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Nonlinear absorption in silicon and the prospects of mid-infrared silicon Raman lasers

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We present the first experimental results of nonlinear absorption in silicon at the mid infrared wavelengths. Nonlinear losses due to two-photon and free-carrier absorption that are found to degrade near infrared silicon Raman devices become negligible at photon energies less than half the bandgap (i.e., $\lambda > 2.2$ µm in wavelength). Moreover, the low loss window for linear absorption in silicon extends from 1.2 to 6.5 µm. These factors along with the excellent thermal conductivity and high optical damage threshold renders silicon an ideal material for building Raman lasers and amplifiers that operate in the mid infrared wavelengths. This new technology will expand the application space of silicon photonics beyond data communication and into biochemical sensing, laser medicine, and LIDAR.

1 Introduction By circumventing the problem of indirect bandgap, Raman scattering offers a path to optical amplification and lasing in silicon [1]. To create the recently demonstrated silicon Raman lasers [2, 3] nonlinear losses due to absorption by free carriers that are generated by two-photon absorption (TPA) had to be eliminated using pulsed pumping or reverse-biased carrier sweep-out. Even when such measures are taken, operation in the near IR band is limited to low duty cycle pulse pumping, or in the case of CW operation, to low output powers and poor efficiency. The latter limitation originates from the fact that at high pump intensities, the use of PN junction is only partially effective because free carriers screen the junction's electric field [4].

In this paper, we report the first measurements of nonlinear absorption in silicon in the mid-IR wavelengths and show that two-photon and free-carrier absorption processes can be reduced to negligible levels by using pump lasers with photon energy less than half the band gap. This implies that when pumped with laser wavelength longer than ~2.2 µm, the two-photon absorption process is eliminated. This combined with the negligible linear loss and the excellent thermal and optical damage properties offers the possibility of realizing efficient silicon Raman lasers and amplifiers at mid IR wavelengths.

2 Experimental results The measurement of nonlinear losses in silicon was performed with the objective of ascertaining the wavelength dependence of free-carrier and two-photon absorption. Pulsed pump laser sources were used in these measurements and were coupled into bulk silicon samples. Silicon samples with [111] orientation, 1 inch diameter, 1 inch length and resistivity of 2000 Ω cm were used in these measurements. A standard CaF_2 lens with 15 cm focal length was used to focus the laser beam and the silicon sample was moved towards the focus of the lens to increase the intensity of the coupled optical beam. The following solid state pump sources were used in this work: (i) Ho-YAG crystal operating at 2.09 µm, free-running mode with a pulse width of 100 µs and energy of ~1 J, (ii) Er-YAG laser operating at 2.936 µm, Q-switched with a pulse width of 100 ns and energy of ~25 mJ [5]. Both these

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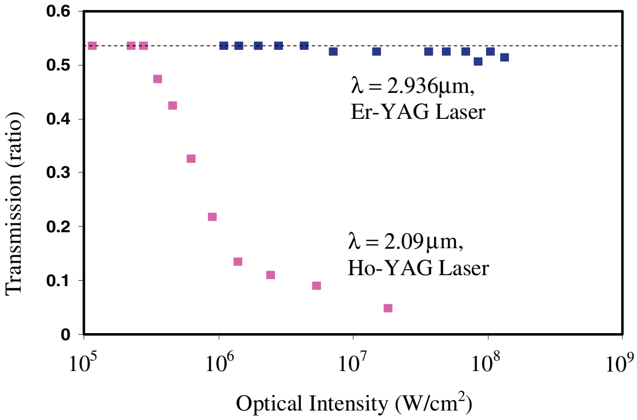

Figure 1 Optical transmission in silicon as a function of intensity. Two different pump sources at 2.09 µm and 2.936 µm were used in these experiments. The enhanced nonlinear losses at 2.09 µm due to TPA and FCA and the absence of these losses at 2.936 µm are clearly seen.

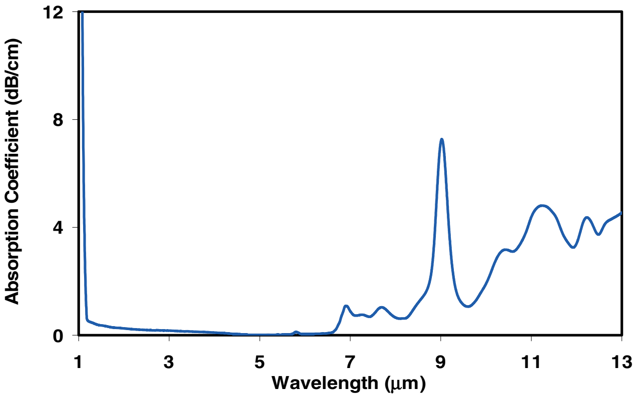

Figure 2 Linear absorption in silicon measured using an FTIR apparatus.

lasers had a spot diameter of ~2.1 mm. At the output end, a slow photodetector was used to measure the energy of the pulse.

Figure 1 shows the transmission through the silicon sample as a function of pump intensity at wavelengths of 2.09 µm and 2.936 µm. The silicon sample was double-side polished and the reflection loss per facet is ~29%. Hence, the maximum transmission was measured to be ~53%. At 2.09 µm pump wavelength which corresponds to a photon energy of more than half the band gap, the transmission reduces considerably with increasing pump intensity. This loss can be attributed to the two-photon absorption (TPA) process and the losses due to free-carriers generated by TPA. However, as pump photons are reduced in energy below half the band gap, the two-photon absorption process vanishes. This is observed in the transmission results corresponding to 2.936 µm pump wavelength. Although the pulse widths of the pump sources were different, the peak intensity achieved in the latter case is much higher to compensate for the reduced pulse width. The slight decrease in transmission with increasing intensities could be due to the three-photon absorption (3PA) process. However, this process is expected to be extremely weak to cause any significant free carrier losses. Thus, the absence of nonlinear absorption at pump photon energies less than half the band gap eliminates a key loss mechanism in silicon Raman devices.

The negligible linear absorption in silicon is another key attribute that makes it attractive for building efficient mid-infrared nonlinear optical devices. The linear absorption in silicon has been extensively studied over the years [6, 7]. Here we measured the absorption coefficient in our samples using an FTIR apparatus. Figure 2 shows the absorption coefficient of silicon in units of dB/cm as a function of wavelength in the range of 1–13 µm. The low loss window following the indirect band gap absorption extends from 1.2 to ~6.5 µm wavelength range. This broad low loss window clearly underscores the potential of silicon as the guiding medium for realizing active and passive functionalities in the near IR (telecom) as well as mid IR wavelengths. Beyond 7 µm the increase in losses could be due to impurities and multiphonon absorption processes.

3 Prospects of mid infrared silicon Raman devices

The experimental measurements presented in the previous section clearly suggest that the nonlinear loss mechanisms become insignificant in the mid infrared wavelength regions hence eliminating the main problem with near infrared silicon Raman lasers. This combined with (i) the unsurpassed quality of commercial silicon crystals, (ii) the low cost and wide availability of the material, (iii) extremely high optical damage threshold of 1–4 GW/cm^2 (depending on the crystal resistivity), and (iv) excellent thermal conductivity, renders silicon an ideal Raman crystal for MWIR wavelengths. When compared with other popular Raman crystals like $Ba(NO_3)_2$, $LiIO_3$, $KGd(WO_4)_2$ and $CaWO_4$ [8] silicon clearly has the best combination of relevant parameters.

The above factors indicate that the silicon Raman laser should be considered as a tool for covering the technologically important MWIR spectrum. Exploiting the mature silicon fabrication technology, low loss integrated cascaded microcavities can be employed to realize higher order Stokes emission. This represents a low cost and practical approach to extending the wavelength coverage of existing pump lasers to wavelength bands that are outside their reach. This new technology will expand the application space of silicon photonics beyond data communication and into biological, medical and military systems.

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