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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 (α_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].
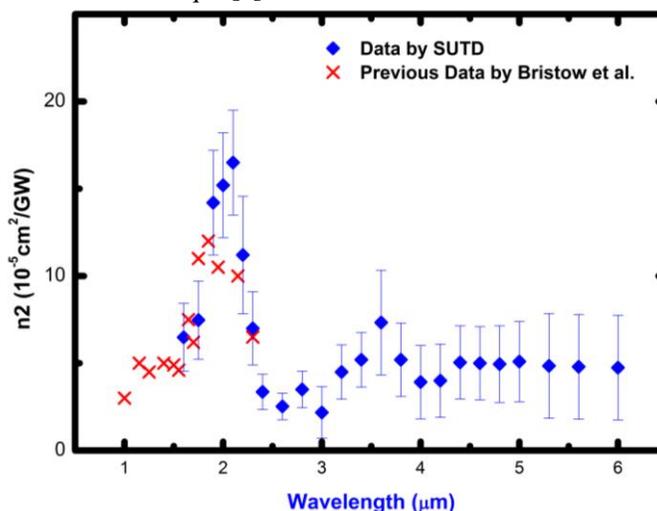

FIG. 2. Variation of n_2 in silicon at mid-IR wavelengths from 1.6-6 μm: crosses (data from ref. [6]) and diamonds (data measured by SUTD).

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 5.2×10^{-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].
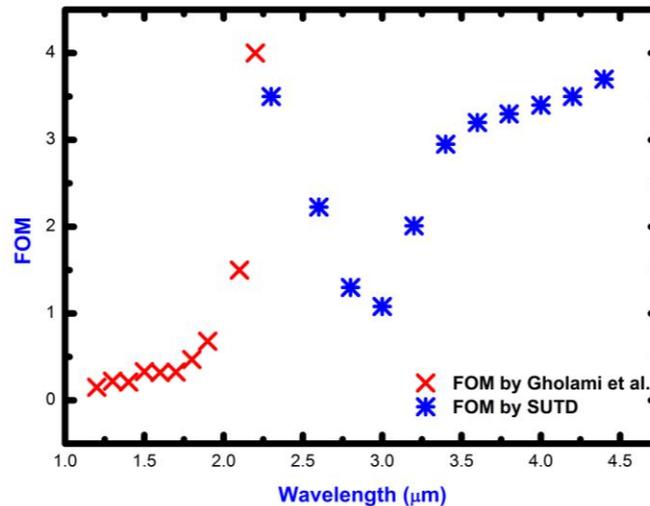

FIG. 2. Nonlinear figure of merit (FOM) with presence of MPA: crosses (data from ref. [7]) and stars (data measured by SUTD).

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.

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