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Integrated high-quality factor silicon-on-sapphire ring resonators for the mid-infrared

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We demonstrate high-quality (Q) factor grating-coupled ring resonators in a silicon-on-sapphire platform, operating at wavelengths between 4.3 and 4.6 µm. Total Q-factors of 151 000 and intrinsic Q-factors of 278 000 are measured, representing the highest Q-factors measured at the mid-infrared in Si. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4791558]

The mid-infrared (IR) wavelength region (2–20 µm) is of great interest for a variety of applications as wide-ranging as trace gas sensing, free-space communications, and thermal imaging. While high-power sources and sensitive detectors at the mid-IR range have finally reached maturity, the passive photonic devices needed to properly access these applications on-chip are still a work in progress.

Silicon has previously been proposed as an ideal material for the mid-IR due to its low material losses below 8 µm. Additionally, due to the absence of two- or even three-photon absorption, the mid-IR wavelengths offer us the opportunity to efficiently exploit the optical nonlinearities of Si, opening up a whole host of applications in nonlinear wavelength conversion and signal amplification. However, the traditional silicon-on-insulator (SOI) platform is of limited utility at these wavelengths, since SiO2 is a highly lossy material in the mid-IR, with losses of over 2 dB/cm at wavelengths longer than 3.5 µm.1,3 While our group has previously demonstrated Si membrane photonic crystal cavities (PhCs) operating at 4.5 µm,4,5 many mid-IR photonics applications will require an integrated, on-substrate platform. Also, applications in nonlinear optics require higher in-coupled powers than those attainable through the free-space coupling method employed in Refs. 4 and 5. Silicon-on-sapphire (SOS) provides an attractive platform for on-substrate mid-infrared photonics, due to the low loss of sapphire through much of the mid-IR.1,2 SOS waveguides operating at 2.75 µm,6 4.5 µm,7 5.18 µm,8 and 5.5 µm,9 microring resonators operating at 2.75 µm,6,10 and 5.5 µm,9 and grating couplers operating at 2.75 µm6,10 have already been demonstrated. In this paper, we demonstrate grating-coupled SOS microring resonators operating in the 4.3–4.6 µm range, with loaded quality (Q) factors of 151 000 and intrinsic Q-factors of 278 000.

Coupling high optical powers into MIR resonators has proven to be a challenging task.4,7,9 The fiber-coupling inverse taper method of spot size conversion10 commonly used at telecommunications (telecom) wavelengths is difficult to achieve with high efficiency, due to the immaturity of fiber technology at the mid-infrared. Grating couplers, on the other hand, can provide highly efficient coupling of light from a free space beam into an optical waveguide. This method has already been well studied at the telecom wave-}

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improve collection of light at the output. By using this approach,\textsuperscript{7,9} we were able to increase out-coupling efficiency from 9\% (for a 1.6 $\mu$m waveguide without a horn) to 25\%, assuming a lens with numerical aperture of 0.5.

The setup used to characterize our devices is shown in Figure 2. Light from a tunable continuous-wave quantum cascade laser (QCL) from Daylight Solutions, Inc., with emission from 4.27 to 4.63 $\mu$m and linewidth of <45 MHz, is sent through a ZnSe objective (numerical aperture of 0.22) and focused onto the input grating. A second ZnSe lens (numerical aperture of 0.5) is placed at right angle to the first lens in order to collect light from the end facet. Finally, the light is focused onto a thermoelectrically cooled HgCdTe (MCT) detector.

Transmission data from our as-processed ring resonators are shown in Figure 3(a). Results from a device with a value of $d = 300$ nm is shown. Resonances were also measured in devices with $d = 400$ nm and 550 nm, with no resonances seen for $d = 700$ nm. The free spectral range (FSR) of our resonators was measured to be 12.4 nm around 4.4 $\mu$m, which closely matches the expected FSR of a ring with radius $r = 60 \mu$m and theoretical group waveguide index of 4.1 at 4.4 $\mu$m. For a ring resonator coupled to a waveguide, the total (loaded) Q-factor $Q_t$ is given by the relation $Q_t^{-1} = Q_0^{-1} + Q_c^{-1}$, where $Q_0$ is the intrinsic Q-factor (determined by radiation losses and material absorption, including surface states) of the ring resonator, and $Q_c$ is the coupling Q-factor (determined by the coupling strength with the waveguide). Power transfer between the waveguide and the ring resonator is maximized when $Q_0 = Q_c$, a regime known as critical coupling. For $Q_0 < Q_c$, the ring resonator is considered undercoupled, and for $Q_0 > Q_c$, the ring resonator is considered overcoupled. In our measurements, the coupling decreased with increasing $d$, indicating that our devices operate in the undercoupling regime. The experimentally obtained transmission spectra were fitted to theoretical curves obtained by solving a set of coupled mode equations\textsuperscript{15} that take into account the scattering-induced coupling of clock-wise and counter-clock-wise propagating modes, which can be observed as mode-splitting for very high-Q resonators. Using this approach, we inferred maximum loaded Q values of $Q_t = 41,000$ and intrinsic Q-factors of $Q_0 = 127,000$. In order to improve the performance of our devices, we decided to subject them to the post-fabrication micro-electronic treatments described in Refs. 5 and 16, namely Piranha etch/HF cycling and annealing. The former treatment decreases absorption due to surface states and reduces surface roughness, while the latter treatment reduces absorption due to water.\textsuperscript{5} A cycle of Piranha etch (3:1 H$_2$SO$_4$ : H$_2$O$_2$) and HF acid performed three times in succession (process detailed in Ref. 16) had the most dramatic effect (annealing had limited effect on these devices), increasing loaded Qs to as much as 94,000 and drastically improving the coupling across all
devices. The response from one of the best devices (with \( d = 300 \text{ nm} \)) is seen in Figure 3(b). After post-processing, we were also able to see resonances for devices with \( d = 700 \text{ nm} \), indicating that \( Q_0 \) for these devices had increased with respect to \( Q_t \). From fitting the transmission spectrum, we deduced intrinsic Q-factors as high as \( Q_0 = 127 \text{ 000} \) (see inset, Figure 3(b)).

To minimize scattering losses due to fabrication imperfections, we applied the resist reflow method to our devices.\(^{17}\) In our case, resist reflow consisted of a 5-min post-lithography bake in an oven at 140 °C. Because of the fine features within our grating couplers, we had to use lower bake temperatures for reflow than those typically used for microresonators.\(^{17}\) After the reflow, the sample underwent etching, cleaving, and Piranha etch-HF acid cycling as described above. The results are shown in Figure 4. Q-factors increased noticeably after the reflow, with total Q-factors as high as \( Q_t = 151 \text{ 000} \), corresponding to a resonance linewidth of 440 MHz, and intrinsic Q-factors as high as \( Q_0 = 278 \text{ 000} \). These Q-values are the highest measured in the 4–5 μm wavelength range in Si. We note that for all device geometries we tested (a total of 12), Q-factors obtained with resist reflow were higher than Qs of the devices where the reflow was not used.

Using our Q values, we can estimate the loss of our ring resonators to be about 0.74 dB/cm at 4.5 μm. We note that this loss value takes into account light scattering (due to surface roughness) and material absorption (due mostly to surface states), and also bending losses of the ring resonator (which are negligible in large diameter devices that we studied). This is slightly higher than the lowest waveguide loss values measured in silicon devices at the mid-IR (0.6 dB/cm at 3.39 μm in the case of SOI waveguides).\(^{18}\) Our comparatively higher losses may be due to scattering losses from twinning defects inherent in SOS.\(^{19}\)

In conclusion, we have realized mid-IR integrated on-chip optical networks operating at the 4.5 μm wavelength range, based on the SOS material platform. Grating-coupled ring resonators, with intrinsic Q-factors as high as 278 000, were demonstrated. High Q-factor resonators in the mid-IR are of great interest for trace-gas sensing in particular, and the realization of portable spectroscopy systems in general. Another exciting application of our platform is on-chip non-linear wavelength conversion via four-wave mixing, as well as the potential realization of chip-scale frequency combs operating in the mid-IR.

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