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Optical nonlinearity in silicon at mid-infrared wavelengths

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Abstract: We report the wavelength dependency of third-order nonlinearity and multi-photon absorption of silicon in the spectral range from 1.6 µm to 6 µm, including the nonlinear figure of merit [1].

OCIS codes: (190.0190) Nonlinear optics; (190.7110) Ultrafast nonlinear optics.

I. Introduction

The interest in the development of high Kerr nonlinearity with weak multi-photon absorption (MPA) processes has increased over the past decade, because of their importance for ultra-fast all-optical signal processing [2]. However, in the mid-infrared (mid-IR), its nonlinearity has not been well characterized. The multi-photon absorption places a fundamental limitation on the usefulness of any high $\chi^{(3)}$ material in all-optical switching schemes [3] based on an intensity-dependent refractive index [4], especially strong two-photon absorption (TPA) in silicon. At telecom wavelengths, relatively high peak intensity is normally required to trigger the third-order Kerr nonlinearity, but also leads to a strong TPA [4]. Therefore, the combination of high Kerr nonlinearity ($n_2$) and relatively weaker MPA ($\alpha_n$) beyond the TPA region makes silicon highly promising for nonlinear applications at mid-IR wavelengths.

The third-order nonlinear coefficients ($n_2$) and multi-photon absorption processes have been previously reported up to 2.75 µm [5], which shows a decrement of $n_2$ towards longer wavelength from the peak value at 1.9 µm [6]. Here, we extend the measurements further to 6 µm in the mid-IR range.

II. Mid-IR Z-scan Experiments

We explore the measurements of degenerated MPA coefficients and nonlinear refractive index $n_2$ in silicon, in this broad mid-IR range, using the Z-scan technique [5].

![Variation of $n_2$ in silicon at mid-IR wavelengths from 1.6-6 µm: crosses (data from ref. [6]) and diamonds (data measured by SUTD).](image)

The dispersion of $n_2$ from 1.6-6 µm is measured and shown in Fig. 1. A sharp increment of $n_2$ from telecom wavelength towards mid-IR range is observed with a peak at 2.1 µm, following by a dip at longer wavelength, which matches with the reference data in the literature (red crosses in Fig. 1) [7]. In order to further explore the dispersion of $n_2$ at mid-IR wavelengths, the Z-scan measurements are extended to longer wavelength beyond 2PA region up to 6 µm. According to Kramers-Kronig (KK) relations [8], two-photon resonance leads to the peak of $n_2$ at the edge of transition wavelength (2.2 µm), which is in line with measured results in Fig. 1. The value of $n_2$ appears to decay...
rapidly after entering 3PA region, and saturates at a relatively constant value of $5.2 \times 10^{-14}$ cm$^2$/GW. The variation of $n_2$ appears to be consistent with KK transform [9] as shown in Fig. 1. These results are a strong indication of consistent strength of Kerr nonlinearity at mid-IR wavelength.

III. Calculation of nonlinear figure of merit and discussion

In Fig. 2, we use normalized FOM data at the 2PA region from F. Gholami et al. [5] to bridge up with our FOM results beyond 2.2 µm. It can be clearly observed in Fig. 2 that the FOM is lower at short wave-IR region, and increases sharply with increasing wavelengths, due to decaying MPA in the mid-IR region. In the region of 3PA, in contrast to that for 2PA, 3PA coefficient exhibits an increment for the red-shift of the wavelengths, resulting in a drop in FOM. In addition, the value of $n_2$ is observed to decay beyond 2PA region, thus, the calculated FOM rolls over until it reaches the 3PA-4PA transition wavelength at 3.3 µm. Due to the dramatic decrement of MPA in 4PA dominant region, the nonlinear FOM exhibits a steady rise beyond 3PA region, which is almost identical to the magnitudes in the 2PA dominant short wave-IR region [10].

IV. Conclusion

In summary, we report the measurements of degenerated MPA and Kerr nonlinear coefficients covering the near-IR and mid-IR spectral region up to 6 µm. The results indicate a good strength of Kerr nonlinearity and significant enhancement in nonlinear FOM at longer mid-IR wavelengths (3-6 µm), which appears to be a promising candidate for on-chip all-optical signal processing.

V. References