Global design rules for silicon microphotonic waveguides: sensitivity, polarization and resonance tunability

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Abstract: In a rigorous design study of silicon-in-silica waveguides and resonators we address critical parameters for tunable filters. 6:1 aspect-ratio TE and 2:1 TM waveguide designs optimize resonance-frequency dimensional tolerances, proximate metal-electrode loss and other constraints.

OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (230.7370) Waveguides.

High-index-contrast (HIC) microphotonic circuits employ strong index confinement to provide high Q's in small resonators with a free spectral range (FSR) in the 10's of nm. They enable widely tunable integrated add-drop filters for transparent optical networks [1,2], or large field enhancement for nonlinear devices. Low-index-contrast, silica planar lightwave circuits tend to employ square waveguide cross-sections. HIC microring resonators have relied on square or wide-and-flat guides, likely motivated by available thicknesses of core layers ~200-300nm (Si_3N_4, SOI) [3,4]. Polarization-insensitive devices may be built from such single-polarization waveguides using a diversity scheme. Air-clad, Si-rich nitride (index 2.2:1) guides of ~2:1 aspect ratio were introduced in high-order microring-resonator filters to prevent polarization crosstalk, and reduce resonance frequency sensitivity to guide width [2]. However, a rigorous consideration of the optimal design of HIC waveguides and resonators has been lacking.

In this paper, we investigate optimal designs of silica-clad silicon-core (Si) waveguides in terms of waveguide cross-section and field polarization, with respect to an extensive set of practically relevant criteria: sufficiently large feature sizes; low sensitivity of resonance frequencies and waveguide-cavity couplings to dimensional variations; high Q and large FSR; small propagation loss due to waveguide roughness; and efficient thermo-optic tuning. With a view toward thermally tunable high-order microring resonators, we find that dimensional sensitivity of the resonance frequency, and proximity of metallic heaters (causing optical absorption) ultimately determine the choice of design. The results give two very different optimal designs for the choice of TE or TM device operation (about 700x120nm and 480x260nm, respectively). In comparison, the Si waveguides typically employed for TE excitation (~450x200nm) are much more sensitive to dimensional error, rendering high-order filters difficult to realize.

We parameterize our study throughout by waveguide aspect ratio (A_R), for designs using TE and TM excitation. Fig. 1a maps the set of largest single-TE-mode (SM-TE) and single-TM-mode (SM-TM) rectangular Si waveguides for all A_R. Larger cross-section increases confinement and achievable FSR, for a given bending loss. For microring resonators excited by evanescent side-coupling single-mode waveguides are suited. Only one resonator mode must be excited to avoid spurious spectral resonances and to prevent coupler loss due to low-Q spurious modes [2]. Mode effective indices specify confinement (bend loss) while in HIC guides mode group indices enter into the tunability $\Delta\lambda/\lambda_o \approx \Delta n_{eff}/n_{group}$, the $FSR \approx c/n_{group} l_{round-trip}$, and cavity Q due to propagation losses, $Q_{loss} \approx 0.27 n_{group}/(\lambda_o L_{dBcm})$.

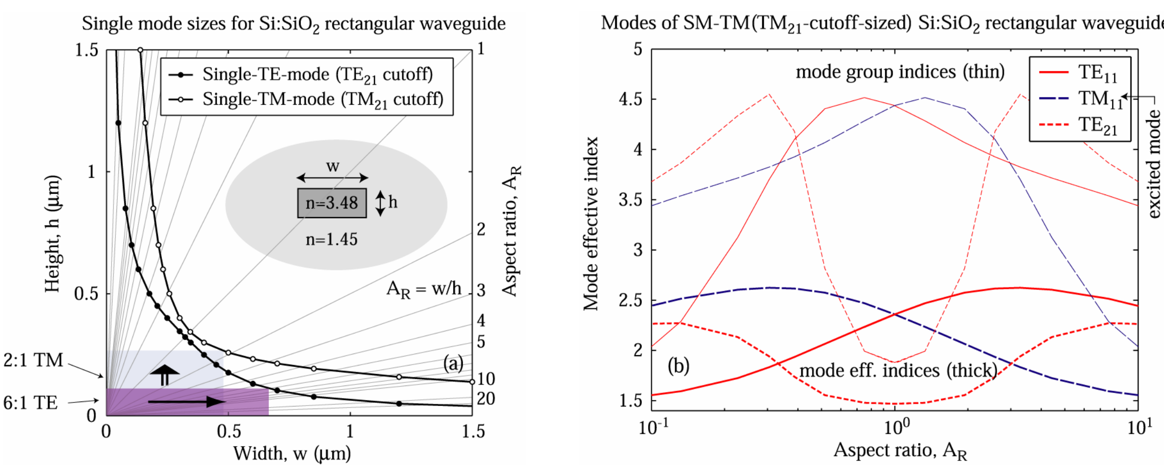

Fig. 1. (a) Single-TE-mode (TE_{21} cutoff, 2 modes) and single-TM-mode (TM_{21} cutoff, 3 modes) rectangular silicon waveguide dimensions of all aspect ratios; (b) TM waveguide effective and group indices for all 3 modes vs. aspect ratio.

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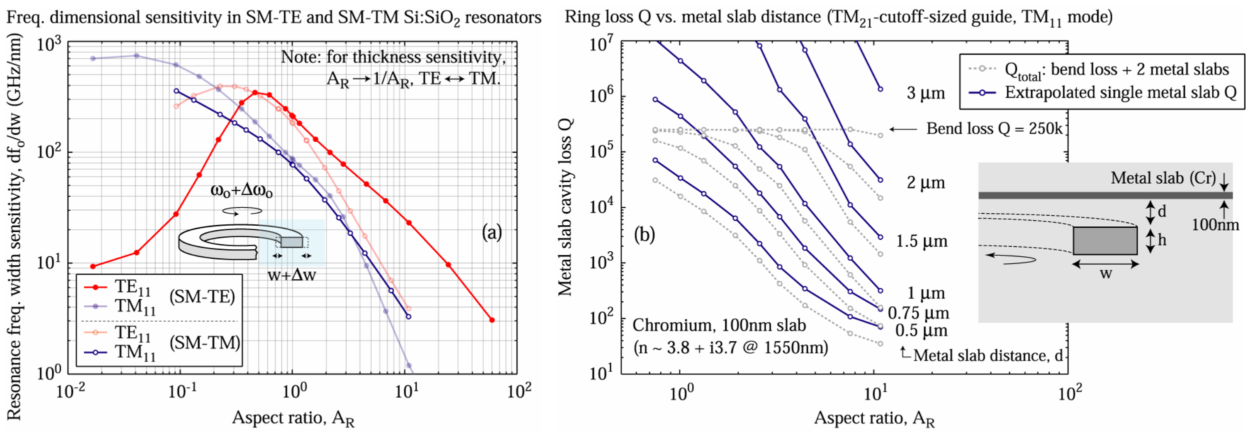

Fig. 2. (a) Resonant frequency sensitivity to microring waveguide width for TE and TM designs (for thickness sensitivity $A_R \to 1/A_R$, TE ↔ TM); (b) ring loss Q due to 100nm Chromium metallic slab (heater) at displacements above ring.

Fig. 1b shows effective and group indices of SM-TM designs. Three modes are allowed in this case – TE_{11}, the used TM_{11}, and TE_{21} – because, by symmetry, TE and TM modes will not couple. This somewhat unconventional "overmoded" SM-TM design, where the employed TM mode is not the fundamental (best confined) mode, is justified by the analysis of propagation loss [6] that shows that TM modes in wide, thin waveguides can radiate less than TE. The TM-polarized case is a viable option if the sidewall roughness quenches the Q of the TE resonances sufficiently to prevent spurious resonant responses due to small perturbative excitations.

Where active tuning and stabilization of *individual* cavities is undesirable, sensitivity of resonance frequencies to dimensional errors is critical. It impacts the feasibility of producing multiple resonators with the same, or prescribed relative, resonance frequencies. Fig. 2a shows that near-square waveguides that might offer polarization-independent operation (without a diversity approach) have ~200GHz/nm sensitivity to width (and thickness) error making polarization insensitive operation very difficult to achieve. Typical TE guides with $A_R = 2$ show ~100GHz/nm and require dimensional control to picometers. Recent frequency-matched HIC filters showed that a sensitivity of 40GHz/nm is manageable with high-fidelity nanofabrication [2,5]. Fig. 2a shows that TE guides with $A_R>6$ and TM guides with $A_R>1.8$ have less than 40GHz/nm sensitivity. Larger A_R choices further reduce sensitivity.

On the other hand, upper bounds on the aspect ratio are imposed by confinement related issues, such as bend loss (Q), FSR, coupling to the Si substrate, and thermal tunability. For thermally tunable Si add-drop filters optical loss due to optical field overlap with metallic heaters is the most critical parameter. Fig. 2b shows that for TM guides with $A_R>2$, a 100nm Cr slab placed above the waveguides must be displaced over 1μm above a ring resonator to avoid spoiling a loss Q of 250k, suitable for a 40GHz-wide filter [2]. TE waveguides are better confined, so $A_R \leq 7$ can be used with a 1μm waveguide-to-heater gap. There is approximately a linear temperature drop from the heaters, through the oxide cladding, to the Si substrate acting as a heat sink. Since the buried oxide in an SOI wafer (under the waveguide layer) can typically not exceed 3μm, the temperature at the microring is significantly reduced from the metal heater temperature (~25%) by the heater-to-waveguide gap. To keep power (and electromigration) within limits, the metal must be placed close to the resonator. Si resonators thermally tune only ~2THz with ΔT ~200K. Hence, FSRs of ~2THz suffice, and these are supported by TE guides $0.5 < A_R < 15$ and TM guides $0.05 < A_R < 3$.

In this presentation, we describe the first global optimization of Si waveguides. We have found that Si filter microring resonator waveguide designs are constrained primarily by dimensional sensitivity and tuning requirements. Two designs emerge: TE-excited waveguides of A_R=6, and TM-excited ("oversized") waveguides of A_R=2.

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