Waveguide-based Mid-Infrared Up-conversion Detectors

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Abstract: Nonlinear optical up-conversion detectors for 3.4 µm radiation are realized using Ti:PPLN waveguides. Both, sum-frequency generation (SFG) and difference-frequency generation (DFG) are investigated. Overall power conversion efficiencies of more than 8 % are achieved.
OCIS codes: (040.3060) Infrared; (060.2605); Wavelength conversion devices; (190.7220) Upconversion

1. Introduction

Nonlinear-optical Difference-Frequency Generation (DFG) is an important means to generate radiation at mid-infrared (MIR) wavelengths at which conventional lasers are otherwise unavailable, for example for highly sensitive trace-gas absorption spectroscopy [1]. On the other hand, DFG and especially Sum-Frequency Generation (SFG) can also be used to realize hybrid up-conversion detectors (UCD), which convert MIR radiation to a shorter wavelength in the near-infrared (NIR) or even visible [2,3]. We demonstrate the realization of waveguide-based UCDs for the MIR range, which offer superior nonlinear conversion efficiencies when compared to bulk-optical devices of similar dimensions. Quasi phase-matching in periodically poled Ti:$LiNbO_3$ waveguides, enabled by electric-field assisted periodic poling of the $LiNbO_3$ substrate, is exploited.

2. Ti:PPLN Waveguides

Optical waveguides of 90 mm length are fabricated by Ti-indiffusion of 18-µm wide strips of 160 nm thickness into a $LiNbO_3$ substrate. Fundamental TM-mode distributions are shown in Fig. 1, together with calculated index profiles at 3.4 µm, 1550 nm, and 1064 nm wavelength, respectively. At the longer wavelengths in the MIR the waveguide is monomode. At the shorter wavelengths of pump and either generated difference or sum-frequency wave, the waveguide is multimode.

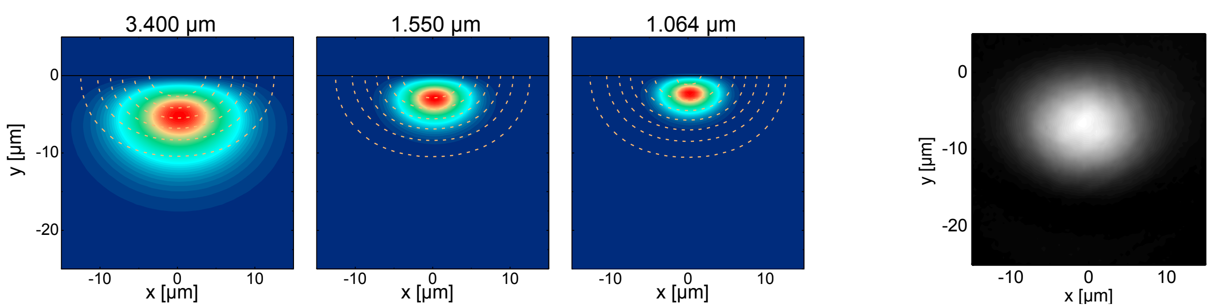

Fig. 1: (Left) Calculated fundamental waveguide modes at 3.4 µm, 1550 nm, and 1064 nm wavelength, respectively. An 18-µm wide Ti-strip with 170 nm thickness is assumed to calculate the indiffusion profile (broken lines). (Right) Measured intensity profile at 3.4 µm. Due to insufficient resolution of the MIR optics, the measured mode appears more symmetric.

To enable quasi-phasematching of the nonlinear processes the substrate is periodically poled with a periodicity of 26.65 µm. A dichroic dielectric pump reflection mirror is deposited on the waveguide end face to allow co-directional interactions (Fig. 2, left; see also next sections). Assuming a 1550 nm pump in case of SFG, and a 1064 nm pump in case of DFG, and a MIR wavelength of 3.4 µm, phase-matching can be achieved using the same device for both interactions. In the case of DFG, even parametric gain could be exploited at higher pump power levels, whereas SFG has a limited conversion efficiency (Fig. 2, right). On the other hand, DFG is always accompanied by phase-matched parametric fluorescence, which might deteriorate the performance of a DFG-based UCD.

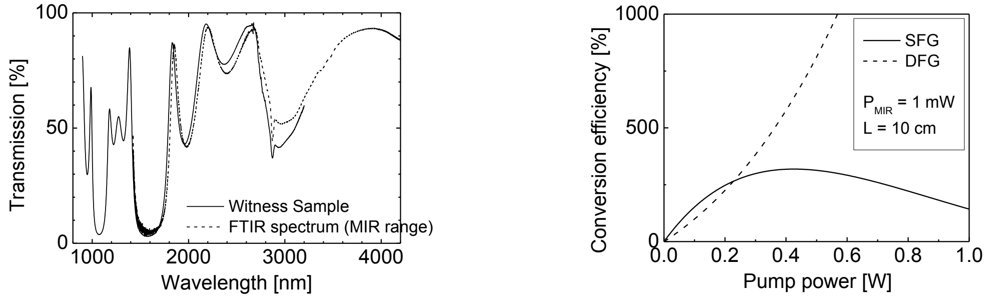

Fig. 2: (Left) Spectral transmission characteristics of the dielectric pump reflection mirror. (Right) Calculated waveguide internal SFG and DFG efficiency vs. pump power. The signal wavelength is 3.4 µm. Pump wavelengths: 1550 nm in case of SFG, 1064 nm in case of DFG.

3. SFG-UCD

The SFG-based UCD is designed for a pump wavelength of 1550 nm (Fig. 3, left). Frequency mixing with the incident 3.4-µm radiation then leads to a SF-wavelength of 1064 nm. A wavelength-tunable external cavity laser (ECL) with up to 5 mW output power is used as pump source. An erbium doped fiber amplifier (EDFA) boosts the pump power up two 1.7 Watts. The pump is routed through a WDM coupler and fiber butt-coupled to the waveguide. After passing the waveguide to the left, the pump is reflected by the dichroic dielectric mirror ($R_{pump} \approx 96\%$, $T_{MIR} \approx 76\%$). It is then re-injected to the fiber at the output on the right, together with the generated SF-wave. About 99% of the remaining pump is then routed to the 1550-nm port of the first WDM. The residual 1% of pump can readily bury the up-converted signal. One method to remove residual pump by fiber-optic means is to cascade WDM couplers [4]. In addition, the pump also generates a considerable amount of parasitic second harmonic radiation within the waveguide, which cannot be removed efficiently using the same type of WDM coupler. In order to suppress both, the residual pump, as well as the residual second harmonic radiation (and any other spurious light) sufficiently, a fiber-Bragg-grating (FBG) is used in combination with a 1064-nm fiber-optic circulator to serve as narrow-band spectral filter. The signal output from the circulator is finally routed to the InGaAs photodiode. There is only a negligible influence on the noise of the photodiode when enabling the pump radiation with hundreds of milliwatts of power, using this arrangement and lock-in technique.

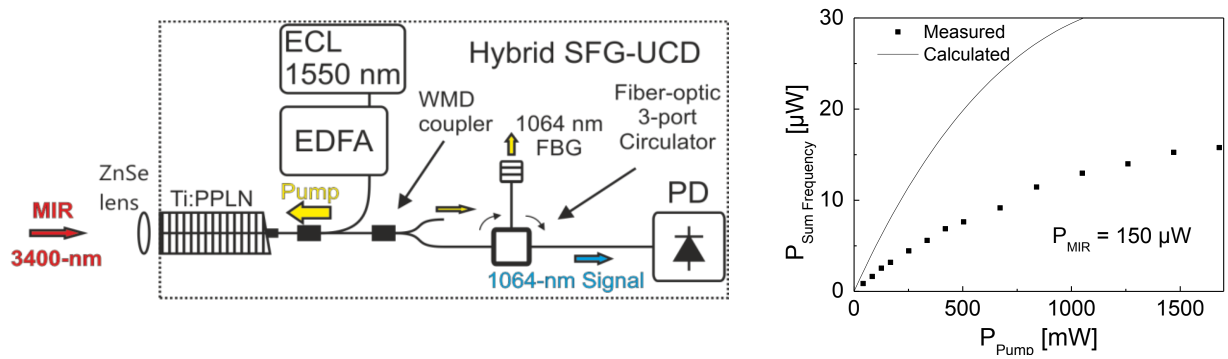

Fig. 3: (Left) Schematic experimental setup of the SFG-UCD. The filtering cascade (4.7 dB transmission loss) for the generated SF-signal at 1064 nm wavelength blocks both, residual pump radiation from the EDFA, as well as second harmonic of the pump. (Right) Measured SF-power in front of the photodiode as function of external pump power.

In Fig. 3, right, the generated sum-frequency (SF) power in front of the photodiode is given as function of external pump power emitted by the EDFA, for 150 µW of incident MIR radiation. At the output of the waveguide the SF-power is higher by 4.7 dB, which corresponds to the losses of the wavelength filtering cascade. A comparison with modeling results shows that a waveguide internal quantum efficiency close to 100% is achieved at the highest pump power. However, photorefractive effects lead to a deterioration of the performance over time at external pump power levels above 1 Watt, though the device is operated at a temperature of 167°C. After reducing the pump power, the initial conversion efficiency is recovered. Heating to even higher temperatures reduces photorefraction further. With 1 Watt of external pump power, an optical power conversion efficiency of 8.2% is achieved yielding a NEP ~ 0.3 $pW/Hz^{1/2}$ of the UCD with respect to the incident MIR radiation.

4. DFG-UCD

In order to realize the DFG-based UCD, the setup is modified as follows: The 1550-nm pump with amplification is replaced by a 1064-nm diode laser. As wavelength filtering, an arrangement of optical circulator and FBG is used as in the SFG-UCD, however with an operating wavelength at the difference-frequency of 1550 nm (Fig. 4, left).

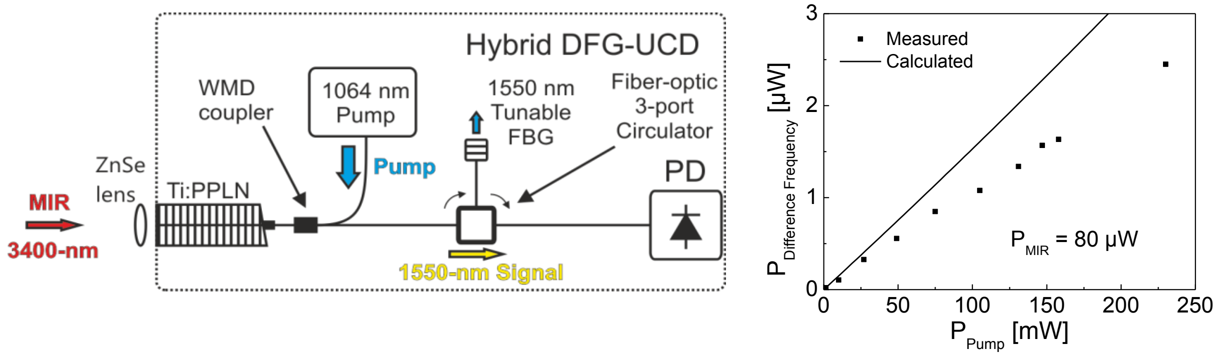

Fig. 4: (Left) Schematic experimental setup of the DFG-UCD with filtering cascade for the generated DF-signal at 1550 nm wavelength. (Right) Measured DF-power in front of the photodiode as function of external pump power.

In case of the DFG-based UCD, parametric gain of the generated radiation can in principle be exploited. On the other hand, amplified parametric fluorescence occurs at the phase-matched wavelengths - with about 100 mW of external pump, a fluorescent power in the nW-range is measured. Due to excess bandwidth of the current filtering scheme, it cannot be effectively blocked.

The pump-power dependence of the generated DF-power is plotted in Fig. 4, right, for 80 µW incident MIR radiation in this case. In contrast to the SFG-based UCD, the converted power increases linearly, because the nonlinear process does not saturate. However, significant parametric gain is not observed at the available power levels. Experimentally, a conversion efficiency of 3.1% at 230 mW of external pump, or 13 %/W normalized to pump power, is achieved. In this case, a NEP = 0.8 pW/Hz$^{1/2}$ is obtained with respect to the incident MIR radiation, using a lock-in technique with chopped MIR radiation.

5. Conclusions

The efficiency of the SFG-based UCD of 8.2% exceeds the reported conversion efficiency of 5x10^{-3} % of a comparable up-conversion detection scheme, using bulk optical crystals [2], by nearly three orders of magnitude. A noise equivalent power NEP = 0.3 pW/Hz$^{1/2}$ is measured using 1 Watt of external pump power and a commercial InGaAs PIN photo detector with an active area of 100 µm diameter.

The DFG-based UCD has an efficiency of 3.1 % limited by the available pump power of 230 mW. This translates to a NEP = 0.8 pW/Hz$^{1/2}$. At higher pump power levels a strong onset of parametric gain would improve the performance of the UCD, though parametric fluorescence is generated at the phase-matched wavelengths yielding a permanent noise floor. However by using the lock-in technique a deterioration of the detector sensitivity can be avoided to a large degree. The DFG-based approach has been used to realize a free space optical communication link with subsequent wavelength conversion from 1550 nm to the MIR and back to 1550 nm, with the same pump wavelength in both wavelength converters [5].

6. References

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