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Abstract
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Reference

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Mid-infrared single-photon counting

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We report a procedure to detect mid-infrared single photons at 4.65 μm by means of a two-stage scheme based on sum-frequency generation, by using a periodically poled lithium niobate nonlinear crystal and a silicon avalanche photodiode. An experimental investigation shows that, in addition to a high timing resolution, this technique yields a detection sensitivity of 1.24 pW with 63 mW of net pump power. © 2006 Optical Society of America

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Single-photon counting (SPC) devices have been thoroughly used in the past few years in a myriad of applications, such as imaging, metrology, astronomy, spectroscopy, and quantum communications. The high popularity of this detection technology is due mainly to the high sensitivity, high timing resolution, and low noise it is able to achieve, especially in the case of silicon avalanche photodiodes (Si APDs).\(^1\)

Nonetheless, existing SPC technology is available for a limited wavelength range, comprising the visible and near-infrared (NIR) windows. Recently, the advent of quantum cascade laser (QCL) technology has broadened the available wavelength range for free-space optical systems, especially the entire mid-infrared (MIR) window (3–20 μm).\(^2\) Moreover, recent studies show that adverse atmospheric effects can be mitigated by use of sources operating inside this wavelength range.\(^3\) These results have created a demand for sensitive and fast detectors operating in MIR wavelengths.

In this Letter we propose a detection scheme that exploits the available SPC modules for detection of MIR radiation. The procedure comprises two stages: first, the MIR photons are upconverted to the NIR by sum frequency generation (SFG) and, second, they are detected with a Si APD. Note that the idea of using frequency conversion for detection of IR radiation is not new\(^4\) with experiments dating from the 1960s\(^5\) to the present.\(^6\)

To characterize the performance of this approach, three figures of merit are proposed: the overall quantum efficiency, the detection sensitivity, and the timing resolution.

The overall quantum efficiency (\(\eta_{\text{tot}}\)) of the detector is defined as the probability that an incoming photon will generate a counting event. The quantum efficiency can be factorized into a product \(\eta_{\text{tot}} = \eta_{\text{SFG}} \eta_{\text{opt}} \eta_{\text{det}}\), where \(\eta_{\text{SFG}}\) is the quantum efficiency of the APD, \(\eta_{\text{opt}}\) comprises the losses in all optical components, and \(\eta_{\text{SFG}}\), called the quantum SFG efficiency, gives the probability that a MIR photon will be upconverted inside the nonlinear crystal. Assuming no phase mismatch, the Boyd–Kleinman approximation yields\(^7,8\)

\[
\eta_{\text{SFG}} = \frac{32 \pi^2 d_{\text{eff}}^2 P_{\text{pump}} \exp(-\alpha L) L h}{\varepsilon_0 c \lambda_{\text{signal}} \lambda_{\text{pump}} n_{\text{SFG}}^2}, \tag{1}
\]

where \(d_{\text{eff}}\) is the effective second-order electric susceptibility of the medium, \(\alpha\) is the total attenuation factor for the three beams, \(L\) is the crystal length, \(n_{\text{SFG}}\) is the refractive index at the sum frequency, and \(h\) is the Boyd–Kleinman focusing factor.\(^8\) For a 1 cm long PPLN crystal, expression (3) gives a SFG efficiency of \(1.9 \times 10^{-3}/\text{W}\) of pump power, considering perfect overlap between Gaussian beams.\(^9\)

The detection sensitivity (\(\text{SNR}_0\)) is a measure of the minimum signal level that can be detected. It indicates the amount of power, in watts, to obtain a signal-to-noise ratio of unity, according to the expression

\[
\text{SNR}_0 = \frac{h c}{\lambda_{\text{signal}} \eta_{\text{tot}}} \langle n_{\text{tot}} \rangle, \tag{2}
\]

where \(n_{\text{tot}}\) is a random variable describing the detection noise statistics and \(\langle \cdot \rangle\) denotes an average value. In our case, it comprises two statistically independent sources of noise, namely, dark counts \(n_{\text{DC}}\) (inherent in the Si APD) and background noise \(n_{\text{BG}}\), such that \(\langle n_{\text{tot}} \rangle = \langle n_{\text{DC}} \rangle + \langle n_{\text{BG}} \rangle\). Background (optical) noise consists in all counts generated of external photons other than the signal photons. In the case of a MIR detection system, it will be composed mostly of blackbody radiation photons.

Thermal light from blackbody radiation follows a Bose–Einstein (geometric) probability distribution, with a mean number of photons per mode given by \(\exp(h \nu/kT) - 1^{-1}\).\(^\text{10}\) Assuming that only one spatial mode is upconverted, the background noise count rate can be approximated as

\[
\langle n_{\text{BG}} \rangle = \eta_{\text{tot}} \int_{\nu_0}^{\infty} \frac{T(\nu) d\nu}{\exp(h \nu/kT) - 1} \approx \frac{\eta_{\text{tot}} \Delta \nu}{\exp(h v_0/kT) - 1}, \tag{3}
\]

where \(T(\nu)\) is the overall normalized transfer function of the optical components, which we approximate here as a delta function centered around \(v_0\).
with a bandwidth $\Delta \nu$, where $\nu_0 = c/\lambda_{\text{signal}}$. Note that for high overall efficiency values the contribution of background noise can become much greater than the dark counts of the Si APD. A careful analysis of Eqs. (2) and (3) shows that, in this situation where the total noise is dominated by background radiation, the sensitivity will no longer depend on the overall efficiency and will reach its minimum value of $h \nu_0 \Delta \nu [\exp(h \nu_0 / kT) - 1]^{-1}$.

Finally, the timing resolution (or jitter) $\tau$ of the SPC module indicates the uncertainty in the arrival time of a single photon. In this setup, this value is completely determined by the Si APD, which can yield values as low as 40 ps.

The experimental part of this work consists of the measurement of the two parameters mentioned above: the overall efficiency $\eta_{\text{tot}}$ and the total noise counts $\langle n_{\text{tot}} \rangle$, which together determine the sensitivity. The schematic depicted in Fig. 1 shows the configuration used in all measurements.

In this setup, the QCL (Alpes Lasers) generates 20 ns pulses of vertically polarized MIR light at 4.65 $\mu$m, with a repetition rate of 750 kHz. Using a dichroic mirror (DM), we combine this beam with a pump beam of 63 mW net power, coming from a diode laser at 980 nm, inside a temperature-controlled 1 cm long PPLN crystal. Phase-matching conditions have been found for two different grating periods, corresponding to crystal temperatures of 25°C and 93°C. A polarization controller (PC) is placed after the pump laser to ensure vertical polarization.

To remove the pump beam after the crystal, a 10 nm wide bandpass filter at 810 nm (F1) was used in conjunction with a low-pass filter at 930 nm (F2). The PPLN phase-matching bandwidth of 1.47 THz is limited to fit the spectral width of the upconverted beam exactly (inset in Fig. 1) by a 0.35 nm wide (160 GHz) interference filter at 810 nm (F3) for background noise reduction. The upconverted signal is localized inside an 830 nm single-mode fiber (SMF), with the help of a lens (Z), and is detected by an ungated EG&G active quenching Si APD that was kept isolated from ambient light. The positions and focal lengths of all lenses (L1–L4) were selected such that the beam parameters for the signal and pump beams are as close as possible to the conditions of maximum overlap.7,8

### Table 1. Detection Efficiency Results

<table>
<thead>
<tr>
<th>Noise Source</th>
<th>25°C</th>
<th>93°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{QCL}}$ (kHz)</td>
<td>$55.0$</td>
<td>$55.0$</td>
</tr>
<tr>
<td>$\eta_{\text{tot}}$</td>
<td>$125 \pm 1$</td>
<td>$3.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\eta_{\text{opt}}$</td>
<td>$52%$</td>
<td>$13.7%$</td>
</tr>
<tr>
<td>$\eta_{\text{det}}$</td>
<td>$87.8$</td>
<td>$133.1$</td>
</tr>
</tbody>
</table>

In the first measurement, the QCL was attenuated to an average power of a few nanowatts. The signal photon rate $n_{\text{QCL}}$, the total detection rate $n_{\text{det}}$, and the detection efficiencies are summarized in Table 1.

The upconversion efficiency $\eta_{\text{SFG}}$ was found to be 5.06 $\times 10^{-5}$, which corresponds to $8.03 \times 10^{-4}$ W of pump power. This is off by a factor of 2.4 with respect to the theoretical value. This difference can be attributed to the nonnegligible absorption of radiation at 4.65 $\mu$m by the lithium niobate (measured to be approximately 40%), which deviates from the optimal focusing conditions of the ideal situation.7

The second goal of the experiment was to characterize the noise rates. Whereas the dark counts are measured with all sources switched off, the background noise is measured by switching off the QCL but keeping the pump beam on. This measurement has been performed for the two phase-matching crystal temperatures, and the values are presented in Table 2.

Since the crystal is not completely transparent at 4.65 $\mu$m, a higher temperature yields a higher number of blackbody photons that are created inside the crystal in the same spatial mode. These values also comprise residual pump photons that manage to bypass the filters.

Now that the system has been characterized, the QCL can be calibrated to generate only one photon per pulse. Considering a pulse rate of 750 kHz and the overall efficiency value in Table 1, this corresponds to a detection rate of 2.7 Hz. To make the noise counts negligible, the QCL pulses were reduced to 1 ns and a time-to-amplitude converter (TAC) was used to make coincidence counts between detection events in the Si APD and electrical pulses in the QCL. The result can be seen in Fig. 2; after several minutes, one can reconstruct the nonattenuated pulse shape of the upconverted light. It is important to realize that, even though only three photons out of 750 000 are detected, one has the precise information about which one-photon pulses have been detected. This is a feature unique to photon counters, and crucial for quantum communications applications.

Finally, one can now calculate the $\text{SNR}_{\text{q}}$ by using expression (2), which yields $2.82$ $\mu$W at 93°C and 1.24 $\mu$W at 25°C. Table 3 shows a comparison for the sensitivity and the time response between our results.

![Fig. 1. (Color online) Schematic of general experimental setup. Inset: spectrum of upconverted beam immediately after the nonlinear crystal with a 0.36 nm FWHM. The resolution of the spectrometer was set to 0.1 nm.](image-url)
and two commercially available MIR detectors at this wavelength: a room-temperature detector (Vigo System PVI-5) and a state-of-the-art liquid-nitrogen-cooled detector (Fermionics PV-650).

In conclusion, it has been shown that the frequency upconversion approach for photon counting in the MIR yields a single-mode, fast, and sensitive detector, despite the low quantum efficiency. If there is a need for higher efficiency values, this can be done by either increasing SFG efficiency (by increasing the pump power) or the transmission of the optical components, which would also decrease the sensitivity. Moreover, by using a coincidence count technique, we have been able to demonstrate the detection of MIR light pulses that contain only one photon.

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References

9. We are assuming here that $d_{\text{eff}}=16 \text{ pm/V}$ for PPLN.

Table 3. Comparison with Commercially Available MIR Detectors at 4.65 μm

<table>
<thead>
<tr>
<th>Detector</th>
<th>τ (ns)</th>
<th>SNR₀ (pW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vigo System PVI-5</td>
<td>15</td>
<td>1.63 x 10⁶</td>
</tr>
<tr>
<td>Fermionics PV-650</td>
<td>20</td>
<td>223</td>
</tr>
<tr>
<td>PPLN 25°C+</td>
<td>0.3ᵃ</td>
<td>1.24</td>
</tr>
<tr>
<td>EG&amp;G AQR-15FC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ᵃTiming resolution.