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S/N ratio of an upconversion detector dominated by upconverted spontaneous parametric down-conversion noise

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Abstract: We designed an upconversion detector (UCD) for 1575 nm operation. The signal-to-noise ratio of the UCD is investigated by considering the dependence of upconversion efficiency and upconverted spontaneous parametric down-conversion noise on pump power.

OCIS codes: (140.3613) Lasers, upconversion; (230.0040) Detectors; (040.3060) Infrared.

1. Introduction

Nonlinear frequency upconversion is a promising technology for infrared (IR) signal detection. Using a nonlinear crystal and a high-power pump (mixing) beam, an upconversion detector (UCD) spectrally translates the IR signal into the visible or near-IR region where better detectors are available. The use of UCD has already been demonstrated for applications such as hyperspectral imaging [1], gas analysis [2], and single-photon detection [3]. In comparison to conventional detectors (e.g. InGaAs, InSb and HgCdTe based detectors), the UCD is able to operate at room temperature and simultaneously achieve IR detection with higher quantum efficiency, relatively lower noise level and higher detection bandwidth. However, in a common UCD design where the pump wavelength is shorter than that of the IR signal, the upconversion process itself can induce undesirable noise which results in reduced UCD detectivity, especially when a pump beam with high mixing power is applied [4]. In this work, we investigate the relationship between the signal-to-noise (S/N) ratio of a UCD and the power of the applied pump beam at 1064 nm where the 1575 nm signal is upconverted to 635 nm in a periodically poled lithium niobate (PPLN) crystal.

2. Theory

With the assumption of plane-wave interaction and non-depletion of the pump beam, the quantum efficiency (QE) of a PPLN based upconversion is given by [2]:

$$\eta = \frac{32 d_{eff}^2 I_p}{\varepsilon_0 c n_p n_{IR} n_{up} \lambda_{up} \lambda_{IR}} L^2 \mathrm{sinc}^2\left(\frac{\Delta k L}{2}\right), \tag{1}$$

where d_{eff} is the effective nonlinear coefficient, I_p is the pump intensity, λ_i is the wavelength, n_i is the refractive index, (the subscripts $i = up$, IR and p correspond to the upconverted, the IR and the pump beams, respectively), L is the PPLN crystal length, Δk is the phase mismatch given by $\Delta k = |k_{IR} + k_p - k_{up}| - 2\pi/\Lambda$, where Λ is the PPLN poling period and k_i is the wavenumber of the beams in the PPLN crystal. Optimal upconversion efficiency can be achieved by tuning the temperature of the crystal.

One of the main noise sources in upconversion detection is the upconverted spontaneous parametric down-conversion (USPDC) noise and it arises due to presently unavoidable poling error of the nonlinear crystal [5]. The USPDC noise power is proportional to the square of the pump power. When USPDC noise dominates all other noise sources in excess of optical shot noise, the S/N ratio of the UCD is given by:

$$S/N = \frac{P_{IR}\omega_{up}\eta}{\omega_{IR}\sqrt{2B\hbar\omega_{up}(P_{IR}\omega_{up}\eta/\omega_{IR} + P_{USPDC})}}, \tag{2}$$

where P_{IR} is the IR signal power, B is the detection bandwidth, $\hbar$ is the reduced Plank's constant, ω_i is the angular frequency, P_{USPDC} is the power of the USPDC noise which was experimentally observed to increase with pump power P_p with approximately quadratic dependence [4], i.e. $P_{USPDC} = \alpha P_P^2$, where α is a fitting parameter.

3. Experiment and results

Equation 1 shows that the UCD can achieve higher QE when a larger pump power is applied. Meanwhile, larger pump power P_p also induces higher USPDC noise. In order to experimentally investigate the dependence of S/N ratio on pump power, a UCD dedicated for 1575 nm signal detection is utilized. The upconversion detector is based on a 1064 nm ring-cavity laser. A 25-mm long PPLN crystal with a poling period of 12 μm is embedded into the laser cavity where the 1575 nm signal is mixed with the 1064 nm intracavity pump beam. The UCD setup is shown in Fig. 1(a) and more details of the detector can be found in our previous work [6]. The QE and the background noise power (i.e. power around 635 nm when the 1575 nm signal is switched off) are measured at different circulating 1064 nm pump power levels. The measurement results are shown in Fig. 1(b).

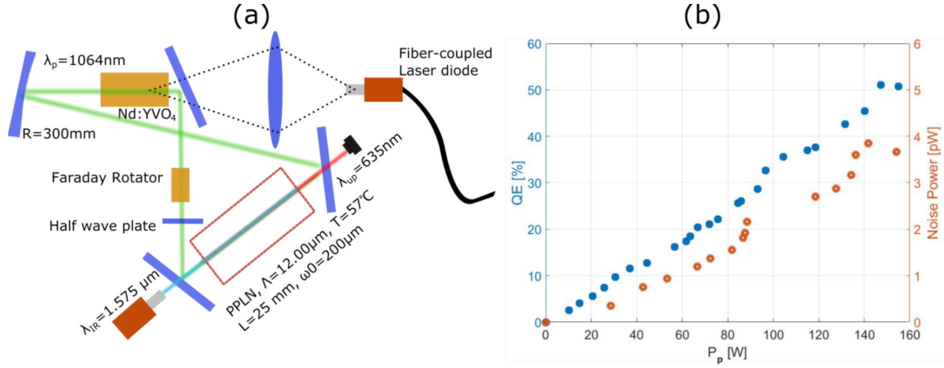

Fig.1. (a) Schematic diagram of the UCD. (b) Upconversion quantum efficiency and USPDC noise power versus pump power.

The S/N of the UCD as a function of 1575 nm signal power is calculated using Eq. 2 with different QE (i.e. different 1064 nm pump power), where the value of α used to obtain P_{USPDC} is from the fitting result of the measured noise power in Fig. 1(b). For comparison, the S/N of an InGaAs APD (Thorlabs, APD110C) is also calculated.

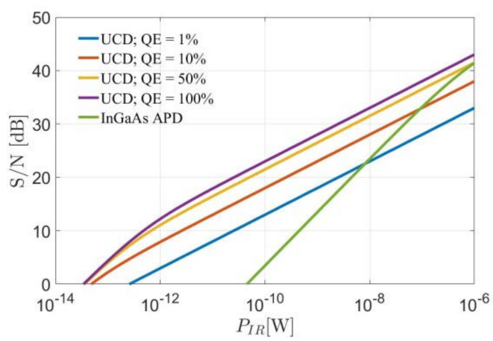

Fig. 2. S/N for the upconversion detector and the InGaAs APD we used in our study. The responsivity of the APD is 10 A/W, its noise figure is 10 and its noise equivalent power is 0.46 $\mathrm{pW}/\sqrt{\mathrm{Hz}}$. The detection bandwidth used for the S/N calculation is B = 10 kHz.

Figure 2 shows that the UCD has better performance than the APD for IR signal power $P_{IR} < 10^{-9}$ W. The S/N of the UCD can be improved by increasing the quantum efficiency (i.e. increasing the pump power), but at the compromise of increased USPDC noise. Therefore, the S/N for very weak signal ($P_{IR} < 10^{-13}$ W) detection cannot be further improved by simply increasing the pump power because it reaches a point in which the USPDC noise dominates the shot noise. In order to circumvent the USPDC noise and thereby improve the S/N further for weak IR detection, a long-wavelength pumped UCD should be considered in future implementations.

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