Experimental evaluation of curved polymer waveguides with air trenches and offsets

Brie Howley, Xiaolong Wang, and Ray T. Chen[a)]
Microelectronic Research Center, University of Texas at Austin, Austin, Texas 78758

Yihong Chen
Omega Optics, Austin, Texas 78758

(Received 27 September 2005; accepted 19 May 2006; published online 25 July 2006)

Excess waveguide bend loss can be minimized through the use of offsets and air trenches. Offsets, used for reducing the junction loss between straight and curved waveguides, and air trenches, which prevent bend radiation loss, were simulated by a three-dimensional, semivectorial beam propagation method. Low loss polymer waveguide bend structures, employing both offsets and trenches, were fabricated. A reduction of the 180° bend insertion loss from 17.7 to 3.0 dB with a bending radius (BR) of 1.5 mm is experimentally confirmed at $\lambda = 1.55\ \mu$m. BR ranging from 5 to 0.5 mm are evaluated with decent match when compared with simulation results. The polarization dependent loss is BR dependent with a maximum value of 0.4 dB when the BR is reduced to 0.5 mm. The experimental results confirm that the joint use of air trenches and junction offsets is effective in reducing the bend radii of low index contrast polymer waveguides in planar lightwave circuits.
 [DOI: 10.1063/1.2218038]

I. INTRODUCTION

Planar lightwave circuit (PLC) technology has become a standard method for fabricating passive and active optical components such as arrayed waveguide gratings,[1] delay lines,[2] and optical switches.[3] Several material systems have been used to produce PLCs including silicon on insulator (SOI), silica, and polymers.[4] High index contrast (large Δn, where Δn is defined as the difference between the indices of refraction of the core and cladding) waveguide material systems such as SOI have the drawback of greater coupling losses to optical fiber due to numerical aperture (NA) and mode size mismatch. Additionally, high index contrast systems exhibit larger scattering loss than low index contrast systems for an equal waveguide sidewall roughness formed during the dry etch process. The propagation loss of waveguides formed from the Si/SiO_2 material system has been reported to be proportional to the third power of the sidewall roughness.[5]

Low index contrast systems such as polymers and SiO_2 can provide lower propagation losses and low fiber to waveguide coupling losses due to the small difference of refractive index between the core and cladding which leads to similar boundary conditions between the waveguide and fiber. In comparison with the silicon dioxide material system, polymer waveguides are easy to fabricate on almost any substrate. Spin-on polymer waveguide fabrication processes open the possibility of monolithic integration with active PLC components such as lasers, modulators, and detectors.[6,7] The high temperatures required to grow SiO_2 waveguide materials could potentially alter the device performance of active devices present on a substrate. Polymer waveguides can be formed at room temperature so that active devices' thermal budgets are not affected.

A major drawback of any low index contrast system for a PLC application is the large footprint attributable to the requirement of large waveguide bend radius for low loss.[8] Polymers have the advantage of a widely tunable refractive index,[4] but this still leaves a compromise between coupling loss and bend loss. The large bend radius requirement for low index contrast systems is not practical for devices requiring large scale integration such as optical delay lines[2] and is detrimental to the device yield.

Air trenches have been proposed to reduce the radii by increasing the index contrast of a curved waveguide segment.[9–12] By increasing the index contrast within the waveguide bend region, the mode is tightly confined in order to prevent bend radiation losses while the propagation losses are not significantly affected. Another modification to the waveguide design used to decrease bending losses is the offset. Waveguide offsets shift straight waveguide segments laterally with respect to curved waveguides in order to decrease the mode mismatch.[13,14] This in turn minimizes the junction loss between the curved and linear waveguide segments.

Despite comprehensive theoretical and simulated results of trench and offset structures, there have been no experimental data to validate the simulated offset and trench results in fabricated devices. Additionally, trench and offset structures have never been investigated for use with a polymer waveguide. In this paper an experimental comparison is reported between fabricated polymer waveguides and simulation results to determine the usefulness of trench and offset structures for polymer PLCs. A general explanation of the waveguide trench and offset is presented in Sec. II. Section III describes the design of the trench and offset structures for

[a)]Electronic mail: chen@ece.utexas.edu

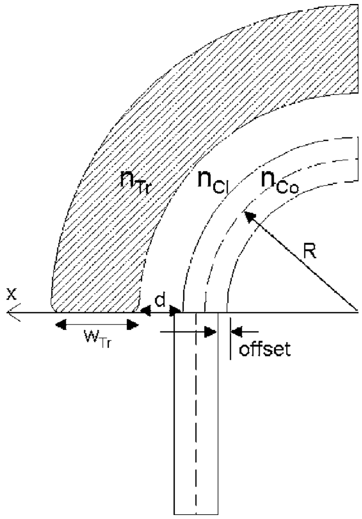

FIG. 1. A diagram of the waveguide core using offset and trench (hatched area) structures.

fabrication, and Sec. IV presents a comparison between experimental and simulated results followed by the concluding remarks.

II. TRENCH AND OFFSET BACKGROUND

A. Trench

Although an asymmetric index distribution is an effective mean for reducing bend loss,[15] it is difficult to fabricate a cladding with multiple refractive index values in only a curved section. A curved waveguide with an air trench structure is a relatively simple way to confine the mode through the bend. Yamauchi *et al.*[16] describe the configuration parameters of a trench and waveguide bend and explain the expected effects with the use of an equivalent index transformation. Figure 1 illustrates a top view of a step index channel waveguide junction between straight and curved waveguide segments. The structure utilizes both a trench, which is assumed to be filled with air ($n_{tr}=1$), and an offset. The core and cladding indices are n_{co} and n_{cl}, respectively, and the waveguide has a bend radius R. The width of the trench w_{tr} and the separation between the inside radius of the trench and the outside radius of the waveguide core, d, are also labeled. By placing the air trench sufficiently close to the waveguide core (reducing d), the evanescence tail is reduced and a decreased bend loss should be observed.

B. Offsets

In a straight channel waveguide ($R=\infty$), the electric field intensity pattern of the fundamental mode is symmetric about the center of the waveguide core, Fig. 2(a). In contrast, the fundamental mode in a curved waveguide, with the same core cross section, has the field peak displaced laterally towards the outside of the bend, and the mode is asymmetric with a width different from that of the straight waveguide, Fig. 2(b). Because the mode fields are mismatched, transition losses will occur at the junction of two waveguides with different radii, causing a reduction in the power transfer between the two waveguides. A lateral offset at the junction of the two waveguides may be used to reduce the mode mismatch. To a first approximation, it can be concluded that the loss between waveguide segments of different radii will be minimized when they are offset to make their field peaks coincide.[17]

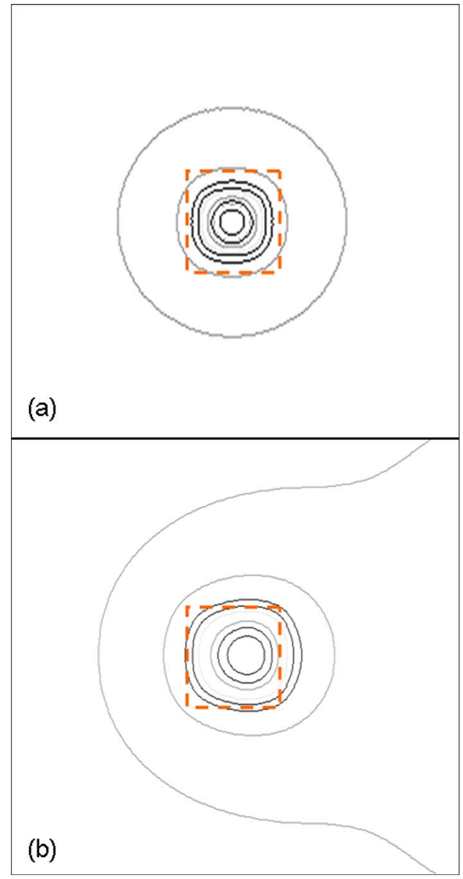

FIG. 2. (Color online) Mode profile of a 6×6 μm^2 channel waveguide that is straight (a) and with a radius of $R=3$ mm (b). The outline of the waveguide core is superimposed on the mode intensity contours. $n_{co}=1.46$, $n_{cl}=1.45$, and $\lambda=1.55$ μm.

Subramaniam *et al.*[17] have compared experimentally measured loss values of offset rib waveguides to simulation results. However, to date there has not been any comparison between simulations and fabricated waveguides utilizing trenches with offsets. The following section will provide an overview of the design of these trench and offset structures which is followed by a comparison of the simulation results to fabricated structures.

III. DESIGN OF TRENCH AND OFFSETS FOR FABRICATION

A. Trenches

In order to properly design the waveguide, trench, and offset structures to work with our polymer material system, we simulated the performance characteristics using a three-dimensional, semivectorial beam propagation method (BPM). All simulations were based on core and cladding materials with refractive indices of 1.46 and 1.45, respec-

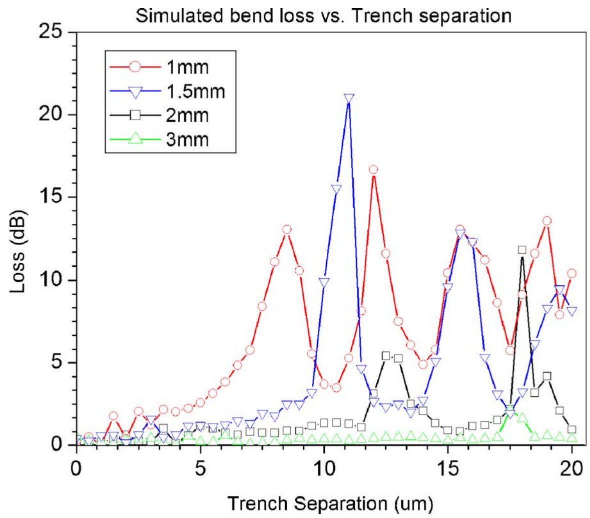

FIG. 3. (Color online) Simulated 180° bend loss as a function of the trench separation of four waveguide bend radii. Waveguide core is $6\times 6\ \mu\text{m}^2$, $n_{co}=1.46$, $n_{cl}=1.45$, $n_{tr}=1$, $\lambda=1.55\ \mu\text{m}$, and TE polarization.

tively, and that the core was $6\times 6\ \mu\text{m}^2$ square in order to maintain single mode behavior at the wavelength of $1.55\ \mu\text{m}$.

The first group of parameters determined was the trench width (w_{tr}) and the separation distance (d) between the air trench and waveguide core. The trench width should be at least 1–1.5 times as large as the core width to prevent the evanescent tail from spanning the trench.[9] A wider trench also keeps the height to width aspect ratio low to maintain vertical sidewalls during the etching process. However, an excessively wide trench may interfere with compact placement of other PLC structures. A trench width of $20\ \mu\text{m}$ was chosen to maintain an aspect ratio of 1.

Figure 3 shows the simulated bend loss as a function of the separation distance between the waveguide core and the air trench for 180° bending radii of 1, 1.5, 2, and 3 mm.

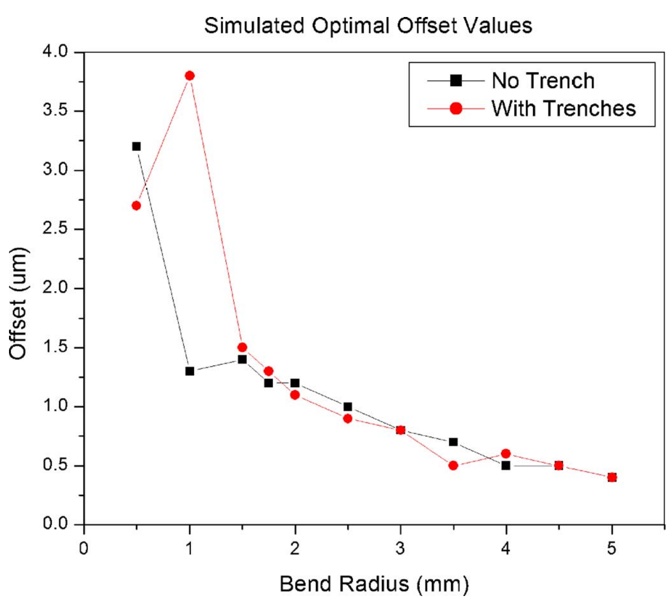

FIG. 4. (Color online) Simulated optimal offset values for $6\times 6\ \mu\text{m}^2$ waveguides with and without trench structures. $d=7\ \mu\text{m}$, $n_{co}=1.46$, $n_{cl}=1.45$, $n_{tr}=1$, $w_{tr}=20\ \mu\text{m}$, $\lambda=1.55\ \mu\text{m}$, and TE polarization.

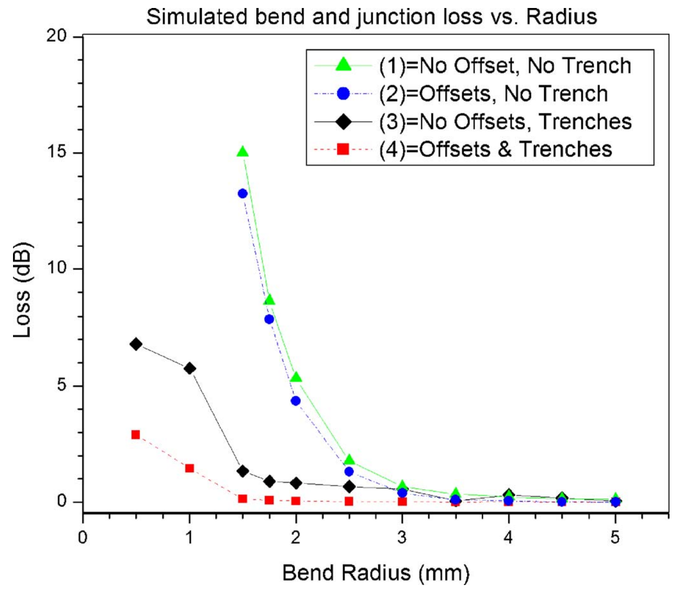

FIG. 5. (Color online) The BPM simulated bend and junction loss for a 180° bend as a function of waveguide bend radius for cases (1)–(4). The waveguide dimensions are $6\times 6\ \mu\text{m}^2$ and the trench separation is optimized at $7\ \mu\text{m}$ with an operating wavelength of $1.55\ \mu\text{m}$.

Several features are notable from these results. The first is oscillations of the bend loss that occur as the trench separation is increased. This is an expected result, consistent with the work of Yamauchi *et al.*,[16] and is caused by the curved waveguide guided mode coupling to a quasiwaveguide mode in the area between the core and trench, resulting in a peak in the bend loss. As the trench separation increases, higher order quasiwaveguide modes are formed which repeatedly match the propagation constant of the curved waveguide guided mode, resulting in oscillations of the bend loss. The second notable feature of Fig. 3 is that as the bend radius increases, the oscillations become smaller and first occur at larger separations. This is due to the index contrast of the waveguides adequately confining the propagating mode at larger bend radii.

In order to suppress these severe oscillations of the bend loss, the trench separation should be kept small, especially for smaller bend radii. However, there was a concern that having the low index trench in close proximity to the core would cause high polarization dependent loss (PDL) through the bend. Typically, structures with high cross-sectional asymmetry along the principal polarization directions exhibit polarization sensitivity.[12] From these considerations, a trench separation of $7\ \mu\text{m}$ for all radii was chosen with the understanding that radii of 1 mm and less would exhibit 5 dB or more bend loss with this separation distance.

B. Offsets

Two-dimensional mode overlap integrals were performed in order to determine the optimum offset distance and junction loss between straight and curved waveguide sections for each waveguide bend radius. Figure 4 shows the simulated optimal offset values for bends with and without trenches. The extreme variability of the simulated offset val-

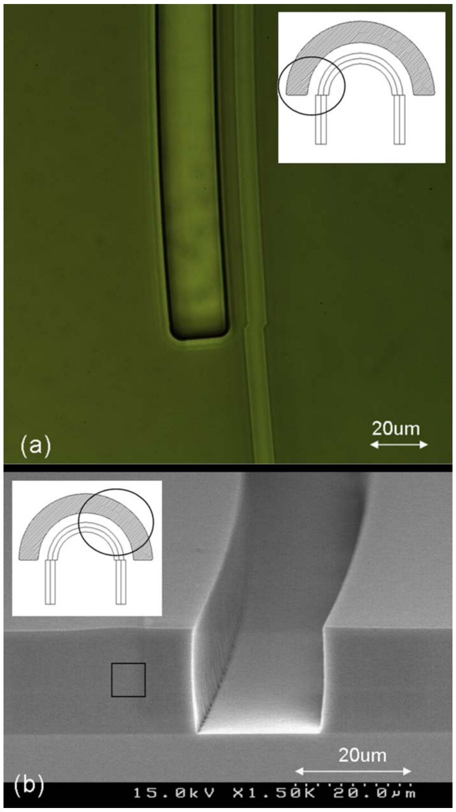

FIG. 6. (Color online) (a). Top view of a waveguide junction employing both a trench and an offset. (b). SEM cross-sectional image of the trench structure. Approximate location of the waveguide core is indicated by the square to the left of the trench.

ues at small bend radii is contributed to the straight input/output waveguides trying to couple to the waveguide radiation mode of the bend.

C. Bend loss

Simulations were performed to evaluate the bend and junction loss versus bend radius of four different cases: (1) standard bends employing neither offsets nor trenches, (2) waveguide junctions employing optimal offsets, (3) waveguides with trench structures, and (4) both optimal offsets and trenches. The 180° bends were simulated with a BPM equivalent index transformation in order to avoid paraxial effects. This method has been shown to be accurate for bends with radii much larger than the core width dimension.[13] Figure 5 shows the results of these simulations. For case (1), there is an exponential increase in the bend loss as the radius decreases, as would be expected for any dielectric waveguide.[8] For case (2), the curve shifts down because the offsets decrease the loss of the two straight to curved waveguide junctions. The simulated reduction in loss for this case, in comparison with case (1), increases as the bend radius decreases. In case (3), there is a noticeable improvement in the loss for bend radii less than 3 mm. Between approximately 1.5 and 3 mm the loss remains flat. However, as expected from Fig. 3, the loss rises sharply with smaller bend radii because of the relatively large trench separation. Finally, due to the use of offsets, case (4) shows an improvement over case (3) for bend radii ranging from

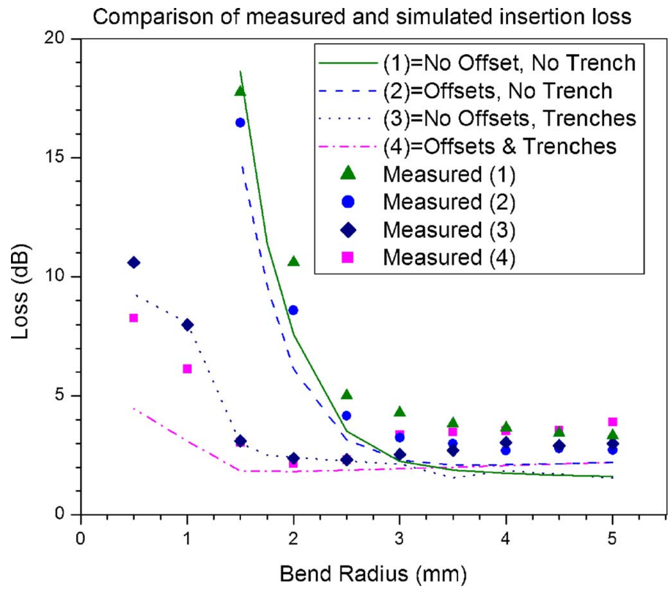

FIG. 7. (Color online) Simulated and measured insertion losses of 180° waveguide bends as a function of the bend radius. Data points are measured values and lines are fitted curves to the simulation data points.

2.5 to 1.5 mm. A 90% transmission value (0.45 dB insertion loss) for a 180° waveguide bend can be used to quantify the performance of the offset and trench features. The 90% transmission value occurs at bend radii of approximately 3.3, 2.9, 3.1, and 1.4 mm for cases (1), (2), (3), and (4), respectively.

IV. EXPERIMENTAL PROCEDURE AND RESULTS

An ultraviolet (UV) curable perfluorinated acrylate material, supplied by ChemOptics Inc., was used to fabricate low loss polymer waveguides. A viscous perfluorinated acrylate cladding layer was spin coated onto a silicon wafer substrate. The layer thickness was controlled by the spin speed. After spinning, the polymer was cured by exposure to an

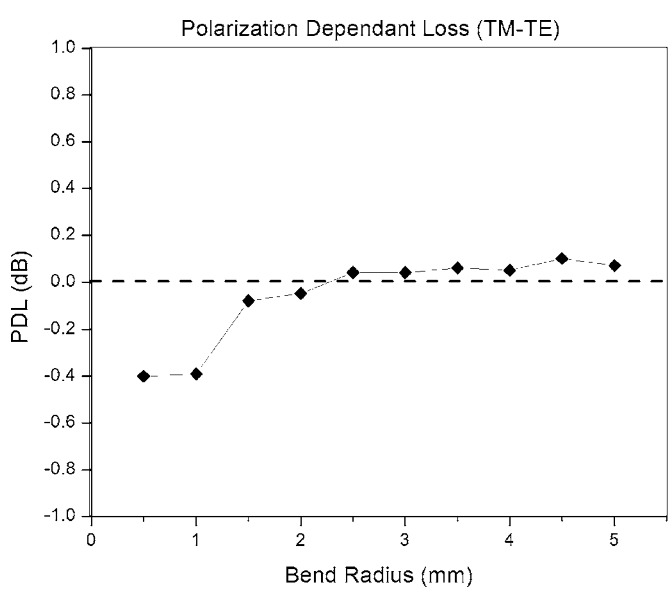

FIG. 8. Measured PDL for waveguide bends employing trenches and offsets.

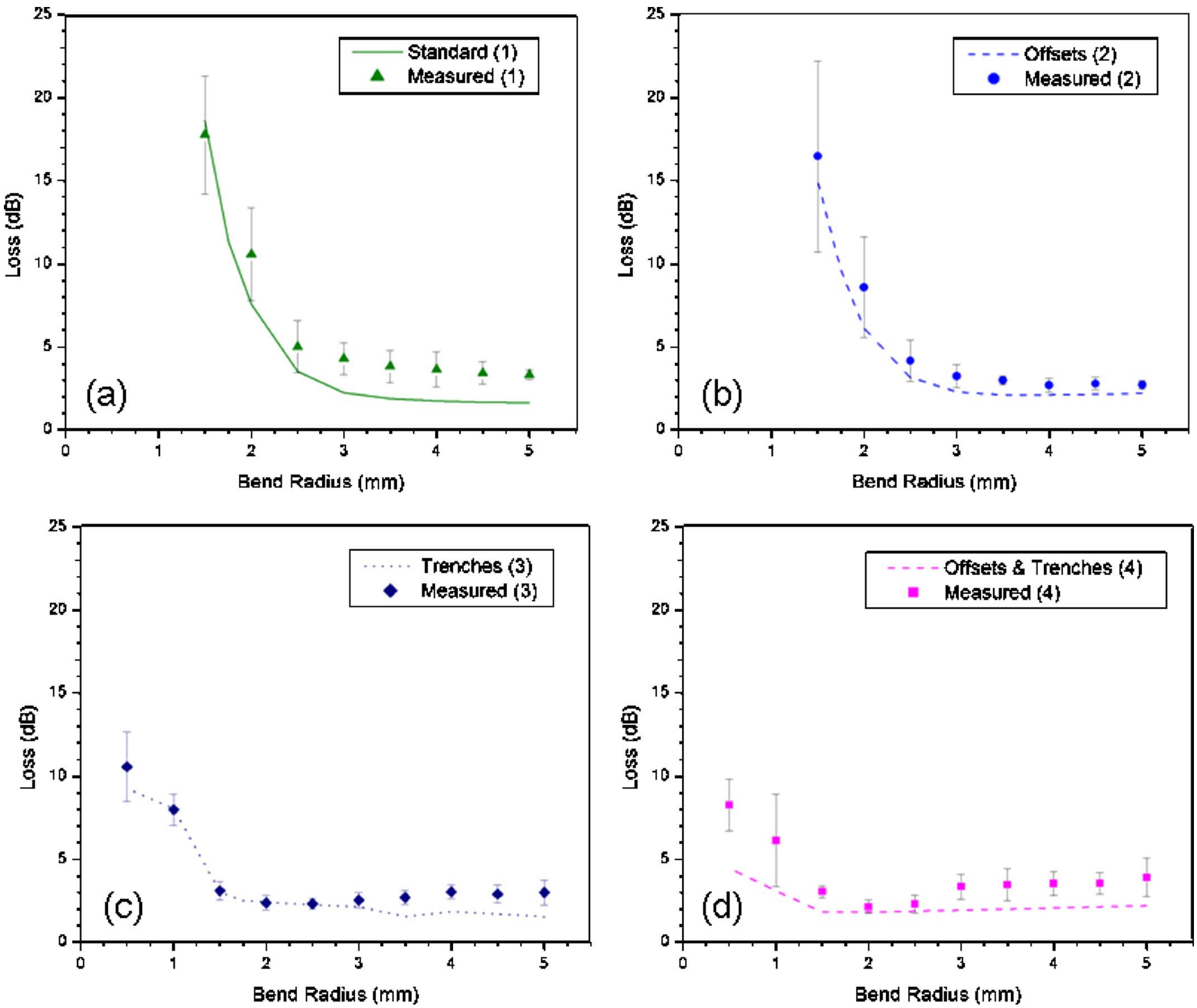

FIG. 9. (Color online) Comparison between measured and simulated insertion loss values for 180° waveguide bends of cases (1)–(4).

intense UV light source for several minutes in a nitrogen environment. A subsequent core layer material was spun and cured in a similar fashion. The refractive indices, measured with a Metricon prism coupler, of the core and cladding materials after curing were 1.460 and 1.450, respectively. A SiO_2 hard mask was deposited with low temperature plasma enhanced chemical vapor deposition (PECVD) and was patterned by AZ5209 photoresist and an *i*-line contact lithography tool. Reactive ion etching (RIE) was used to etch the core material to the bottom cladding layer. The core was intentionally overetched to insure that all core material was removed. The hard mask was then removed and a top cladding material was spun and cured. A second hard mask layer was deposited and patterned in a similar fashion to form the trenches. RIE was used to etch the cladding material in the trenches to the silicon substrate. The channel waveguide cores were 6 μm wide by 6 μm high, and the trench depth was measured by an alpha-step profilometer to be 21 μm deep. Figure 6(a) shows an optical microscope picture of a fabricated waveguide core with offset and trench structures. The trench corners are rounded to prevent the effects of stress in the polymer. Figure 6(b) shows a cross-sectional scanning electron microscope (SEM) image of the trench structure. The location of the waveguide core is outlined by the square on the inside radius of the trench.

Straight single mode waveguides were measured to have a propagation loss of 0.45 dB/cm at the wavelength of 1.55 μm. The coupling loss due to mode size mismatch and reflection loss between the polymer waveguides and a single mode optical fiber were measured to be 0.7±0.1 dB/facet. This is consistent with the coupling loss value of 0.75 dB calculated from a two-dimensional (2D) mode overlap integral simulation and reflection loss calculation.

180° waveguides arcs with 2 mm straight waveguide segments at each end were patterned for measurement of the waveguide bending loss. The 2 mm straight waveguide segments were intended to provide ample length for mode transformation to and from the optical fiber as well as a way to test the performance of the offset structures. A fiber array was used to couple 1.55 μm light into and out of the waveguide bends. Each of the fibers of the fiber array was tested and found to exhibit less than 0.1 dB loss. Insertion loss measurements of the waveguide arcs were performed in order to evaluate the effectiveness of the fabricated trench and offset structures. The measurements were performed on arcs with bend radii ranging from 500 μm to 5 mm in 500 μm increments.

Figure 7 shows the insertion loss measurement results of cases (1)–(4). Each data point is the average of four measured samples. The lines in Fig. 7 represent the calculated insertion loss values based on the simulated bend and junction losses for cases (1)–(4). The calculations were made by adding the waveguide propagation loss ($0.45\ \mathrm{dB\,cm^{-1}}$) and the coupling losses of the input and output single mode fiber array (2×0.70 dB) to the simulated bend and junction loss. The simulated and measured values suggest that for bend radii greater than 3 mm, the use of trenches and offsets has an insignificant effect on the insertion loss. However, for small bend radii of less than 3 mm, trenches improve the bend loss performance significantly. The use of trenches, or the combination of both trenches and offsets, can result in smaller radius bends having less insertion loss than bends with greater radii because of smaller propagation losses. For the polymer waveguides tested, the bend radius can be reduced to approximately 1.5 mm without significant increases in the loss, a 50% bend radius reduction over the standard waveguide bend. The use of offsets with trenches also reduces the bending loss further although not as strongly as would be suggested by simulations.

The PDL (TM-TE) was also measured for each bend radius of the waveguides employing both trenches and offsets. Measurement results are shown in Fig. 8. For bend radii greater than 1 mm, the PDL was positive and less than 0.1 dB. For the 0.5 and 1.0 mm bends, the PDL was −0.39 and −0.40 dB, respectively, with TM polarization exhibiting slightly more loss than TE. The trend for the magnitude of the PDL to increase as the bend radius decreases is due to an increased interaction of the TM mode with the roughness of the trench sidewall.

Figure 9 separates the simulated and measured data into each of the four cases to evaluate the trends more clearly. The error bars of Fig. 9 represent ±1 standard deviation in the measured data. The measured insertion loss values reasonably match the simulated values. However, the measured values have a larger standard deviation at small bend radii. This could be contributed to random RIE induced defects on the sidewalls of the cores and trenches in some samples, which if present cause scattering of light in the bends. This phenomenon would be more prevalent in bends of lesser radii because of higher field intensities near the trench and core sidewalls. It is expected that this effect would become more severe as the trench separation is decreased.

V. CONCLUSION

Polymer channel waveguide samples were fabricated and characterized. Insertion loss measurements of 180° bends revealed the dependence of the bending loss on the bend radius, as predicted with BPM simulations. Simulations and measurements show that bend loss could be slightly reduced with offsets. With bend radii less than 3 mm, air trenches were more effective at reducing the bending loss. However, as the radius is decreased below 1.5 mm, the bend loss increases quickly even when air trenches are used.

It may be possible to maintain low loss and decrease the bend radii further by decreasing the separation between the trench and waveguide core. However, experimental data values show that there is a large variation in the measured insertion loss at small bend radii. This is contributed to random defects induced by the core and trench etching processes which have more of an effect as the bend radius decreases. Additionally, decreasing the trench separation further is expected to increase the PDL of the waveguide bend.

By choosing the correct trench and offset design parameters, the bend radius of low index contrast polymer waveguides can be reduced by 50% or more. This bend radius reduction will improve the design and fabrication of compact, high yield PLCs.

[1] Y. H. Min, M. H. Lee, J. J. Ju, S. K. Park, and J. Y. Do, IEEE J. Sel. Top. Quantum Electron. **7**, 806 (2001).
[2] B. Howley, Y. Chen, X. Wang, Q. Zhou, and R. T. Chen, IEEE Photonics Technol. Lett. **17**, 1944 (2005).
[3] J. Y. Yang, Q. J. Zhou, and R. T. Chen, Appl. Phys. Lett. **81**, 2947 (2002).
[4] L. Eldada, Opt. Eng. (Bellingham) **40**, 1165 (2001).
[5] K. K. Lee, D. R. Lim, L. C. Kimerling, J. Shin, and F. Cerrina, Opt. Lett. **26**, 1888 (2001).
[6] R. T. Chen *et al.*, Proc. IEEE **88**, 780 (2000).
[7] R. T. Chen Opt. Laser Technol. **25**, 347 (1993).
[8] F. Ladouceur and J. D. Love, *Silica-Based Buried Channel Waveguides and Devices* (Chapman and Hall, London, 1996), Chap. 10.
[9] J. Yamauchi, M. Ikegaya, and H. Nakano, Microwave Opt. Technol. Lett. **5**, 251 (1992).
[10] C. Seo and J. C. Chen, J. Lightwave Technol. **14**, 2255 (1996).
[11] M. Rajarajan, S. S. A. Obayya, B. M. A. Rahman, K. T. V. Grattan, and H. A. El-Mikati, Appl. Opt. **39**, 4946 (2000).
[12] M. Popovic, K. Wada, S. Akiyama, H. A. Haus, and J. Michel, J. Lightwave Technol. **20**, 1762 (2002).
[13] L. Lerner, Electron. Lett. **29**, 733 (1993).
[14] T. Kitoh, N. Takato, M. Yasu, and M. Kawachi, J. Lightwave Technol. **13**, 555 (1995).
[15] S. Tomljenovic-Hanic, J. D. Love, and A. Ankiewicz, Electron. Lett. **38**, 220 (2002).
[16] J. Yamauchi, T. Ando, M. Ikegaya, and H. Nakano, IEICE Trans. Electron. **E77-C**, 319 (1994).
[17] V. Subramaniam, G. N. De Brabander, D. H. Naghski, and J. T. Boyd, J. Lightwave Technol. **15**, 990 (1997).