High-Q ring resonators in thin silicon-on-insulator

Tom Baehr-Jones, Michael Hochberg, Chris Walker, and Axel Scherer[a)]
California Institute of Technology, Pasadena, California 91125

(Received 2 February 2004; accepted 11 June 2004)

We have fabricated high-Q microrings from thin silicon-on-insulater SOI layers and measured Q values of 45 000 in these rings, which were then improved to 57 000 by adding a PMMA cladding. The optimal waveguide designs were calculated, and the waveguide losses were analyzed. These high-Q resonators are expected to lead to interesting devices for telecommunication filters and sources as well as optical refractive index sensing. © *2004 American Institute of Physics*.
[DOI: 10.1063/1.1781355]

Over the past several years, there has been substantial interest in the application of microring resonator structures as laser sources[1] and as optical filter elements for dense wavelength division multiplexing systems.[2] Here we describe a silicon-on-insulator (SOI) structure that is particularly advantageous. In the first place, it has low waveguide loss; from the measured Q values of 45 000 and 57 000, we can extrapolate an uncoupled Q value of 94 000 and a waveguide loss of 7.1 dB/cm in the unclad case, and −6.6 dB/cm in the PMMA clad case. Although higher Q values have been obtained for optical microcavities,[3] we believe that our geometry has the highest Q for a resonator based on a single mode silicon waveguide. But also noteworthy is the large amount of power contained outside the core silicon waveguide, which may be important in some applications; the modes that will be described have approximately 57% of the power outside the waveguide, as compared to 20% for a single-mode 200-nm-thick silicon waveguide, and 10% for a single-mode 300-nm-thick silicon waveguide.

We chose to study wafer geometries that minimize the thickness of the SOI waveguiding layer as well as the buried oxide, but still yield low loss waveguides and bends. A number of different waveguide widths were compared by finite difference based mode solving. The geometry we chose consists of a 500-nm-wide waveguide formed in a 120-nm-thick silicon layer, atop a 1.4 μm oxide layer, which rests on a silicon handle. Such a configuration supports only a single well-contained optical mode for near infrared wavelengths. The dispersion characteristics are shown in Fig. 1 for both unclad and PMMA-clad waveguides. Our interest in unclad structures stems from the ease of fabrication, as detailed in the following, as well as the flexibility an open air waveguide may provide for applications.

These modes were determined by using a finite difference based[4] Hermitian eigensolver, the details of which are beyond the scope of this letter. It is possible to calculate the loss directly from the mode pattern with an analytic method valid in the low-loss limit, which the authors intend to publish in a forthcoming paper. The waveguide loss at 1.55 μm calculated in such a fashion is approximately −4.5 dB. This loss figure was in agreement with the extrapolated results of FDTD simulation.

It should be noted that since −4 dB/cm loss is attributed to substrate leakage, the waveguide loss can be improved by the addition of a cladding, which tends to pull the mode upwards. This notion is supported by the measured decrease in waveguide loss upon the addition of a PMMA cladding. It can be shown that the substrate leakage loss attenuation coefficient is nearly proportional to

$$e^{-2\sqrt{n_{\mathrm{eff}}^2-n_o^2}k_0A}$$

if k_0 is the free space wave number, n_{eff} is the effective index of the mode, n_o is the effective index of the oxide layer, and A is the thickness of the oxide. In our case, the e-folding depth of the above-mentioned function turns out to be 180 nm, which explains why the substrate leakage is so high.

SOI material with a top silicon layer of approximately 120 nm and 1.4 μm bottom oxide was obtained in the form of 200 mm wafers, which were manually cleaved, and dehydrated for 5 min at 180 °C. The wafers were then cleaned with a spin/rinse process in acetone and isopropanol, and air dried. HSQ electron beam resist from Dow Corning Corporation was spin coated at 1000 rpm and baked for 4 min at 180 °C. The coated samples were exposed with a Leica EBPG-5000+ electron beam writer at 100 kV. The results reported here are for devices exposed at a dose of 4000 μc/cm^2, and the samples were developed in MIF-300 TMAH developer and rinsed with water and isopropanol. The patterned SOI devices were subsequently etched by using an Oxford Plasmalab 100 ICP-RIE within 12 mTorr of chlorine, with 800 W of ICP power and 50 W of forward power applied for 33 s. Microfabricated devices such as the one shown in Fig. 2 were tested by mounting the dies onto an optical stage system with a single-mode optical fiber array. A tunable laser was used first to align each device, and then

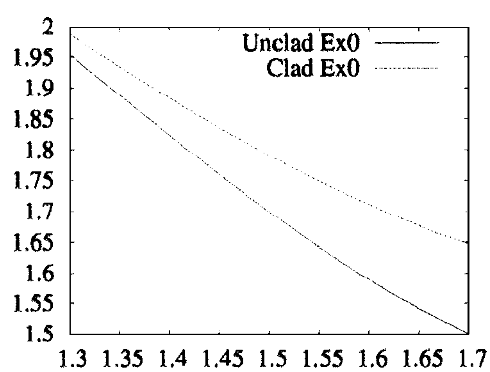

FIG. 1. Dispersion plots for the fundamental mode (Ex polarized) of the clad and unclad waveguides, shown as effective index vs wavelength in μm.

[a)]Electronic mail: etcher@calteh.edu

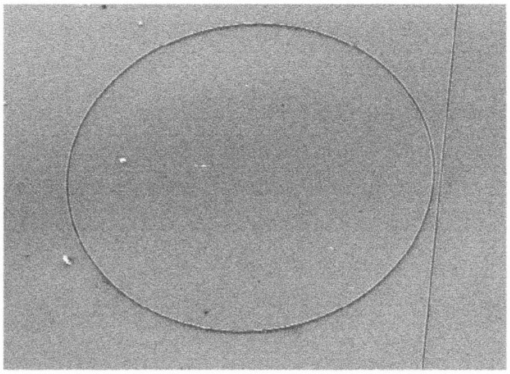

FIG. 2. SEM image of one of the ring resonators studied.

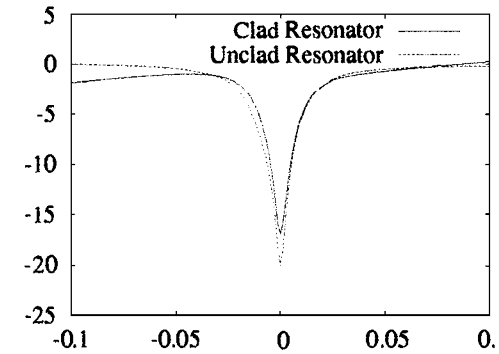

FIG. 3. Normalized transmission of light through the system (and past the ring) in dB, as a function of wavelength detuning in nm for both clad and unclad waveguides, shifted to overlay resonance peaks.

swept in order to determine the frequency domain behavior of each of the devices. Light was coupled into the waveguides from a fiber mode by the use of grating couplers.[5] Subsequently the devices were spin-coated with 11% 950 K PMMA in Anisole, at 2000 rpm, baked for 20 min at 180 °C, and retested.

The theoretical development of the expected behavior of a ring resonator system has been detailed elsewhere;[6] however in this case the dispersion of the waveguide compels the addition of a dispersive term to the peak width. We take λ_0 to be the free space wavelength of a resonance frequency of the system, n_0 to be the index of refraction at this wavelength, $(\partial n/\partial\lambda)_0$, the derivative of n with respect to λ taken at λ_0, L to be the optical path length around the ring, α to be the optical amplitude attenuation factor due to loss in a single trip around the ring, and finally t to be the optical amplitude attenuation factor due to traveling past the coupling region. In the limit of a high Q, and thus $(1-\alpha)\ll 1$ and $(1-t)\ll 1$, we have

$$Q=\frac{\pi L}{\lambda_0}\frac{\left(n_0-\lambda_0\left(\frac{\partial n}{\partial\lambda}\right)_0\right)}{(1-\alpha t)}.$$

The waveguide mode was coupled into a ring resonator from an adjacent waveguide. The strength of coupling can then be lithographically controlled by adjusting the distance between the waveguide and the ring. This ring was fabricated with a radius of 30 μm, a waveguide width of 500 nm, and a separation between ring and waveguide of 330 nm. For the clad ring presented, the measured Q is 45 000, and the extinction ratio is −22 dB, for the resonance peak at 1512.56 nm. The PMMA clad ring had a similar geometry, and achieved a Q of 57 000, but with an extinction ratio of −15.5 dB. Typical observed transmission spectra are shown in Fig. 3. The typical amount of optical power in the waveguide directly coupling into the resonator was about 0.03 mW. A dependence of the spectrum on this power was not observed, to an order of magnitude.

From the mode-solving results for the unclad waveguides, we have $(\partial n/\partial\lambda)\ (1.512)=-1.182\ \mu\mathrm{m}^{-1}$, and $n(\lambda=1.512)=1.688$. Using this result and the earlier relations, the waveguide loss can be calculated from the measured Q value. Specifically, an extinction that is at least −22 dB indicates that a critically coupled Q in this geometry is greater than 38 500, which then implies a waveguide loss of less than −7.1 dB/cm. In similar fashion, the PMMA clad waveguide resonator with a Q of 57 000 but only −15.5 dB of extinction allows a worst case waveguide loss of −6.6 dB/cm. This also implies an instrinsic Q of 77 000 for the unclad resonator, and an intrinsic Q of 94 000 for the PMMA clad resonator.

It is worth noting that these devices have a slight temperature dependence. Specifically, the resonance peak shifts correspondingly with the change in the refractive index of silicon with temperature, moving over 2 nm as temperature shifts from 18 to 65 °C. The Q rises with higher temperatures slightly, from 33 k at 18 °C to 37 k on one device studied. This shift can probably be explained entirely by the dependence of Q on the effective index.

Funding from DARPA supporting this effort under Contract No. NAV N000421-02-D-3223 DO0001 is gratefully acknowledged. The authors also wish to thank Dow Corning for providing the electron beam resist and SiGen for supplying SOI wafers.

[1]M. N. Armenise, V. M. N. Passaro, F. De Leonardis, and M. Armenise, J. Lightwave Technol. **19**, 1476 (2001).
[2]C. Vazquez, S. Vargas, J. M. S. Pena, and P. Corredera, IEEE Photonics Technol. Lett. **15**, 1085 (2003).
[3]T. J. Kippenberg, S. M. Spillane, D. K. Armani, and K. J. Vahala, Appl. Phys. Lett. **83**, 797 (2003).
[4]A Taflove, *Computational Electrodynamics: The Finite Difference Time Domain Method* (Artech House, Boston, 1995).
[5]D. Taillaert, W. Bogaerts, P. Bienstman, T. F. Krauss, P. Van Daele, I. Moerman, S. Verstuyft, K. De Mesel, and R. Baets, IEEE J. Quantum Electron. **38**, 949 (2002).
[6]A Yariv, Electron. Lett. **36**, 321 (2000).