NRC Publications Archive Archives des publications du CNRC

Formation of bowtie-shaped excitation in a photonic-microfluidic integrated devices

Watts, Benjamin, R.; Kowpak, Thomas; Zhang, Zhiyi; Xu, Chang-Qing; Zhu, Shiping

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.1002/mop.26309>

Microwave and Optical Technology Letters, 53, 11, pp. 2583-2586, 2011-11-01

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=4c9e192f-3368-461f-9e6d-08ede47a29e5>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=4c9e192f-3368-461f-9e6d-08ede47a29e5>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research
Council Canada

Conseil national de
recherches Canada

Canada

Figure 9 Measured scattering parameters of LTCC filter

proposed filter (with aperture on ground plane) is 5 GHz while the bandwidth of the filter without aperture in ground plane is 2.8 GHz. It is understood that aperture in ground plane enhanced the bandwidth by 44%.

3. EXPERIMENTAL RESULTS

An experimental filter is realized using LTCC process. The chosen LTCC process uses green tapes (DuPont 951) having thickness of 720 μm and dielectric constant of 7.8. Loss tangent of the tape is 0.014 at 10 GHz. As a first step, tapes are cut into required sizes. Holes are punched and filled. Vias having diameter of 200 μm are used for electrical interconnection between top and bottom ground layers. The fired via dimensions are 175 μm . Via filling was done using DuPont 6141 paste which is specially used for DuPont 951 tape. Conductive and resistive pastes are applied on each tape as needed. Inspection is done layer by layer before firing them, which is the key advantage of LTCC process. Then the sheets are laminated-together and fired in one step. This is done in a precisely controlled oven. Process chart used for the fabrication is shown in Figure 5. Firing takes place at low temperatures (typically at about 850°C) and the firing profile is shown in Figure 6. Silver and silver-palladium based conductors are used in the fabrication. In LTCC process, a meshed ground plane is preferred to solid ground plane for the reason of better bonding of tapes. A meshed ground with unit cell having width of 200 μm and spacing of 200 μm is used as shown in Figure 7. Lamination was done in isostatic lamination at 21MPa pressure for 10 minutes at 70°C. Figure 8a shows

Figure 10 Measured group delay

the developed compact LTCC filter. Figures 8(b) and 8(c) show the top and bottom views of the fabricated filter respectively. Aperture (slot) that enhances the filter's bandwidth can be seen.

Response of LTCC filter is measured using a vector network analyzer. A comparison is made between measured and simulation results in Figure 9. Measured pass band is from 2.95 to 8.05 GHz with a maximum insertion loss of 1.5 dB and a minimum return loss of 11 dB. Figure 10 shows the comparison between the measured and simulated group delay. Size of the realized LTCC filter is $20 \times 10 \times 0.72 \text{ mm}^3$. The availability of LTCC thin tapes with high dielectric constant enabled miniaturization of the filter.

4. CONCLUSIONS

An LTCC UWB filter having pass band from 3 to 8 GHz was designed and realized in LTCC medium. It was shown that multiple parallel coupled line sections in defected ground structure topology provided the UWB characteristics. The filter was analyzed using circuit models of coupled lines and results obtained were compared against the full wave simulations and experimentation. Reasonable agreement is obtained between them. This wide band filter presented in this article can be a potential candidate filter for UWB systems due to its simple structure and good performance.

REFERENCES

1. D. Packiaraj, K.J. Vinoy, M. Ramesh, and A.T. Kalghatgi, High selectivity miniaturized broadband filter, *Microwave Opt Technol Lett* 53 (2011), 184–187.
2. T.H. Duong and I.S. Kim, Steeply sloped UWB bandpass filter based on stub-loaded resonator, *IEEE Microwave Wirel Compon Lett* 20 (2010), 441–443.
3. S.W. Wong and L.Z. Zhu, Quadruple-mode UWB band pass filter with improved out-of-band rejection, *IEEE Microwave Wirel Compon Lett* 19 (2009), 152–154.
4. C.Y. Hsu, C.Y. Chen, and C.H. Huang, A UWB filter using a dual-mode ring resonator with spurious pass band suppression, *Microwave J* 48 (2005), 130–136.
5. K. Huang and T. Chiu, LTCC wideband filter design with selectivity enhancement, *IEEE Microwave Wirel Compon Lett* 19 (2009), 452–454.
6. C.I. Mobbs and J.D. Rhodes, A generalized Chebyshev suspended substrate stripline band pass filter, *IEEE Trans Microwave Theory Tech* 31 (1983), 397–402.
7. Zeland Software Inc., IE3D 11.5, Zeland Software Inc., Fremont, CA, 2006.

© 2011 Wiley Periodicals, Inc.

FORMATION OF BOWTIE-SHAPED EXCITATION IN A PHOTONIC-MICROFLUIDIC INTEGRATED DEVICES

Benjamin R. Watts,¹ Thomas Kowpak,² Zhiyi Zhang,³ Chang-Qing Xu,¹ and Shiping Zhu²

¹Department of Engineering Physics, McMaster University, 1280 Main Street West, Hamilton, ON, Canada L8S 4L7; Corresponding author: Zhiyi.Zhang@nrc-cnrc.gc.ca

²Department of Chemical Engineering, McMaster University, 1280 Main Street West, Hamilton, ON, Canada L8S 4L7

³Institute for Microstructural Sciences, National Research Council of Canada, 1200 Montreal Road, Ottawa, ON, Canada K1A 0R6; Corresponding author: Zhiyi.Zhang@nrc-cnrc.gc.ca

Received 4 February 2011

ABSTRACT: Narrowly confining the beam intensity in a well-defined region in the center of cell flow is a necessary step to perform

reliable flow cytometry testing but has so far not been achieved in a photonic–microfluidic integrated device. We were able to focus the excitation beam to a very narrow bowtie shape with a near uniform intensity across the flow stream for excitation for a flow cytometry application. Beam geometry was achieved by integrating a one-dimensional lens system with planar waveguides and a microfluidic channel on one substrate using one patterning material via a one-shot process. This letter reports the method used to achieve such shaped beams and the performance of the shaped beams. © 2011 National Research Council Canada & Wiley Periodicals, Inc. *Microwave Opt Technol Lett* 53:2583–2586, 2011; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.26309

Key words: planar waveguides; microfluidics; integration; devices; beam shaping

1. INTRODUCTION

Flow cytometry is a very powerful biological analysis tool where a population of cells' chemical and physical characteristics can be determined and subpopulations or anomalies can be identified, leading to applications in diagnosis and monitoring of diseases [1, 2] sorting applications [3], and drug development [4]. A conventional flow cytometer is suitable for analyzing a large amount of samples (50,000–100,000 cells/s [3]) and has the ability to inspect multiple parameters simultaneously (up to 17-color [5]), creating an incredible ability to discriminate tiny and subtle cell populations. By replacing the large flow cell of a conventional machine with a microfluidic channel, a microchip-based flow cytometer is obtained and is able to more efficiently handle and analyze a smaller sample volume, leading to a reduced consumption of costly labeling reagents [6, 7]. These devices also create the possi-

Figure 1 A picture showing the resultant beam shape of illumination intensity from different integrated inputs: (i) Input from an integrated waveguide, (ii) integrated lens (or lenses), (iii) the proposed beam shape achieves focussing in flow direction and increases uniformity in cross-channel direction, and is similar to (iv) a free-space focussed beam where focussing is in both the cross-channel and channel height directions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

bility of integrating other functional units into the same substrate, such as mixing and cell sorting [8], for simplifying and automating sample handling for broad and complex operations. The integration of photonic elements into the same layer as the microfluidic channel of a microchip-based flow cytometer offers a means to make a microchip-based flow cytometer that is truly portable and inexpensive by alleviating the need for bulky and shock sensitive free-space optics—a true micro-total analysis system device. Optical waveguides [9–13], sources and detectors [10, 11], apertures [12], filters [11, 13], and lenses [12, 14–17], have all been integrated with a microfluidic channel and have shown to improve device functionality and portability. However, such a photonic–microfluidic integrated flow cytometer has not demonstrated true cytometry function due to absent features from conventional cytometers—such as beam shaping.

Shaping the excitation beam in a photonic–microfluidic-flow cytometer is extremely difficult as the beam must be narrow enough to ensure that only one cell is in the beam at a time—to eliminate double detections—while the intensity of the beam across the flow must be uniform enough to allow for reliable detection efficiency, i.e., uniform detection signals from identical particles. Nonuniform detection is problematic as beams are typically Gaussian in shape across the sample flow and a slight deviation of the particle from the flow axis means a deviation from the center of the Gaussian beam and thus, different illumination intensity. This nonuniform excitation leads to variances in the scattering signal, which degrades the coefficient of variation—the measure that defines the performance in a cytometer. These problems persist in current devices: beams from integrated waveguides diverge as they cross the microfluidic channel [Fig. 1(i)] creating a variable and wide beam width with decreasing intensity across sample flow. Lenses have been used to improve the beam in the channel by focusing or collimating the beam [Fig. 1(ii)], but have only improved the excitation intensity for detection without addressing the beam waist or uniformity across the channel [12, 14–17]. We proposed the design and use of an integrated lens system to form an ideal “bowtie-shaped” excitation region that contains both a narrow beam waist and near uniform intensity for reliable excitation illumination [Fig. 1(iii)]. The bowtie-shaped beam is similar to the beam that is formed via cross-cylindrical lenses from free-space optics in a conventional flow cytometer [Fig. 1(iv)], however, beam control is only within the plane of the device. The formed regions have narrow beam waists to avoid double detections, with a large enough depth of focus to allow for near uniform illumination across the cell flow for reliable detection.

2. DESIGN AND EXPERIMENTS

To form a targeted excitation beam, devices integrate both a waveguide and lens system together, to maximize coupling and

Figure 2 (a) A schematic structure of a device with the planar integration of waveguide, lens system, and microchannel; (b) Picture of a fabricated device. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

alignment of photonic elements, in a single planar layer with the microchannel [Fig. 2(a)]. The output of a multimodal waveguide—selected for power carrying and coupling capabilities—is focused into a defined spot in the microfluidic channel through the specifically designed one-dimensional (1D) lens system. The lens systems were designed with commercially available optical design software (ZEMAX) and are based on a condenser lens system designed to accommodate large input numerical aperture (NA)—to maximize the deliverable power and allow flexibility of input light source geometry—and generate a tuneable waist size coincident with maximum intensity. A system of multiple lenses was used as they have been shown to be able to form a better defined beam in the channel through control of aberrations that are inevitable with a single lens. Designs not only maximize intensity—as has been previously done—but concentrate on shaping the beam through control of image aberrations to precisely define an optical spot geometry. Through adjusting the curvature of the surface from spherical to elliptical or hyperbolic, each of the lens surfaces in the system contributes to specifically warping the image in the channel to form the desired spot geometry. Multiple lens surfaces allow precise control of aberrations and allow simultaneous tuning of the beam waist and uniformity of the beam in the channel. The result is a tuned bowtie-shaped beam where the center of the bowtie is crucial to detection efficiency of cytometry. Lens designs focus the input from a 50- μm wide waveguide to different beam waist sizes in the middle of a microfluidic channel—sizes of 10 and 3.6 μm were selected to show flexibility as many biological cells range from 1 to 10 μm . Effort was made to create as uniform a region of intensity in both the flow direction and cross-channel direction to ensure uniform, reliable excitation. Ability to focus the beam was restricted to the dimension of the device; however, beams are confined by the substrate and top layers and the 1D focusing matches well with the 1D hydrodynamic focusing capability on such devices.

Device fabrication utilized a one-shot manufacturing process to create devices in a 27- μm thick layer of SU-8 by removing material to form features [10]. The layer was baked and developed to form a transparent layer at optical frequencies. The careful selection of substrate, device layer, and capping layer ensured vertical confinement of the light within the device layer. Figure 2(b) shows a picture of the fabricated device. Beams were characterized in the channel by filling the microchannel with a fluorescent laser dye (Nile Blue 690 Perchlorate, Exciton) that has an absorption peak at 630 nm and an emission peak at 660 nm. Fluorescence was captured via a CCD camera equipped with a 12 $\times$ zoom lens, a 10 $\times$ objective, and a 660 $\pm$ 10 nm band pass filter. Exposure times were adjusted to obtain good contrast for images.

3. RESULTS AND DISCUSSION

Images were captured for a control device with no lens [Fig. 3(a)], and for the device designed to create a 3.6- μm beam waist [Fig. 3(b-ii)], and 10- μm beam waist [Fig. 3(c-ii)]. Simulated results for both designs are superimposed next to the image to confirm the accuracy of the designs [Figs. 3(b-i) and 3(c-i)]. From simple inspection of the captured images, it is easy to see that the lens systems offer large improvements to the shape of the beam over nonfocused input from a waveguide. The bowtie-shaped beams formed are ideally shaped as they form tightly focused beam waists in the center of the channel where a hydrodynamically focused stream of cells flow, while creating a region of uniform intensity across a significant width of the channel. The full-width-half-max (FWHM) of the shaped beams

Figure 3 (a) Image of the beam from a lensless device in the microchannel; (b) (i) Simulation and (ii) fluorescent image from a lens system to form a 3.6 μm beam waist; and (c) (i) Simulation and (ii) fluorescent image from a lens system to form a 10- μm beam waist. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

are 6.5 and 11.7 μm for the 3.6- and 10- μm designs, respectively, ensuring that the lens systems are able to form a beam to target any cell size.

Further analysis on the shaped beam was done by converting each pixel in the image to a numerical value dependent on the pixel intensity: 0 being the value in the absence of light, 255 being the value when the pixel is saturated—and then analyzing successive horizontal rows of pixels to construct a plot of the

Figure 4 Plot showing the maximum beam intensity of the 3.6- μm (blue) and 10- μm (red) devices as a function of cross-channel position showing a region of near uniform intensity across the particle flow—in the 20–30- μm region. The control device (green) has lower intensity with near-uniform intensity—though the beam is not practical as its FWHM is much too large. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

maximum intensity of the beam as a function of its position across the channel [Fig. 4]. Figure 4 confirms that the intensity from the shaped beams is drastically improved over the control device (no lens system) and the high intensity cross-channel plateaus are formed in the center of the channel. The plateau of uniform illumination—where the beam is within 5% of the maximum intensity in the center of the channel—is measured to be 10.4- and 6.2- μm long, for the 10- and 3.6- μm lens systems respectively, spanning the center of the channel. These plateau regions are difficult to form as the depth of focus is minimized considerably when focusing a beam to a spot in the channel. However, by using aberrations to warp the Gaussian shape, we have formed large regions where uniform excitation is possible across the entire sample flow. In fact, if the plateaus are measured using the standard depth of focus, it is found that these regions span 26.2 and 14.1 μm for the 10- and 3.6- μm devices, respectively—significant portions of the entire channel, and that intensity varies by 25% from the maximum intensity over this region.

It should be noted that there is a noticeable trade-off on the size of the beam waist and the plateau of uniform intensity: the smaller the waist, the smaller the plateau that can be formed, as evidenced by the much smaller region defined by the 3.6- μm device. This is due to the inverse relationship between beam waist and divergence. This is of little consequence because when smaller cells are analyzed, our designs shrink the beam waist to eliminate the occurrence of double detections while the uniform region is kept large enough to accommodate the particle to deviate within the cell flow. A larger maximum intensity is also noted for larger beam waist due to the larger input NA of the lens system allowing greater collection of light from the waveguide.

4. CONCLUSIONS

Exact formation of ideal beam shapes for cytometric analysis has been demonstrated experimentally. These formed beams are highly desirable in a flow cytometry application because they exploit the ability to control aberrations in the lens design to specifically tailor beam shapes to form as near an ideal a shape for illumination as possible. These bowtie-shaped beams will significantly improve the sensitivity of a photonic-integrated microchip-based flow cytometer by offering an improved area of illumination over previously shown devices [16]. Beam shaping on a photonic-integrated microfluidic flow cytometer is a major step forward to achieving feasible devices for clinical, laboratory, and point-of-care medical applications.

ACKNOWLEDGMENTS

This project was partially funded by a grant provided by Canadian Photonics Fabrication Research (CPFR) and supported by Ascentta Inc. and SensiLaser Technologies Inc. The authors thank Ping Zhao and Frances Lin of the National Research Council Canada (NRC) for their help in device fabrication.

REFERENCES

1. J.V. Giorgi, J.L. Fahey, D.C. Smith, L.E. Hultin, H.L. Cheng, R.T. Mitsuyasu, and R. Detels, Early effects of HIV on CD4 Lymphocytes in vivo, *J Immunol* 138 (1987), 3725–3730.
2. D. Campana and F.G. Behm, Immunophenotyping of leukemia, *J Immunol Meth* 243 (2000), 59–75.
3. R.G. Ashcroft and P.A. Lopez, Commercial high speed machines open new opportunities in high throughput flow cytometry (HTFC), *J Immunol Meth* 243 (2000), 13–24.

4. F.W. Kuckuck, B.S. Edwards, and L.A. Sklar, High throughput flow cytometry, *Cytom* 44 (2001), 83–90.
5. S.P. Perfetto, P.K. Chattopadhyay, and M. Roederer, Seventeen-colour flow cytometry: Unravelling the immune system, *Nat Rev Immunol* 4 (2004), 648–655.
6. M.A. McClain, C.T. Culbertson, S.C. Jacobson, and J.M. Ramsey, Flow cytometry of *Escherichia coli* on microfluidic devices, *Anal Chem* 73 (2001), 5334–5338.
7. N. Pamme, R. Koyama, and A. Manz, Counting and sizing of particles and particle agglomerates in a microfluidic device using laser light scattering: application of particle-enhanced immunoassay, *Lab Chip* 3 (2003), 187–192.
8. A. Wolff, I.R. Perch-Nielsen, U.D. Larsen, P. Friis, G. Goranovic, C.R. Poulsen, J.P. Kutter, and P. Telleman, Integrating advanced functionality in a microfabricated high-throughput fluorescent-activated cell sorter, *Lab Chip* 3 (2003), 22–27.
9. K.B. Mogensen, J. El-Ali, A. Wolff, and J.P. Kutter, Integration of polymer waveguides for optical detection in microfabricated chemical analysis systems, *App Opt* 42 (2003), 4072–4079.
10. O. Hofmann, X. Wang, A. Cornwell, S. Beecher, A. Raja, D.D. C. Bradley, A.J. deMello, and J.C. deMello, Monolithically integrated dye-doped PDMS long-pass filters for disposable on-chip fluorescence detection, *Lab Chip* 6 (2006), 981–987.
11. S. Balslev, A.M. Jorgensen, B. Bilenberg, K.B. Mogensen, D. Snakenborg, O. Geschke, J.P. Kutter, and A. Kristensen, Lab-on-a-chip with integrated optical transducers, *Lab Chip* 6 (2006), 213–217.
12. K.W. Ro, K. Lim, B.C. Shim, and J.H. Hahn, Integrated light collimating system for extended optical-path-length absorbance detection in microchip-based capillary electrophoresis, *Anal Chem* 77 (2005), 5160–5166.
13. C.L. Bliss, J.N. McMullin, and C.J. Backhouse, Integrated wavelength-selective optical waveguide for microfluidic-based laser-induced fluorescence detection, *Lab Chip* 8 (2008), 143–151.
14. S. Camou, H. Fujita, and T. Fujii, PDMS 2D optical lens integrated with microfluidic channels: Principle and characterization, *Lab Chip* 3 (2003), 40–45.
15. S.-K. Hsiung, C.-H. Lin, and G.-B. Lee, A microfabricated capillary electrophoresis chip with multiple buried optical fibres and micro-focusing lens for multiwavelength detection, *Electrophor* 5 (2005), 1122–1129.
16. J. Seo and L.P. Lee, Disposable integrated microfluidics with self-aligned planar microlenses, *Sens Act B* 99 (2004), 615–622.
17. Z. Wang, J. El-Ali, M. Engelund, T. Gotsaed, I.R. Perch-Nielsen, K.B. Mogensen, D. Snakenborg, J.P. Kutter, and A. Wolff, Measurements of scattered light on a microchip flow cytometer with integrated polymer based optical elements, *Lab Chip* 4 (2004), 372–377.

© 2011 Wiley Periodicals, Inc.

A NOVEL DOHERTY POWER AMPLIFIER WITH SELF-ADAPTIVE BIASING NETWORK FOR EFFICIENCY IMPROVEMENT

Shichang Chen and Quan Xue

State Key Laboratory of Millimeter Waves, Department of Electronic Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong SAR; Corresponding author: zjsxchensc@gmail.com

Received 14 February 2011

ABSTRACT: A Doherty power amplifier (DPA) with a self-adaptive biasing circuit is presented in this letter. The proposed structure is integrated into the gate biasing network of the peaking power amplifier (PA), and then the gate voltage can be adaptively adjusted with the input power. Due to the presence of this simple but effective circuit, the