

Direct UV Written Optical Waveguides in Flexible Glass Flat Fiber Chips

Faisal Rafiq Mahamd Adikan, Seyed Reza Sandoghchi, Chong Wu Yi, Robert Edward Simpson, Mohd Adzir Mahdi, Andrew Simon Webb, James Christopher Gates, and Christopher Holmes

Abstract—A glass-based substrate technology that fills the gap between a truly flexible extended length distributed sensor medium and the multifunctionality of optical chips is demonstrated. Flat fiber chips will open further degrees of freedom to control the behavior of light via mechanical manipulation. A flexible flat format will also allow straightforward incorporation into smart structures. Coupled with low manufacturing costs, these flexichips can also be a key enabler to disposable high-end sensing devices or fully distributed point sensors. In this study, Bragg gratings were used to demonstrate the optical flatness of the flat fiber core layer. Furthermore, the effective index values obtained from the grating experiment were input into a dynamic model, subsequently proving the influence of the dumbbell-shaped flat fiber cross section on the resultant UV written waveguides. Evanescent field sensing was also demonstrated by adopting a stepped Bragg approach.

Index Terms—Integrated optics, optical design and fabrication, sensors.

I. INTRODUCTION

A MECHANICALLY flexible optically flat glass substrate technology that allows incorporation of densely packed integrated photonic circuits and devices—planar chips in ribbon geometry [1]—combines the many advantages afforded by optical fibers and conventional optical chips. Contrary to their de-facto polymer-based counterparts, these glass substrates are inherently compatible with optical fibers, can withstand higher ambient temperatures, and are chemically inert. In the past, producing these substrates, and subsequently incorporating circuitries, requires multistage processing involving costly equip-

ment [2], [3], which are important considerations toward wider adoption and deployment. In this paper, a new substrate technology called flat fiber is introduced. Derived from optical fiber processes, the chips can be fabricated over kilometer-lengths, eliminating the size limitations of its predecessors. Important devices such y-splitters and Bragg gratings were incorporated into the substrate core layer via direct UV writing. One of the main beneficiaries of such flexichips is the increasingly important field of sensing.

II. FLEXIBLE EXTENDED LENGTH SENSOR CHIPS

The ubiquitous application of optical-based sensors in disparate fields, ranging from microfluidic to aerospace, oil and gas, and structural engineering [4]–[7] can be grouped into several categories depending on their sensing mechanism, physical make up, and what is being sensed. One way of looking at these sensors is whether they are fully distributed, or point (localized) sensors. A fully distributed sensor implies the use of optical fibers as both the sensing and transport medium. An example would be Brillouin-based sensors, which detect unique phonon footprints as its sensing mechanism. These sensors find use in detecting leakage along kilometers of submerged petroleum pipelines [7]. Point sensors, on the other hand, can exist in either fiber or integrated optical chip formats. Bragg-based sensors, for example, are generally considered as point sensors. Owing to advances in device fabrication in integrated optics, a number of these sensors could fit on millimeter-sized glass chips with the capability to sense multiple substances with index differences on the order of 10^{-6} [8]. Optical fibers are the natural choice when it comes to distributed sensing as they display low loss, are mechanically flexible, and can be fabricated over kilometer-lengths. The inert nature of glass also adds to their advantage. In contrast, integrated optical chips offer multifunctionality and batch processing, with the ability to include reference sensors that decouple the measurement from environmental factors such as temperature. The chips are, however, limited in size and mechanically rigid, making them susceptible to unwanted strain effects and resulting in polarization sensitivity. These effects discourage their wider deployment. The limitations of the planar format have stimulated the development of a substrate platform that, among other things, overcomes the mechanical and size limitations of its chip-like predecessor while maintaining the advantages of multifunctionality and dense form factor, thus, filling the gap between a truly flexible, distributed sensor medium, and the multifunctionality of optical chips. A flexible, extended length optical chip will open further degrees of freedom to control the behavior of light via mechanical manipulation also allowing incorporation into structures such as pillars

Manuscript received April 14, 2011; revised August 20, 2011; accepted October 3, 2011. This work was supported by the University of Malaya High Impact Research under Grant VC/HIR/012.

F. R. M. Adikan is with the Department of Electrical Engineering, Faculty of Engineering, and Photonics Research Centre, University of Malaya, Kuala Lumpur 50603, Malaysia (e-mail: rafiq@um.edu.my).

S. R. Sandoghchi is with the Department of Electrical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia (e-mail: rezasandoghchi@gmail.com).

W. Y. Chong is with the Photonics Research Centre, University of Malaya, Kuala Lumpur 50603, Malaysia (e-mail: wuyi80@yahoo.com).

R. E. Simpson is with the Innovation Research Center, Japanese National Institute for Advanced Industrial, Science and Technology, Tsukuba-shi 305-8568, Japan (e-mail: robert.simpson@aist.go.jp).

M. A. Mahdi is with the Department of Computer and Communication Systems Engineering, Universiti Putra Malaysia, Serdang, Selangor 43400, Malaysia (e-mail: mdadzir@eng.upm.edu.my).

A. S. Webb, J. C. Gates, and C. Holmes are with the Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, U.K. (e-mail: asw@orc.soton.ac.uk; jcg@orc.soton.ac.uk; chh@orc.soton.ac.uk).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/JSTQE.2011.2171921

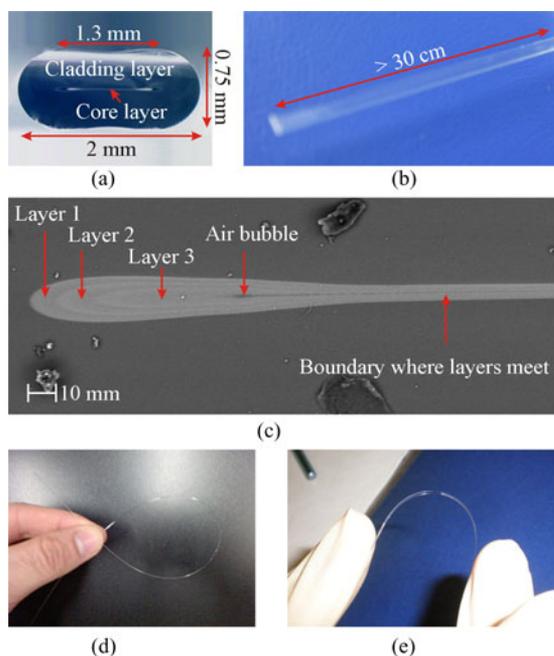


Fig. 1. Images depicting the flat fiber. (a) Cross section of a flat fiber, showing a “dumbbell-shaped” profile, with a thick cladding layer. (b) Perspective view of the sample, which can be fabricated to meter lengths. (c) SEM image of the core layer of the flat fiber, showing the air bubble. The core layer is seen to comprise of three layers, reflecting the number of MCVD passes made during the deposition process. (d) Illustration of the potential flexibility of flat fiber manufactured from a thin-wall glass substrate tube. (e) 5-cm length of flat fiber with 2-D mechanical flexibility.

in buildings and oil platforms. Coupled with low manufacturing costs, these flexichips can also be a key enabler to disposable high-end microfluidic sensing devices or fully distributed point sensors, ultimately enabling inexpensive, accurate detection of pollutants and perhaps more importantly identifying the pollution source and rate of diffusion.

Recently, one such attempt to produce these flexible extended length substrates resulted in what are referred to as flat fibers. Adapted from modified chemical vapor deposition (MCVD) fiber fabrication, hollow silica preforms with deposited core layers are produced and subsequently collapsed into a rectangular geometry by applying a vacuum during the fiber drawing process. This results in extended lengths of mechanically flexible flat glass [9]. Fig. 1(a) and (b) shows the flat fiber and its dimensions, while Fig. 1(c) shows an SEM image of the core layer of the flat fiber. The existence of an “air bubble” at the edge of the core where the initially circular preform was “squeezed” into a somewhat rectangular shape is also evident. The core layer is silica doped with germanium, boron, and phosphorous, thus promoting photosensitivity [10], [11].

The mechanical flexibility of the flat fiber in the longitudinal direction is a result of its dimensions. Reducing the thickness of the glass increases its flexibility and can be achieved simply by scaling down the preform further during the fiber drawing process. This, however, reduces both dimensions of the glass and limits the “usable” lateral width for waveguide inscription. Instead, a glass tube of thinner wall thickness can be used as the substrate which, when drawn into fiber, maintains a suitable area for UV-writing but a reduced cladding thickness. Trials have

indicated that maintaining the “rectangular” cross-sectional profile is more difficult using this approach but the overall flexibility is greatly improved, as shown in Fig. 1(d). A second option involves wet etching. Here, thick flat glass fibers were reduced in thickness to 200 μm by hydrofluoric acid treatment, thus, allowing fiber-like mechanical flexibility in a single plane, as depicted in Fig. 1(e).

In its current physical form, the only technique able to define waveguide structures within the sample’s core layer is direct laser writing. This can be in the form of femtosecond writing or direct UV writing, which relies on photosensitivity of the doped core layer. More complicated optically passive devices such as y-splitters and Bragg gratings have been fabricated in flat fiber using the latter approach [9]. In contrast to the more conventional photolithography technique, direct UV writing allows rapid prototyping of functional devices within short periods of time, and without the need of photolithographic masks.

Modeling of electromagnetic behavior within the resultant waveguides is nontrivial, since several parameters are unknown following UV writing, including the refractive index change, the resultant waveguide dimensions, and also other effects such as hydrogen out-diffusion [12]. In the case of flat fibers, the “dumbbell-shaped” cross-sectional profile, and the progressively thicker core layer approaching the extreme edges of the substrate where the air bubbles are located, adds to the complexity of the task. The ability to accurately model the channels within the flat fiber would permit an understanding of the more complicated physical behaviors that are unique to the sample, including access to the waveguide channels via both top and bottom surfaces, opening the possibility for asymmetrical excitations and glass polling.

In this manuscript, we show that Bragg gratings can be written along the cross section of flat fiber via direct grating writing (DGW) in order to investigate the optical flatness of the core layer. Effective refractive index values obtained from this experiment were then used in a dynamic model developed to determine parameters of the inscribed optical waveguides, namely the refractive index increase post-UV writing, the waveguide thickness, and width. The sensing abilities of flat fiber are then demonstrated.

For this study, the DGW technique was used to define Bragg gratings [13]. The technique involves utilizing the interference pattern generated by crossed UV laser beams ($\lambda_{UV} = 244 \text{ nm}$) and allows simultaneous definition of channel waveguides and grating structures. UV interference pattern is generated by crossing two tightly focused coherent UV beams at a fixed point in space. A photosensitive sample is then aligned with this interference spot and translated relative to it. If the writing laser is not modulated during the writing process (i.e., continuously on), the effect of the interference pattern is averaged out, producing channel waveguides similar to those achieved using single beam writing. An interference pattern is produced on the sample if the writing spot laser is modulated, thus producing grating structures. Successful fabrication using this approach places stringent requirements on the flatness of the core layer to ensure that the beams overlap throughout the duration of grating fabrication.

A series of identical gratings were defined along the cross-sectional width of a flat fiber sample. This allowed the lateral

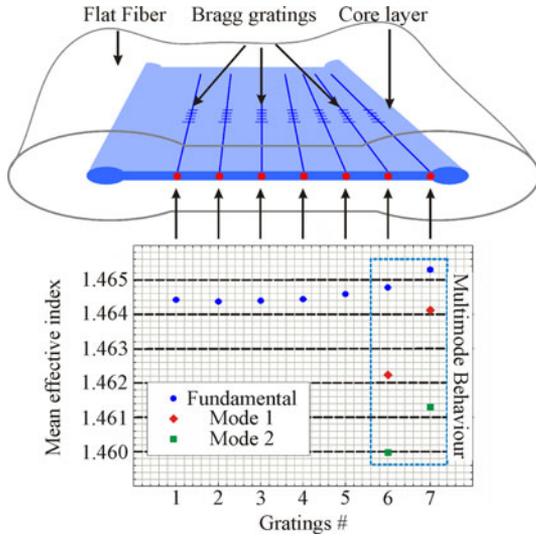


Fig. 2. Direct UV written Bragg gratings in flat fiber substrate. Mean effective refractive index variation across the cross section of the sample core layer. Gratings 6 and 7 exhibit multimode behavior as the core layer thickness increases approaching the edge (solid lines are for indicative purpose only).

surface uniformity of the flat fiber core to be determined. Gratings were spaced $100 \mu\text{m}$ apart such that variations in the cross-sectional thickness of the sample were apparent in the form of Bragg wavelength shifts. The UV dosage used, or generally referred to as fluence (as defined in [13]), was $14 \text{ kJ}\cdot\text{cm}^{-2}$. The variation of effective index across the cross section of the sample and the approximate location of each grating is shown in Fig. 2. In a separate experiment, the propagation loss of channels was found to be about $0.3 \text{ dB}\cdot\text{cm}^{-1}$ while their birefringence was around 3.3×10^{-4} . Despite the “dumbbell-shaped” profile of the flat fiber, the fact that gratings have been successfully demonstrated provides strong indication that the core layer of the sample is flat along the direction of propagation. This is also an important step in demonstrating the potential of these flat fiber substrates to play the role of fully distributed flexible point sensors. Also note that gratings 6 and 7 display multimode behavior that can be attributed to the increase in layer thickness approaching the edge of the sample, enabling higher modes to be supported.

Following early qualitative proof of flat fiber capabilities and characteristics, detailed quantitative characterization of flat fiber parameters and induced channel waveguides was performed. The refractive index values for both core n_{core} and cladding n_{clad} layers were experimentally found to be 1.4595 and 1.4550, respectively. These values were input into a model based on general wave and waveguide equations to determine both the refractive index increase following direct UV writing, and the actual dimensions and positions of the defined channels. The model generalizes the various possible combinations of the aforementioned parameters in the form of topological maps. A point on these maps indicates a possible solution to the underlying wave equations. Typical examples of these maps are shown in Fig. 3(a). For this study, the thickness of the waveguides was varied between 6 and $14 \mu\text{m}$. The width and refractive

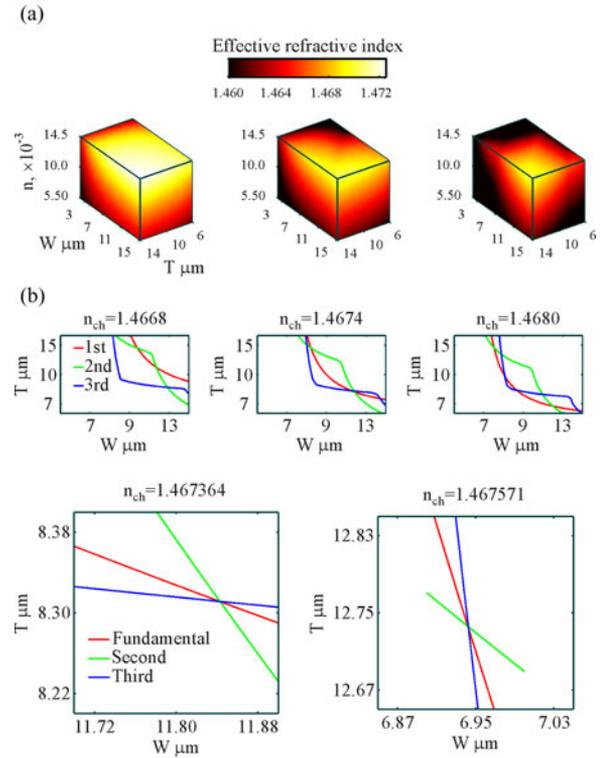


Fig. 3. Dynamic model developed to obtain actual refractive index increase post-UV writing, and the waveguide dimensions. Labels T , W , and n_{ch} represent the thickness, width and refractive index of the waveguides, respectively. (a) Topological maps generated that combines various waveguide parameters that will determine the effective index of a mode; from left to right: first, second, and third mode, respectively. (b) Intersection points of the dynamic model that provides the width, waveguide thickness, and refractive index values for channel 6. The smaller graphs at the top indicate the sequence in the iteration process in converging toward possible solution(s)/intersecting point(s). The larger graphs at the bottom depict the exact points of intersection, indicating possible solutions. By applying available experimental parameters, one of the solutions, in this case the one on the right was discarded.

index were kept between 3 and $15 \mu\text{m}$, and 1.460 and 1.472, respectively. Modal analysis was performed for each combination using finite-element method, producing effective index value(s), with some conditions producing multimodal behavior. Multimodal channels with multiple effective index value would generate a single plane and the point where all the planes intersect would determine the correct combination of the unknown parameters. This process is shown in Fig. 3(b) where the effective index values for channel 6 were input to the model.

Since all seven channels were fabricated under identical UV writing conditions, the waveguide width and index increase is the same. As such, the difference in effective index values (as indicated in Fig. 2) is attributed to the thickness variation of the flat fiber’s core layer. To this end, a relation between waveguide thickness and effective refractive index was developed using the dynamic model. The actual thickness values were measured by SEM and were found to be consistent with those calculated by the aforementioned model (see Fig. 4). Despite the $100 \mu\text{m}$ spacing between two adjacent gratings, it is evident that the

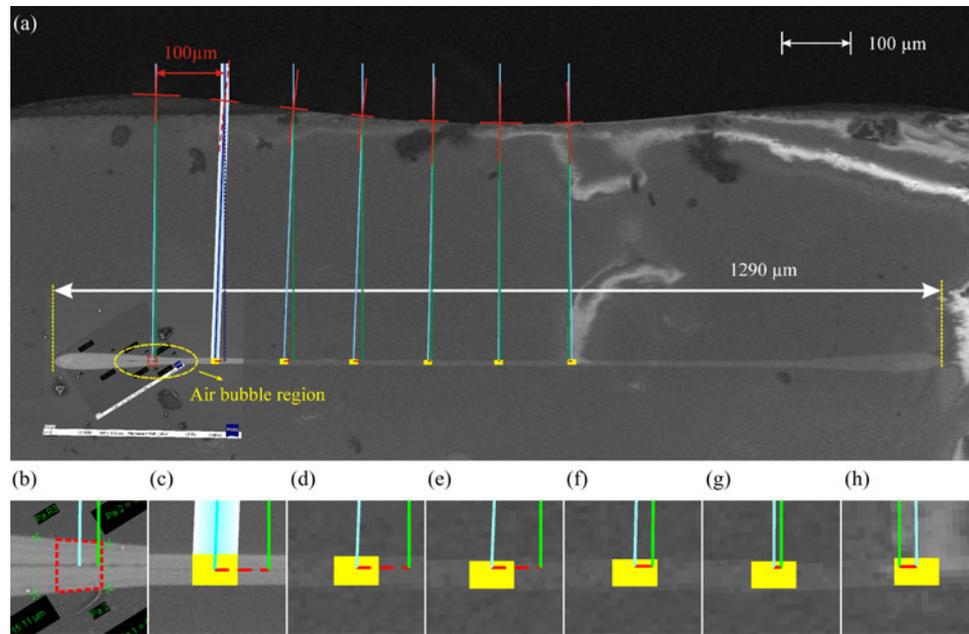


Fig. 4. SEM imaging of the flat fiber cross section. (a) Composite image of the flat fiber with channels spaced $100\ \mu\text{m}$ apart, in accordance to experimental settings. The locations indicated by the yellow boxes were calculated using the dynamic model, and then validated experimentally. (b) Location of channel 7 is determined to be within the air bubble, thus producing anomalous effective index values. (c)–(h) Green line indicates the expected position of the channels as derived from the UV writing parameters whereas the blue line indicates the actual path taken by the refracted UV beam. The yellow boxes indicate the calculated dimensions of the UV written channels. It can be seen that these calculated values match the thickness of the core layer perfectly for all seven channels.

resultant UV written channels were spaced unevenly along the cross section. This was due to the contour of the cladding layer, refracting the UV beam as it travels toward the core layer. This is shown by the blue and green lines in Fig. 4.

Further calculations were performed in order to match the simulated values with those measured for channel 7. The measured effective index values for channel 7 could not be obtained under the typical consideration of core–cladding boundary conditions. An attempt to do so would generate channel parameters that are not achievable under similar conditions to the other six channels. It was discovered that this peculiar modal behavior exhibited by channel 7 is due to the presence of the air bubble. It was also found that the air bubbles are not dimensionally uniform along the propagation axis, and this is currently the subject of further investigations.

Finally, to demonstrate sensing capabilities via evanescent field interaction with the surrounding medium, one side face of the flat fiber was polished back to expose the core layer. This would prevent from having to etch more than $300\ \mu\text{m}$ deep to create an interaction window on top of the sample to gain access to the gratings. A series of 1-mm-long Bragg gratings stepped closer to the polished edge were UV written, as depicted in Fig. 5(a). The final grating is in close proximity to the edge. Owing to the staggered or stepped design of the gratings location, the corresponding evanescent fields of each grating will have different penetration depths into the substance that surrounds it. The approach enables distinguishing of bulk index changes from those limited to the surface by comparing each of the Bragg wavelength shifts. Fig. 5(b) depicts the Bragg shifts

when exposed to both air and refractive index oil with index of 1.3. The s-bend structures employed in realizing the staggered configuration, coupled with the level of photosensitivity of the sample used, resulted in weak gratings. However, the Bragg peaks are distinguishable, and work in optimizing UV writing parameters to ensure stronger peaks are underway. The wavelength shift of the grating closest to the edge is $400\ \text{ps}$, resulting from the interaction between the evanescent field in grating 4 and the refractive index oil. These results provide further support to the realization of a fully flexible multifunctional sensor chip, as depicted schematically in Fig. 5(c). However, issues pertaining to the use of practical lasers, the duration of the writing, which will depend on the length of these sensors and the propagation loss of the chip will need addressing before a fully deployable technology can be adopted.

In conclusion, the demonstrated flat fiber represents a new exciting field of research that brings together diverse areas of science such as materials, fabrication process, integrated optics, and optical fibers. The results presented in this manuscript highlight the potential of this new substrate in filling the gap between optical fiber as a transport and sensing medium, and integrated optics. Electromagnetic interaction within close proximity to the air bubble, the dumbbell-shaped cross-sectional profile, higher flexibility, asymmetrical surface interaction, and the inclusion of photonic crystal structures are some examples of the work that will emerge from this new technology. It is also hoped that the technology will pave way to new applications involving sensors and integrated devices, particularly those requiring both fully distributed and point interaction capabilities.

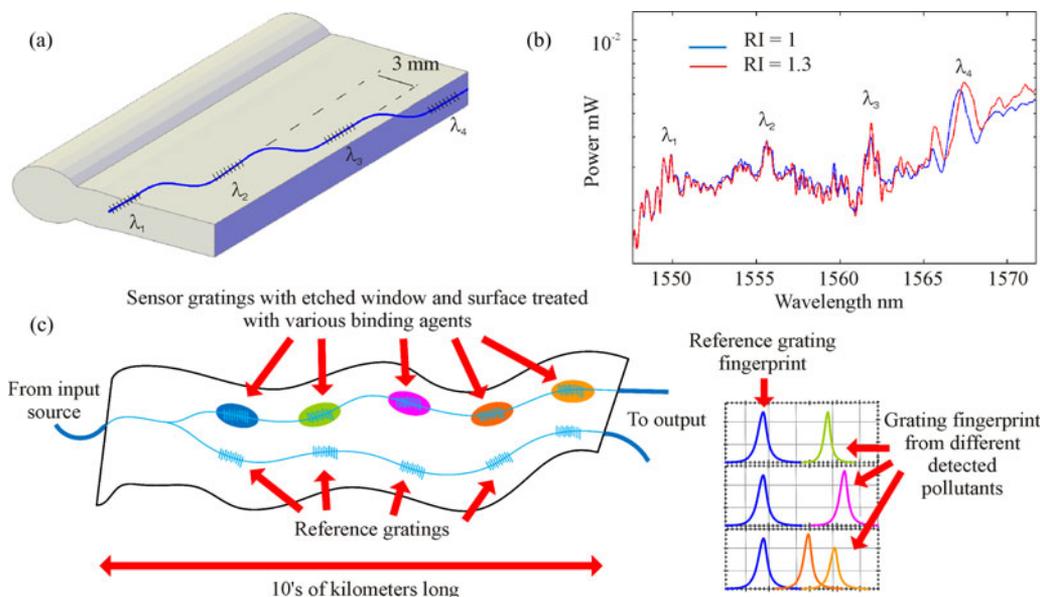


Fig. 5. Flat fiber as a sensing medium. (a) Schematic diagram of a cleaved and surface polished flat fiber with “stepped” Bragg gratings. (b) Bragg wavelength shift with change in surrounding medium. (c) Conceptual depiction of a fully flexible flat fiber distributed point sensor. The ability to also include other devices such as y-splitters and reference gratings underlines the multifunctionality of the chip, which in this case, can be deployed over kilometer-distances. Surface treatment of the etched windows would allow for sensing of multiple pollutants where each pollutant displays a unique Bragg fingerprint.

REFERENCES

- [1] J. Lousteau, G. Jose, D. Furniss, A. B. Seddon, T. M. Benson, and A. Jha, “A novel approach for the fabrication of planar waveguides from heavy metal oxide glasses,” *J. Non-Crystalline Solids*, vol. 355, pp. 1973–1979, 2009.
- [2] D. Harwood, “Fabrication of substrates for planar waveguide devices and planar waveguide devices,” Great Britain Patent WO/2002/046113, Jun. 13, 2002.
- [3] G. E. Berkey, L. A. Moore, and M. D. Pierson, “Projection lithography photomasks and method of making,” U.S. Patent 6 689 516, 2004.
- [4] C. Monat, P. Domachuk, and B. J. Eggleton, “Integrated optofluidics: A new river of light,” *Nature Photon.*, vol. 1, pp. 106–114, 2007.
- [5] D. Psaltis, S. R. Quake, and C. Yang, “Developing optofluidic technology through the fusion of microfluidics and optics,” *Nature*, vol. 442, pp. 381–386, 2006.
- [6] D. Graham-Rowe, “Sensors take the strain,” *Nature Photon.*, vol. 1, pp. 307–309, 2007.
- [7] H. Nakstad and J. T. Kringlebotn, “Oil and gas applications: Probing oil fields,” *Nature Photon.*, vol. 2, pp. 147–149, 2008.
- [8] S. Watts, “Bragg gratings: Optical microchip sensors,” *Nature Photon.*, vol. 4, pp. 433–434, 2010.
- [9] A. S. Webb, F. R. M. Adikan, J. K. Sahu, R. J. Standish, C. B. E. Gawith, J. C. Gates, P. G. R. Smith, and D. N. Payne, “MCVD planar substrates for UV-written waveguide devices,” *Electron. Lett.*, vol. 43, pp. 517–519, 2007.
- [10] D. L. Williams, B. J. Ainslie, J. R. Armitage, R. Kashyap, and R. Campbell, “Enhanced UV photosensitivity in boron codoped germanosilicate fibres,” *Electron. Lett.*, vol. 29, p. 45, 1993.
- [11] K. O. Hill, Y. Fujii, D. C. Johnson, and B. S. Kawasaki, “Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication,” *Appl. Phys. Lett.*, vol. 32, pp. 647–649, 1978.
- [12] M. Svalgaard, “Effect of D₂ outdiffusion on direct UV writing of optical waveguides,” *Electron. Lett.*, vol. 35, pp. 1840–1842, 1999.
- [13] G. D. Emmerson, C. B. E. Gawith, S. P. Watts, R. B. Williams, P. G. R. Smith, S. G. McMeekin, J. R. Bonar, and R. I. Laming, “All-UV-written integrated planar Bragg gratings and channel waveguides through single-step direct grating writing,” *IEE Proc. Optoelectron.*, vol. 151, pp. 119–122, 2004.



Faisal Rafiq Mahamd Adikan received the Ph.D. degree from the Optoelectronics Research Centre, University of Southampton, Southampton, U.K., in 2007. His Ph.D. research was focused on flat fiber and produced an international patent.

He is currently the Head of the Photonic Light-wave Circuit Group in the Photonics Research Centre, University of Malaya, Kuala Lumpur, Malaysia, and is involved in developing novel fabrication processes to incorporate optically active materials into a glass matrix. He specializes in glass-based integrated optical devices for use in telecommunication and sensing applications. Apart from research and teaching, he is also an active member of the Faculty of Engineering, holding a number of administrative posts including the Coordinator of the Telecommunication Engineering program. He has published more than 70 journal and conference papers on optics and engineering education. He also deputy-chaired two Technical Postgraduate Symposiums, and is the current chairman for the Sports and Recreational Club, Faculty of Engineering. He also established the Junior Lecturer Forum, an informal platform for young staff members to discuss matters concerning career development.

Dr. Rafiq was the recipient of the Section Prize for the Best Engineering Research during Presentations at the House of Common (British Parliament) in 2006. He also received the SPIE Educational Scholarship in Optical Science and Engineering in 2004, and the Best Paper for Photonic Category during an international conference in 2003.



Seyed Reza Sandoghchi received the B.Eng. degree (Hons.) with first class in telecommunication engineering in electrical engineering from the Sadjad Institute of Higher Education, Mashhad, Iran, in 2005 and the M.Eng. degree in electrical engineering from the University of Malaya, Kuala Lumpur, Malaysia. His dissertation investigates the refractive index profile characterization methods.

His research works mainly include modeling and simulation of optical devices, and developing characterization systems. He has been involved in establishment of fiber drawing facilities in the University of Malaya, where he is currently with optical fiber fabrication team in Flat Fibre Laboratory.



Chong Wu Yi received the B.S. degree in physics and the M.S. degree from the University of Malaya, Kuala Lumpur, Malaysia, in 2003 and 2007, where he is currently working toward the Ph.D. degree at the Photonics Research Centre.

He has been involved in the research of fiber amplifiers and planar lightwave circuit fabrication. His current research interests include ultrafast laser-matter interaction, direct laser writing as well as laser micro- and nanomachining.



Robert Edward Simpson received the Ph.D. degree from the Optoelectronics Research Centre, University of Southampton, Southampton, U.K., where he studied optically induced transitions in chalcogenide glasses.

He is currently with the Japanese National Institute for Advanced Industrial Science and Technology, where he is also involved in research on phase transitions in superlattice data-storage materials.

Dr. Simpson received a two-year fellowship from the Japanese Society for Promotion of Science to

study at the Japanese National Institute for Advanced Industrial Science and Technology, in 2008.



Andrew Simon Webb received the B.Sc. degree in physics and electronics from Keele University, Staffordshire, U.K., in 1988. He is currently working toward the Ph.D. degree at the University of Southampton, Southampton, U.K.

Since 2001, he has been a Silica Fiber Fabrication Engineer at the Optoelectronics Research Centre, University of Southampton. He has co-authored more than 30 publications and patents. His current research interests include developing novel MCVD rare-earth doped preform fabrication techniques, optical fiber drawing, and production of specialty optical fibers.

Mr. Webb is a member of the Institute of Engineering and Technology, a member of Institute of Physics, and a Student Member of the Optical Society of America.



Mohd Adzir Mahdi (SM'04) received the bachelor's degree (Hons.) with first class in electrical, electronics and system engineering from the Universiti Kebangsaan Malaysia, Selangor, Malaysia, in 1996. Later, he received the master's and Ph.D. degrees with distinctions in optical fiber communications from the University of Malaya, Kuala Lumpur, Malaysia, in 1999 and 2002, respectively.

Since January 2003, he has been with the Faculty of Engineering, Universiti Putra Malaysia, where he was an Associate Professor and is now a Full Professor.

Prior to the current appointment, he was an Optical Design Engineer at IOA Corporation, Sunnyvale, CA and a Research Officer at Research and Development Division, Telekom Malaysia Berhad. He was a Visiting Researcher at Marconi SpA, Genova, Italy, Monash University, Victoria, Australia, Chalmers University of Technology, Gothenburg, Sweden, Hong Kong Polytechnic University, University of California, Davis, and Georgia Institute of Technology, Atlanta. Since 1996, he has been involved in photonics research specializing in optical amplifiers and lasers. He has authored and coauthored more than 340 scientific papers in journals and conference proceedings. His research interests include optical fiber amplifiers and lasers, optical fiber communications, and nonlinear optics.

Dr. Mahdi is a member of the Optical Society of America, and the International Association of Engineers. He received the IEEE LEOS Graduate-Student Fellowship, the Australia-Malaysia Institute Research Fellowship, the Leading Scientists and Engineers of OIC Member States (COMSTech), the COMSTech Young Scientist, and the TWAS Young Affiliate Fellow.



James Christopher Gates received the M.Phys. degree in physics from the University of Southampton, Southampton, U.K. in 1999, and the Ph.D. degree from the Optoelectronics Research Centre, University of Southampton, in 2003. His Ph.D. thesis investigated the optical properties of various photonic devices at a nanometre scale using an interferometric near-field technique.

He continued researching in the field of nanophotonics in the Department of Physics, University of Southampton, before returning to the ORC in the same university in 2006. He is currently a Research Fellow at the ORC. He is currently developing planar integrated optical devices for a wide range of applications in telecommunications and detection.



Christopher Holmes received the Ph.D. degree from the Optoelectronics Research Centre (ORC), University of Southampton, Southampton, U.K., where he studied direct UV written waveguide devices.

He is currently a Researcher at ORC, and his research work focuses on new fabrication techniques via micromilling in creating cantilevers and flat fiber sensors.