{m}$ in order to avoid clipping the waveguide mode with the corner of an adjacent air trench. The parameters of the air-trench bend AWG are given in Table I. The input and output waveguides are indexed from top to bottom with waveguides 1 and 8 labeled in Fig. 3.

III. FABRICATION

We have fabricated air-trench bend AWGs in PFCB on polyimide substrates (OptiCOMP Networks, Cambridge, MA). The

Fig. 3. Air-trench bend AWG. Light enters an input waveguide on the bottom left of the figure and exits through the output waveguides on the bottom right of the figure. The zoomed-in region shows the air trench locations for some of the arrayed waveguides.

TABLE I
DESIGN PARAMETERS FOR AIR-TRENCH BEND AWG

Symbol	Parameter	Value
L_f	Focal length	5213.992 μm
λ_o	Center wavelength	1550 nm
n_c	Array channel index	1.4836
n_s	Slab refractive index	1.4836
n_g	Group index for n_c	1.4991
x	Output waveguide spacing	25 μm
d	Grating waveguide spacing	25 μm
ΔL	Path-length difference	114.923 μm
m	Diffraction order	110
$\Delta \lambda$	Wavelength spacing	1.6 nm
$\Delta \nu$	Frequency spacing	200 GHz
FSR	Free spectral range	1741.33 GHz
N out	Total output channel	8 Channels
N array	Total phase-delay waveguides	18 waveguides

fabrication process is adapted from the one reported in [18] for PFCB waveguide air-trench bends on silicon wafers. The reason we choose polyimide instead of silicon as the substrate is that the PFCB on top of silicon often develops cracks in the PFCB film stack during fabrication steps that take place on top of the full

TABLE II
PHYSICAL PROPERTIES OF PFCB, SILICON AND POLYIMIDE

	CTE (ppm/C)	Thermal conductivity (W/m*K)
PFCB	60	
Silicon substrate	2.4 - 4.2	~ 150
Polyimide substrate	56	~ 0.2

(a)

(b)

(c)

Fig. 4. (a) Microscope image showing typical cracking for PFCB film stack on silicon. (b) Worst case cracking problem which can occur during spin coating ZEP 520 A. (c) Comparable result for PFCB on polyimide wafers in which cracking is totally avoided.

film stack. Film cracking is normally not a problem when processing the core layer to form single mode waveguides and multimode interference (MMI) slab regions. However, as discussed in [19], fabrication processes that occur on top of the complete film stack (i.e., after the overclad has been applied on top of the waveguides that have been etched in the core layer) often end up promoting the development of cracks owing to stress in the film stack. As pointed out in [19], this stress forms during thermal curing of the PFCB layers because of the coefficient of thermal expansion mismatch between PFCB and silicon. As shown in Table II, the polyimide substrate has a coefficient of thermal expansion (CTE) close to that of PFCB, which greatly diminishes the formation film stress during the curing process.

To illustrate this point, consider the microscope images in Fig. 4. As discussed in [18], the fabrication process for EBL-based air-trench bends has many fabrication steps since the EBL is done in an SEM, which requires separate EBL alignment marks for each write field. We have found that a PFCB film stack on a silicon substrate is likely to exhibit cracking during

Fig. 5. Etch result for air trenches in PFCB on a polyimide substrate using the step by step etch process discussed in the text.

wet chemical processes such as metal lift-off and electron beam resist spin coating and developing. For example, Fig. 4(a) shows a microscope image of a set of PFCB waveguides on a silicon substrate in which each waveguide has a different number of bends. The dark oval regions are where the EBL alignment marks are located. Typical stress-induced cracking is visible around the oval regions. Fig. 4(b) shows worst case cracking after spin coating an electron beam resist (ZEP 520A). As shown in Fig. 4(c) for the same fabrication process on top of a polyimide wafer, no cracking is present. By using polyimide substrates, the repeatability and yield of the fabrication process is dramatically improved from about 10% to higher than 80% in our university cleanroom facilities.

However, use of polyimide substrates has a serious drawback compared to silicon. As indicated in Table II, polyimide has a much lower thermal conductivity than silicon. This results in slower heat removal from the PFCB film during anisotropic ICP RIE etching to form the air trenches, thus raising the PFCB temperature. This in turn increases the rate of the random (isotropic) component of the etch and results in more etch undercut, sidewall roughness, and sidewall tilt. To help reduce PFCB heating during the anisotropic plasma etch process, we used an heuristic approach to develop a step-by-step etch recipe in which the 21-min etch is divided into 21 one-minute etch steps, separated by 1.5 min of gas flow with no plasma in the chamber to permit cooling of the sample. A typical etch result for PFCB air trenches on polyimide substrates using this

step-by-step etch process is shown in Fig. 5. There is more sidewall roughness compared to PFCB air trenches on silicon substrates (see, for example, [18, Fig. 9]). The effect on optical bend loss is shown in Fig. 6 in which the measured bend loss is 0.31 ± 0.02 dB/bend (93% bend optical efficiency) for TE polarization, which is about a factor of two higher than the measured loss for bends on silicon (0.124 dB). Nonetheless, the only effect of this larger bend loss is an increased device insertion loss. As shown in Fig. 7, the spectral response for PFCB air-trench bends on polyimide still has excellent uniformity across a 100-nm wavelength range (1480 to 1580 nm).

We use the step-by-step etch process to fabricate the air trench bends in our AWG devices. Fig. 8(a) shows fabricated arrayed waveguide gratings after the deep air trench etch, and Fig. 8(b) shows the area of fabricated input/output waveguides near the slab waveguide region. Note in Fig. 8(a) that the left- and right-most sets of bends in the arrayed waveguide section have bending angles slightly different from 45° since the waveguides from the MMI slab regions emerge at slightly different angles. The bend angles vary from 42.66° to 47.34° . Fig. 9 shows an SEM image of etched air trenches in the arrayed waveguide section. Note that the size of the trenches has been reduced from $70 \mu\text{m} \times 20 \mu\text{m}$ as in Fig. 5 to $50 \mu\text{m} \times 10 \mu\text{m}$ to facilitate closer packing of the waveguides. The sidewall roughness, however, is similar.

Note in Figs. 3 and 8(a) that there are only 18 arrayed waveguides connecting the slab waveguide regions, which is

Fig. 6. Measured optical power through a set of equal-length PFCB waveguides on polyimide that have a different number of bends in each waveguide. Details on the measurement method can be found in [9] and [10].

Fig. 7. Spectral response of PFCB waveguide air-trench 45° bends shows excellent uniformity across a 100-nm wavelength range.

less than the number of arrayed waveguides in a typical 8×8 AWG design (usually > 50). The small number of arrayed waveguides affects device performance such as insertion loss and channel cross talk. The number of arrayed waveguides in fabricated AWGs is limited by our particular EBL-based fabrication process in which a maximum alignment field size of $1\,000\,\mu\text{m} \times 1\,000\,\mu\text{m}$ is used. Because of the corner area required for the alignment marks and other limitations of our fabrication process, the actual useful field is approximately $760\,\mu\text{m} \times 760\,\mu\text{m}$. Only 18 waveguides can be placed in this area if a minimum waveguide spacing of $35\,\mu\text{m}$ is maintained. This limitation can be easily removed if the air trench bend patterning step is done in a modern optical stepper, which has an alignment accuracy consistent with what can be achieved in our low-end SEM-based EBL.

IV. MEASUREMENT AND DISCUSSION

Characterization of air-trench bend AWG performance is done in a Newport PM500 Autoalign System with an Agilent 8164A tunable laser (1480–1580-nm tuning range) as the optical source. Light from the laser is coupled into a polarization maintaining (PM) fiber that is butt coupled to one of the AWG input waveguides. The end of the fiber nearest to the sample is rotated to control the polarization state of the light coupled into a waveguide. Light from one of the eight output waveguides is butt coupled to a single mode fiber which is connected to an optical power meter. Two computer-controlled precision 3 axis motion stage stacks with 50-nm accuracy are used to optimize the input and output fiber positions to maximize the power through each waveguide.

Fig. 8. AWG microscope images. (a) Fabricated arrayed waveguide gratings after the deep air-trench etch (i.e., the waveguides above the two MMI slab waveguide regions in Fig. 3 and which connect the two MMIs). (b) Input waveguides (left) for the left MMI slab region and output waveguides (right) for the right MMI slab region. Note: the dark oval regions are where the EBL alignment marks are located.

A typical transmission spectrum for a fabricated air-trench bend AWG is shown in Fig. 10 for TE polarization. The input waveguide used in this measurement is one of the center waveguides (waveguide 4). The measured channel spacing is 1.6 nm, and the channel width is 0.65 nm at -3 dB.

A. Insertion Loss

The insertion loss, including on-chip loss and coupling loss between fibers and waveguides, is in the range of 16.2–19.3 dB for all eight output waveguides. This loss can be attributed to several sources. First, the total fiber-to-chip coupling loss is typically 3.2–3.6 dB in our measurement setup without using refractive index-matching fluid. Second, we estimate that the waveguide propagation loss is ~ 0.7 dB based on the typical 0.4-dB/cm waveguide propagation loss measured in our labs for straight waveguides and the roughly 1.6-cm-long on-chip propagation length (including the MMI slab regions). Third, each waveguide bend introduces some loss. There are eight air-trench bends in each optical path. Based on an average of 0.35-dB/bend loss, the loss from the air-trench bends for each optical output is ~ 2.8 dB.

Finally, there is additional loss due to the MMI regions. In order to measure the loss for the MMI slab waveguides, individual MMIs with eight input waveguides and 18 output waveguides are fabricated. A single PM fiber with TE polarized light is butt-coupled to a center input waveguide (waveguide 4), and the light emitted from all 18 waveguides is measured. The total power from these waveguides is 20% of the input power, which

represents a 7-dB loss. Subtracting 3.2 dB to account for the total fiber to waveguide coupling losses, we estimate the excess loss for the MMI slab waveguides to be 3.8 dB. As is well known, use of more arrayed waveguides can significantly decrease this loss.

The total loss from the above contributions is 14.5 dB. This leaves 1.7 to 4.8 dB unaccounted for. We believe that this is due to fabrication defects in the waveguides of the AWG sample used for the measurements presented in this paper.

B. Channel Crosstalk

The adjacent channel crosstalk is ≤ -7 dB. The channel crosstalk is relatively high and is primarily due to two factors. One is the asymmetric sidelobes in the AWG spectrum and the other is the fact that there are only 18 waveguides in the arrayed waveguide section. Fig. 11 shows a typical spectral response for one of the output waveguides. The asymmetric sidelobes in the spectrum is likely caused by a nonlinear phase error related to the Goos–Hanchen shift for the different bend angles in the arrayed waveguide section. As mentioned in Section II, some of the bends in the arrayed waveguide section have bend angles slightly different from 45° . In our initial design and fabrication of AWG samples, we offset the position of all of the bends by the same amount to account for Goos–Hanchen shift. However, this shift should be slightly different depending on the bend angle. We believe that taking this into account in fabricated samples will lead to reduced sidelobe asymmetry and hence lower channel crosstalk.

C. Thermal Stability

The spectral response at different temperatures is measured in order to evaluate the thermal stability of air-trench bend AWGs. Fig. 12 shows the measured transmission spectrum of a center output channel (channel 4) at room temperature (21.5°C) and at a higher temperature (63.2°C). Over this temperature range the temperature-dependent wavelength shift is -0.012 nm/ $^\circ\text{C}$. This value is much smaller than the thermal shift of the spectral response of conventional AWG devices made with PFCB waveguides on a silicon substrate which is typically -0.25 nm/ $^\circ\text{C}$ [20], and is comparable to that of silica based conventional AWGs (-0.012 nm/ $^\circ\text{C}$) [21]. This is primarily due to two reasons. As discussed in [22], the first is that use of a substrate with a higher CTE such as polyimide can reduce the thermal wavelength shift of the AWG. The thermal wavelength shift for a conventional AWG with a substrate CTE α_{sub} can be predicted by [22]

$$d\lambda_0/dT = (dn_c/dT + n_c\alpha_{\text{sub}}) \times (\lambda_0/n_c)$$

where λ_0 represents the central wavelength, and n_c is the effective refractive index of the waveguide. Based on the PFCB copolymers used in this experiment with $dn_c/dT = -1.4 \times 10^{-4}/\text{K}$ and α_{sub} for polyimide as given in Table II, the calculated thermal wavelength shift is -0.059 nm/ $^\circ\text{C}$, which is significantly larger than the measured shift for our air trench bend AWG. This leads to the second reason for the small shift, which is the shorter path length in the arrayed waveguides of the

Fig. 9. Etched PFCB air trenches in the arrayed waveguide section.

Fig. 10. Typical transmission spectrum of an 8×8 PFCB air-trench bend AWG. The mainlobes are labeled for each output waveguide. The line style for Output 5 is bold to permit the sidelobe pattern, which is typical for all of the outputs, to be observed. Noted that the main crosstalk tends to arise from adjacent channel sidelobes.

air-trench bend AWG such that the thermo-optical effect [which in a single waveguide is proportional to $\Delta n(T) * (\text{pathlength})$] does not change as much as in a conventional AWG that has much longer path lengths in the arrayed waveguides. Hence, the optical path difference between waveguides in the arrayed waveguide region has less dependence on temperature and there is correspondingly less wavelength shift. As a final comment, note in Fig. 12 that the insertion loss increases when the temperature is raised. This is largely owing to thermally dependent misalignment in the fiber butt coupling.

The temperature-dependence measurement result reveals an important advantage of air-trench bend AWGs in that the device thermal shift is significantly reduced by shrinking the device dimensions. This lowers the environmental requirements for device operation, such as precise temperature control and effectively decreases the device packaging cost, which is the major part of the final device cost. As mentioned before, the results reported in this paper should be obtainable in other low index and low index contrast (LILIC) material systems, such as silica.

Fig. 11. Typical spectral response for a single AWG output waveguide.

Fig. 12. Measured transmission spectrum of a center channel at room temperature (21.5 °C) and at a higher temperature (63.2 °C).

D. Polarization Dependence

As shown in Fig. 13, the measured polarization-dependent wavelength shift is 1.3 nm. This value is related to the PFCB film birefringence ($n_{TE} - n_{TM} = 2.0 \times 10^{-3}$). For a conventional AWG, we can expect a polarization-dependent wavelength shift of 2.1 nm based on [23]

$$\Delta\lambda = \frac{\Delta n \Delta L}{m}$$

where Δn is the material birefringence, $m = 110$ is the diffraction order, and $\Delta L = 114.923 \mu\text{m}$ is the path difference of the arrayed waveguides. The measured polarization-dependent wavelength shift for the air-trench bend AWG is smaller than that of conventional AWG made with the same materials. This is again partially due to the shorter paths in the arrayed waveguides of the air-trench bend AWG.

V. CONCLUSION

An ultracompact AWG for wavelength division multiplexing using air-trench 45° bends has been demonstrated with PFCB waveguides on a polyimide wafer. Air-trench 45° bends are used in both the arrayed waveguide region and the input/output

Fig. 13. Measured polarization-dependent wavelength shift.

waveguide region to totally avoid curved waveguide bends to realize the smallest possible AWG device. The chip area for an air-trench bend AWG occupies only 1/20 of the conventional type. The wavelength thermal shift of the AWG device has been significantly reduced by shrinking the device dimensions.

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