Metal Grating Patterning on Fiber Facets by UV-Based Nano Imprint and Transfer Lithography Using Optical Alignment

Stijn Scheerlinck, *Student Member, IEEE*, Peter Dubruel, Peter Bienstman, *Member, IEEE*, Etienne Schacht, Dries Van Thourhout, *Member, IEEE*, and Roel Baets, *Fellow, IEEE*

***Abstract*—UV-based nano imprint and transfer lithography (NITL) is proposed as a flexible, low cost and versatile approach for defining sub-micron metal patterns on optical fiber facets in a single-processing step. NITL relies on a specially prepared mold carrying the pattern that is to be transferred to the facet. The fiber's light-guiding properties allow control of the position of the metal structures by optical alignment.**

***Index Terms*—Alignment, gold grating, nano imprint lithography, optical fiber, silicon-on-insulator.**

I. Introduction

TAILORING the optical properties of materials by nanostructuring is an important area of research. Metallic nanostructures in particular have recently attracted a lot of interest. Resonant field enhancement [1], sub-wavelength field confinement [2] and strong diffraction properties [3] are currently investigated by several groups. Integration with optical devices such as lasers, laser diodes or optical fiber facets is thereby regarded a promising route to exploit the potential of these metallic nanostructures for highly miniaturized, portable and potentially cheap devices for applications ranging from surface enhanced Raman scattering (SERS) and chemical/biological sensing to near-field optical microscopy, optical data storage and circuit probing [4]–[6].

The fabrication of such integrated components on small facets is rather challenging. It requires a top-down approach allowing for deep sub-wavelength resolution patterning with nanometer accuracy on very small substrates. This is not straightforward as various conventional steps for high resolution patterning such as spin coating or etching are very challenging—if not impossible—on this type of substrates. Although direct-write techniques such as electron-beam lithography and focused ion beam (FIB) milling have been developed for small facet patterning, these approaches are only interesting for prototyping [7]–[9]. They are time-consuming, require pre- and/or post-processing steps, are lacking flexibility towards choice of materials and compromise optical material characteristics [10]. Moreover, they are not suitable for parallel fabrication. An interesting approach to solve these problems while offering a route to parallel fabrication of metal nanopatterned optical fibers was demonstrated in [11], where a nanoscale aperture is fabricated by FIB milling and subsequently transferred to the fiber by molding and bonding. However, several processing steps are necessary after the molding to mechanically align the metal structure with nano-aperture to the fiber core.

Nano imprintlithography is emerging as a large scale and cost-efficient method for very high resolution patterning [12]. The primary advantage of nano imprintlithography is its ability to beat the diffraction limit of light and make features in the submicrometer and nanometer regime whereby the resolution is only limited by the resolution of the mold. Nano imprintlithography is also recognized for its flexibility towards choice of materials and shapes to be structured [13]. Although a UV-based NIL process has been demonstrated on fiber facets [14], there exist few or no reports of NIL-based metal nanopatterning on small facets.

In previous work, we proposed a nano imprint and transfer (NITL) technique to define submicron period metal gratings on fiber facets [6]. We demonstrated an active alignment scheme to align the gratings with the optical fiber core in a single processing step. We applied this technique for the fabrication of optical fiber probes for photonic integrated circuits based on a waveguide-to-fiber gold grating coupler [15].

In this work, we describe the UV-NITL fabrication process in more detail. In particular, we focus on two different alignment schemes and discuss the experimental results.

II. Fabrication

A. Process Flow

The principle of UV-NITL for metal patterning of fiber facets is depicted by the process flows (a), (b), and (c) in Fig. 1. Process flow (a) is an illustration of the standard UV-NITL process. The standard process starts from a straight-cleaved fiber and a

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S. Scheerlinck, P. Bienstman, D. Van Thourhout, and R. Baets are with the Photonics Research Group, Department of Information Technology (INTEC), IMEC-Ghent University, 9000 Gent, Belgium (e-mail: stijn.scheerlinck@intec.ugent.be; Peter.Bienstman@intec.ugent.be; Dries.Vanthourhout@intec.ugent.be; Roel.Baets@intec.ugent.be).

P. Dubruel and E. Schacht are with the Biomaterials Research Group, Department of Organic Chemistry, 9000 Gent, Belgium (e-mail: peter.dubruel@ugent.be; Etienne.Schacht@ugent.be).

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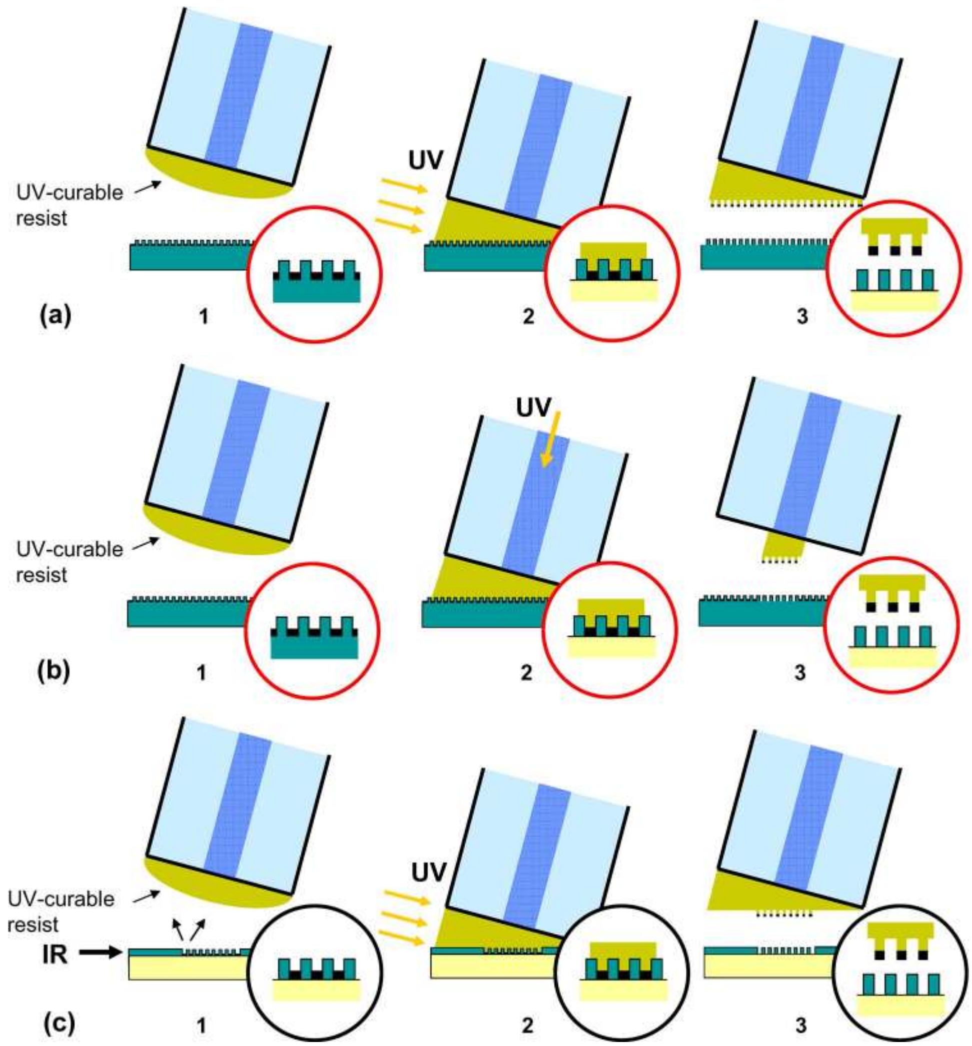

Fig. 1. UV-nano imprint and transfer lithography (NITL) on a fiber facet using a specially prepared mold carrying the metal pattern in the mold trenches. (a) Standard UV-NITL process: (1) positioning of the fiber with low-viscous UV-curable resist, (2) imprinting and curing by external UV-irradiation, (3) pattern transfer and mold release. (b) Self-aligned UV-NITL process: (1) positioning, (2) imprinting and UV-curing through the fiber core, (3) pattern transfer and mold release. (c) UV-NITL using active alignment: (1) power-monitored positioning of the fiber with low-viscous UV-curable resist using infrared light scattered out of the mold waveguide, (2) imprinting and curing by external UV-irradiation, (3) pattern transfer and mold release.

specially prepared mold. The mold acts as carrier of the metal pattern that is to be transferred to the fiber facet. In particular, the mold trenches are partially filled with the metal, whereas no metal is present on the top of the features (see the insets of Fig. 1). The process consists of three steps. First, a low-viscous UV-curable resist is allowed to fill the space between the fiber facet and the mold cavities. Second, the resist is cured and adheres to the metal in the trenches. Finally, the fiber is removed from the mold whereby the metal pattern is transferred from the carrier to the fiber.

The major advantage of this technique is in the transfer of the nanostructures. The processing difficulties due to the small size of the fiber facet are solved by applying the lithography processes themselves to a carrier chip or wafer of larger size and by transferring the fabricated structures from the larger carrier to the much smaller fiber facet. The molds can thus be fabricated using rather conventional lithography processes such as e-beam lithography, focused ion beam (FIB) milling or deep-UV (DUV) lithography. This allows fabricating nanoscale features of very high accuracy. The subsequent transfer of the structures requires further preparation of the molds. This is the subject of the next paragraph.

Another advantage is in the use of a low-viscous resist. The polymer can be applied in a straightforward manner by dipping the fiber into the resist. The low viscosity of the resist allows for rapid and flexible patterning. In particular, by tilting the fiber, the pattern can be defined at a non-perpendicular angle with respect to the optical fiber axis.

A further advantage is the alignment capability of the UV-NITL process. With alignment, we mean that the position of the metal pattern with respect to the fiber core can be controlled. A first option is self-alignment, illustrated by process flow (b) in Fig. 1. A second option is active alignment illustrated by process flow (c) in Fig. 1. Both will be demonstrated in the next section.

Although the fabrication principles described in this paper are focused towards metal patterns, the processes can be adapted towards other materials like dielectrics or semiconductors. The

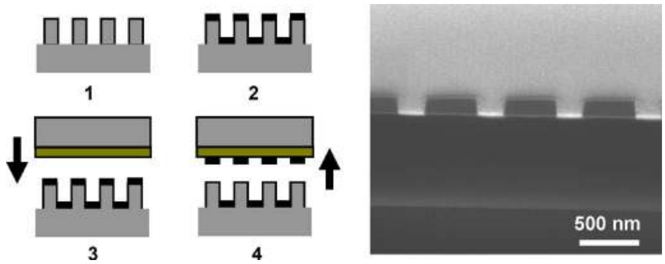

Fig. 2. Left: mold preparation for the UV-NITL process. 1) Anti-adhesion treatment. (2) Metal evaporation. 3) Contact with a sticky substrate. 4) Mold release. Right: SEM-picture of the mold after the preparation process: the mold carryies the metal pattern in the trenches.

principle of NITL as described above is based on adhesion control between the different materials involved. Asymmetry in adhesion between the metal and the resist and between the metal and the mold allows the metal pattern to be transferred from mold to fiber. Adhesion control is obtained by appropriate mold preparation.

B. Mold Preparation

The preparation of the mold is done in the following way, schematically depicted in Fig. 2(a). First, the mold is treated with an anti-stiction coating. Then metal is evaporated. A second substrate with a sticking layer is brought into contact with the mold so that the metal on top of the mold features is transferred from the carrier substrate to the sticky substrate. What is left, is the original mold carrying the metal pattern in the mold trenches. The initial anti-adhesion treatment of the mold is necessary to minimize adhesion between the silicon and the UV-curable resist and between the silicon oxide and the gold layer during the transfer process. The mold preparation process described here can be carried out on a chip- as well as on a waferscale.

We prepared an SOI mold with 220 nm top silicon layer and a 2 μm thick buried oxide layer. The fabrication of gratings was done on a 200 mm SOI wafer using DUV lithography and ICP etching of the top silicon layer. The grating depth was thus fixed to 220 nm. The wafer was cut into pieces and the rest of the process described here was carried out on a 2 cm $\times$ 2 cm mold substrate. The anti-adhesion coating of the SOI mold was applied by silanisation using (tridecafluoro-1,1,2,2-tetrahydrooctyl)trichlorosilane ($C_8H_4Cl_3F_{13}Si$, ABCR GmbH) in a pentane solution (0.1%) and subsequent rinsing using acetone, IPA and water. The trichlorosilane groups react with the surface hydroxyl groups under separation of HCl and an anti-adhesion layer was formed at the surface [16]. Next, 20 nm of gold were evaporated onto the mold by Joule evaporation. The position of the sample with respect to the evaporation boat was carefully controlled in order to obtain a high degree of directionality during the evaporation process so that very little metal is deposited on the sidewalls. The mold was then brought into contact with a silicon substrate which was made sticky by spin-coating a 200 nm layer of BCB (BenzoCycloButene, Cyclotene 3022-35, Dow Chemicals). During contact a pressure of 1 bar was applied and the substrates were heated to a temperature of 150 degrees C for good adhesion between the gold on the top grating lines and the BCB. The cross section picture in Fig. 2 was taken after removal of the sticky substrate: it shows that the gold on top of the grating lines was successfully removed while the gold in the trenches remained. It also shows that no gold is present on the sidewalls.

III. Experimental Results

UV-NITL was used to fabricate gold gratings on fiber facets. Each fiber was prepared by completely stripping the capping of the fiber and cleaning with IPA (iso-propyl alcohol). Then, the fiber was cleaved using a standard fiber cleaver tool. The mold chip was prepared as described above and put on a vacuum chuck to remain fixed. The fiber was mounted on a micro-mechanical x,y,z-stage. A drop of low-viscous UV-curable resist was dispensed onto the mold (PAK-01, Toyo Gosei Co.) and the fiber was dipped into the drop before being moved to the position of the grating. Then, the drop was squeezed between the fiber facet and the mold by bringing the fiber closer to the mold surface. Doing so, the mold cavities formed by the nanopattern were filled with the resist. After curing by UV-light at room temperature, the fiber was lifted from the mold. Fig. 3 depicts the result of fabricating a one-dimensional 630 nm period gold grating on the fiber according to the three different process flows depicted in Fig. 1. We discuss the results in the following.

A. Standard Process

Fig. 3(a.1) and (a.2) show the result of the UV-NITL process as depicted in Fig. 1(a) after UV-irradiation. The full grating area on the mold was 500 μm $\times$ 1000 μm. The gold grating area transferred to the fiber is defined by the area of the resist volume in contact with the mold. It is slightly bigger than the cross section of the fiber cladding.

B. Self-Alignment

A key advantage of UV-NITL on fiber facets is the ability to control the position of the pattern using the light guiding properties of either fiber or mold. Alignment of the metal pattern to the fiber core is important for those applications where maximal interaction with the optical fiber mode is wanted.

Self-alignment is a very elegant solution to align the grating with the fiber core. Fig. 3(b.1) and (b.2) show the result of the UV-NITL process as depicted in Fig. 1(b). This technique is based on UV-curing through the fiber core so that only the cylinder-shaped resist volume extending from the fiber core gets cured. Consequently, the imprint and transfer of the metal occurs only for the area of this volume in contact with the mold. As a result the metal pattern is perfectly aligned with the fiber core.

In this case the full grating area on the mold was 10 μm $\times$ 10 μm. The single-mode fiber had a core-diameter equal to 9 μm. The fiber was tilted 10 degrees with respect to the vertical. UV-light was applied through the fiber core by connecting the output of an EFOS Ultracure 100ss-plus system with the connector of the single-mode fiber. Curing time was set to 300 s. Remaining uncured PAK-01 was removed by dispensing IPA onto the fiber end and subsequent blow-drying.

The elliptical shape of the grating area is explained by the fiber tilt. Left of the grating in Fig. 3(b.2) some excess material

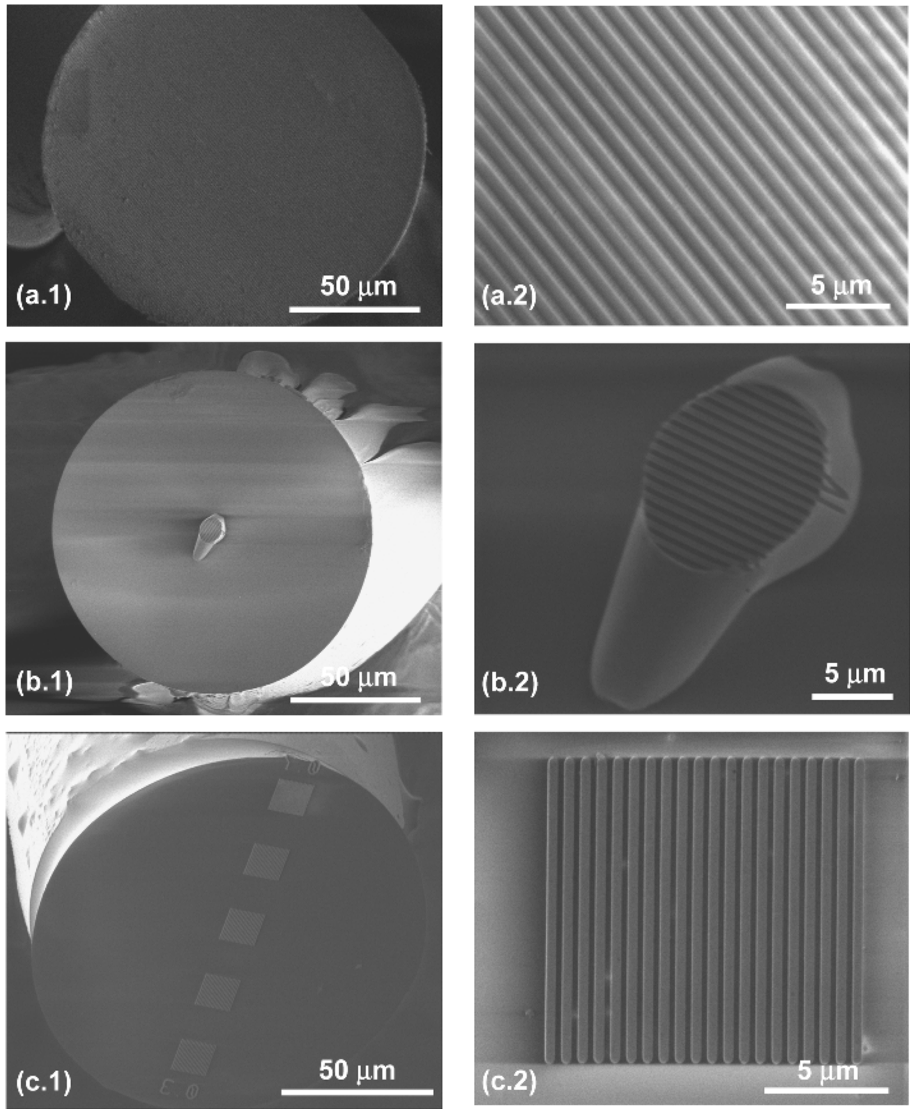

Fig. 3. SEM pictures of metal gratings on fiber facets fabricated by UV-NITL. (a) UV-NITL of a gold grating. (a.1) Facet view. (a.2) Detail of the grating. (b) UV-NITL of a gold grating using self-alignment by UV-curing through the fiber core. (b.1) Facet view. (b.2) Detail of the grating. (c) UV-NITL of gold gratings using active alignment. (c.1) Facet view. (c.2) Detail of the central grating.

can be seen. These are pieces of the gold grating lines that did not break off at the edge of the cured polymer portion but a bit further. This problem is inherent to the self-alignment process and gets worse when thicker metal layers are transferred. However, it is limited to one-dimensional periodic patterns. With 2-D patterns, such as metal dots instead of lines, this problem does not occur. We note that the self-alignment process also works successfully with multimode fibers.

Components fabricated by the self-aligned UV-NITL process are critically subject to damage and handling. The smaller the size of the core and the larger the tilt of the fiber, the more fragile is the fabricated component. For some applications this might not be a problem. For those applications where the fragility is problematic, an active alignment procedure is preferred instead of self-alignment.

C. Active Alignment

Fig. 3(c.1) and (c.2) show the result of the UV-NITL process as depicted in Fig. 1(c) after UV-irradiation. This technique is made possible by designing the mold in such a way that it contains a waveguiding layer. The silicon-on-insulator (SOI) material system is very well suited for this purpose with the top silicon layer serving as a lossless waveguide for infrared light.

The alignment works as follows. The fiber is connected to a power meter and infrared light is coupled into the silicon waveguide layer of the mold. When the light enters the grating zone it is scattered out of the waveguide. The amount of scattered light captured by the fiber is monitored by the power meter and allows optimization of the fiber's position by in-plane translation.

Scattering of light out of an SOI waveguide by a 630 nm period gold grating in the trenches is illustrated by the field plot in Fig. 4(a). The amount of light captured by the fiber is calculated using CAMFR, a 2-D fully vectorial simulation-tool based on eigenmode expansion and mode propagation with perfectly matched layer (PML) boundary conditions [17], and plotted in Fig. 4(b). It is clear from the graph that the optimal position of the fiber for which most of the scattered light is captured, is at

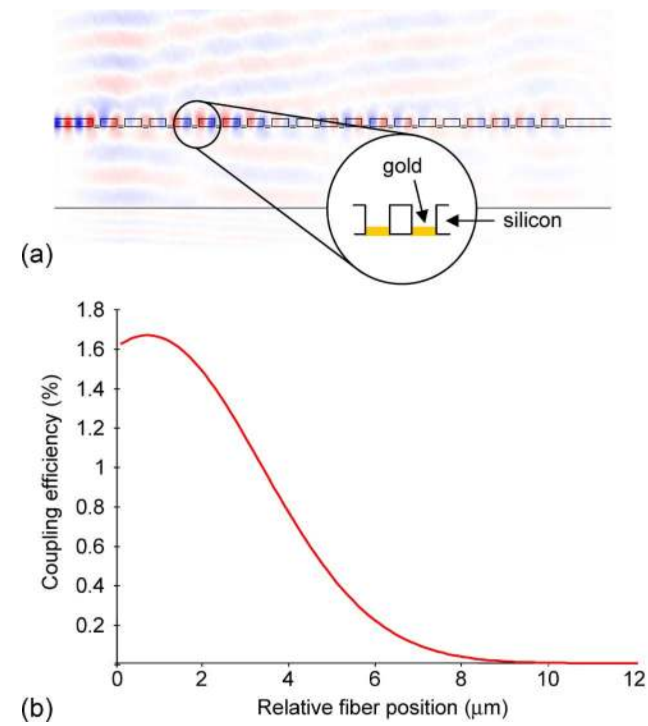

Fig. 4. (a) Light scattered by a gold grating in the trenches of a 630 nm period grating in the top silicon layer of an SOI waveguide. (b) Coupling efficiency of the scattered light as a function of fiber position.

about 1 μm from the edge of the grating. This point can serve as a reference point for further alignment of the grating pattern to the fiber core.

Gratings of size 10 μm $\times$ 10 μm with different filling factors and gold in the trenches were defined on the mold. The fiber was tilted 10 degrees with respect to the vertical. Light from a broadband superluminescent LED (SLED) source with central wavelength of 1535 nm was sent into the top silicon waveguide layer of the mold. The fiber was connected to a photodetector. By moving the fiber over the grating area, the optimal position could be found and the whole system was irradiated with UV-light after an additional translation of 3 μm of the fiber into the direction of the grating. The result after curing is shown in Fig. 3(c.1) and (c.2). As the full area of the resist in contact with the mold was irradiated, the neighbouring gratings with different filling factors were also transferred.

The active alignment process described here allows aligning gratings with a small footprint to the fiber core while the intermediate polymer layer that connects the gold grating with the fiber serves as a support. To this end, components made by the active-alignment process with UV-curing from an external source are much less fragile than components made by the self-alignment process.

We note that the fabricated component is an interesting candidate for wafer-scale probing and testing of SOI nanophotonic integrated circuits [6]. Such a probe requires accurate control of the metal grating to the fiber core and control of the angle of the grating plane with respect to the optical fiber axis.

IV. Conclusion

In this paper, a novel approach for single-step metal nanopatterning fiber facets is demonstrated: UV-based imprint and transfer lithography (NITL). The process starts from a specially prepared mold carrying the desired metal pattern in the mold trenches and relies on a low-viscous UV-curable resist applied between mold and straight-cleaved fiber to transfer the pattern onto the fiber facet. Optical alignment procedures were described and demonstrated including a self-alignment process and an active alignment process. The fabrication results were discussed.

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References

[1] D. A. Genov, A. K. Sarychev, V. M. Shalaev, and A. Wei, "Resonant field enhancements from metal nanoparticle arrays," *Nano Lett.*, vol. 4, pp. 153–158, 2004.
[2] W. L Barnes, A. Dereux, and T. W. Ebbesen, "Surface plasmon subwavelength optics," *Nature*, vol. 424, pp. 824–830, 2003.
[3] S. Scheerlinck, J. Schrauwen, F. Van Laere, D. Taillaert, D. Van Thourhout, and R. Baets, "Efficient, broadband and compact metal grating couplers for silicon-on-insulator waveguides," *Opt. Exp.*, vol. 15, pp. 9639–9644, 2007.
[4] E. Cubukcu, E. A. Kort, K. B. Crozier, and F. Capasso, "Plasmonic laser antenna," *Appl. Phys. Lett.*, vol. 89, p. 093120, 2006.
[5] E. J. Smythe, E. Cubukcu, and F. Capasso, "Optical properties of surface plasmon resonances of coupled metallic nanorods," *Opt. Exp.*, vol. 15, pp. 7439–7447, 2007.
[6] S. Scheerlinck, D. Taillaert, D. Van Thourhout, and R. Baets, "Flexible metal grating based optical fiber probe for photonic integrated circuits," *Appl. Phys. Lett.*, vol. 92, p. 031104, 2008.
[7] A. Partovi, D. Peale, M. Wuttig, C. A. Murray, G. Zydzik, L. Hopkins, K. Baldwin, W. S. Hobson, J. Wynn, J. Lopata, L. Dhar, R. Chichester, and J. H. Yeh, "High-power laser light source for near-field optics and its application to high-density optical data storage," *Appl. Phys. Lett.*, vol. 75, pp. 1515–1517, 1999.
[8] F. Chen, A. Itagi, J. A. Bain, D. D. Stancil, T. E. Schlesinger, L. Stebounova, G. C. Walker, and B. B. Akhremitchev, "Imaging of optical field confinement in ridge waveguides fabricated on a Very Small Aperture Laser (VSAL)," *Appl. Phys. Lett.*, vol. 83, pp. 3245–3247, 2003.
[9] P. S. Kelkar, J. Beauvais, E. Lavallee, D. Drouin, M. Cloutier, D. Turcotte, P. Yang, L. K. Mun, R. Legario, Y. Awad, and V. Aimez, "Nano patterning on optical fiber and laser diode facet with dry resist," *J. Vac. Sci. Technol. A*, vol. 22, pp. 743–746, 2004.
[10] J. Schrauwen, D. Van Thourhout, and R. Baets, "Focused-ion-beam fabricated vertical fiber couplers on silicon-on-insulator," *Appl. Phys. Lett.*, vol. 89, p. 141102, 2006.
[11] G. M. Kim, B. J. Kim, E. S. Ten Have, F. Segerink, N. F. Van Hulst, and J. Brugger, "Photoplastic near-field optical probe with sub-100 nm aperture made by replication from a nanomould," *J. of Microscopy*, vol. 209, pp. 267–271, 2002.
[12] S. Y. Chou, P. R. Krauss, and P. J. Renstrom, "Imprint of sub-25 Nm Vias and trenches in polymers," *Appl. Phys. Lett.*, vol. 67, pp. 3114–3116, 1995.
[13] L. J. Guo, "Nanoimprint lithography: Methods and material requirements," *Adv. Mater.*, vol. 19, pp. 495–513, 2007.
[14] J. Viheriala, T. Niemi, J. Kontio, T. Rytkonen, and M. Pessa, "Fabrication of surface reliefs on facets of singlemode optical fibres using nanoimprint lithography," *Electron. Lett.*, vol. 43, pp. 150–152, 2007.
[15] S. Scheerlinck, J. Schrauwen, F. Van Laere, D. Taillaert, D. Van Thourhout, and R. Baets, *Optics Exp.*, vol. 15, p. 9639, 2007.
[16] M. Bender, M. Otto, B. Hadam, B. Spangenberg, and H. Kurz, "Multiple imprinting in UV-based nanoimprint lithography: Related material issues," *Microelectron. Eng.*, vol. 61–62, pp. 407–413, 2002.
[17] P. Bienstman and R. Baets, "Optical modeling of photonic crystals and VCSEL's using eigenmode expansion and perfectly matched layers," *Opt. Quantum Electron.*, pp. 349–354, 2001.

Stijn Scheerlinck (S'03) received the electronic engineering degree from Ghent University, Gent, Belgium, in 2003, and received the Ph.D degree at the Department of Information Technology (INTEC) in 2009.

Since then, he has been with the Photonics Research Group, Department of Information Technology, Ghent University-IMEC (Interuniversity Microelectronics Center). His research interests covers fabrication of micro- and nanophotonic components.

Peter Dubruel graduated as a Licentiate in chemistry at the Ghent University, Gent, Belgium, in 1998, and received the Ph.D. degree in polymer chemistry at the Ghent University in 2003 (Faculty of Sciences, Polymer Chemistry & Biomaterials Research Group). In 2005, he obtained an Alexander von Humboldt Research Fellowship for a nine month research stay in Germany (Mainz, University Hospital, Institute of Pathology).

In October 2006, he took up a position as Professor in Polymer Chemistry and Biomaterials at the Ghent University. His research interests mainly cover polymers for biomedical applications. Currently, he is President of the Young Scientist Forum from the European Society for Biomaterials.

Peter Bienstman received the degree in electrical engineering and the Ph.D. degree at the Department of Information Technology (INTEC), from Ghent University, Gent, Belgium, in 1997 and 2001, respectively.

He is currently an Associate Professor at the Universtiy of Ghent. During 2001–2002, he spent a year in the Joannopoulos research group at MIT. His research interests include several applications of nanophotonics (biosensors, photonic information processing, ...) as well as nanophotonics modelling. He has published over 50 papers and holds several patents.

Dr. Bienstman is a member of IEEE-LEOS.

Etienne Schacht graduated as Licentiate in Chemistry and received the Ph.D. degree in polymer chemistry from the Faculty of Sciences, Polymer Chemistry Research Group, Ghent University, Gent, Belgium, in 1969 and 1974, respectively.

He spent one year (1975–1975) at the University of Massachusetts, Amherst. In 1980, he was assigned Professor in polymer chemistry at the University of Gent. He has been active for more than 25 years in the field of polymers for biomedical applications. He was founding member of IBITECH (Institute for Biomedical Technology, Ghent University), is past President of the Belgian Polymer Group and is currently board member of the European Society for Biomaterials.

Dries Van Thourhout received the degree in physical engineering and the Ph.D. degree from Ghent University, Ghent, Belgium in 1995 and 2000, respectively.

From October 2000 to September 2002 he was with Lucent Technologies, Bell Laboratories, Holmdel, NJ, working on the design, processing, and characterization of InP–InGaAsP monolithically integrated devices. In October 2002, he joined the Department of Information Technology (INTEC), Ghent University, Gent, Belgium. Currently he is member of the permanent staff of the photonics group. He is Lecturer or Co-Lecturer for four courses within the Ghent University Master in Photonics program (Microphotonics, Advanced Photonics Laboratory, Photonic Semiconductor Components and Technology). He is also coordinating the cleanroom activities of the research group. His research focuses on the design, fabrication and characterization of integrated photonic devices. Main topics involve silicon nanophotonic devices, heterogeneous integration of InP-on-silicon, integrated InP-based optical isolators. Besides he is working on the development of new fabrication processes for photonic devices, e.g., based on focused ion beam etching and die-to-wafer bonding. He holds three patents, has authored and coauthored over 60 journal papers and has presented invited papers at several major conferences.

Roel Baets is Full Professor at Ghent University, Gent, Belgium, and leads the Photonics Research Group of Ghent University, a research group associated with IMEC.

With about 250 journal publications and 500 conference papers as well as about 15 patents he has made contributions to research on semiconductor laser diodes, passive guided wave and grating devices and to the design and fabrication of photonic ICs, both in III-V semiconductors and in silicon. His current research interests focus on photonic integrated components for new application areas, such as smart sensors and biomedical instrumentation.

Dr. Baets is coordinator of the European Network of Excellence ePIXnet and of the European "Erasmus Mundus" Master of Science in Photonics program. He has been granted several scientific prizes and is a Fellow of the IEEE.