Mid-IR Silicon Raman Lasers

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Abstract: Silicon is arguably the best Raman medium for the mid-wave infrared spectrum. This new technology can expand the application space of silicon photonics beyond data communication and into biochemical sensing, laser medicine, and LIDAR.

Index Terms**—Silicon Raman lasers, Mid-IR silicon lasers, two-photon absorption, Er:YAG and erbium-based solid state lasers, MWIR silicon laser**

Mid-wave infrared (MWIR) lasers operating in the 2 – 6 μm are needed by a number of applications such as wind LIDAR, remote biochemical sensing and IR countermeasures (IRCM). They have also found use in other applications such as ring down and FTIR spectroscopy, as well as clinical uses where tissue ablation is achieved by targeting the resonant absorption peaks in water, the amide bonds in collagen, and other tissue chromophors in the MWIR region. Additionally, industrial uses such as hydrocarbon detection from vehicles, oil fields, and industrial smoke stacks are of interest.

Solid state Raman lasers (SSRL) have made remarkable advances in recent years. Compared to the optical parametric oscillators (OPO), the SSRL utilizes a much simpler architecture for IR frequency shifting of the pump [1]. SSRLs, although not as broadly tunable as OPOs, can be tuned via the pump wavelength. The recent demonstration of the first silicon Raman laser [2] combined with excellent transmission of silicon in the mid-IR suggests that silicon should be considered as a MWIR Raman crystal [3]. Operating in the 1550nm near IR band, the main limitation of silicon Raman lasers at the present is the loss due to free carriers that are generated by the two photon absorption process [4-5]. Active carrier sweep out using a p-n junction has been proposed as a mean to mitigate this problem [4-5] and CW operation has been demonstrated using this technique [6]. However, the PN junction is only partially effective. At high pump intensities, the carriers screen the junction field rendering the junction ineffective [7]. This phenomenon limits the output power and results in poor efficiency. In addition, this approach causes electrical power being dissipated onto the Raman crystal [7], a problem that does not exist in conventional Raman lasers.

Fortuitously, the two photon absorption vanishes in the MWIR regime hence eliminating the main problem with 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 a very attractive Raman crystal.

Table I compares Silicon with popular Raman crystals that are presently being used. The latter category include $Ba(NO_3)_2$, $LiIO_3$, $KGd(WO_4)_2$ and $CaWO_4$ [11]. It is seen that Silicon is quite competitive with these crystals in terms of MWIR transmission range and Raman gain. Thermal conductivity of the crystals is an important parameter in design of high power Raman lasers. When this is considered Silicon has superior performance compared to other crystals.

Table I: Comparison of various Raman solid state laser materials (from [11]) with Silicon

Properties of Raman media	**Silicon**	**$Ba(NO_3)_2$**	**$LiIO_3$**	**$KGd(WO_4)_2$**	**$CaWO_4$**
Trasmission Range (μm)	1.1-6.5	0.38-1.8	0.38-5.5	0.35-5.5	0.2-5.3
Refractive index	3.42	1.556	1.84 (o) 1.711 (e)	1.986 p[mm]p 2.033 p[gg]p	1.884 (o) 1.898 (e)
Raman shift at 300K (cm^{-1})	521	1047.3	770 822	901 768	910.7
Spontaneous Raman linewidth (cm^{-1})	3.5	0.4	5.0	5.9	4.8
Raman gain (cm/GW)	20 (1550nm)	11 (1064nm)	4.8 (1064nm)	3.3 (1064)	-
Optical damage threshold (MW/cm^2)	~1000-4000	~400	~100	-	-
Thermal conductivity (W/m-K)	148	1.17	-	2.6 [1 0 0] 3.8 [0 1 0] 3.4 [0 0 1]	16

The linear absorption in Silicon was measured using a standard FTIR apparatus. Figure 1 shows the absorption coefficient of Silicon in units of dB/cm as a function of wavelength in the range of 1-13μm. The high losses around 1μm is due to indirect band gap absorption corresponding to energy of 1.12eV. An extremely low loss window following this absorption peak extends from 1.2 to ~ 6.5μm wavelength range. Beyond 7μm the increase in losses could be due to impurities and overtones of the vibration resonance of Silicon atoms.

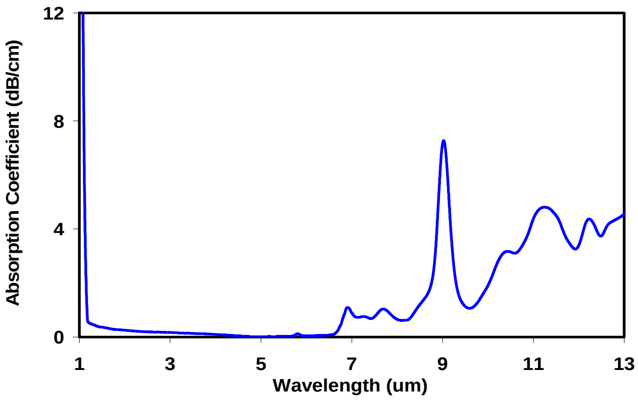

Figure 1: Linear absorption in Silicon measured using an FTIR apparatus.

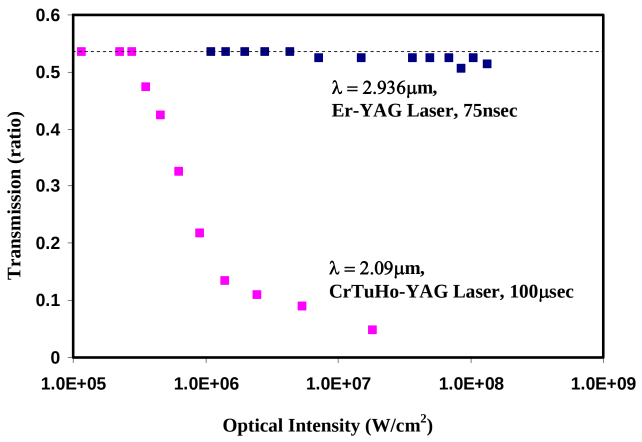

Figure 2: Optical transmission in Silicon as a function of intensity. Two different pump sources at 2.09μm and 2.936μm were used in these experiments. The enhanced nonlinear losses at 2.09μm due to TPA and FCA and the absence of these losses at 2.936μm is clearly seen.

Figure 2 shows nonlinear absorption measurements made on a 1 inch thick silicon sample at the pump wavelengths of 2.09µm and 2.936µm. The Silicon sample was polished on both sides and the reflection loss per facet is ~ 29%. Hence, the maximum transmission was measured to be ~53%. At 2.09µm pump wavelength which is close to the indirect band edge for the two-photon absorption process, the transmission reduces considerably with increasing pump intensity. This loss can be attributed to the TPA and FCA processes. As the pump photons are reduced in energy below half the band gap, two-photon absorption process is expected to vanish. This is clearly observed in the transmission results corresponding to 2.936µm pump wavelength.

The data presented in Table 1, Figures 1 and 2 clearly suggest that silicon Raman lasers should be considered as a source for covering the technologically important MWIR region of the spectrum. The absence of the nonlinear losses, which severely limit the performance of these lasers in the near IR, combined with unsurpassed crystal quality, high thermal conductivity and excellent damage threshold render silicon a very attractive Raman medium. Exploiting the mature silicon fabrication technology, low loss waveguides with long interaction and integrated cascaded microcavities can be employed to realize higher order Stokes emission and hence to extend the wavelength coverage of existing pump lasers into MWIR. 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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