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Theoretical modelling and experimental demonstration of a mid-infrared femtosecond upconversion system

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Mid-infrared (mid-IR) imaging and spectroscopic techniques have been rapidly evolving in recent years, primarily due to a multitude of application within diverse fields like biomedical imaging, chemical sensing and cancer diagnostics [1]. Most complex chemicals have unique spectral signatures in the mid-IR region, facilitating unambiguous identification based on their absorption features. Owing to the limitations of conventional detectors in the mid-IR spectral range, sum frequency generation (SFG) in a second order nonlinear crystal can be used to convert the mid-IR signal to the visible/near-IR, enabling easy detection using silicon-based detectors. Ultrashort-pulsed upconversion is of particular interest for performing pump-probe experiments and studies of fast relaxation dynamics of chemicals and molecules [2].

In this work, we report the first demonstration of femtosecond mid-IR upconversion imaging using SFG in the Fourier plane of a $4f$ imaging setup. The theory developed in [3] is not valid in the short-pulsed regime (below approximately 1 picosecond) because it does not account for the reduced interaction length in the crystal (temporal walk-off between the interacting pulses) due to group velocity mismatch (GVM). We develop a theoretical model to describe femtosecond upconversion imaging, considering the broad spectrum associated with femtosecond pulses and reduced interaction length associated with GVM. This model enables the calculation of key parameters of a short-pulsed upconversion imaging system. We find a significant increase in angular and spectral acceptance bandwidth for mid-IR signal in the short-pulsed regimes, due to drastic reduction in interaction length, resulting in exceptionally large upconversion imaging field of view (FoV) as depicted in Fig 1 (a). The resolution of the system is studied experimentally by illuminating a USAF resolution target with a mid-IR signal followed by detection of the upconverted signal. An example of an upconverted image is shown in Fig 1 (b), where a resolution of 14.2 line pair/mm is obtained.

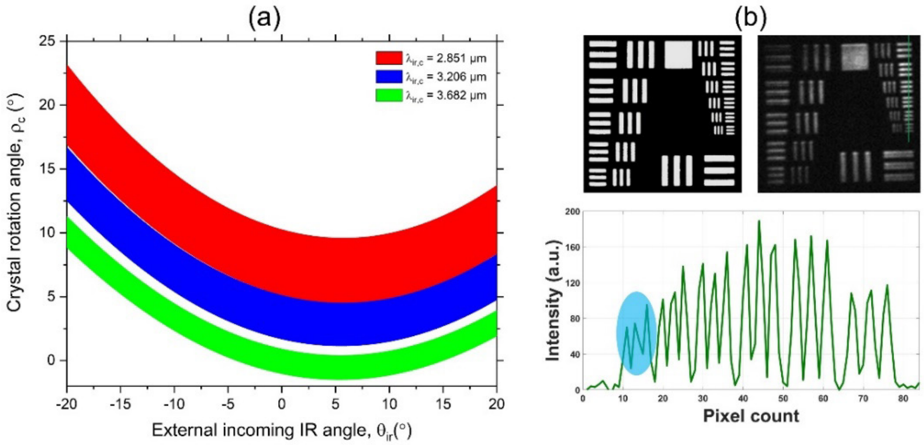

Fig. 1 (a) Theoretical calculation of phase matching curve indicating a large FoV associated with short-pulsed upconversion system. Three colours represent three mid-IR regions used for the experiment. The graph is obtained by simultaneously solving the energy conservation and phase matching condition considering the broad nonlinear spectral acceptance width (indicated by the thickness of each colour). For a ρ_c of 9.5°, we have FoV of more that 30° for the central mid-IR wavelength of 2.851 µm. (b) The upconverted image (right) of the USAF resolution target (left). The intensity plot containing the smallest feature (highlighted) is shown at the bottom. The smallest feature in the resolution target is clearly resolved.

Broad spectral and angular acceptance widths enables large FoV spectroscopy and single shot imaging (eliminates the need to adjust the phase-match condition). The developed theory is in good agreement with the experimental observations and can thus be used to derive the properties of a short-pulsed upconversion system.

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