A platform for fast and affordable prototyping of photonic integrated circuits

H. Nikbakht[1], C. Lu[1], B. van Someren[2], and B. I. Akca[1]

[1] LsaserLaB, Department of Physics and Astronomy, Vrije Universiteit Amsterdam, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands
[2] Elf Software, 3061 WS Rotterdam, The Netherlands

One of the biggest challenges of photonic integrated circuits (PICs) is the expensive and time-consuming prototyping. In order to test a new concept, one can easily spend thousands of Euros and several months. A new prototyping technique that can overcome these challenges will accelerate the progress in this field. In this work, we introduce a new PIC prototyping method that is cost-effective and has a short lead-time. We do this by employing an optical waveguide structure based on patterning a UV-curable polymer strips on a thin silicon nitride core. Since the fabrication of these waveguides is done by a single lithography step (patterning the polymer layer), it is considerably faster, and it requires much less equipment to fabricate than the conventional methods. To work as a PIC fabrication platform, the waveguides should have small propagation and bending losses. We designed the material stack in such a way that minimizes the mode volume (minimum bending radius of 100 μm) as well as the propagation loss (<3 dB/cm). Using this method, we fabricated several PICs including arrayed waveguide gratings, broadband 3dB couplers, ring resonators, Sagnac loop mirrors, and coupled cavities.

1. Introduction

Photonic integrated circuits (PICs) hold great promise for future applications such as quantum computers, neuromorphic networks, portable imaging system and disposable sensors. The current technology for fabricating such devices is based on patterning materials such as silicon, silicon nitride, silicon carbide, etc, which requires several fabrication steps [1,2]. Processing of these materials needs to be done in a cleanroom environment and usually several iterations are needed to optimize the design. Direct access to such fab facilities is limited, and researchers that do not have such access need to get this service from commercial companies, which is not only expensive but also has a long waiting time. Such a lengthy process also makes debugging the design almost meaningless. As an alternative solution, multi-project wafer run services have been started [3]. However, the cost/mm^2 is still high (~ 10k Euros) and the lead time is even longer.

Two main challenges force one to utilize such an expensive and sophisticated fabrication process. Due to the high refractive index of mentioned materials, the waveguides must be small to remain single-mode. Therefore it seems that using a lower refractive index (RI) material with a more straightforward patterning process is the solution. However, another challenge arises with a low RI. Reducing the RI contrast between the core and the cladding increases the bending loss [4,5]. So, the bending radius of the waveguides in a device with low RI contrast must be large, making the overall footprint of the PIC is also big. In addition to big device size, large PICs suffer from propagation loss as well.

We designed and demonstrated a material stack that can be used to make PICs at a very low cost and considerably short time. In this method, we pattern photoresist and do not etch the high index material (silicon nitride, Si_3N_4 in this case) which simplifies the fabrication dramatically. Due to the small RI contrast, pushing the resolution to the sub-

micron regime is not required and simple photolithography techniques can be used to make these devices. In addition to being cost-effective and fast, the material stack that we designed also allows us to make relatively sharp bends with a minimum bending radius of 100 µm. In this paper, we will discuss the material stack and also demonstrate some of the devices that we fabricated and characterized by using this fabrication approach.

2. Design

This platform utilizes strip-loaded waveguides with a high index layer as the core and a patterned low index polymer photoresist layer as the guiding cladding (Figure 1a). This material stack minimizes the mode volume resulting in a negligible bending loss at bending radii above 100 µn. A mode calculation of this structure shows that the power is distributed between high and low RI materials and the interaction of the mode with the sidewalls of the photoresist polymer is relatively small (Figure 1b). This results in reduced scattering from the roughness in the waveguide walls. Here, Si_3N_4 is used as the high index layer and different photoresists as the guiding cladding strip.

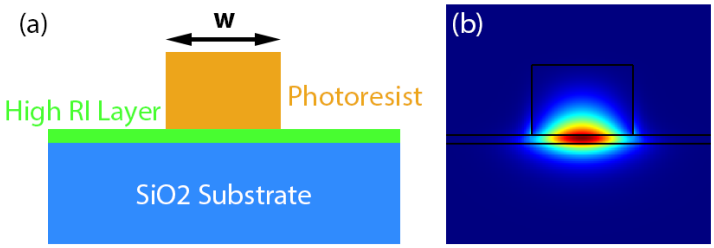

Figure 1. (a) Schematic view of the waveguide layer stack. (b) TE mode propagating in that waveguide at 1550 nm wavelength.

Figure 2 shows the fabrication steps of a simple PIC chip with the conventional method. It consists of five steps, in which etching is the most challenging step, especially for some materials such as lithium niobate, which is very hard to etch [6]. On the contrary, the proposed method only requires the first two steps.

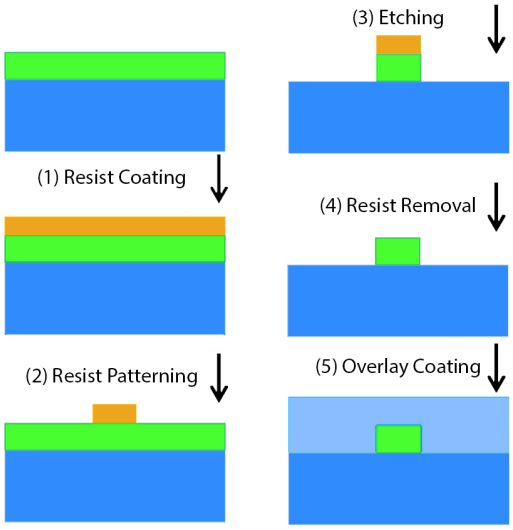

Figure 2. Process flow for fabrication of a simple PIC with the conventional method. By using the proposed method, only the two first steps are required.

The width of the patterned photoresist (w in Figure 1a) strip is in the range of 1-2 µm, which makes it possible to fabricate by contact mask photolithography or other diffraction-limited UV photolithography techniques, which is the most widely available equipment in the cleanrooms. Another advantage of this platform is the possibility of reducing roughness in the patterned photoresist layer by heating it to its glass transition temperature. At that temperature, the surface tension of the photoresist reduces the roughness resulting in smaller scattering loss of the waveguides. The use of polymer photoresists also enables us to reuse the substrates. Some wafers, such a lithium niobate on insulator, are pretty expensive, and if one can reuse them, it would be a considerable saving in the research budget. Most of the polymer photoresists are soluble in acetone or their specific remover. Considering that the pattern is only transferred to the polymer photoresist, one can reuse the substrate by washing the polymer layer.

Experimental results

We designed several PIC components (broadband non-uniform directional couplers, Sagnac loop mirrors, Fabry-Perot coupled microring resonators, ellipse ring resonators, race track resonators, arrayed waveguide gratings, and so on) to test the performance of our platform. The main focus is to show that this method can achieve sufficiently small bending and propagation losses. In Fig. 3, we show the transmission measurement results (Fig. 3b&d) and the images of the fabricated structures (Fig. 3a&c) of two devices that we characterized; a race-track resonator and an arrayed waveguide grating (AWG).

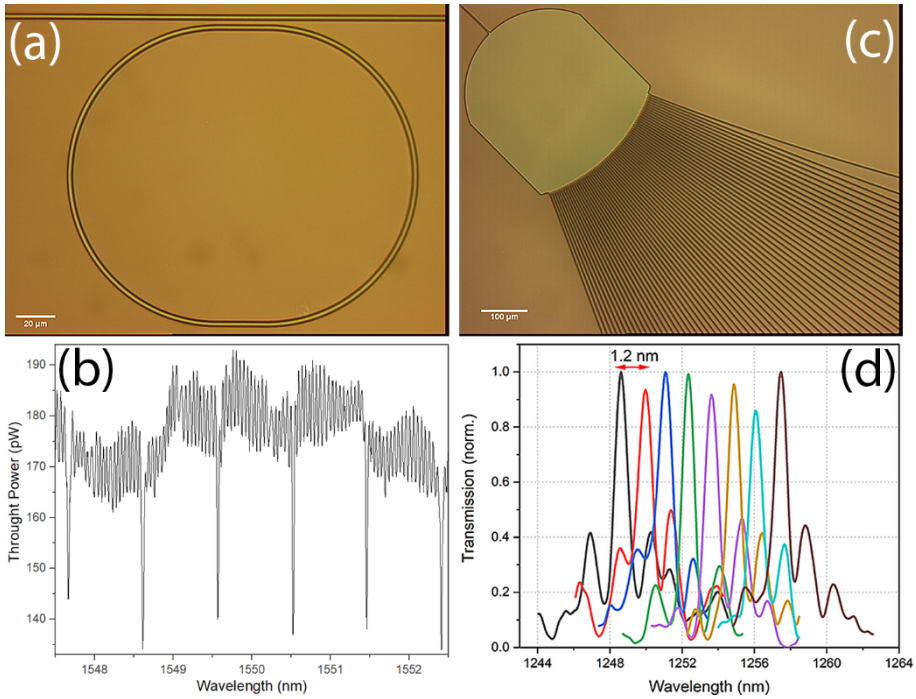

Figure 3. (a) Optical microscope image and (b) transmitted spectrum of a race-track resonator and (c) an array waveguide grating and (d) its transmission spectrum at different output ports.

The full width at half maximum (FWHM) of this race-track resonator is 16 pm, leading to a QF of about 9.7×10^4. The bending radius of this structure was 100 µm. The AWG was designed at the 1250 nm wavelength range with 8 output channels that are 1.2 nm apart. We observed high crosstalk values. One reason was the non-uniform exposure of our in-house lithogprahy device (partially working device), which caused phase

variations over the wafer. Moreover, there was a design related problem that resulted in a shorter free propagation region. In our future mask, we will fix this problem and moreover we will use a more professional lithography machine in a cleanroom environment.

Conclusions

In short, we demonstrated that our new fabrication platform that can provide PICs with low bending and propagation losses in a very short time for a small budget. This will change the way we prototype PIC devices. We have already tested several new ideas that we were only on a paper until now due to limited fabrication possibilities of our group. In a very short time and by using only a couple of hundreds of Euros, we tested more than ten new designs and optimized their performances as well. We believe this new approach will be enabler for many other researchers.

References

[1] W. Bogaerts, D. Taillaert, B. Luyssaert, P. Dumon, J. Van Campenhout, P. Bienstman, D. Van Thourhout, R. Baets, V. Wiaux, and S. Beckx, "Basic structures for photonic integrated circuits in Silicon-on-insulator," Opt. Express 12, 1583-1591, 2004.

[2] S. K. Selvaraja, P. Jaenen, W. Bogaerts, D. Van Thourhout, P. Dumon and R. Baets, "Fabrication of Photonic Wire and Crystal Circuits in Silicon-on-Insulator Using 193-nm Optical Lithography," in Journal of Lightwave Technology, vol. 27, no. 18, pp. 4076-4083, Sept.15, 2009, doi: 10.1109/JLT.2009.2022282.

[3] N. M. Fahrenkopf, C. McDonough, G. L. Leake, Z. Su, E. Timurdogan and D. D. Coolbaugh, "The AIM Photonics MPW: A Highly Accessible Cutting Edge Technology for Rapid Prototyping of Photonic Integrated Circuits," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 25, no. 5, pp. 1-6, Sept.-Oct. 2019, Art no. 8201406, doi: 10.1109/JSTQE.2019.2935698.

[4] K. Shang, S. Pathak, C. Qin and S. J. B. Yoo, "Low-Loss Compact Silicon Nitride Arrayed Waveguide Gratings for Photonic Integrated Circuits," in IEEE Photonics Journal, vol. 9, no. 5, pp. 1-5, Oct. 2017, Art no. 6601805, doi: 10.1109/JPHOT.2017.2751003.

[5] Katsunari Okamoto, Chapter 2 - Planar optical waveguides, Fundamentals of Optical Waveguides (Second Edition), Academic Press, 2006, Pages 13-55.

[6] Boes, A., Corcoran, B., Chang, L., Bowers, J., Mitchell, A., Status and Potential of Lithium Niobate on Insulator (LNOI) for Photonic Integrated Circuits, Laser & Photonics Reviews 2018, 12, 1700256. https://doi.org/10.1002/lpor.201700256