Silicon-on-Insulator-Based Retroreflective Optical Marker Chips for Simultaneous Identification and Localization

Marie Verbist, *Student Member, IEEE*, Wim Bogaerts, *Member, IEEE*, Jonathan Schrauwen, *Student Member, IEEE*, and Roel Baets, *Fellow, IEEE*

***Abstract*—We demonstrate an omnidirectional, retroreflective optical marker in silicon on insulator that enables simultaneous identification and localization of objects. The most important chip requirement—its retroreflectivity—is realized by a large number of equally designed reflective ring resonator circuits, which operate at different angles of the incident light. The markers are characterized by an infrared camera that captures the response during flood exposure by a tunable infrared laser.**

***Index Terms*—Grating coupler, marker, nanophotonics, ring resonator, silicon on insulator (SOI).**

I. Introduction

CURRENT marker techniques, such as bar codes and RF identification (RFID), do not allow efficient localization of the marked objects. Localization with bar codes requires complex image processing, while RFID localization has a very poor resolution due to the large wavelength of the radiowaves. This limits the applications of these techniques in the automation industry. The use of infrared light can overcome this problem. Although it requires the objects to be in line of sight (as with bar codes), the spatial resolution will improve drastically.

The system we propose, shown in Fig. 1, can be compared to the RFID system. Instead of a transceiver that sends and receives radiowaves, we use a tunable infrared laser and an infrared camera. These two components, which are connected to a computer, will locate and identify the objects that have been marked with an optical marker chip.

Therefore, the markers need to perform two crucial tasks. First of all, they need to produce a unique signal that identifies them. Second, they have to make sure that this signal reaches the infrared camera. This is possible only if the marker sends its response back in the direction of the incident source light, i.e., it is retroreflective. Since the position of the marker with respect to the source is not known, the angle of incidence of the source light is also not known. Completely independent of this angle

Manuscript received January 5, 2009; revised March 23, 2009. Current version published October 7, 2009. This work was supported in part by the European Union through the Network of Excellence ePIXnet. The work of M. Verbist was supported by the Institute for the Promotion of Science and Technology, Flanders IWT, under a grant. The work of W. Bogaerts was supported by the the Flemish Research Foundation, Fonds Wetenschappelijk Onderzoek (FWO-Vlaanderen) under a postdoctoral fellowship.

The authors are with the Department of Information Technology (INTEC) of the Interuniversity Microelectronics Center and Ghent University B-9000 Ghent, Belgium (e-mail: marie.verbist@intec.ugent.be).

Digital Object Identifier 10.1109/JSTQE.2009.2021567

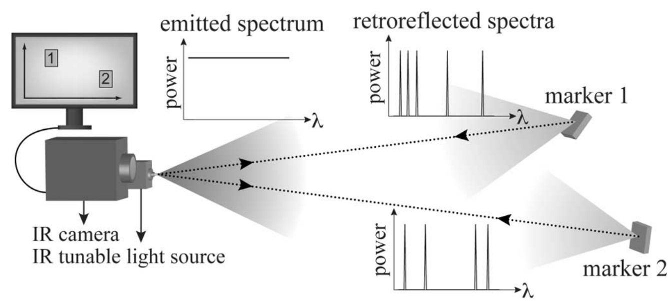

Fig. 1. General concept: an infrared light source sweeps a certain wavelength range. The markers send a specific spectrum back in the direction of the received light. The infrared camera captures this response, from which both identification and location can be retrieved.

and for all possible angles, the marker thus has to:

1) generate a wavelength-dependent identification code;
2) send it back retroreflectively.

It is not at all straightforward to perform this combination of tasks in an omnidirectional way. Usually, only one task is performed, such as in corner reflectors [1] or thin-film filters [2].

We have designed a photonic circuit that realizes both tasks. It performs a unique filter operation on the captured source light and sends the filtered version back in the direction of the source. The filter operation retains one or several distinct peaks at specific wavelengths. The resulting spectrum is unique for every chip and serves as its identification code. By positioning the infrared camera close to the light source, the response of the marker chips can be captured. The light source—a tunable laser—sweeps a certain range of wavelengths, while the camera makes an image at every wavelength. The image will show a bright spot at certain coordinates whenever the marker at these coordinates is at resonance. This allows us to reconstruct the spectrum of the light sent back by each marker. This way, both the marker's location and the identity can be retrieved.

First, the earlier concept is translated into the design of a photonic integrated circuit in silicon on insulator (SOI) [3]–[5], using a well-considered combination of known components, such as grating couplers [6]–[9], 3-dB splitters, and ring resonators [10], [11]. Section III deals with the fabrication of the chip. Since the first measurements showed a large interference pattern, this section also covers the postprocessing step that is necessary to eliminate the source of this interference. Next, the measurement setup is presented and the measurements are discussed, which show that it is possible to identify and locate the marker at all angles. Section V suggests some improvements for the next-generation optical markers.

II. Marker Design

To obtain a miniaturizable marker, we use an SOI photonic integrated circuit [3]. Because of the high refractive index contrast between core and cladding, light can be guided through curved waveguides with a radius of curvature as low as a few micrometers [4]. Ring resonators, which will perform the filter operation, can therefore be spectacularly miniaturized [10]. Furthermore, we can rely on very mature CMOS technology for the fabrication of these devices.

Ring resonators are chosen for their small footprint and high Q-factor. Their spectra consist of a very sharp peak at the resonance frequency, which is repeated after a certain distance, called the free spectral range (FSR). Adding more rings with different resonance frequencies between the same straight waveguides creates a drop spectrum that shows several distinct peaks within one FSR. In this way, unique identification codes can be created that are repeated within every FSR. The larger the FSR and the higher the Q-factor, the more codes can be produced this way.

When designing a passive chip, a high coupling efficiency into and out of the chip is crucial. Coupling from the outside world to the chip and back is achieved by focusing grating couplers [6], [7] that have a coupling efficiency of about 30% in our case. This efficiency can, in principle, be improved to values beyond 80% [9]. For a given wavelength, these periodic gratings operate with maximum efficiency at one angle. This angle is determined by the Bragg condition of the periodic grating and its orientation. Since the grating is finite in size, a certain bandwidth is coupled over a certain cone of angles. In our case, the grating has a size of about 400 μm^2 and a 3-dB bandwidth of 40 nm. It should be noted that grating couplers couple only TE-polarized light. Therefore, it is best to use a circularly polarized source, because regardless of the marker's orientation, there will be a sizable TE-polarized component that can be coupled in.

The entire system relies on the retroreflectivity of the marker chips. A sufficiently large fraction of the light has to be sent back in the same direction for the camera to detect it. For a known fixed angle of incidence, this can be achieved by directing the filtered light back to the same grating coupler, where it is coupled out. The light will be sent back in a cone around the same angle at which it was received, i.e., the circuit is retroreflective, since the same Bragg equation governs the coupling angle.

Fig. 2 shows a schematic representation of how this retroreflectivity is combined with the signal filtering by a ring resonator. The incoupled light is split by a 3-dB splitter, and reaches the ring resonator through both waveguides. Only wavelengths near the resonance of the ring resonator will be sent back to the 3-dB splitter and the grating coupler. In this way, the circuit is retroreflective for only the dropped wavelength.

However, obtaining retroreflectivity for any arbitrary direction of the incident light is less straightforward. This problem is solved by combining many retroreflective substructures that operate at a slightly different fixed angle. Fig. 3 shows two possible configurations of the substructures. Configuration (a) consists of 100 substructures, with five different grating periods and 20 different orientations. Configuration (b) has 120 substructures, with again five different grating periods, but 24 different orientations. This last configuration is twice the size of configuration (a) (1 mm^2 versus 0.5 mm^2), which means that the use of space is less efficient. Configuration (b), however, places all ring resonators as close to each other as possible in the center of the structure. Therefore, the variations in the resonance frequency that arise from wafer-scale fabrication methods, such as photolithography, will be minimized. Configuration (b) will thus perform slightly better. In the fabrication process that was used, we have measured local uniformity of wavelength filters in the subnanometer range and longer range uniformity of 1–2 nm [5].

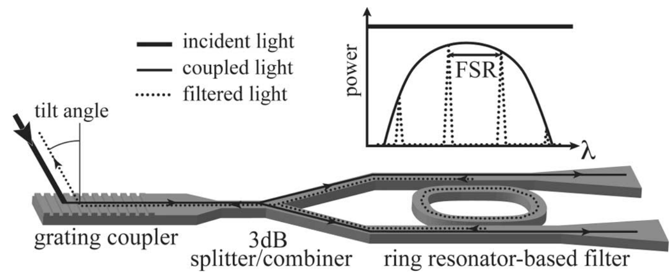

Fig. 2. Schematic representation of the structure that couples light in for a fixed direction, filters it, and sends it back under the same angle as it was received.

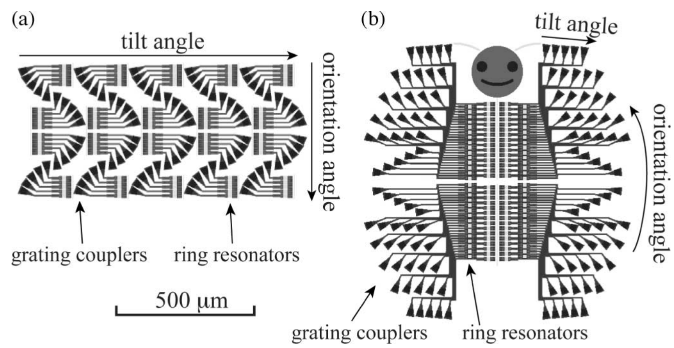

Fig. 3. Configurations (a) and (b) combine, respectively, 100 and 120 grating couplers with five different tilt angles.

III. Fabrication

A. CMOS Fabrication

One of the many advantages of SOI chips is that they can be fabricated using CMOS fabrication techniques. This allows for mass fabrication and cost reduction. We used common SOI wafers with a 220-nm-thin silicon layer (n = 3.45) on top of a 1-μm-thick oxide cladding layer (n = 1.45). The structures are defined in an optical resist with deep UV lithography and then directly etched into the silicon layer. More details about this fabrication process can be found in [3].

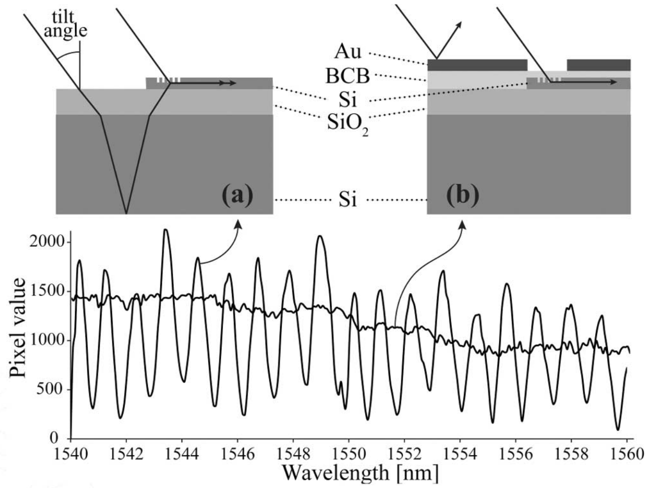

Fig. 4. (a) Interference is caused by incoupling of light that enters the chip and reflects at the substrate. (b) It is eliminated by means of a highly reflecting gold layer (100 nm) on top of a planarizing micrometer-thick BCB layer. The superimposed periodic interference pattern dissappears from the measurements.

As noted before, this fabrication process introduces small variations in the dimensions of structures. For example, two waveguides that are spaced far apart on a chip might not have exactly same thickness. This is why the design of Fig. 3(b) will lead to slightly more reliable results.

B. Reducing Interference

Grating couplers [6] are usually used for coupling light with an optical fiber at the optimal angle. In this situation, only the grating coupler itself is illuminated and not much of the surrounding areas. In our case, the light source is located far from the chip, whose location is still unknown. It is thus the intention that the entire chip be illuminated. Early measurements, however, reveal a problem due to this flood exposure. Large interference patterns are superimposed on the useful signal, thus destroying it completely. Fig. 4 illustrates how and where this interference occurs. Everywhere on the air–chip interface, a large fraction of source light is transmitted and propagated toward the bottom of the substrate where it is reflected upward. At a certain distance from the grating, this upward reflection reaches the grating couplers under the optimal angle for coupling. The directly coupled light will therefore interfere with the light bounced off the substrate. This effect could be confirmed from optical measurements that show a periodic interference pattern with a period that corresponds to the right path-length differences. To eliminate this effect, as well as scattering at waveguide structures, the entire chip—with the exception of the grating couplers—is covered with a highly reflective layer (Au) by sputtering and liftoff. To optimally suppress the scattering, gold is deposited on a planarizing benzocyclobutene (BCB) polymer coating. This way, a very good planarization is obtained [see Fig. 4(b)]. This also resulted in interference-free measurements, which prove the effectiveness of the 100-nm-thick planarized gold layer. Alternatively, an absorbing layer could be used.

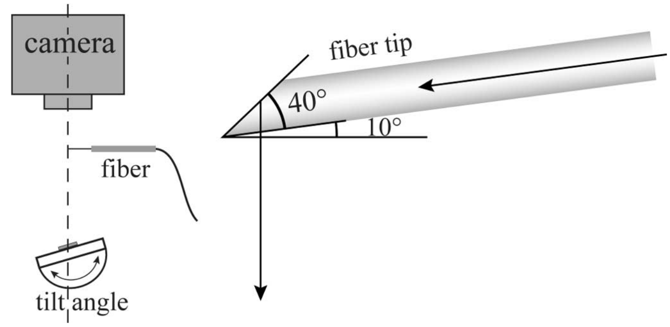

Fig. 5. Measurement setup uses a fiber that is cleaved or polished at an angle of 40°. This fiber can thus be placed almost horizontal. This is needed to avoid blocking the camera.

IV. Measurements

A. Camera-Based Measurement Setup

In the ideal setup, the light source is on the chip–camera axis, which avoids a mismatch between the backreflected light and the position of the camera. To obtain this situation without blocking the camera, a fiber is polished at 40°. By placing the fiber almost normal to the chip–camera axis, the source light will be sent along this axis, as shown in Fig. 5. The fiber itself does not significantly disturb the camera images because it is far out of focus. The distance between the chip and the camera was about 12 cm, and the tip of the fiber was positioned 3–4 cm above the chip. The power of the laser was set at 2 mW, which was more than sufficient for this distance. Considering the femtowatts sensitivity of our camera, it should, in principle, be possible to increase the distance between source/camera and chip to several meters. It is important to note that the efficiency of any camera can be drastically improved by increasing the integration time.

B. Spectra

The camera takes an image at every wavelength that is sent out by the laser. The marker chips will send this light back to the camera only if the wavelength is near the resonance of one of its rings. From the temporal and spatial information of the camera images, the identity and position of the marked object can be retrieved. This is done by attributing a spectrum to all image coordinates. In principle, for every pixel, the gray value can be set out as function of the wavelength to obtain the spectra of the light that reaches the camera. This will, however, not be very practical, since it would be very sensitive to noise and vibrations. In practice, the maximal pixel value over certain areas will be registered. The size of these areas could, for instance, be defined according to the size of the objects or might even be changed dynamically when an object is found in a certain area to obtain the exact location. From the spectrum of the area where an object is located, the identity of this object can be interpreted easily through its unique spectrum.

Our measurement setup is controlled by a program in which these areas can be defined manually. This even allows us to register the spectrum of one single grating coupler.

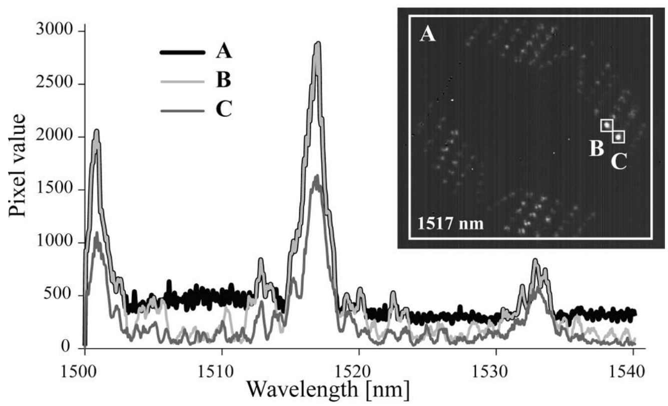

Fig. 6. Camera image and corresponding spectra of configuration shown in Fig. 3(b), placed at a random orientation and tilt angle. The spectra are measured over three areas: (A) over the entire chip and (B) and (C) over each of the active grating couplers.

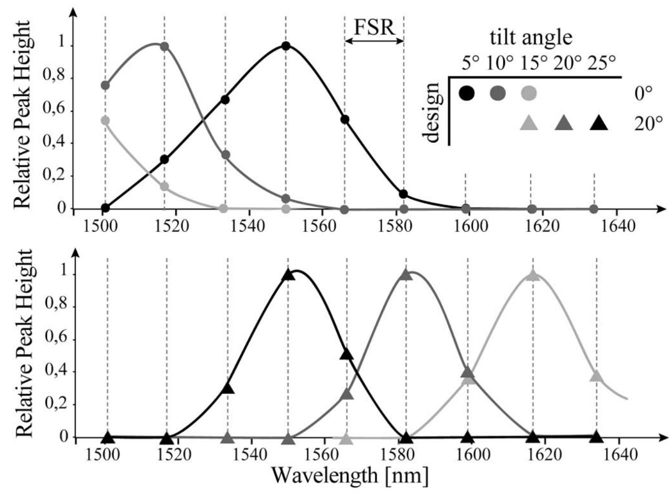

Fig. 7. Bandwidth of two grating couplers estimated from the peak heights of measurements shown in Fig. 6 at five different tilt angles. Changing the tilt angle causes a large shift of the bandwidth coupled in by the same grating coupler.

C. Measurements

All measurements are performed using marker chips with the configuration shown in Fig. 3(b). One marker chip is placed under the measurement system at a random orientation and tilt angle. At all frequencies, camera images show some scattered light at the edges of every grating coupler. When the swept source reaches the resonance frequency, the image shows that two grating couplers are able to couple the light into and out of the chip. This image is shown in Fig. 6. The two operating grating couplers are designed for the same tilt angle, but for a different orientation. This tells us that we could still reduce the number of grating couplers with different orientations, since one responsive grating coupler is sufficient.

We manually define three different areas in the camera image and record the spectra over these areas. Area A covers the entire chip. Areas B and C are chosen closely around each of the active grating couplers. It is easy to see that the response of B is somewhat stronger than the response of C. The angle of incidence is thus closest to the ideal coupling angle of the grating coupler in area B. More importantly, the peaks of A and B overlap at the resonance frequencies. The noise, consisting of scattered light at gold edges near other grating couplers, is low enough to obtain a good SNR. It should be clear that the noise does not add up, because the maximal pixel value, instead of the average pixel value, is registered.

When tilting the chip, the coupled wavelength range shifts due to a change of the Bragg condition. This can be understood when we consider that the actual grating period that is "felt" by the incident light becomes smaller when the tilt angle increases. For a larger tilt angle, the central wavelength of the coupled light will thus shift to smaller wavelengths. It is possible to see the response of the marker only when sweeping a large range of wavelengths, much larger than one FSR of the ring resonators.

To observe this shift, we estimated the central wavelength and bandwidth of the grating couplers at five different tilt angles from the peak heights of the corresponding measurements. The results are shown in Fig. 7. At a tilt angle of 5°, the responsive grating coupler (designed for a 0° tilt angle) has central wavelength of about 1550 nm. At a tilt angle of 10°, the central wavelength is shifted over about 35 nm, which is slightly more than two FSRs. At 15°, the same shift is expected, but the actual central wavelength is outside of the swept wavelength range. Fortunately, as can be seen in the second graph, the grating coupler designed for 20° becomes responsive at this point. For a 15° tilt, the central wavelength at this grating coupler is almost 1620 nm. For tilt angles of 20° and 25°, the response of this second grating coupler shows a comparable blue wavelength shift.

The overlap of the response of the grating couplers at 15° is very important. It shows that the response of the chip can be measured at any angle, provided a large enough wavelength range is swept.

V. New Generation of Optical Markers

This first prototype has proven that it is possible to retain the identity and position of the marked object. The design can, however, still benefit from a thorough optimization. From the presented measurements, some particular suggestions can be made for the next generation of optical markers.

First of all, the coupling angles of the gratings can be distributed more efficiently. There can be a smaller set of orientation angles, since the current design shows two simultaneously operating grating couplers. More different tilt angles are needed to reduce the frequency shift and ensure a good SNR at all angles. The number of grating couplers could also be reduced by half if 2-D gratings were used [8]. These gratings are designed to couple two polarizations, and can therefore cover two orientations in our case. This will not reduce the number of filters.

The grating couplers should be optimized to enhance their bandwidth. This could ultimately allow us to measure the response of the chip within one FSR, reducing the requirements of the swept source. A further increase in the coupling efficiency would allow larger distances between the marked objects and the light source [9].

Changing the size of the grating couplers has two important implications. First of all, the total power that is incident on the grating couplers scales with its size. A smaller sized grating will, however, have a larger bandwidth and a larger coupling cone of angles. This means that there is a tradeoff between the required number of grating couplers and the power that each grating couplers can couple.

The design of the ring resonators should be optimized according to Q-factor and FSR. Combining more ring resonators could lead to a very large number of possible identification codes. It would also be a good idea to include one or more reference rings, which have the same resonance frequency for all markers. This will be very useful to eliminate external effects, such as temperature, which alter the resonance frequency.

Finally, for future markers in practical situation, the interference problem could best be solved by using an absorbing layer instead of a reflecting layer. The absorbing layer could even be below the oxide layer, so it need not be patterned. This would lead to even lower levels of noise in the measurements.

VI. Conclusion

We have demonstrated a new optical marker that uses infrared light to obtain simultaneous identification and localization of objects. Omnidirectional retroreflectivity is achieved by combining 120 similar substructures. Measurements show that the marker chip can be identified and located at all angles, and allows us to optimize the design.

References

[1] G. Kubicke, C. Bourlier, and J. Saillard, "High-frequency bistatic scattering by depolarizing, nearly omnidirectional reflectors: Higher order polyhedral reflectors," *IEEE Trans. Antennas Propag.*, vol. 56, no. 9, pp. 3029–3035, Sep. 2008.

[2] S. Onoda, N. Tsukamoto, M. Ogino, K. Yamashita, O. Yumoto, K. Inoue, and Y. Komatsu, "A proposal of temperature sensing using a thin-film bandpass filter and dual-wavelength push-pull reflectometry," *IEEE Photon. Technol. Lett.*, vol. 20, no. 9–12, pp. 688–690, May 2008.

[3] W. Bogaerts, R. Baets, P. Dumon, V. Wiaux, S. Beckx, D. Taillaert, B. Luyssaert, J. Van Campenhout, P. Bienstman, and D. Van Thourhout, "Nanophotonics waveguides in silicon-on-insulator fabricated with CMOS technology," *J. Lightw. Technol.*, vol. 23, no. 1, pp. 401–412, Jan. 2005.

[4] Y. A. Vlasov and S. J. McNab, "Losses in single-mode silicon-on-insulator strip waveguides and bends," *Opt. Exp.*, vol. 12, no. 8, pp. 1622–1631, 2004.

[5] S. Selvaraja, W. Bogaerts, D. Van Thourhout, and R. Baets, "Fabrication of uniform photonic devices using 193 nm optical lithography in silicon-on-insulator," in *Proc. 2007 IEEE LEOS Annu. Meeting Conf.*, vol. 1/2, pp. 48–49.

[6] D. Taillaert, "Grating couplers as interface between optical fibres and nanophotonics waveguides," Ph.D. dissertation, Dept. Electr. Eng., Univ. Ghent, Ghent, Belgium, 2007.

[7] F. Van Laere, T. Claes, J. Schrauwen, S. Scheerlinck, W. Bogaerts, D. Taillaert, L. O'Faolain, D. Van Thourhout, and R. Baets, "Compact focusing grating couplers for silicon-on-insulator integrated circuits," *IEEE Photon. Technol. Lett.*, vol. 19, no. 23, pp. 1919–1921, Dec. 2007.

[8] D. Taillaert, H. Chong, P. I. Borel, R. M. De La Rue, and R. Baets, "A compact two-dimensional grating coupler used as a polarization splitter," *IEEE Photon. Technol. Lett.*, vol. 15, no. 9, pp. 1249–1251, Sep. 2003.

[9] G. Roelkens, D. Vermeulen, D. Van Thourhout, R. Baets, S. Brision, P. Lyan, P. Gautier, and J. M. Fedeli, "High efficiency diffractive grating couplers for interfacing a single mode optical fiber with a nanophotonic silicon-on-insulator waveguide circuit," *Appl. Phys. Lett.*, vol. 92, no. 13, pp. 131101-1–131101-3, 2008.

[10] P. Dumon, "Ultra-compact integrated optical filters in silicon-on-insulator by means of wafer-scale technology," Ph.D. dissertation, Dept. Electr. Eng., Univ. Ghent, Ghent, Belgium, 2007.

[11] M. K. Chin and S. T. Ho, "Design and modeling of waveguide-coupled single-mode microring resonators," *J. Lightw. Technol.*, vol. 16, no. 8, pp. 1433–1446, Aug. 1998.

Marie Verbist (S'08) graduated in electrical engineering in 2008 from Ghent University, Ghent, Belgium, where she is currently working toward the Ph.D. degree in photonics at the Department of Information Technology (INTEC).

She is engaged in work on the use of diamond as a material for nanophotonics. Her current research interests include design, fabrication, and characterization of waveguides and components for nanophotonics.

Ms. Verbist is a member of the IEEE Photonics Society.

Wim Bogaerts (S'97–A'98–M'03) graduated in applied physics from Ghent University, Ghent, Belgium, in 1998. He received the Ph.D. degree from the Department of Information Technology (INTEC) and the Interuniversity Microelectronics Center (IMEC), Ghent University, in 2004.

He specializes in the modeling, design, and fabrication of nanophotonic components. He is currently a Fonds Wetenschappelijk Onderzoek (FWO-Vlaanderen) Postdoctoral Fellow in the photonics group of IMEC, Ghent University, where he coordinates the activities in silicon photonics.

Dr. Bogaerts is a member of the IEEE Photonics Society and the Optical Society of America.

Jonathan Schrauwen (S'04) received the degree in applied physics from Ghent University, Ghent, Belgium, in 2004, and the Ph.D. degree from the Department of Information Technology, Ghent University, in 2009.

He joined the Department of Information Technology, Ghent University, where he worked on focused-ion-beam fabrication of photonic components and is currently working as a Postdoctoral Researcher.

Dr. Schrauwen is a member of the IEEE Photonics Society.

Roel Baets (M'88–SM'96–F'07) received the degree in electrical engineering from Ghent University, Ghent, Belgium, in 1980, the M.Sc. degree in electrical engineering from Stanford University, Stanford, CA, in 1981, and the Ph.D. degree from Ghent University in 1984.

Since 1981, he has been with the Department of Information Technology (INTEC), Ghent University, where he has also been a Professor in the engineering faculty since 1989 and leads the Photonics Research Group [associated laboratory of the Interuniversity Microelectronics Center (IMEC)], which focuses on new concepts for photonic components and circuits for optical communication, optical interconnect, and optical sensing. From 1990 till 1994, he was a Part-Time Professor at the Technical University of Delft, The Netherlands. Since 2004, he has been a Part-Time Professor at the Technical University of Eindhoven, Eindhoven, The Netherlands. He has mainly worked in the field of photonic components. He is the author or coauthor of about 250 journal publications and 500 conference papers. He holds about 15 patents, and has made contributions to research on semiconductor laser diodes, passive guided wave, and grating devices, and also the design and fabrication of photonic ICs, both in III–V semiconductors and silicon. He has been involved in various European research projects and has also coordinated some of them. He was coordinator in the European Network of Excellence ePIXnet.

Prof. Baets is a member of the Optical Society of America, the IEEE Photonics Society (LEOS) (formerly known as the IEEE Lasers and Electro-Optics Society), the International Society for Optical Engineers (SPIE), and the Flemish Engineers Association. He has been a member of the program committees of a.o. the Optical Fiber Communication Conference and Exposition (OFC), the European Conference on Optical Communication (ECOC), the IEEE Semiconductor Laser Conference, the European Solid-State Device Research Conference (ESSDERC), the Conference on Lasers and Electro-Optics (CLEO) Europe, the LEOS Annual Meeting, the Photonics Europe, and the European Conference on Integrated Optics (ECIO). He was the Chairman of the IEEE-LEOS-Benelux Chapter from 1999 to 2001. From 2003 to 2005, he was an elected member of the Board of Governors of the IEEE-LEOS.