Backscattering in silicon photonic devices

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Abstract— **We report on the backscattering induced by sidewall roughness in silicon on insulator optical nanowires, its dependence on the waveguide geometrical and optical parameters and its impact on silicon photonic devices. In silicon ring resonators cavity-enhanced backscattering, increasing with the square of the resonator's finesse, emerges as a severe impairment.**

Keywords- optical waveguides; silicon photonics; roughness; backscattering; ring resonators

Surface roughness at the walls of optical waveguides is one of the main sources of radiation loss [1] and backward coupling with counterpropagating guided modes [2]. Both these effects become stronger when the waveguide index contrast increases and the waveguide size is reduced to sub-wavelength scale. As a result, the fabrication of low-loss silicon on insulator (SOI) nanowaveguides requires the reduction of sidewall roughness down to a few nanometers scale [3]. If propagation loss of state-of-the-art SOI waveguides are now sufficiently low (< 1 dB/cm) to fulfill the requirements of many applications, on the side of roughness induced backscattering many issues are still open. This is mainly because, to the best of our knowledge, backscattering in SOI waveguides has never been quantified experimentally, so that there is not a real awareness of its actual implications on practical applications.

In this work we report on an experimental investigation on the effects of backscattering in silicon on insulator optical nanowires, showing its dependence on the waveguide geometrical and optical parameters and evaluating its impact on silicon photonic devices. The dramatic effects of cavity enhanced backscattering on the spectral response of silicon ring resonators are shown, demonstrating that backscattering could hinder the full exploitation of SOI waveguides in many practical applications.

I. Backscattering in SOI Nanowires

We measured the backscattering of conventional SOI nanowires with a rectangular silicon core of height h = 220 nm and width w, buried in a silica cladding [Fig. 1(a)]. The silicon core sidewalls have a surface roughness with a standard deviation of about 2 nm and a correlation length of about 60 nm. This roughness results in a propagation loss of 2.5 dB/cm in 490-nm-wide single mode waveguides. Details on the interferometric technique employed for the backscattering measurements can be found in [4].

Fig .1(b) shows the power spectral density (PSD) of the backscatter produced by a 1-mm-long waveguide, averaged over a spectral range of 60 nm (from 1520 to 1580 nm). Some noteworthy considerations arise from this figure. First, due to the higher sensitivity to sidewall roughness, transverse electric (TE) polarization (circles) suffers from a much higher backscattering level than transverse magnetic (TM) polarization (diamonds), the difference between the two polarizations increasing from about 10 dB in larger waveguides (w = 600 nm) to about 20 dB in narrower waveguides (w = 300 nm). Second, given a certain degree of roughness, backscattering strongly depends on the waveguide geometrical and optical parameters. Experimental data agrees with theoretical predictions (dashed lines), stating that backscattering is related to the waveguide mode effective index n_{eff} through the square of its partial derivative with respect to w, i.e. it scales as $(dn_{eff}/dw)^2$ [4]. This dependence results in the higher slope of TE backscattering versus w in Fig. 1(b). Third, even though the backscattered power represents only a small

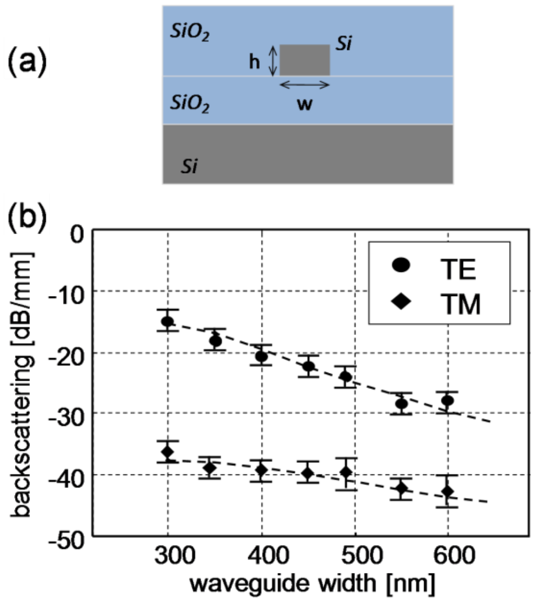

Figure 1. (a) Cross-section of a SOI nanowire; (b) measured backscattering of SOI waveguides versus *w* for TE (circles) and TM (diamonds) input polarization. Dashed lines show a numerical fit with a theoretical perturbative model.

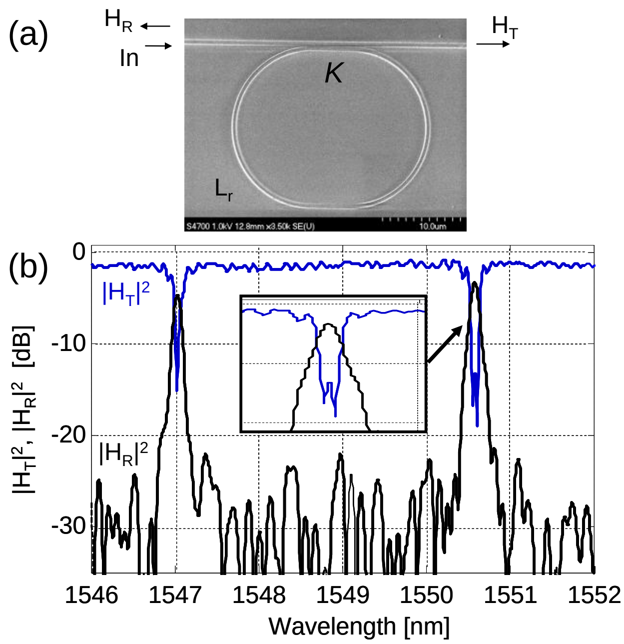

Figure 2. (a) Top view photograph of a silicon APF with a racetrack RR coupled with a bus waveguide; (b) Measured transmission ($|H_T|^2$) and backreflection ($|H_R|^2$) of the silicon APF coupled with a 3-mm-long bus waveguide for K = 0.2.

fraction of the overall radiation loss (<10 %), it can be more detrimental than propagation loss. For example, in a 490-nm-wide waveguide (α = 0.25 dB/mm), a backscattering of -24 dB/mm is responsible for only 0.015 dB/mm loss. Yet, the backscattered light is not lost, but it originates a backreflected signal that is not acceptable in many applications. Widespread examples are devices for optical communications, where return loss specifications above 40 dB are typically required. Note that this value is not fulfilled by a single mode 490-nm-wide longer than 50 µm and that the effect becomes more severe in narrower waveguides. The use of TM polarization, which is rarely employed in this kind of waveguides, could be a possible strategy to mitigate backscattering impairment.

II. Backscattering in Silicon Ring Resonators

The effects of backscattering in SOI nanowires are further magnified when the waveguide is employed to realize resonant structures such as ring resonators (RRs) [6,7]. In such devices, multiple round trips along the waveguide enhance backscattering according to the square of the resonator's finesse and cause strong transfer function distortions. To investigate the effect we fabricated several all-pass filters (APFs) consisting of a racetrack RRs with a radius of 20 µm and coupled to a bus waveguide by a 16-µm-long straight coupling section. In these devices, we used 490-nm-wide waveguides, with a sidewall roughness reduced below 2 nm standard deviation, resulting in a propagation loss of less than 2 dB/cm at a wavelength of 1550 nm.

Figure 2(b) shows the TE intensity transmission ($|H_T|^2$) and backreflection ($|H_R|^2$) of an APF with a power coupling coefficient K = 0.2 with the bus waveguide. As expected, at the RR's resonances (around 1547 nm and 1550.6 nm), transmission loss is enhanced. However, the roundtrip losses of the measured RR do not entirely justify the observed notches' depth. In the APF of Fig. 2(b), with a quality factor Q = 13000, the roundtrip loss of 0.2 dB would be expected to originate a notch of less than 4 dB at resonance. Our results clearly show that the missing light is actually scattered back and, for sufficiently low values of K, can even exceed the transmitted power. For instance, in the considered APF, transmission is less than -15 dB at 1550.5 nm, while reflection is as high as -5 dB. At different resonances the backscattering level (and hence the transmission notches) can change, because the RR enhances the waveguide backscattering, which varies almost randomly versus wavelength. Note also that the multiple round trips in the RR strongly correlate backscattering, so that the cavity-enhanced backscattering does not exhibit a noise-like PSD. Off-resonance the effect of the RR disappears and the backscattering of the bus waveguide emerges. The backscattering level of the straight waveguide, with a length of 3 mm, is 30 dB below transmission, resulting in -35 dB/mm average backscattering.

III. Conclusion

In conclusion, our results point out that in silicon optical waveguides backscattering, being three order of magnitude higher than in low index contrast waveguides, can be a severe impairment in many practical applications. For instance, it has strong implications on the behaviour of integrated RRs, where it can dramatically modify the spectral response even at moderate Q values.

Acknowledgment

This work was partially supported by the European Project SPLASH (6th FP). The authors are grateful to M. Sorel, R. M. De La Rue, A. Samarelli and to the technical staff of the James Watt Nanofabrication Centre at the University of Glasgow for the fabrication of the devices.

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