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Silicon waveguides and ring resonators at 5.5 μm

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We demonstrate low loss ridge waveguides and the first ring resonators for the mid-infrared, for wavelengths ranging from 5.4 to 5.6 μm. Structures were fabricated using electron-beam lithography on the silicon-on-sapphire material system. Waveguide losses of 4.0 ± 0.7 dB/cm are achieved, as well as Q-values of 3.0 k. © *2010 American Institute of Physics*. [doi:10.1063/1.3514234]

Silicon waveguides have been primarily operated at wavelengths in the near-infrared (NIR), typically around 1.4–1.6 μm. This has been convenient due to the large number of commercial optical components available in this regime. The mid-IR (MIR) wavelengths, typically defined to range from 2–20 μm,[1] have proven to be useful for a number of applications. Many astronomy experiments depend upon the detection of MIR wavelengths.[2] Chemical bond spectroscopy benefits from a large range of wavelengths from visible to past 20 μm.[3] Thermal imaging (such as night vision) depends upon MIR wavelengths as a source of black-body radiation.[4]

Silicon waveguides for MIR wavelengths have previously been theorized and fabricated;[5] in fact, an optical parametric amplifier at 2.2 μm[6] was recently shown in silicon waveguides. But there had not been results at longer wavelengths until our recent demonstration of waveguides on a silicon-on-sapphire (SOS) substrate for wavelengths near 4.5 μm.[7] With low-loss waveguides, it is possible to construct high-Q ring resonators. Ring resonators in the NIR have had a number of applications, including biosensing,[8] modulation,[9] and wavelength conversion.[10] Here we show SOS based waveguides and the first ring resonators at wavelengths between 5.4–5.6 μm. We demonstrate a waveguide loss of 4.0 ± 0.7 dB/cm and a ring resonator Q-value of 3.0 k.

We fabricated ridge waveguides with dimensions 1.8×0.6 μm on an SOS substrate. The mode structure and method for mode solving is described in our previous work. Near 5.5 μm wavelengths, only the TE0 mode should guide.[7] Figure 1 shows the optical mode pattern and dispersion plot. The ridge waveguides were fabricated on a 100 mm diameter epitaxial SOS wafer fragment with an electron-beam lithography system using standard maskless lithography techniques.[11]

Our chip contained a variety of both simple ridge waveguides and ring resonators. The simple waveguides were designed to have a number of different lengths in order to characterize waveguide loss. Two of these guides were designed with dimensions of 1.2×0.6 μm as control structures, and failed to achieve guiding as predicted. Ring resonators were fabricated with a variety of different radii and edge-to-edge spacing (coupling spacing from waveguide to ring). The primary Q-value result of 3.0 k was obtained from a ring with a 40 μm radius and 0.25 μm edge-to-edge spacing. A micrograph of this ring is shown in Fig. 2.

All waveguides tested terminated on both ends with a wider 8.0×0.6 μm waveguide in order to improve edge coupling efficiency. These wider sections were roughly 5 mm long (before cleaving) and were connected to the main guides with a simple taper. The chip was cleaved manually through these runouts. Approximately half of the 5 mm long section remained on each side of the devices after cleaving. Since the length of this portion of the device was identical for all devices tested, it did not affect the waveguide loss measurement, as is shown later.

Figure 3 shows a diagram of our test setup. We achieved a total dynamic range near 85 dB and attained an insertion loss of around 25 dB coupling into the waveguides.[11]

The possibility of TM guiding was also investigated by rotating the input polarization 90°. We found a signal at least

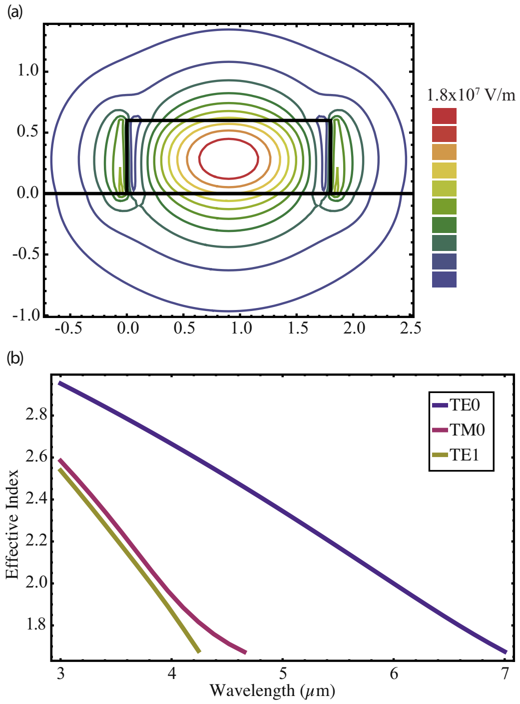

FIG. 1. (Color online) (a) A contour plot of the optical mode pattern of the waveguide. Dimensions are in micrometers. (b) A dispersion diagram for SOS waveguides.

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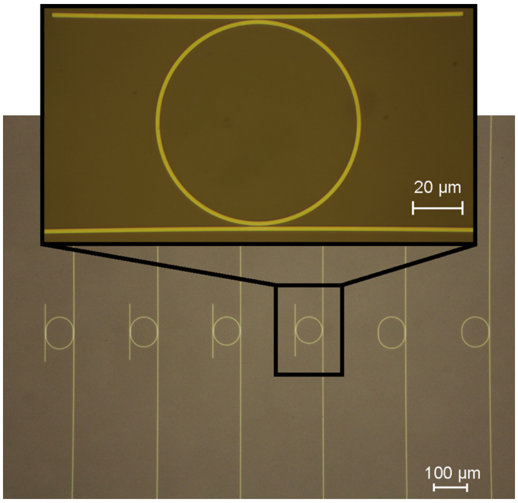

FIG. 2. (Color online) Optical micrographs of the primary ring resonator device found to have a Q-factor of 3.0 k (top) and a group of ring resonators of various dimensions (bottom).

15 dB lower than for the TE input, which was close to the noise floor. We suspect the source of the small signal seen is simply scattering off the waveguide end facets, or possibly due to a very small amount of TE light remaining in the system.

Measured waveguide loss was 4.0 ± 0.7 dB/cm. Waveguide loss was determined by a least-squares linear regression of transmission power from eight separate guides of varying lengths between 4.1 and 16.4 mm. Primary loss measurements were taken with the laser operating around 100 mW and 5.5 μm. Similar losses were seen with the laser operating near 6 mW, suggesting that there is minimal nonlinear loss.

Wavelength transmission spectra were taken on multiple ring resonators. We focused measurements on a ring with a radius of 40 μm, edge-to-edge spacing of 0.25 μm, and a drop port. Adding a drop port will lower the Q value but make it easier to obtain a large extinction when on resonance. This ring yielded a Q-value of 3.0 k, a free spectral range (FSR) of roughly 29.7 nm, and an associated group index of 3.99. Without prior knowledge of the waveguide loss, it was difficult to optimally design the ring resonators. At a waveguide loss of 4.0 dB/cm, it would theoretically be possible to achieve a critically coupled Q-value as high as 25 k. This discrepancy is almost certainly due to the presence of the drop port, and we expect to greatly improve these numbers in the future. The theoretical FSR of a ring of this size is 29.2 nm (with a theoretical group index of 4.05), which is in close agreement with our typical measured FSR.

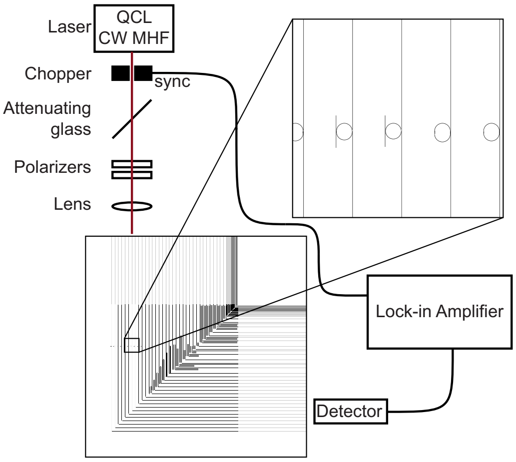

FIG. 3. (Color online) A diagram of the test setup including an image of the chip tested.

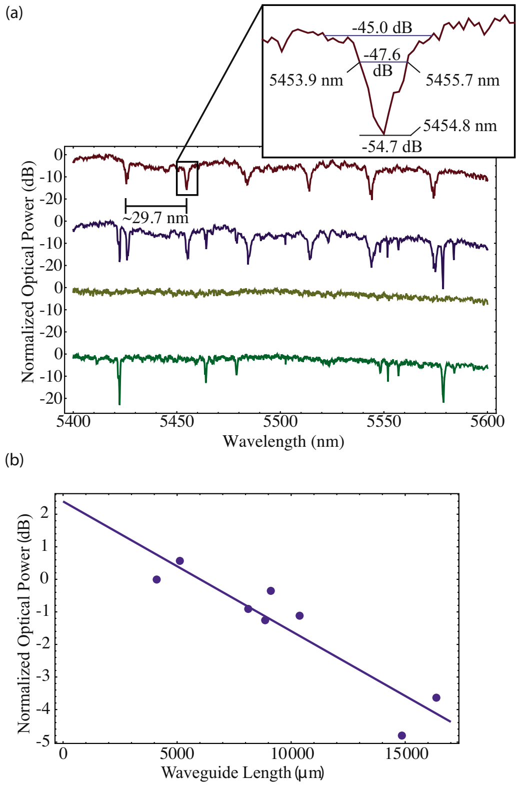

FIG. 4. (Color online) (a) Transmission spectra for the primary ring reported: tested in a nitrogen-purged environment (top) and tested under normal atmospheric conditions (second). Transmission spectra for a regular waveguide: tested under a nitrogen-purged environment (third) and tested under normal atmospheric conditions (bottom). A Q-factor of 3.0 k and an FSR of 29.7 can be seen. (b) A plot of transmitted optical power for various devices of a variety of waveguide lengths. The optical power is arbitrarily normalized with the transmission for the shortest device corresponding to 0 dB. A least-squares linear approximation is shown, demonstrating waveguide losses of 4.0 ± 0.7 dB/cm.

Atmospheric absorption becomes an increasing problem at longer wavelengths in the MIR. For most of our measurements, we simply performed testing at a wavelength where there was no observable absorption from the atmosphere. We also conducted further wavelength sweeps of the primary ring result in a nitrogen-purged environment, in order to obtain a cleaner transmission spectrum. We found that all absorption peaks were removed, giving a much clearer indication of resonator peaks as seen in Fig. 4.

In conclusion, we have shown that it is possible to fabricate low loss ring resonator devices with Q-values as high as 3.0 k on a SOS substrate for wavelengths from 5.4–5.6 μm. We expect it will be possible to improve the Q-values in the near future, due to the low waveguide loss measured.

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[11] See supplementary material at http://dx.doi.org/10.1063/1.3514234 for further details on lithography and on the test setup.