Silicon Waveguides and Resonators with Sub-0.1 dB/cm Propagation Loss and Over 7 Million Q in a Foundry Process

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Abstract: Propagation loss is characterized vs. waveguide width in a 220 nm silicon photonics foundry platform to form a compact model. Test paperclips and racetrack resonators with quality factors up to 7.6 million reveal losses as low as 0.064 dB/cm.

Standardized process silicon-on-insulator (SOI) foundry platforms are becoming increasingly the route to implementing high-index-contrast photonic integrated circuits (PICs), with benefits that include process fidelity and repeatability, fast turnaround, low cost via multi-project wafer (MPW) processing, as well as integrability with electronics in complementary metal-oxide semiconductor (CMOS) platforms [1]. The rectangular strip silicon waveguide is an elementary building block of any PIC. Emerging applications have placed increasingly greater demands on the waveguide propagation loss or, equivalently, the Q of resonators. In recent work [2, 4], we demonstrated low loss waveguides and resonators with $Q > 6.6$M in a foundry platform, by using wide, multimode waveguides in single mode operation. Here, we present a study of the propagation loss vs. width for a 220 nm thick strip waveguide fabricated in the AIM foundry platform [3], by using test structures that operate in the fundamental mode in the C band. We analyze the loss trends across a broad range of widths (250 - 9000 nm) that correspond to a range of confinement levels, and specifically overlap strength with the sidewall roughness, which was the target of our design, of the fundamental mode in the waveguide. The widest waveguides show propagation losses between 0.065 and 0.075 dB/cm, which are possible to measure by the use of racetrack shaped resonators in the "loss-ring" (far undercoupled) configuration. The resonator test structures are designed to be modular to allow an arbitrary width and length of straight waveguide section in a round-trip [4]. Having a set of resonators with different lengths of straight waveguide section for a chosen width provides a method for measuring low values of propagation loss. For wider waveguide widths, increasing the fraction of round trip cavity length represented by the wide straight waveguide reduces the average loss per unit length and can hence drastically increase the cavity intrinsic quality factor (Q_{int}). We report ultra-high quality factors of 7.6 to 4.1 million with racetrack resonators that utilize high confinement straight waveguides with widths between 1.5 and 9 µm.

Waveguide "paperclip" structures with primary parameters of straight waveguide length L_{row} and number of rows N [Fig. 1(b)], are common tools to derive propagation loss [5], and ideally should be invariant in all components (bends, tapers, etc.) except for the length of straight section per row (L_{row}) for a given set. Every paperclip has a total straight length $L_{totstr} = NL_{row}$, and can be fitted as loss vs. differential length. We used 5 sets of 3 paperclips to measure the propagation loss, implementing L_{totstr}'s of: 0, 1.3, 2.6 cm for 250 nm wide waveguide, 0, 1.7, 3.4 cm for widths of 400,

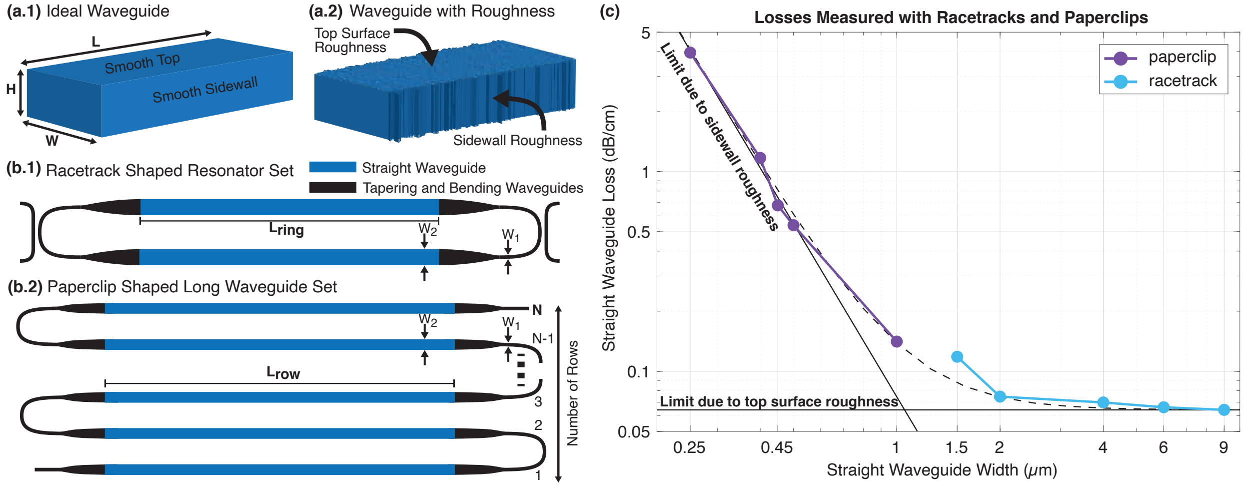

Fig. 1: **(a)** 3D representation of strip waveguide with and without top/bottom and sidewall roughness which contribute to loss. **(b)** Racetrack resonator and paperclip loss test structures. **(c)** Measured waveguide loss vs. width at 1550 nm wavelength.

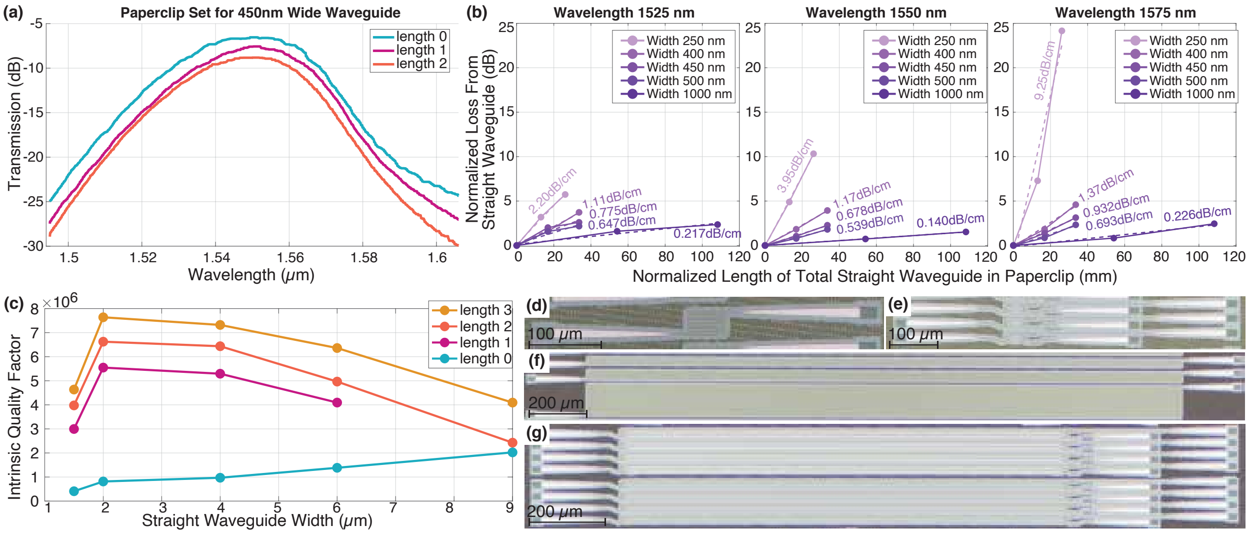

Fig. 2: **(a)** Transmission from a set of paperclips. **(b)** Propagation loss extraction by linear fit to 3 waveguide lengths at each of 3 wavelengths. **(c)** Intrinsic Q of 19 distinct loss resonators. **(d-g)** Top-view optical micrographs for (d) 'length 0' paperclip for 450 nm wide waveguide, (e) 'length 0' loss rings for 2 μm wide waveguide, (f) 'length 1' paperclips for 250, 450, and 1000 nm (top to bottom) wide waveguides, (g) 'length 1' loss rings for 4 (top) and 2 (bottom) μm wide waveguides.

450, 500 nm, and 0, 5.4, 10.8 cm for 1000 nm wide strips. The transmission was measured for each paperclip [set for 450 nm wide strip is shown in Fig. 2(a)], and sampled at several wavelengths. The extracted propagation losses are shown in Fig. 2(b) for 1525, 1550, 1575 nm wavelengths, and the loss at 1550 nm is plotted in Fig. 1(c) vs. waveguide width. The loss decrease rate with increasing waveguide width matches theoretical models of loss due to sidewall roughness. Flatter rate at wide widths indicate another loss mechanism, top/bottom surface roughness. [6].

For low loss waveguides, the paperclip structure is highly area inefficient, requiring 10s-100s of cm of waveguide length to see a few dB difference between the transmission spectra of paperclips in a set. A better method to measurement of small losses is a resonator [7]. For a straight-waveguide loss measurement, we use racetrack shaped resonators with the straight waveguide embedded in the cavity, and the cavity designed so that the straight waveguide under test ideally dominates the round-trip loss (or, at least is not too small so that it can be accurately disembedded). The Q_{int} of a resonator is related to its round trip length and loss, $Q_{int} = \frac{0.2\pi n_g}{\lambda_o \ln(10)} \frac{100 L_{rt}}{Loss_{dBrt}}$ [7] (L_{rt} in meters). In our racetracks, we vary the straight waveguide length while tapering and bending components remain fixed, $L_{rt} = 2L_{ring} + L_{fix} = \frac{c}{n_g FSR}$. The loss contributions of the fixed bend/taper components can be extracted by measuring the round trip loss of a racetrack with small/zero straight section (L_{ring}). The measured intrinsic Q for 5 resonator arrays are presented in Fig. 2(c), for waveguide widths of 1.5, 2.0, 4.0, 6.0, and 9.0 μm, where 'length 0' resonators consist of only bends and tapers. These waveguide losses are in Fig. 1(c) (light blue), and show a saturating loss with increasing width. The main contribution to propagation loss at wider widths is likely the top/bottom surface roughness. The longest resonators have FSR of 14.5 GHz, with Q_{int}'s of 4.6, 7.6, 7.3, 6.4, 4.1 million.

Physics-based theoretical models consistent with the measured data in Fig. 1(c) allow few-parameter compact models of loss in the process, and enable waveguide loss to be rigorously used in design trades. We also show that in this process there are diminishing returns in going wider than 2 μm to reduce waveguide loss at the expense of complex and sensitive tapers and bends. A set of standardized, compact structures of the kind we have used, or an improved version, could be a useful process calibration tool, included in the kerf region on wafers, to monitor loss vs. width.

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