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Low-Contrast Top Gratings in High-Contrast SOI waveguides for Integrated Holographic Filters

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***Abstract*—We design integrated holographic filters with any transfer function by weakly modulating the top cladding of SOI waveguides. Our calculations are confirmed by full-vectorial simulations. Grating are fabricated with focused ion beam.**

I. INTRODUCTION

Fabrication of silicon photonics becomes ever more refined, enabling more functionality and complexity of photonic circuits [1]. Spectral filters based on photonic crystals, arrayed waveguide gratings or ring resonators are well understood and have excellent performance. Still, even with these devices it is difficult to create filters with complex transfer functions.

Volume holography, a powerful method for encoding optical information [2], presents a solution. Allowing light to travel over a large distance through the holographic structure, significantly increases the possibilities for light processing. But holography is typically based on a very low index contrast, which is difficult to realize in Silicon on Insulator waveguides, but is needed to obtain a high spectral resolution.

In this paper we take a look at such holographic filters in Silicon-on-Insulator (SOI), using local focused-ion-beam writing into the top cladding of a high-contrast silicon waveguide.

II. WEAK GRATING THEORY

A grating can be represented by a variation of the effective refractive index n_{eff} along the propagation direction x: $\Delta n(x)$. In a weak grating $\Delta n(x) \ll n_{eff}$, so we assume a uniform background index $n_{eff,0}$. Also, scattering at each tooth is sufficiently small to neglect second-order reflections. This means that a pulse $E_0\delta(t)$ interacts with the grating by producing a single reflection at each point x with an amplitude of $E_{refl} = \alpha_R E_0 \Delta n(x)$, where α_R is a constant [3]. This reflection is delayed by a transit time of $t = \frac{2n_{eff,0}x}{c}$. The impulse response in reflection is then

$$E_{refl}(t) = \alpha_R E_0 \Delta n\left(\frac{ct}{2n_{eff,0}}\right). \qquad (1)$$

The spectral transfer function of this filter (in reflection) can then be calculated as the Fourier transform of E_{refl}/E_0.

$$T(f) = \mathcal{F}\left[\alpha_R \Delta n\left(\frac{ct}{2n_{eff,0}}\right)\right] \qquad (2)$$

Vice versa, when starting from a target transfer function, Δn can thus be calculated using the inverse Fourier transform.

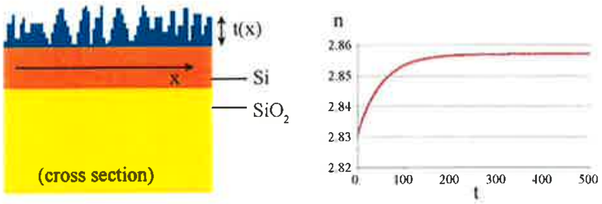

Fig. 1. Implementation of $\Delta n(x)$ as top cladding thickness $t(x)$ (left) and the effective refractive index of the slab waveguide in function of t(right).

III. IMPLEMENTATION OF $\Delta n(x)$ IN SOI

In silicon photonics, waveguides are defined in a high-contrast silicon-on-insulator layer [1]. Many parameters affect the effective index of such an SOI waveguide: thickness, width, refractive index of core and cladding, temperature, dopants, ... The grating's effective index variation $\Delta n(x)$ can thus be implemented in equally numerous ways, which will mostly depend on the available processing techniques. The difficulty is having sufficient control over the technology to define *small* variations of n_{eff} with the required accuracy, exactly because the material system has such a high inherent refractive index contrast. In this paper, we implement $\Delta n(x)$ as a modulation of the cladding thickness t on top of an SOI waveguide. This can be on a waveguide or on a slab region without lateral confinement, where the grating can be curved, focusing the reflection into a separate output waveguide.

Simulations in the full-vectorial mode solver CAMFR [4] yield the refractive index n as function of t, and thus the inverse: $t(n)$. By mapping $\Delta n(x)$ to the thickness we obtain $t(x)$, the profile over the propagation length. This describes the top cladding modulation corresponding to a given spectrum.

Depending on the fabrication scheme, additional transformations can be added. In our case, we apply a discretization of t, corresponding to multiple passes of the focused ion beam.

IV. CALCULATIONS AND SIMULATIONS

We consider the following grating parameters:

- We use Al_2O_3 as a top cladding ($n_{Al2O3} = 1.62$).
- The thickness t ranges from 0 to 235 nm.
- To simplify the fabrication, t is discretized to 10 values.
- The length L of the grating is 100 μm (FIB writing field).

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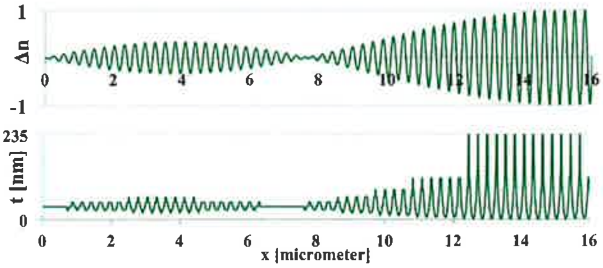

Fig. 2. Effective refractive index $n(x)$ leads to top layer thickness $t(x)$.

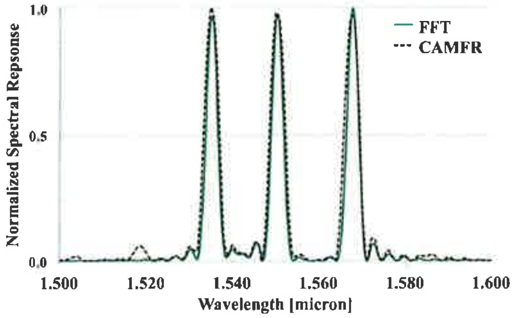

Fig. 3. The calculated spectrum (full green) of the grating shows a very good agreement with the CAMFR simulation (dotted black).

We consider a target reflection spectrum with peaks at three wavelengths (1535nm, 1550nm and 1565nm). The resulting $\Delta n(x)$ is a superposition of three sine functions. Fig. 2 shows $\Delta n(x)$ and the corresponding top layer thickness $t(x)$ after discretization and truncation. To study the effect of these additional transformations, we use weak grating theory again: by applying the regular Fourier transformation, the reflected spectrum of the modified grating is retrieved.

To verify the results of the weak grating approximation, we simulated the same grating in CAMFR. Fig. 3 shows a very good agreement between the weak grating theory and the full-vectorial CAMFR simulations. This indicates that the weak grating theory calculations produce accurate results. We are therefore able to design holographic gratings without the use of time and memory consuming simulation tools, and instead rely on the fast fourier transform (FFT) algorithm.

V. FABRICATION

One possible method to define arbitrary weak grating in a silicon waveguide is through the use of Focused Ion Beam (FIB) milling. The key strength of this technique is location-dependent etch depth, which enables us to generate custom thickness variations. Also, the direct writing enables a flexible and short experiment cycle. The drawbacks of FIB are the limited scalability and the damage induced by implanted ions. To avoid this damage, we use Al_2O_3 as top cladding material, which efficiently protects the silicon underneath [5]. to reduce etch time, we could deposit a thin protective layer of Al_2O_3.

We control the ion beam directly through stream files, which list the beam coordinates and the corresponding dwell time t_D.

Fig. 4. Cross-section of part of a holographic grating, fabricated by FIB etching.

Knowing the relation between t_D and the etch depth, we can generate the stream file from the calculated grating.

When using a FIB, some etched material will redeposit on previously etched parts. Also, the etch rate slightly depends on the topology of the grating: etching a flat surface is slower than etching near an edge. These two issues are typically solved by using a short dwell time and a large number of passes. But for larger gratings, positional drift of the sample can then compromise the resolution. We solved this issue by etching a large number of windows, which overlap as they move along the propagation direction. Fig. 4 shows a part of a holographic grating. This also illustrates some fabrication-induced deficiencies. While the left part of the grating should have a strong modulation, the structure is etched deep overall. This is due to proximity effects, where the etching of deep valleys will also etch the surrounding area and lower the high neighboring peaks. This should be overcome by calibration, by applying a smarter transformation of $\Delta n(x)$ to t_D.

VI. CONCLUSIONS AND FUTURE WORK

We designed weak gratings for custom reflection spectra in Silicon waveguides. The design procedure is very straightforward as long as the index contrast is low. To obtain this low contrast in a silicon waveguide, we have used a top cladding modulation to obtain a spectrum with three isolated wavelengths. Our calculations were confirmed by full-vectorial simulations. To fabricate these gratings, we have performed initial experiments with focused ion beam writing.

ACKNOWLEDGMENT

This work was supported by the Institute for the Promotion of Science and Technology in Flanders (IWT) under a grant.

REFERENCES

[1] 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," *J. Lightwave Technol.*, vol. 27, no. 18, pp. 4076–4083, SEP 15 2009.

[2] C. Peroz, A. Goltsov, S. Dhuey, P. Sasorov, B. Harteneck, I. Ivonin, S. Kopyatev, S. Cabrini, S. Babin, and V. Yankov, "High-Resolution Spectrometer-on-Chip Based on Digital Planar Holography," *IEEE Photonics. J.*, vol. 3, no. 5, pp. 888–896, OCT 2011.

[3] T. Mossberg, "Planar holographic optical processing devices," *Opt. Lett.*, vol. 26, no. 7, pp. 414–416, APR 1 2001.

[4] P. Bienstman and R. Baets, "Optical modelling of photonic crystals and vcsels using eigenmode expansion and perfectly matched layers," *Opt. Quantum Electron.*, vol. 33, pp. 327–341, 2001.

[5] J. Schrauwen, D. Van Thourhout, and R. Baets, "Iodine enhanced focused-ion-beam etching of silicon for photonic applications," *J. Appl. Phys.*, vol. 102, p. 103104, 2007.

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