Hybrid Up-Conversion Detector for Mid-Infrared Radiation using Ti:PPLN Waveguides

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***Abstract*—We developed a fiber-coupled "hybrid detector" for mid-infrared radiation. Ti-indiffused waveguides in periodically poled $LiNbO_3$ are exploited to perform sum-frequency generation, followed by near-infrared detection. Superior sensitivity in comparison with a commercial HgCdTe mid-infrared detector has been achieved at 3.4 µm wavelength, yielding an improvement in detectivity by a factor of 3.5.**

Keywords-nonlinear optics; infrared detectors; PPLN; integrated optics.

I. Introduction

Mid-infrared (MIR) wavelengths in-between 3 and 4 µm are of considerable interest, especially because fundamental rovibrational transitions of carbon-hydrogen bonds are to be found in this wavelength range. Since there is still a lack of practical lasers for the MIR, nonlinear difference frequency conversion is a popular approach to generate these wavelengths [1]. Suitable detector materials for MIR wavelengths have long been available, e.g. HgCdTe, InSb, GaSb and PbSe. However, the detectivities of MIR detectors are typically two orders of magnitude lower than those of near-infrared (NIR) detectors. Thus, wavelength conversion of MIR radiation to the NIR with power conversion efficiencies above one percent would increase detection sensitivity, if added noise is kept under control. This scheme can also be combined with single photon detectors [2]. The sensitivity improvement relates mainly to the conversion efficiency, filtering of residual (pump-) radiation, and the ratio of detectivities of the respective MIR and NIR detectors used. In addition, such a scheme enables the use of conventional telecom fibers to guide radiation from the location of measurement to the actual photodetector.

In this contribution, we describe our development of such a hybrid detector using optical waveguides, and present results achieved. Compared to a commercial HgCdTe detector, our hybrid detector yields a detectivity improvement by a factor of 3.5. We see the potential to enhance current performance of the hybrid detector by one order of magnitude.

II. Description of the Hybrid Detector

In fig. 1, a scheme of the hybrid detector is shown. We use Ti-indiffused waveguides, monomode at λ = 3.4 µm, in periodically poled $LiNbO_3$ (Ti:PPLN) to get an efficient nonlinear interaction. A poling periodicity of 26.65 µm is chosen for quasi-phase-matched (QPM) sum-frequency generation (SFG).

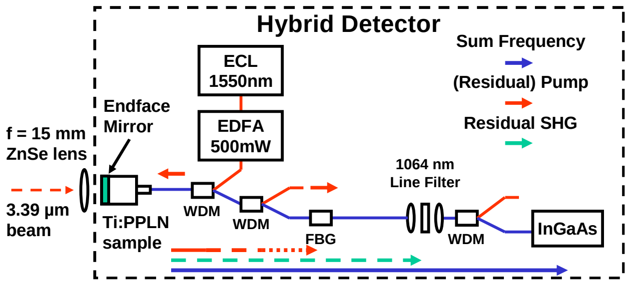

Figure 1. Schematic of Hybrid Detector. ECL: External Cavity Laser, EDFA: Erbium Doped Fiber Amplifier, FBG: Fiber Bragg Grating, SHG: Second Harmonic Generation, WDM: Wavelength Division Multiplexer, InGaAs: InGaAs detector. Lock-In and polarization control not shown.

The waveguide sample with an overall length of 92 mm, including a tapered section of 4 mm, is clamped in an 85 mm long oven. To detect radiation from a HeNe laser (P = 60 µW, λ = 3.39 µm) using a pump of λ = 1549.5 nm, a sample temperature of 165.1°C is necessary to generate phase-matched sum-frequency (SF) of λ = 1063.4 nm (fig. 2). A dielectric end face mirror is employed to reflect the pump at the free-space interface and to enable co-directional SF generation (see [3] for details). Pump source is a tunable ECL together with an EDFA (see fig. 1 for abbreviations). An InGaAs detector (Femto GmbH OEC-200) with an integrated amplifier and conversion gain up to 10^{11} V/W detects the SF signal. To remove unwanted (residual pump) radiation, a filtering scheme consisting of three fiber WDM filters (with 20 dB separation of 1064 nm from 1550 nm and ca. 1dB loss at 1064 nm each) as well as a tunable fiber Bragg grating, centered at 1549.5 nm (ca. 1dB loss at 1064 nm), is employed. Overall, a pump suppression of -77.5 dB is achieved. In addition, a dielectric line filter (centered at 1064 nm, transmission is 40% including free-space coupling losses) is used to remove spurious non-phase-matched second harmonic of the pump at 775 nm. A scan of the signal wavelength reveals the phase-matching characteristics of the device (fig. 2). Some asymmetries due to waveguide inhomogeneities are apparent.

III. Hybrid Detector Performance

A figure of merit to describe photodetectors is the specific detectivity

$$D^* = (A\,\Delta f)^{1/2} / NEP, \tag{1}$$

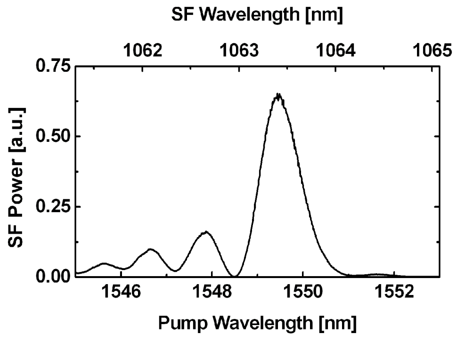

Figure 2. SFG tuning curve. Fundamental wavelength is 3.39 µm.

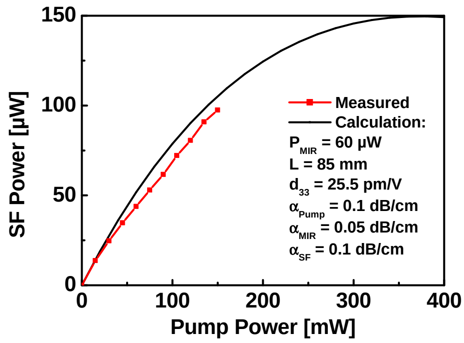

Figure 3. Sum-frequency power as function of pump power (waveguide internal conversion). Calculation parameters are given in the inset.

A is the active detector area, Δf the detection bandwidth, and NEP the Noise Equivalent Power. NEP can be expressed as

$$NEP = S_n \, \Delta f^{1/2} / R, \quad (2)$$

with S_n being the noise spectral density and R the detector responsivity at the specific wavelength. In our experiments, we use a lock-in amplifier (Signal Recovery DSP7265) to measure S_n. NEP can then be determined using the detector's specifications. Note that in such measurements S_n includes intrinsic detector noise as well as additional electrical noise due to electric circuitry. To describe the upconversion detector, we introduce an additional, overall (total) conversion efficiency

$$\eta_{tot} = \tau_{opt} \, \eta_{nl}, \quad (3)$$

where τ_{opt} is the transmission through all optical components (including e.g. coupling efficiencies and fiber optic insertion losses) and η_{nl} the nonlinear conversion efficiency (note that we are considering power, not quantum efficiency). Now we define for the hybrid detector

$$NEP_{hd} = 1/\eta_{tot} \times NEP = 1/\eta_{tot} \times S_n \, \Delta f^{1/2} / R, \quad (4)$$

where NEP is the noise equivalent power of the detector at SF wavelength, with pump switched on, and NEP_{hd} is the noise equivalent power in terms of incident MIR radiation.

For signal detection using the lock-in amplifier, a mechanical chopper wheel is used to modulate the MIR beam with 1 kHz modulation frequency. With 60 µW MIR power and 500 mW pump power, we determined the overall conversion efficiency to be η_{tot} = 5.5 %. We estimate τ_{opt} = 3 %, determined by coupling and propagation losses as well as insertion losses of fiber optic components. Pump transmission (from EDFA output to reflected power at endface mirror) is estimated to be 30 %. With these approximations, η_{nl} yields 174 %, even though the utilized pump power is ~ 150 mW only (cp. fig. 3).

The noise spectral density was determined as S_n = 14.4 µV/Hz$^{1/2}$ with pump enabled. Using (2) and (4), and taking Δf = 1 Hz, as well as R(SF) = 0.7×10^9 V/W, leads to NEP_{hd}(MIR) = 0.36 pW at 500 mW pump power. To compare this result to a conventional MIR detector, we characterized the noise properties of a thermoelectrically cooled HgCdTe detector (OEC GmbH) with integrated current amplification. The characterization reveals S_n = 14 µV/Hz$^{1/2}$, corresponding in this case to NEP = 14 pW at 1 Hz measurement bandwidth. Hence, directly comparing both hybrid and conventional detector gives an improvement in NEP by a factor of 39. In order to make a truly fair comparison however, the different detector areas need still be considered, leading us to an "overall" specific detectivity D*. The detector area of the InGaAs detector is roughly 7.85×10^{-5} cm^2, whereas the detector area of the HgCdTe detector is about 0.01 cm^2. Taking (1), this gives D* (HgCdTe) = 7.1×10^9 cm·Hz$^{1/2}$/W and D* (Hybrid) = 2.5×10^{10} cm·Hz$^{1/2}$/W. According to these normalized values, an improvement by a factor of 3.5 is achieved with the hybrid detector.

To estimate the improvement in conversion efficiency η_{nl} by raising pump power, conversion was modeled using a numeric solver of coupled mode equations (fig. 3). To compare experimental results to theory, the waveguide internal power levels were deduced from measured data. We conclude that an increase in conversion efficiency by a factor of 1.5 is possible by doubling pump power.

IV. Conclusion and Outlook

We have demonstrated a hybrid-MIR-detector, using nonlinear frequency conversion from 3.4 µm to 1064 nm, with a cw pump and a fW-range InGaAs detector. We could show a factor of 3.5 improvement in "overall" detectivity, compared to a thermoelectrically cooled HgCdTe detector. We see the potential to reduce fiber optic losses of the hybrid detector setup by a factor of 6, by replacing several fiber optic components with a more simple and robust wavelength filtering scheme. Also, pump power and thus nonlinear conversion efficiency may be increased (we are limited to about 500 mW by fiber optic WDM-couplers in use). Doubling of pump power, together with the enhancements in the experimental setup, may well lead to an improvement of the overall conversion efficiency by one order of magnitude.

References

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