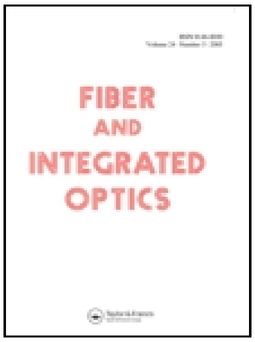


Taylor & Francis
Taylor & Francis Group

Fiber and Integrated Optics

ISSN: 0146-8030 (Print) 1096-4681 (Online) Journal homepage: https://www.tandfonline.com/loi/ufio20

Effect of Residual Resist on Performance of Single-Mode 1 × 4 Optical Splitter in Photosensitive Polymer

Rahul Singhal , M. N. Satyanarayan & Suchandan Pal

To cite this article: Rahul Singhal , M. N. Satyanarayan & Suchandan Pal (2010) Effect of Residual Resist on Performance of Single-Mode 1 × 4 Optical Splitter in Photosensitive Polymer, Fiber and Integrated Optics, 29:6, 480-490, DOI: 10.1080/01468030.2010.524723

To link to this article: https://doi.org/10.1080/01468030.2010.524723

Published online: 19 Nov 2010.

Fiber and Integrated Optics, 29:480–490, 2010

ISSN: 0146-8030 print/1096-4681 online
DOI: 10.1080/01468030.2010.524723

Effect of Residual Resist on Performance of Single-Mode 1 × 4 Optical Splitter in Photosensitive Polymer

RAHUL SINGHAL,[1] M. N. SATYANARAYAN,[2] and SUCHANDAN PAL[3]

[1]Electrical and Electronics Engineering Group, Birla Institute of Technology and Science, Pilani, India
[2]Physics Department, National Institute of Technology Karnataka, Surathkal, India
[3]Optoelectronic Devices Group, Central Electronics Engineering Research Institute (Council of Scientific and Industrial Research), Pilani, India

Abstract *Polymer residues are generally left in the Y-junctions of the conventional splitters. Besides increased insertion loss, the Y-junction residue results in asymmetric distribution of power at device outputs. An analysis of the device performance in the presence of junction residue is presented and a design to overcome the non-uniformities in output power distribution brought about by the presence of the residue is proposed.*

Keywords optical waveguide, polymeric splitter, Y-branch, Y-junction residue

1. Introduction

Polymer waveguides have received increasing attention because of the recent advances in optical polymers and the physical properties that the materials can offer in the context of forming simple inexpensive optical components [1]. Photonic polymer-based devices are particularly attractive because of their ability to be processed rapidly, they are cost effective, and they give high yields. Excellent tailorable optical, mechanical, and physical properties are achievable through using proper polymer and process. Of that matter, polymer material has been accepted as a new-generation material for an optical integrated circuit due to its various advantages as compared to other optical materials.

Photosensitive materials are rapidly finding broader applications in micro-scale design. In recent years, a relatively new type of resist, SU-8, has received a lot of attention in the field of micro-fabrication because of its mechanical stability, biocompatibility, and suitability for fabricating high aspect ratio features [2]. Cured SU-8 is highly resistant to solvents, acids, and bases and has excellent thermal stability, making it well suitable for applications in which cured materials are permanent structures of the device. The SU-8 2000 (formulated in cyclopentanone) [3] series of products from MicroChem Corporation,

Received 8 April 2010; accepted 14 September 2010.
Address correspondence to Mr. Rahul Singhal, Electrical and Electronics Engineering Group, BITS, Pilani Campus, Pilani, 333031, India. E-mail: rahulsinghal@bits-pilani.ac.in

USA can cover a wide range of film thicknesses from 2 μm to 250 μm. SU-8 2000 resists have high functionality and high optical transparency and are sensitive to near-UV radiation. Pre- and post-exposure bake times are comparatively smaller for SU-8 2000 than the traditional SU-8 [4]. Images having exceptionally high aspect ratios, and straight sidewalls are readily formed in thick and thin films by contact proximity or projection printing.

A similar photopolymer, the Norland Optical Adhesive 61 (NOA 61), is a clear and colorless liquid that is cured when exposed to ultraviolet light. When fully cured, NOA 61 has very good adhesion and solvent resistance. Curing time is remarkably fast and is dependent upon the thickness applied and the amount of ultraviolet light energy available. NOA 61 is cured by ultraviolet light with maximum absorption within the range of 320 nm–380 nm with peak sensitivity around 365 nm. Optimum adhesion can also be obtained by aging at 50°C for 12 hr. After aging, NOA 61 can withstand temperatures from −150°C to 125°C. Little work has been reported with NOA 61 as a material for optical waveguide [5–7]. The refractive index of cured NOA 61 is 1.54 while that of SU-8 is 1.57 at 1,550 nm, permitting fabrication of waveguides employing NOA 61 as the clad and SU-8 as the material for the guiding region.

This article presents a TE-mode analysis of a polymeric 1×4 optical power splitter. In the analysis, the refractive index of SU-8 (MicroChem Corporation, USA) at 1,550 nm is used as the core refractive index, while that of NOA 61 (Norland Products, USA) is used for the cladding. The power splitter presented in this work is designed for single-mode operation at 1,550 nm, which is the low loss window for long-haul telecommunication links. Thus, in order to ensure only fundamental mode operation at the desired wavelength, the guide thickness is kept below 2.5 μm. The modal characteristics of the waveguides were independently verified by beam propagation method (BPM) software BeamPROP^{TM} (RSoft Design Group, USA), the same software being used to design the 1×4 power splitters.

2. Structure and Fabrication

Since a Y-branch provides advantages, such as low excess loss, low wavelength dependent loss, and low polarization dependent loss, $1 \times N$ splitters consisting of Y-branches [8–14] are now widely used for optical signal distribution in passive optical networks. A schematic of the Y-branch is shown in Figure 1, which is comprised of a straight guide followed by a Y-branch with cosine s-bend arms [15] and is referred to here as a conventional 1×2 power splitter. The 1×4 power splitter is realized by cascading two symmetrical Y-branching guides. The device length obtained after optimizing different segment lengths for a conventional 1×4 splitter is 1.70 cm.

Fabrication of single-mode polymeric optical splitters is based on simple direct UV photolithography process [16–18]. Fabrication includes preparing the substrate surface for under-clad coating with NOA 61 followed by UV curing and baking. Prior to coating NOA 61 on an Si wafer, the wafer was thoroughly cleaned using piranha-etch at room temperature. The cleaned wafers were then dehydrated at 120°C–140°C in an oven. It was found that the quality of NOA 61 films were critically dependent on the wafer surface. A clean, dry wafer enabled proper adhesion of the spun film to the substrate. NOA 61 was spin-coated at 4,000 rpm for 30 sec, followed by UV curing for 10 min at an average intensity of 48 mW/cm^2, then left for stabilization at 60°C for 15 hr. For UV curing of NOA 61, a high wattage (400 W) UV lamp (Dymax 5000EC, Dymax Corporation, USA) was used. The SU-8 2002 core material was spun on top of an NOA 61-coated silicon substrate at 1,400 rpm for 30 sec and then soft baked using a two-step process

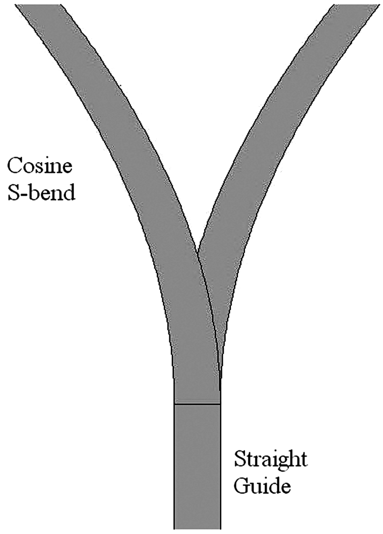


Figure 1. Y-junction in a conventional splitter.

(65°C for 5 min and 95°C for 20 min) to remove any traces of solvent after exposure. Channel waveguide widths of 2 μm to 2.4 μm were realized by UV exposure for 90 sec in contact with photomask using a Karl Suss MA56 mask aligner (Karl Suss-GmbH & Co., Germany). A post-exposure two-step baking process (65°C for 2 min and 95°C for 5 min) was used to cross-link the polymer. The photoresist-coated UV-exposed substrate was developed in propylene glycol methyl ether acetate (PGMEA) for 70 sec and then rinsed in isopropyl alcohol (IPA) for 10–15 sec. A coating of NOA 61 as over-clad was the final step in device development and was done as the under-clad was coated, cured, and baked. Finally, a hard bake at 140°C for 1 hr is good enough to remove any traces of developer or solvent left behind. The fabrication process is summarized by the schematic diagram in Figure 2.

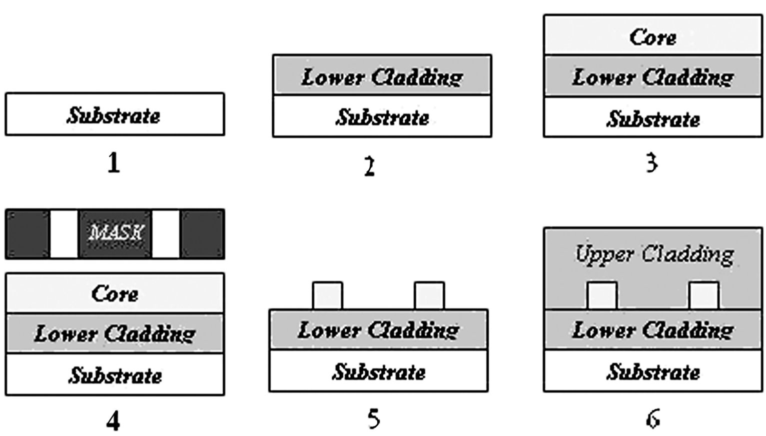
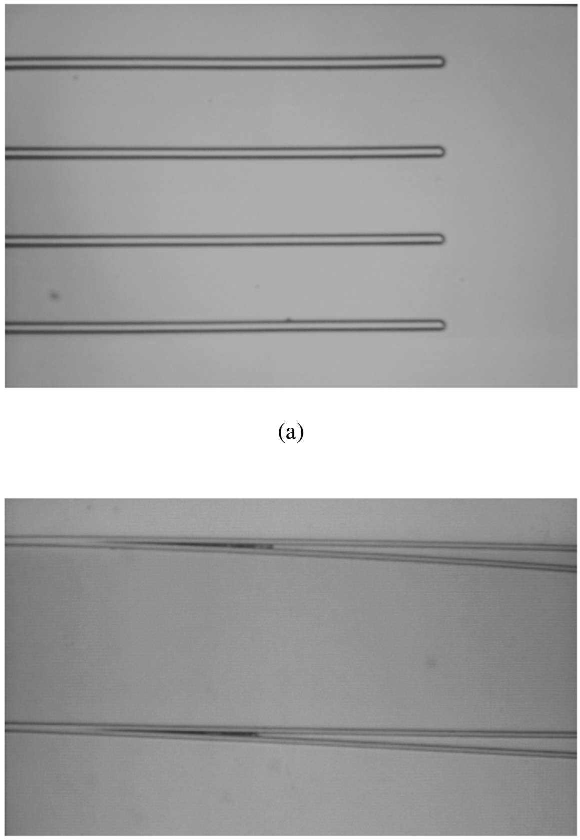


Figure 2. Schematic diagram of steps (1–6) of fabrication process for polymeric waveguides.



(a)

(b)

Figure 3. 1×4 splitter: (a) device outputs and (b) Y-branches.

The thickness of core before exposure and hard bake was found to be 2.4 μm when measured using a Metricon 2010 prism coupler (Metricon Corporation, USA). After pattern development and before hard bake, the height of waveguides were in range from 2 μm–2.4 μm. Optical micrographs of portions of devices are collectively shown in Figure 3. As is evident from the photomicrographs, the fabricated waveguides are smooth walled. There is no cracking or any kind of defect in the fabricated devices. However, a small amount of residual resist remained in the region between the Y-junction guides. The residue left between the Y-junction arms is, in fact, SU-8, which was not removed due to limitations with the resolution of the mask aligner used for photoexposure. The mask aligner employed in this work had a resolution of 2 μm, whereas the waveguides are separated by a distance at the junction region less than the resolution of the mask aligner. The residue can be reduced with an increased UV exposure time during fabrication, but an increased exposure time, as expected, leads to wider waveguides.

3. Proposed Design

During fabrication employing a photomask, the smallest feature size obtainable depends on resolution of the mask aligner used for photolithography. As a result, a small amount of polymer residue may remain at the Y-junction, as shown in Figure 3b. The residue length is defined as the distance from the point of separation of Y-arms to the end of the affected area in the direction of propagation of light. When a conventional design is used, it was observed that the residue lengths were in the range of 240 μm–260 μm in the second stage (i.e., when the output waveguides are separated by a distance of 127 μm) of the device. For the first stage of the device, the residue lengths were in the range 430 μm–450 μm. These residue lengths were estimated from the microscopic examination of several samples. Stages in a cascaded structure have different geometric features, hence, different values of residual lengths. Coupling light into a power splitter that contains such residues at all junctions leads to unequal output power distribution, besides resulting in increased propagation loss. The more the length of the residue, the more is the degraded performance of the device.

The proposed design of Y-branch waveguide [19] is comprised of a waveguide beam expander [20] and cosine S-bend segment. The basic part of waveguide beam expander is a single-dimension linearly tapered waveguide in which the width of channel waveguide is gradually expanded to reduce the effective numerical aperture of the optical beam in the direction of propagation. The tapered waveguide is followed by a straight guide with width equal to the broader end of the tapered waveguide. The simulation here shows that the proposed design leads to improved coupling of optical power in the Y-branch. Figure 4 shows the proposed structure.

The width of the waveguide kept was 2.4 μm for single-mode propagation. In these simulations, the separation between the two output waveguides of a Y-branch was varied and an optimum separation of 1 μm was obtained. A separation of the waveguides larger than 1 μm resulted in increased leakage of light from the broad end of the taper, as expected. The taper length was also carefully optimized to minimize the loss of light from the junction. Here also, the 1×4 power splitter is realized by cascading two symmetrical Y-branching guides. The separation between the output ports of the first stage of device is 254 μm, and the second stage output port separation is 127 μm. At the end of each cosine S-bend segment, a straight waveguide is introduced for coupling power

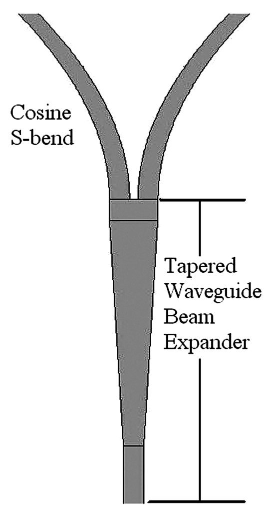


Figure 4. Segments of Y-branching waveguide.

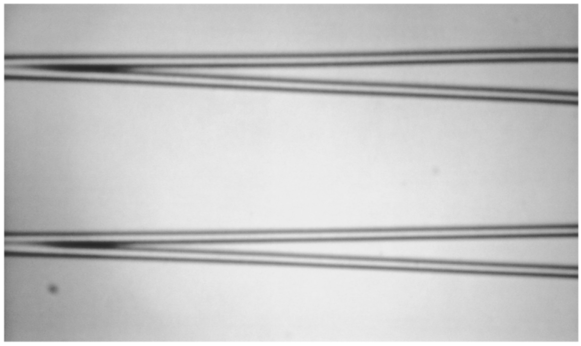


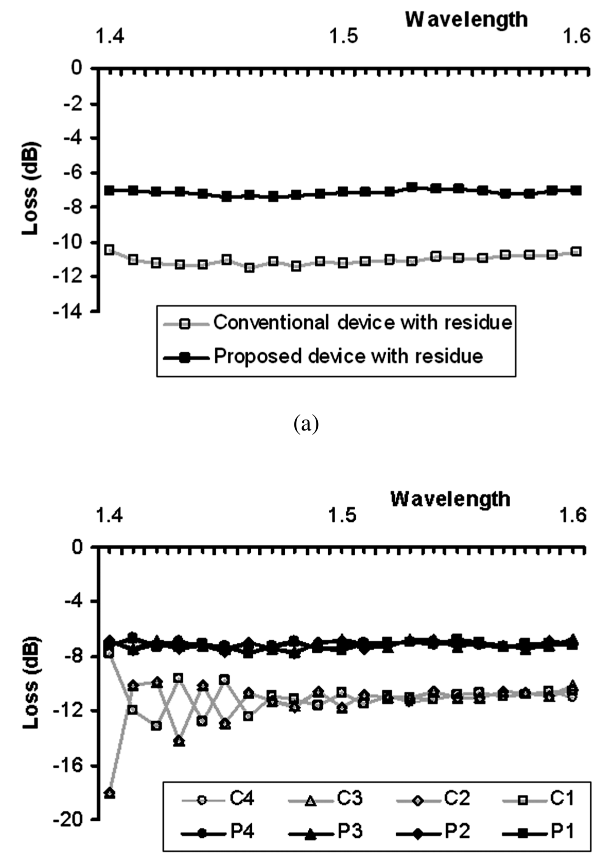
Figure 5. Residue at Y-junction of proposed device.

to the next stage efficiently, also acting as the input section for the next stage. Through a simulation program, the length of each segment used in the schematic is optimized with the main aim of achieving low propagation loss with symmetric distribution of power at all output ends. The overall device length achieved after optimizing segments is 1.43 cm. The fabrication process presented in Section 2 was applied again to fabricate the devices based on the proposed design. The residue was visible in the Y-junction of proposed device as shown in Figure 5, but the area covered by the residue was reduced due to the gap of 1 μm introduced between the Y-arms. The residue lengths from the proposed design lies in range of 100 μm–120 μm for the second stage of device, while for the first stage of the device, it lies in the range of 170 μm–190 μm. The proposed design reduces the length of residue, and thus, an improvement in performance of the device is expected.

4. BPM Simulation Results

One of the important input parameters for the BeamPROP^{TM} (Rsoft Design) is the refractive indices of core and cladding of waveguide. Accurate modeling of waveguides is possible if the bulk refractive indices of SU-8 and NOA 61 are measured. The refractive indices of cross-linked thin films SU-8 and UV-cured NOA 61 were measured using a Metricon 2010 prism coupler. The refractive index for the SU-8 thin film was measured to be 1.57, while that for the UV-cured NOA 61 was 1.54 at 1,550 nm, which agree very well with the reported literature. In the proposed design, the residue at the Y-junction was simulated as SU-8 itself, and a refractive index of 1.57 was used for this region in the simulations. It can be observed from Figure 5 that the residue has the darkest shade in color, which suggests surface roughness due to non-uniform etching. The measurement of surface roughness in the affected area to estimate the average height of residue was not carried out. Thus, change in the height of the residue was ignored during simulations; i.e., the height of residue was kept the same as that of the waveguide, but the residue lengths differ at different stages of the cascaded structure of the device, and the estimated values were included accordingly in design before simulation.

The average splitter loss with residue for the conventional and proposed devices is evaluated through BPM analysis using BeamPROP^{TM} and is plotted in Figure 6. The performance of the device based on the proposed design with junction residue is better than that of a conventional device with junction residue. Power distribution at the device outputs are also plotted in Figure 6b. The proposed design yields a more symmetric power distribution at device outputs than the conventional design. Figures 6a and 6b,



(a)

(b)

Figure 6. (a) Average splitter loss versus wavelength (in μm) and (b) power distribution at device outputs.

in general, show the splitter loss for the conventional and proposed devices for other wavelengths in the third optical window as well.

5. Characterization

The propagation losses for channel waveguides can be estimated through cut-back measurements. The average propagation loss estimated here is 0.125 dB/mm when the loss for several over-cladded channel waveguides of different lengths are measured at 1,550 nm. Propagation losses reported previously have been 0.125 dB/mm [16], 0.15 dB/mm [18], and 0.18 dB/mm [21] at 1,550 nm. The materials used to fabricate waveguides in [16] are SU-8 2000 and NOA 61, and the measurements are done at 1,550 nm for single-mode propagation. The insertion loss for the 1×4 splitter chip in this case includes intrinsic splitting losses estimated through the simulation in Figure 6 along with losses in the waveguide that are independent of the splitter, e.g., Y-junction losses, radiation losses, and coupling losses. Coupling losses also include losses due to Fresnel reflection. Since the waveguides were as narrow as 2 μm by 2 μm, it was very difficult to measure how much light coupled into the waveguide, unless the input face of the waveguide is polished to a very high quality and the input/output ends are pigtailed. Polishing soft materials, such as polymers, is very challenging and requires sophisticated equipment, unlike the ones used for hard materials, such as glasses and crystals, and has not been taken up in this work. The input and output ends of the splitters were simply prepared by cleaving the Si wafer on which they were patterned, an approach adopted by several workers, and the light was input from an optical fiber by butt-coupling. The insertion losses obtained at the chip level are listed in Table 1 for both 632.8 nm and 1,550 nm.

The length of the fabricated device is 1.43 cm, and the average propagation loss estimated at 1,550 nm is 1.25 dB/cm, which accounts for a loss of 1.8 dB for the device. An analysis was carried out when power was coupled to the input of the device through an optical fiber (Nufern PWG1-XP, Nufern, USA) under the condition that the axis of the input waveguide was perfectly aligned to that of the fiber. Power at each output port was measured with no interference from either of the adjacent ports. The fiber-to-waveguide coupling loss is 3.5 dB/port, as their geometrical cross-sections, as well as the mode field diameters, in the fiber and rectangular waveguides differ. In addition, Fresnel reflection at the input and output ports is estimated to be about 0.2 dB/port, resulting in a coupling loss of 3.7 dB/port. Similar butt-coupling losses have been reported earlier in [16, 22] for SU-8 waveguides. Coupling losses for the conventional and proposed devices are the same as the geometric features of waveguides used in the design of both types of devices are the same. It must be reiterated that losses can only be estimated, as the light had been butt-coupled from the optical fiber to the device with the ends of the device prepared only by cleaving.

The theoretical splitting loss of proposed device with residue at Y-junctions is 7 dB at 1,550 nm, as shown in Figure 6. The theoretical splitting loss of 7 dB when added to 1.8 dB of propagation loss along with 7.4 dB of coupling loss between input and each of the output ports will result in $\sim$16 dB of insertion loss for the device. The difference between estimated and obtained results shown in Table 1 may account for Y-junction and radiation losses, which, in this case, is $\sim$1.5 dB. Thus, the excess losses as defined in [23] can be estimated to be around $\sim$10 dB.

Table 1 suggests the average insertion loss at 1,550 nm is 17.5 dB with a variation of 0.3 dB among the output arms of the proposed device compared to the insertion loss of 20 dB with a variation of 1.4 dB for a conventional device. An advantage of $\sim$2.5 dB

Table 1
Insertion loss of the fabricated 1×4 splitter chip

	Wavelength			
	632.8 nm		1,550 nm	
1×4 device	Conventional	Proposed	Conventional	Proposed
Insertion loss (dB)				
Output port 1	19.6	18.1	18.6	17.2
Output port 2	21	19.4	21.4	17.5
Output port 3	22.7	19.9	19.6	17.8
Output port 4	21.4	18.4	20.4	17.5

in the device insertion loss with the symmetric distribution of power at the output ends is observed in the proposed device at 1,550 nm. Even though the proposed design was optimized at 1,550 nm, symmetric distribution of optical power at the output ends of the device and an advantage of more than 2 dB in device insertion loss is also observed at 632.8 nm.

6. Conclusion

Polymer residues are generally left in the Y-junctions of the conventional splitters. Besides increased insertion loss, the Y-junction residue results in asymmetric splitting of optical power. A design incorporating a tapered waveguide beam expander is proposed, which offers better performance with Y-junction residue than the conventional $1 \times N$ splitter in terms of insertion loss and symmetric power distribution at the output ends of the device at 1,550 nm. SU-8 optical waveguides with a width of 2.4 μm, with an optical adhesive NOA 61 over- and under-cladding on silicon substrate, have been realized. The process to fabricate single-mode polymeric channel waveguide-based optical splitters using simple direct ultraviolet (UV) photolithography is optimized and presented. Chip-level characterization of the proposed 1×4 optical power splitter shows improvements of $\sim$2.5 dB in insertion loss and more than 1 dB in output uniformity in comparison to the conventional one at 1,550 nm. Similarly, more than 2 dB and 0.7 dB improvement in the insertion loss and uniformity have been observed at the wavelength of 632.8 nm.

Acknowledgments

The authors thank Department of Information Technology (DIT), Government of India, New Delhi, for supporting this work through a project grant. The authors also thank the members of the Optoelectronic Devices Group (ODG) and Semiconductor Devices Fabrication (SDF) facility of CEERI (CSIR), Pilani for their support in device fabrication. The assistance rendered by Optoelectronics Division, Society of Microwave Electronics Engineering and Research (SAMEER), Mumbai, India, in device characterization is gratefully acknowledged.

References

1. Eldada, L., and Shacklette, L. W. 2000. Advances in polymer integrated optics. *IEEE Journal on Selected Topics in Quantum Electronics* 6:54–68.
2. Liu, J., Cai, B., Zhu, J., Ding, G., Zhao, X., Yang, C., and Chen, D. 2004. Process research of high aspect ratio structure using SU-8 resist. *Microsystem Technologies* 10:265–268.
3. Shaw, M., Nawrocki, D., Hurditch, R., and Johnson, D. 2003. Improving the process capability of SU-8. *Microsystem Technologies* 10:1–6.
4. del Campo, A., and Greiner, C. 2007. SU-8: A photoresist for high aspect ratio and 3D submicron lithography. *Journal of Micromechanics and Microengineering* 17:81–95.
5. Kim, K.-J., and Oh, M.-C. 2008. Flexible Bragg reflection waveguide devices fabricated by post-lift-off process. *IEEE Photonics Technology Letters* 20:288–290.
6. Chang-Yen, D. A., and Gale B. K. 2005. Design and fabrication of a multianalyte-capable optical biosensor using a multiphysics approach. *Proceedings of 3rd Annual International IEEE EMBS Special Topic Conference on Microtechnologies in Medicine and Biology*, Hawaii, May 12–14, pp. 326–328.
7. Wong, W. H., Zhou, J., and Pun, E. Y. B. 2001. Low-loss polymeric optical waveguides using electron-beam direct writing. *Applied Physics Letters* 78:2110–2112.

8. Klekamp, A., Kersten, P., and Rehm, W. 1994. An improved single-mode Y-branch design for cascaded 1:2 splitters. *Journal of Lightwave Technology* 14:2684–2686.
9. Chan, H. P., Cheng, S. Y., and Chung, P. S. 1996. Low loss wide-angle symmetric Y-branch waveguide. *Electronics Letters* 32:652–654.
10. Lin, H.-B., Su, J.-Y., Cheng, R.-S., and Wang, W.-S. 1999. Novel optical single-mode asymmetric—branches for variable power splitting. *IEEE Journal of Quantum Electronics* 35:1092–1096.
11. Yabu, T., Geshiro, M., and Sawa, S. 2001. New design method for low-loss Y-branch waveguides. *IEEE Journal of Lightwave Technology* 19:1376–1384.
12. Wang, Q., He, S., and Wang, L. 2002. A low loss Y-branch with a multimode waveguide transition section. *IEEE Photonics Technology Letters* 14:1124–1126.
13. Tao, S. H., Fang, Q., Song, J. F., Yu, M. B., Lo, G. Q., and Kwong, D. L. 2008. Cascade wide-angle Y-junction 1×16 optical power splitter based on silicon wire waveguides on silicon-on-insulator. *Optics Express* 16:21456–21461.
14. Sakamaki, Y., Saida, T., Hashimoto, T., and Takahashi, H. 2009. Low-loss Y-branch waveguides designed by wavefront matching method. *IEEE Journal of Lightwave Technology* 27:1128–1134.
15. Sum, T. C., Bettiol, A. A., Rao, S. V., van Kan, J. A., Ramam, A., and Watt, F. 2004. Proton beam writing of passive polymer optical waveguides. *Proceedings of SPIE MicroMachining Technology for Micro-optics Nano-optics II* 5347:160–169.
16. Tung, K. K., Wong, W. H., and Pun, E. Y. B. 2005. Polymeric optical waveguides using direct ultraviolet photolithography process. *Applied Physics A* 80:621–626.
17. Pelletier, N., Beche, B., Gaviot, E., Camberlein, L., Grossard, N., Polet, F., and Zyss, J. 2006. Single-mode rib optical waveguides on SOG/SU-8 polymer and integrated Mach-Zehnder for designing thermal sensors. *IEEE Sensors Journal* 6:565–570.
18. Yang, B., Yang, L., Hu, R., Sheng, Z., Dai, D., Liu, Q., and He, S. 2009. Fabrication and characterization of small optical ridge waveguides based on SU-8 polymer. *IEEE Journal of Lightwave Technology* 27:4091–4096.
19. Singhal, R., Satyanarayan, M. N., and Pal, S. 2008. Design of polymeric optical splitter incorporating a taper. *Proceedings of International Conference on Fiber Optics and Photonics—Photonics 2008*, New Delhi, December 13–17, p. 19.
20. Jamroz, W. R., Kruzelecky, R., and Haddad, E. I. 2006. *Applied Microphotonics*. Boca Raton, FL: CRC Press, Taylor and Francis Group.
21. Nordström, M., Zauner, D. A., Boisen, A., and Hübner, J. 2007. Single-mode waveguides with SU-8 polymer core and cladding for MOEMS applications. *IEEE Journal of Lightwave Technology* 25:1284–1289.
22. Dai, D., Yang, B., Yang, L., Sheng, Z., and He, S. 2009. Compact microracetrack resonator devices based on small SU-8 polymer strip waveguides. *IEEE Photonics Technology Letters* 21:254–256.
23. Sohn, I.-B., Lee, M.-S., and Chung, J.-Y. 2005. Fabrication of optical splitter and passive alignment technique with a femtosecond laser. *IEEE Photonics Technology Letters* 17:2349–2351.

Biographies

Rahul Singhal received his M.Tech. in digital communication from Uttar Pradesh Technical University, Lucknow, India, in 2007. He is currently pursuing his Ph.D. at the Birla Institute of Technology and Science, Pilani, India.

M. N. Satyanarayan holds a Ph.D. in physics from the Indian Institute of Science, Bangalore, India, in the area of experimental condensed matter physics and is presently with the National Institute of Technology Karnataka, India. Prior to joining this institute, he was on the faculty at the Birla Institute of Technology & Science Pilani, India, and also worked for several years in industry. His research interests include non-linear optical phenomena and materials, photonic devices, optical communication, etc. He has published many papers in peer-reviewed journals as well as international conferences and also has a review article to his credit.

Suchandan Pal received his B.Tech. and M.Tech. from the Institute of Radio Physics and Electronics (IRPE), University of Calcutta, in 1992 and 1994, respectively. He joined the Central Electronics Engineering Research Institute (CEERI), Pilani, as a scientist in 1995. In 2001, he was awarded the Commonwealth Scholarship and pursued his Ph.D. at City University, London, in the area of fiber Bragg gratings (FBG)-based optical fiber sensing and instrumentation. He returned to CEERI, Pilani in 2004 after completing his Ph.D. In addition to the area of FBGs, his present research interest lies in the area of integrated optics involving the design and technology development of various passive photonic components like optical power splitters, AWG-based multiplexers/demultiplexers, and long-period waveguide gratings on silica-on-silicon and polymer materials for various sensing and communication applications. He has authored and co-authored over 50 scientific and technical papers in various reputed national and international journals and conferences. He is a member of the Institute of Physics (United Kingdom), a fellow of the Optical Society of India and the Institution of Electronics and Telecommunication Engineers (India), and a member of Indian Physics Association and Semiconductor Society of India.