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LETTER

# Efficient mid-infrared single-photon frequency upconversion detection with ultra-low background counts

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**Abstract**
We demonstrate an efficient mid-infrared single-photon detection system with ultra-low background counts based on the frequency upconversion detection technique. The signal photons of 3.39 $\mu$m came from a He–Ne laser and the pump beam was provided by a mode-locked ytterbium-doped fiber laser. Taking into account the pulsed pumping and continuous-wave signaling scheme, the peak conversion efficiency of 64% was achieved at an average pump power of 28.3 mW. The corresponding detection efficiency was inferred to be 6.1% with ultra-low background counts of 400 $s^{-1}$.

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Ultra-sensitive mid-infrared detection has recently drawn a great deal of attention due to the fact that most fundamental rovibrational transitions of carbon–hydrogen bonds have been found in this wavelength range. Mid-infrared spectroscopy analysis could have benefits in testing waste gas and monitoring atmospheric pollution. Additionally, the minimal absorption in atmosphere for this infrared band has stimulated numerous applications, such as free-space communication, remote sensing and infrared homing. Normally, mercury cadmium tellurium (HgCdTe) detectors are employed to access the mid-infrared detection. However, the commercial HgCdTe detector is too inefficient to shoulder mid-infrared sensitive detection, which is now becoming a serious bottleneck in many applications. In contrast, the Si-avalanche photodiodes and InGaAs/InP avalanche photon diodes have shown superior capability in single-photon counting and even photon-number resolving detection for visible photons and near-infrared photons, respectively [1–4]. As well as the never-slackening development of high-efficiency HgCdTe detectors, innovative achievements have also been made to improve mid-infrared detection. For instance, a novel method for sensitive mid-infrared detection in wide-bandgap semiconductors was demonstrated by extreme non-degenerate two-photon absorption [5], and an optical parametric amplifier at the mid-infrared regime was employed to enhance the sensitive detection [6]. Also, a frequency upconversion technique could provide a feasible method by transferring the mid-infrared photons with near unitary conversion efficiency to the visible or near-infrared region where high performance detectors could be harnessed [7]. Although mid-infrared detection based on frequency upconversion was first reported in 2006, the sensitivity was largely limited by the extremely low conversion efficiency (about $5.06 \times 10^{-5}$) [8]. During the past decade, various schemes of single-photon frequency upconversion have been implemented with high conversion efficiency [9–11], some of which could be used to increase the mid-infrared single-photon detection efficiency.

 

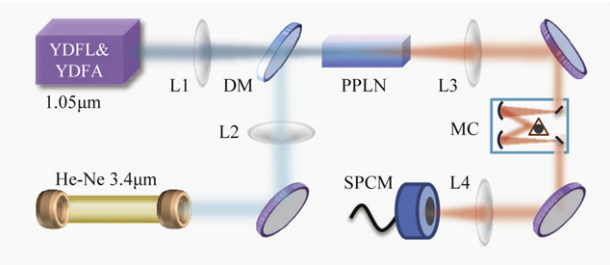


**Figure 1.** Experimental setup of the mid-infrared single-photon frequency upconversion detector. YDFL, Yb-doped fiber laser; DM, dichroic mirror; L1, L2, L3, L4, lenses; PPLN, periodically poled lithium niobate crystal.

In this letter, we present a mid-infrared single-photon detection system by pulsed pumping frequency upconversion. The mid-infrared signal source from a He–Ne laser was spectrally upconverted to the near-infrared region with a conversion efficiency of 64%, then detected by a silicon single-photon counting modulator (SPCM). Thanks to the pulsed excitation, the background noise due to the strong pump field was temporally confined within the time-window of the pumping pulse. The corresponding background was measured to be 400 counts per second (cps). The noise-equivalent power (NEP) was calculated accordingly to be $2.76 \times 10^{-17}$ W Hz$^{-1/2}$ with a detection efficiency of 6.1% in the pulsed pump envelope.

In principle, the complete frequency upconversion could be implemented by means of sum frequency generation (SFG) under a strong pump field in a quadratic nonlinear medium [12, 13]. Periodically poled lithium niobate (PPLN) crystal or waveguide have been chosen, mostly because of their large effective nonlinear coefficient and their periodically poled structure for long quasi-phase-matching distance. Here an MgO-doped PPLN crystal was used for its high nonlinear coefficient and damage threshold and low photo-refractivity. In our system, the pulsed pumping provided a strong pump field with an intense peak power to achieve high conversion efficiency.

## 2. Experimental setup and results

As shown in figure 1, the whole system was composed of the pump and signal sources, frequency upconversion, and photon detection parts. The pump source was provided by an Yb-doped fiber laser, which was passively mode-locked with a repetition rate of 17.9 MHz. A band-pass filter centered at 1.05 $\mu$m was used in the laser cavity in order to control the output wavelength. A fiber Bragg grating together with a circulator was employed at the output to get a narrow spectrum, as shown in figure 2(a), to meet the quasi-phase-matching bandwidth requirement of the MgO:PPLN crystal. After two stages of amplification, the average output power of the pump laser reached about 28.3 mW with a spectrum bandwidth of 0.3 nm. The corresponding pulse duration was deduced to be 5.3 ps from the autocorrelation trace as shown in figure 2(b). The mid-infrared signal source came from a He–Ne laser (PLASMA GNIK-3-1A) with a maximum output power of about 1 mW. The output spectrum was centered at 3.39 $\mu$m with a bandwidth of less than 0.3 nm as shown in figure 3(a), corresponding to the transitions of the 3s–3p energy levels of the Ne atoms. As shown in figure 1, the signal and pump sources were separately collimated and focused to optimize their spatial overlapping in the interaction region, and then combined with a dichroic mirror (DM). A Glan prism was used to enforce the vertical polarization selection from the signal source. A long-pass filter cutting off at 1000 nm was placed at the output of the fiber laser to block the stray light background noise from the amplifiers.

The operating temperature of the MgO:PPLN crystal was controlled at around 28.7 °C with a fluctuation of less than 0.1 °C, which allowed a quasi-phase-matching frequency upconversion for a PPLN grating period of 22.35 $\mu$m. At this temperature, the mid-infrared signal source within the pulsed pump envelope was frequency-upconverted to the near-infrared region for high-efficiency detection. The spectrum of the upconverted photons was centered at 0.8 $\mu$m, as shown in figure 3(b). In order to extract the SFG photons from the strong pump field, a monochromator was employed. The total transmittance of the filtering system was 17.3%, including that caused by mirrors, band-pass filters, and

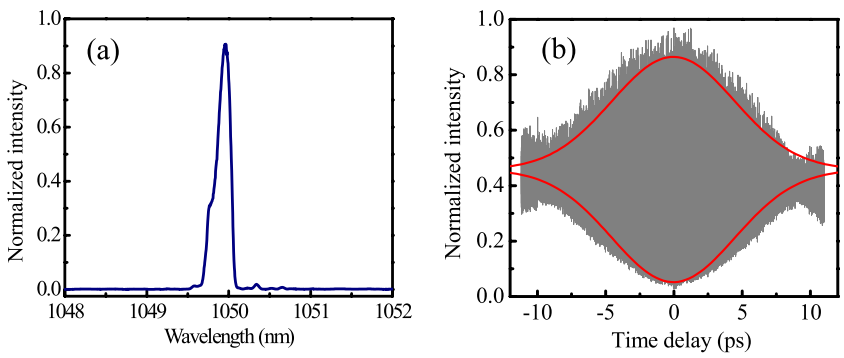


**Figure 2.** (a) Spectrum of the pump source from the YDFL and (b) autocorrelation pulse profile of the pump source from the YDFL. The red curves are the Gaussian fits to the data.

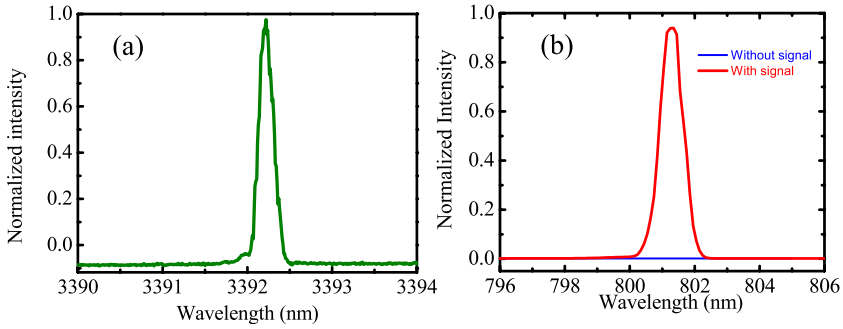


**Figure 3.** (a) Spectrum of the He–Ne laser. (b) Spectrum of the SFG signal (red curve) and the background noise (gray curve).

the monochromator. The sensitive SPCM detected the SFG photons with a quantum efficiency of 55% and dark counts around 200 cps.

The background counts were recorded as a function of the pump power when there was no mid-infrared photon injection. It showed a nonlinear increase with the pump power since the major noise was caused by the parametric fluorescence upconversion as well as the dark counts of the SPCM [14]. A monochromator was placed to isolate the SFG photons from the strong pump. The largest background noise was about 400 cps. There are two reasons for such low background noise. Firstly, parametric fluorescence noise was generated only within the pulsed pumping window of 5.3 ps. Thus, according to the duty cycle ratio, photons due to background noise would seldom be produced and detected. Secondly, the monochromator provided a high distinction level to prevent the photons due to background noise of other wavelengths from being incident on the SPCM at the cost of transmittance. If better filters could be used with both high distinction and high transmittance, higher detection efficiency could be achieved while keeping the background noise at the same low level.

Considering the duty cycle ratio of the pump source, the total energy of the signal photons which was enveloped by each pump pulse was $1.5 \times 10^{-6}$ nJ. In order to detect the upconverted photons with SPCM, a density attenuation of 44.1 dB was inserted in front of the detector. The photon counting of the SPCM was recorded as a function of the average pump power. The maximum detected photon counting of $1.1 \times 10^{6}$ s$^{-1}$, corresponding to $1.8 \times 10^{7}$ s$^{-1}$ upconverted photons, was achieved at a pump power of 28.3 mW. Therefore, the maximum overall detection efficiency was 6.1%. When the transmittance of the filters and quantum efficiency of the SPCM are taken into account, the maximum conversion efficiency of the system can be calculated to be 64% within the envelope of the pump pulses. The conversion efficiency as a function of the pump power is shown in figure 4.

At present, the detectivity ($D^*$) of the HgCdTe detectors is reported to be $1.0 \times 10^{12}$ cm Hz$^{1/2}$ W$^{-1}$ with an active area ($A$) of 1 cm$^2$ at an operating temperature of 77 K [15–17]. The NEP, which indicates the minimum signal level that can be distinguished from the noise level, can be defined as $A^{1/2}/D^*$. The NEP of HgCdTe detectors is

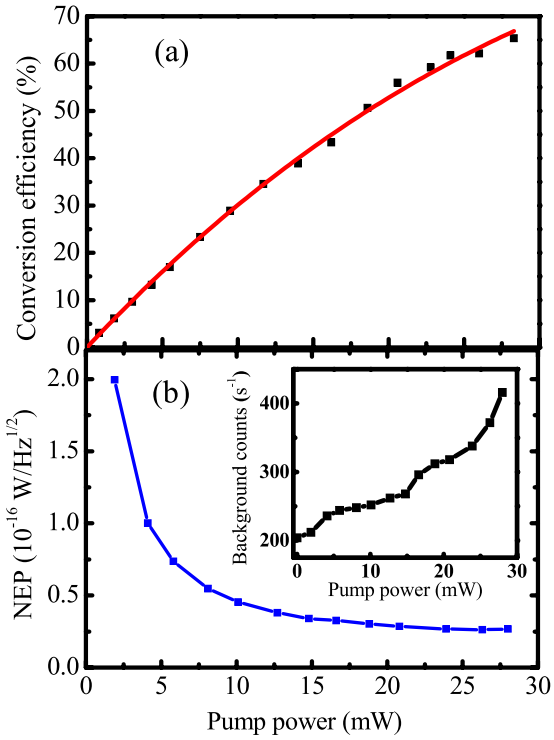


**Figure 4.** Conversion efficiency (a) and NEP value (b) as a function of the pump power recorded by the Si-APD SPCM. Inset: background noise counts as a function of the pump power.

deduced to be $1.0 \times 10^{-12}$ W Hz$^{-1/2}$. This characteristic indicates that the HgCdTe is far from the mid-infrared single-photon detection. In photon-counting systems, the NEP is usually expressed as $h\nu(2RBC)^{1/2}/\eta$ to characterize the sensitivity of the system [18, 19], where $h\nu$, $RBC$ and $\eta$ are the energy of a signal photon, the background noise, and detection efficiency, respectively. As shown in figure 4(b), at the maximum detection efficiency, the NEP was measured to be $2.8 \times 10^{-17}$ W Hz$^{-1/2}$, much lower than that of the HgCdTe detectors. Hence, the frequency upconversion detection technique provided a feasible scheme for sensitive mid-infrared detection.

## 3. Conclusions

In conclusion, we presented a sensitive mid-infrared frequency upconversion detection system with a pulsed

pump source, and the NEP in this system was as low as $2.8 \times 10^{-17}$ W $Hz^{-1/2}$, indicating that the pulsed pump upconversion detection system would be suitable for mid-infrared few-photon detections for different applications, such as pollution surveillance, atmosphere studies, and other important military applications. By using the coincidence frequency upconversion with the synchronized signal and pump sources [10, 20], the total detection efficiency could be markedly increased, which would render the frequency upconversion detector as a promising counter for mid-infrared photons.

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