Toward infrared spectral imaging at high resolution and high sensitivity

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Spectral imaging—a suite of techniques combining image acquisition with extremely high color resolution—plays an ever-increasing role in many fields, such as biomedicine, agriculture, geology, archeology, and environmental control.[1–3] The capability of visualizing, in real time, a tissue or terrain with spatially resolved chemical sensitivity can literally mean the difference between life and death. To appreciate the significance, consider how *in vivo* spectroscopic sensing of malignant tissue empowers the surgeon to minimize collateral damage during tumor removal while keeping the risk of cancer recurrence low.

The mid-infrared (mid-IR) spectral range of 3 to 6 μm is particularly attractive for chemical sensing because it carries unique vibrational "fingerprints" of chemical bonds that form simple or complex molecules.[1–6] In addition, the longwave mid-IR light scatters much less than the visible, thus ensuring a much higher contrast for absorption detection and suppression of background noise. Unfortunately, detection of mid-IR signals, especially for low photon numbers, is notoriously challenging, especially at the room-temperature operation condition.[4–6] Traditionally, to see a low-energy mid-IR photon, its energy is first shifted—or upconverted—into a visible or near-IR spectral range by the process of sum frequency generation (SFG), which causes an inevitable loss of sensitivity and spectral resolution.

In their recent publication,[7] the group at East China Normal University (ECNU) led by Prof. K. Huang and Prof. H. Zeng reports a significant breakthrough in detecting mid-IR at low photon counts. The researchers have improved the noise suppression level by an order of magnitude and dramatically enhanced the spectral resolution in an elegant and very versatile mid-IR scheme based on an optical parametric frequency upconverter placed inside a pump-enhancement cavity. In comparison to earlier single-pass schemes, the involved nonlinear upconverter shows the advantages of pump-power enhancement, spatial-mode confinement, and parametric noise suppression. In the intracavity-pumped upconversion scheme,[8] the SFG crystal is inserted into the pump laser cavity, which transfers the frequency and amplitude noise of the laser cavity to the upconverted signal and smears its linewidth. In the new configuration developed at ECNU, the SFG crystal is inside a passive pump-enhancement cavity that is phase-locked to an external single-frequency-mode pump laser, resulting in a dramatically suppressed optical frequency jitter of the upconverted signal. The passive cavity around the SFG crystal has a significantly lower optical loss, permitting much higher pump enhancement factors compared to intracavity-driven SFG. Furthermore, the enhancement cavity can even be made monolithic by applying reflective coatings to the SFG crystal facets. The detection sensitivity and the dynamic range of the upconverted mid-IR signal are also significantly boosted by supplementing a single-pixel sensor with a high-dynamic-range multipixel photon counter. The achieved mid-IR detection performance with single-photon sensitivity, large dynamic range, and ultrahigh spectral resolution is expected to facilitate a variety of applications, such as free-space communication, trace molecule spectroscopy, and long-range infrared sensing.

The demonstrated upconversion detector is capable of acquiring infrared images in a passive fashion,[8,9] which makes it a prospective tool for thermometric examination and spectral imaging once a suitable spatial resolution, large field of view, and small image distortion are achieved in the future. Furthermore, the promise of a rugged monolithic configuration of the upconverter in combination with single-frequency fiber lasers paves the way to device miniaturization. Notably, the approach developed by Prof. K. Huang and Prof. H. Zeng is generic. With the use of nonoxide nonlinear crystals, it can be extended to far-infrared or terahertz wavelengths to address the long-standing challenge for fast and sensitive detection in these spectral regions.

References

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