Extreme Spectral Transmission Fluctuations in Silicon Nanowires Induced by Backscattering

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***Abstract*—The waveguide is the most fundamental component of integrated photonic circuits. We observe that roughness-induced backscattering in high-contrast silicon waveguides generates over 10 dB spectral transmission variations in centimeter-long silicon waveguides.**

***Keywords*—Optical waveguides, Integrated optics, Silicon photonics, Surface roughness.**

I. Introduction

Silicon-On-Insulator (SOI) has become a major platform for integrated photonic circuits. The ultra-high index contrast allows for extremely compact optical components, while the compatibility with CMOS processing technology brings large-scale and low-cost fabrication on the table. Sub-micron waveguides are definitely the most important and extensively used building block in a circuit, but their detailed behavior is often somewhat ignored. In most cases, the waveguide is simply modelled with a wavelength-independent propagation loss plus a linear dispersion. Yet in reality, a waveguide has unavoidable and performance-limiting imperfections.

Sidewall roughness is probably the most well-known structural imperfection, and it is manifestly present in sub-micron waveguides. The implications of sidewall roughness have been studied for a long time and its influences have been successfully modelled: its foremost effects are radiation loss and backscattering [1], [2]. Due to the sidewall roughness, the forward propagating mode sees a stochastic index perturbation, which breaks the perfect guiding condition and leads to a coupling to radiation modes (*loss*), and to the reverse propagating mode (*backscattering*). *Loss* is relatively simple to understand and model. The *backscattering* on the other hand, is more complicated and has more profound implications for the performance of larger circuits.

There has been quite some research on the essence and impacts of this phenomenon in silicon waveguides, mostly focused on the reflection spectrum of a waveguide. The impact on the transmission spectrum, which often is more important than the reflection spectrum, has been largely overlooked. There has been a good agreement that backscattering can introduce incoherent back-reflected light to the *input* port which has a stochastic nature in the optical domain[1].

In this paper we show that the transmission spectra of different types of silicon waveguides, fabricated in a mature fab, exhibit very strong spectral fluctuations (that are stationary in time) as shown in Fig. 1, not unlike a stochastic series of ultra-high Q resonances (even though the physics behind is quite different). We found that the extinction ratio (ER) of these resonances can exceed 10 dB. We also observe a strong dependence of this fluctuation on the type of waveguide, and more importantly, on the waveguide length. We attribute this to coherent backscattering caused by sidewall roughness, aggravated by parasitic reflections at the interfaces between grating couplers and waveguides, to the point where the transmission of a silicon waveguide can approach zero for arbitrary wavelengths. We experimentally show that the phenomenon is present in different types of silicon waveguides (strip and rib waveguides) to a varying degree and that parasitic

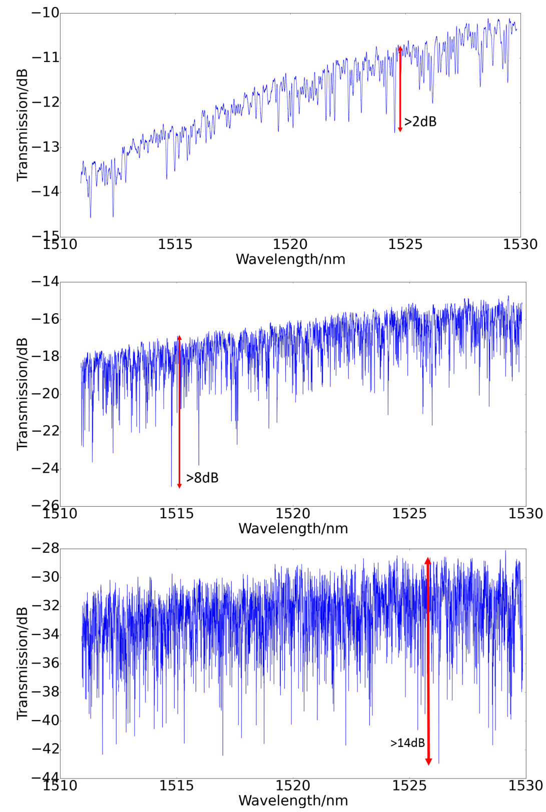

Fig. 1. Measured transmission spectra of fabricated silicon waveguides with lengths of 0.2 cm, 2 cm and 7 cm. They exhibit an increasingly strong wavelength dependency. The largest extinction ratio is 2 dB, 8 dB and 14 dB, respectively. The average slope stems from the grating couplers.

reflections elsewhere in the circuit can significantly increase its impact. The longer silicon waveguides can no longer be considered transparent guiding channels. This phenomenon has already been reported in the slow-light regime of a photonic crystal (PC) waveguide. Here, we show that ordinary silicon waveguides also suffer from this problem.

II. Experiments and simulation

In Fig. 1 we plot the measured transmission spectra of 3 silicon waveguides with lengths of 0.2 cm, 2 cm and 7 cm. These waveguides are fabricated in a standard MPW run at IMEC, but the effect is definitely not unique to this platform. They have a $\approx$450 nm$\times$220 nm cross-section and are open to air. On both ends of a waveguide is a focusing grating coupler to single mode fiber. These interfaces introduce a small parasitic reflection ($R \approx 2\%$). The measurements were conducted using a tunable laser with a 1 pm (125 MHz) step. In each spectrum we observe a wavelength dependency, the strength of which increases with waveguide length. For a 7 cm waveguide, the largest difference in transmission of adjacent wavelength sampling points is over 14 dB, which may be unacceptable behavior for a waveguide channel in certain applications. From our model we project that the transmission of longer silicon waveguides approaches zero for certain wavelengths. This can kill the performance of the device or even the whole circuit, especially when its functionality relies on a narrow-band signal.

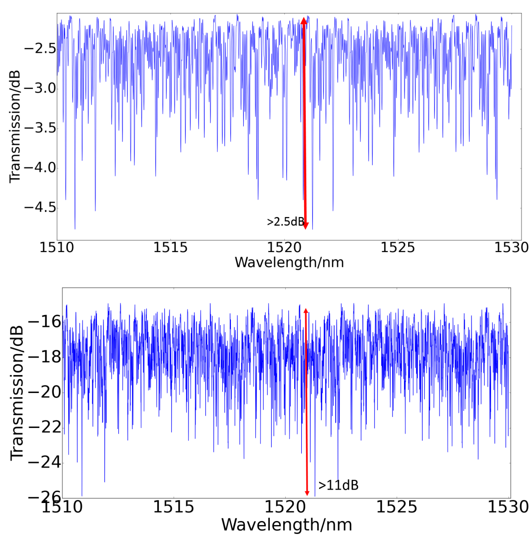

Fig. 2. A simulated transmission spectrum of a waveguide with 1 cm and 7 cm length. The largest extinction ratio is 3 dB and 11 dB, respectively

The reason behind this is that roughness induced coherent backscattering and parasitic reflections at the interfaces transform a silicon waveguide into a complicated stochastic multi-scattering system. To develop a better understanding how backscattering and parasitic reflections contribute to this spectrum, we use the circuit simulator-Caphe [3] to simulate various waveguides. The waveguide is modeled with a stochastic distribution of many scatterers, each with a random phase, reflectivity and correlation length consistent with earlier reports in literature[1]. The number of scatterers grows linearly with waveguide length, which yields the intuition that for a longer waveguide the interference pattern will be stronger and sharper. The loss is constant at the value 2 dB/cm. The parasitic reflection at the interface is chosen to be 2% in power. In Fig. 2 the simulated spectra of two waveguides are given. Their lengths are 1 cm and 7 cm respectively, and the same tendency shows a much larger extinction ratio for longer waveguide.

Lumped parasitic reflections also contribute to the fluctuation. To investigate this, we simulated a 1 cm long waveguide with the same parameters with reflections at the two interfaces ranging from 0 to 10%. The results are plotted in Fig. 3. The maximum difference in transmission spectrum grows with the parasitic reflections. It is therefore essential to use components with low reflections, such as off-axis grating couplers [4].

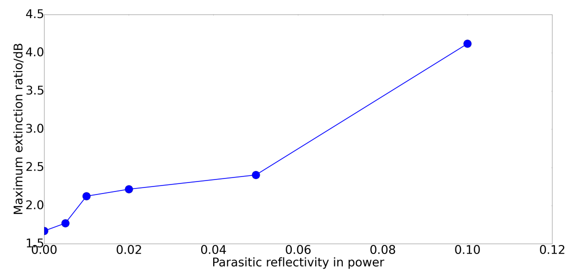

Fig. 3. Maximum extinction ratio in transmission as a fcuntion of parasitic reflections. The waveguide is 1 cm long with 2 dB/cm loss.

III. Conclusion

In this paper we present the experimental observation and analysis of the strong spectral fluctuations in the transmission of a standard silicon waveguide. We attribute this phenomenon to roughness induced backscattering. Its influence on transmission becomes stronger for longer waveguide. Also, it is essential to eliminate lumped parasitic reflections in the circuits, as these severely aggravate the effect of the distributed backscattering. This phenomenon should not only take place in silicon waveguides, but in any high-index-contrast platform. Knowing the extent of the effect for a particular type of waveguide is extremely important to assess the impact on a functional circuit. Novel design efforts are thus necessary for large-scale integrated photonics. The use of low-reflection grating coupler is one effective method to reduce the spectral ripples. Alternatively, the guiding channel could be widened for long-distance photon transport.

References

[1] F. Morichetti, A. Canciamilla, C. Ferrari, M. Torregiani, A. Melloni, and M. Martinelli, "Roughness induced backscattering in optical silicon waveguides," *Phys. Rev. Lett.*, vol. 104, no. 1, pp. 1–4, 2010.

[2] A. Li, T. Vaerenbergh, P. Heyn, P. Bienstman, and W. Bogaerts, "Backscattering in silicon microring resonators: a quantitative analysis," *Laser & Photonics Reviews*, 2016.

[3] M. Fiers, T. V. Vaerenbergh, K. Caluwaerts, D. V. Ginste, B. Schrauwen, J. Dambre, and P. Bienstman, "Time-domain and frequency-domain modeling of nonlinear optical components at the circuit-level using a node-based approach," *J. Opt. Soc. Am. B*, vol. 29, no. 5, pp. 896–900, 2012.

[4] D. Vermeulen, Y. De Koninck, Y. Li, E. Lambert, W. Bogaerts, R. Baets, and G. Roelkens, "Reflectionless grating couplers for silicon-on-insulator photonic integrated circuits," *Opt. Express*, vol. 20, no. 20, pp. 22 278–22 283, 2012.