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Silicon-based MWIR detection using Photon Upconversion

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Abstract

Recent progress in the development of efficient photon upconversion has introduced silicon-based mid-wave infrared imaging as a competitive technique in the field. In this work, a corresponding upconverter system is presented and tested for its applicability in the field of gas sensing.

Key words: MWIR, non-linear optics, intracavity upconversion, silicon-based, gas sensing

Introduction

The mid-wave infrared (MWIR) region with wavelengths ranging between 3 and 5 micrometers is abundant in spectral information, especially in the analytics and sensing of CO, N_2O, CH_4 and others gases of interest. Spectral resolution, measurement speed and sensitivity are key factors for these applications. Conventional MWIR focal plane array (FPA) detectors are limited in sensitivity by high dark noise rates. High end devices require extensive and costly cryogenic cooling. The upconversion of infrared photons allows for the use of silicon-based near-infrared (NIR) detectors. Profiting by the sound properties of silicon light detection, these devices have the potential to circumnavigate some of the major drawbacks of direct semiconductor MWIR detection. While the conversion efficiencies so far excluded the technique from applications, recent work has proposed an approach providing highly efficient conversion [1]. Based on this approach, an upconverter MWIR detection device is examined in the following.

Nonlinear Photon Upconversion

The photon upconversion described here utilizes the process of sum frequency generation (SFG) in a medium with nonlinear optical properties. The SFG is an aspect of the three-wave-mixing, originating from a second-order polarization dependency of the medium emerging at high field strengths. In the considered case, a photon from the MWIR interacts with a photon of an applied NIR pump laser, generating a third photon with sum of the MWIR and laser frequencies.

$$\omega_{MWIR} + \omega_{laser} = \omega_{SFG} \qquad (1)$$

Using this mechanism, signal and even image upconversion have long been known [2]. Viable upconversion yield has been achieved by periodic poling of nonlinear crystals [3] and more recently by the proposal of conversion inside the laser cavity, where the circulating power can be a multiple of the external continuous wave (cw) power feed [1]. Next to the frequency conservation in (1), the conversion depends on the phase matching of the interacting waves in the crystal, expressed as the condition

$$n_{SFG}/\lambda_{SFG} - n_{laser}/\lambda_{laser} - n_{MWIR}/\lambda_{MWIR} = 1/\Lambda_{pp}, \quad (2)$$

where λ_{SFG}, λ_{MWIR} and λ_{laser} are the wavelengths of the interacting waves, n_i is the medium's refractive index at the respective wavelength λ_i and Λ_{pp} is the poling period of the conversion crystal. The refractive indices in the crystal show a temperature-dependent relation, as expressed in the material's Sellmeier equation. Thus, crystal temperature and poling period provide suitable tuning parameters to set the conversion window as can be seen for an example in the tuning curve in Fig. 2. In the case where the MWIR light and the laser are not collinear, the angle between the vectors is a third factor influencing the conversion.

Converter System

To use the high power density inside, the conversion crystal is placed in the second arm of a folded linear laser cavity as proposed in [1]. A sketch of the setup is shown in Fig. 1. The active medium is a neodymium-doped vanadate crystal pumped by an 808 nm laser diode. Laser pumping at 5 W results in an internal power of about 100 W at 1064 nm. The cavity laser mode is passed through the periodically poled lithium niobate (PPLN) crystal cavity to an end mirror (A) that is simultaneously a long pass window for the MWIR light. The MWIR radiation enters the cavity through this mirror and passes through the crystal, which is anti-reflection coated for all spectral components of the SFG process. The upconverted NIR light (with wavelengths between 770 and 870 nm) is extracted by a second dichroic mirror (B). Several filters before and after the converter ensure that only light resulting from upconversion in the crystal can proceed to detection. It has to be noted that the phase match condition allows for two different wavelengths that become degenerate at 4.2 µm to be converted simultaneously according to Fig. 2. A long or short pass filter with cut-on or -off at 850 nm selects the observed upconverted branch. The precise position of the spectral acceptance window is set by tuning the crystal temperature and selecting its poling period.

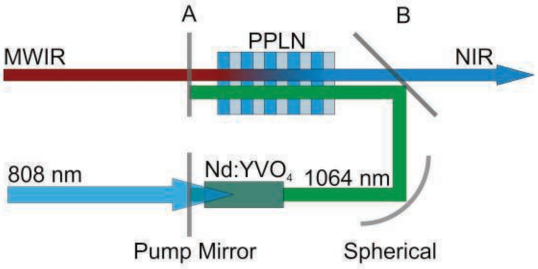

Fig. 1: Schematic view of the converter unit. Optics on both the MWIR (object) and NIR (detector) side of the converter are not shown.

The converter system as a whole is designed to be used as an 'active lens system', meaning it can be adapted in terms of optics and connectors to various types of NIR light detectors, being single pixel or camera arrays, to actively sensitize these silicon-based devices for the MWIR region.

While NIR light detection is so low in dark noise that, in most applications, devices are limited by read-out noise, the converter potentially adds noise by following sources that have to be accounted for: Residue 808 nm pump light has to be contained in the converter with intra-cavity filters and baffling. Upconverted thermal radiation of the PPLN mount and even the crystal itself can also add background signal. Therefore it is favorable to run the conversion at temperatures as low as possible. Lastly, fluctuations in the laser power are linearly translated to the NIR signal and have to be controlled.

Application

To characterize the converter device, the converter was first attached to a single pixel avalanche photo diode (APD). A single 35 mm lens was used to focus collimated light to the detector area. This setup can very sensitively measure collinearly upconverted light on the imaging axis. As a light source, a 4.53 µm quantum cascade laser (QCL) with an output power of about 1 mW was used. The QCL was collimated on the imaging axis of the system. The used crystal poling period was 23 µm, which corresponds to the calculated tuning curve shown in Fig. 2. With the converter running at 50 W internal power and the QCL set to a constant wavelength, the temperature of the PPLN crystal was scanned.

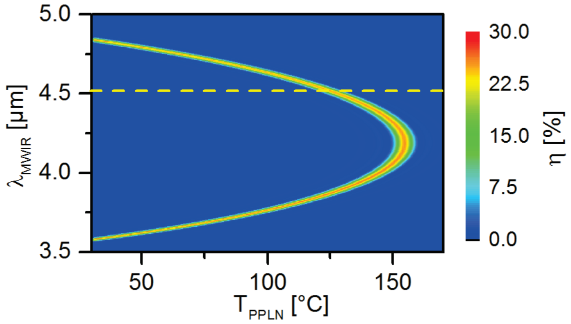

Fig. 2: Conversion tuning curve: Calculated Signal conversion efficiency in a 20 mm long PPLN crystal with a poling period of 23 µm under 100 W laser power at 1064 nm. The dashed line states the temperature scan shown in Fig. 2.

The SFG signal measured with the APD is shown in comparison to the calculated in Fig. 3, which shows a good agreement of the spectral window position and shape.

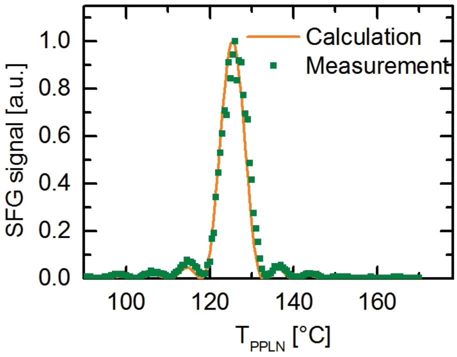

Fig. 3: Calculated and measured conversion profile of PPLN with 23 µm poling period at 4.53 µm QCL illumination over a scan of the crystal temperature.

The converter unit was then attached to a scientific grade CMOS camera for an imaging application test. For this purpose, a 75 mm IR lens was placed in front of the MWIR aperture of the converter. Objects were imaged in the focal plane of the lens, meaning that the converter operated in infinity corrected mode. The upconverted, collimated light was then projected to the camera chip by a 50 mm NIR lens.

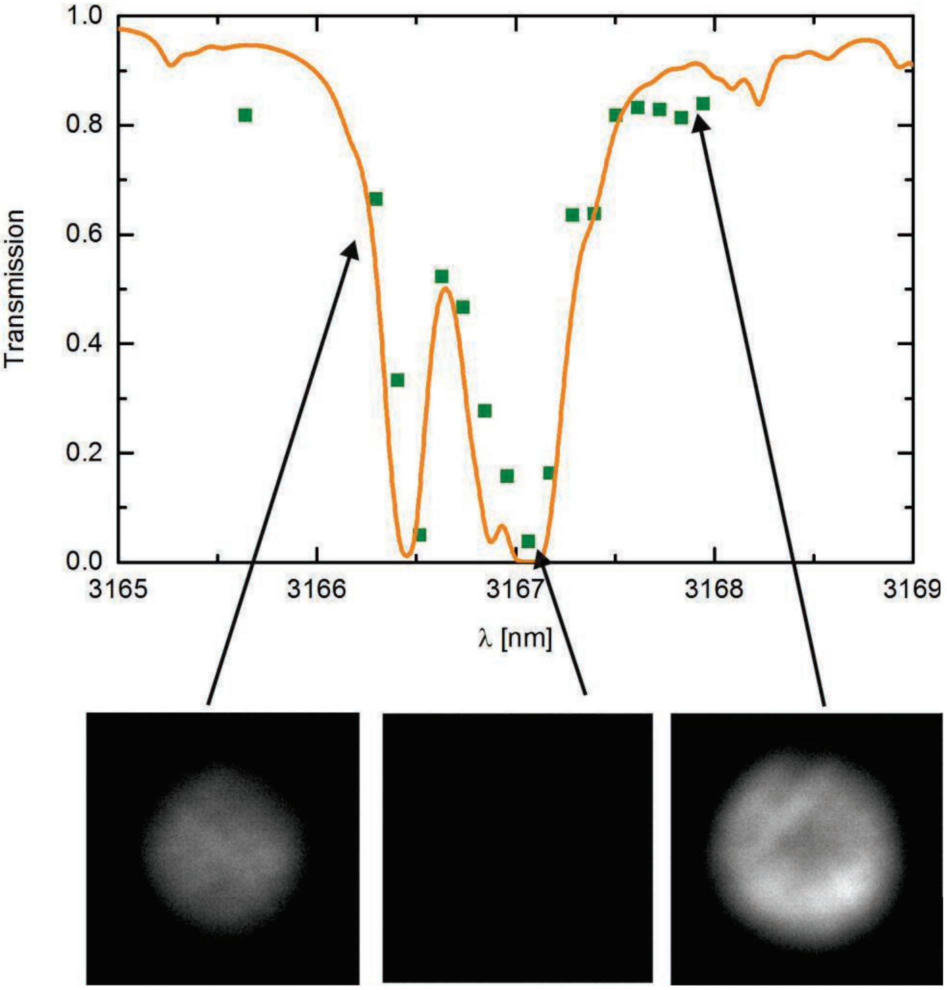

Fig. 4: Methane absorption detected with an imaging system of upconverter module and camera. Orange: HITRAN Data based line calculation, Green: Normalized pixel count of the probe laser spot image over the scan time. Bottom: Probe laser spot on scattering target at different positions in the idler wavelength scan.

As a demonstration of a possible field of application, a transmission measurement was performed with this configuration on a sample cell of methane (CH_4). The cell with a length of 10 cm was flooded with methane at a volume mixing ratio of 0.3, resulting in near zero transmission at 3167 nm. The light source in this case was a 1064 nm pumped optic parametric oscillator (OPO), as used in [4]. The OPO beam was sent through the gas cell to a scattering target where it produced a spot of about 20 mm diameter. A reflective attenuator was used to set the infrared optical power to 40 mW. In this active illumination detection scheme, the OPO pump laser was scanned in wavelength by temperature tuning, pushing the idler wavelengths from 3165 to 3168 nm. Images of the IR probe laser spot were taken for each set with the aforementioned optical setup. The total pixel count for each frame in a rectangle around the spot was background subtracted and normalized to get the relative transmission data. Deviations in the measured points result from a slight mismatch in the OPO wavelength calibration and from reflection losses on the cell windows. However, the double line shape predicted from calculations can be visualized with good agreement. The converter was in this case tuned to a crystal temperature of 49.15 °C at a poling period of 22 µm to match a wavelength of 3165 nm for collinear incidence. In imaging applications, the angle dependency of the phase matching becomes significant. This can be seen in the bottom snapshots in Fig. 4. The spot images do not actually show the full area illuminated by the OPO, but spot sizes of approximately 9 mm. This visible spot size states the angle span in the infinity corrected plane in the crystal where good phase matching for the conversion is achieved. For the same reason, the upconverted count distribution shifts away from the center towards higher MWIR wavelengths although the infrared spot is resting spatially. While the crystal temperature remained constant it is obvious that the phase matching condition shifts over the angle at just a slight change in MWIR wavelength. This angle dependency is a truly interesting property, meaning that the image coordinates contain spectral information, as also described in [5]. The use of this particular feature of image upconversion will be the focus of further development of the upconverter system towards a spectrally resolving measurement system for analytical applications.

Conclusion

An MWIR upconversion device has been built and examined, based on the enabling technique of intracavity sum frequency generation. This converter can be used to make radiation from the MWIR detectable on silicon-based NIR detectors and imaging devices. The underlying physical principle has been briefly outlined. The developed system has been tested with different detector types. The potential for gas sensing applications has been demonstrated at the example of CH_4. The path of further development towards a competitive analytical tool for the MWIR region has been pointed out.

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