New method for mid-infrared spectroscopy at room temperature using non-linear optics in photon-counting regime

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Abstract. We propose a new spectroscopy technique in the mid-infrared (MIR) domain without any cryogenic system. The MIR field emitted by the source is shifted to the near-infrared using sum-frequency generation in a Periodically Poled Lithium Niobate ridge waveguide, and is then detected in the photon-counting regime using a low-noise SiAPD detector. The non-linear process is powered by a continuously tunable pump laser. We present here an experimental proof-of-concept, where the light emitted by a thermal source in the 3-4µm band is spectrally modulated using a Michelson interferometer. By continuously tuning the pump laser wavelength between 1058 nm and 1078 nm, the MIR spectrum is reconstructed, and the imposed spectral modulation period is retrieved successfully with a relative error of less than 5%.

1 Introduction

Mid-infrared (MIR) detection systems face two issues. Firstly, these kind of sensors are noisier than near-infrared (NIR) or visible detectors due to their lower material band gap. Secondly, the thermal radiation from the entire measurement chain severely limits the measurement dynamics. To overcome these problems, it is necessary to cool down the entire measurement chain. In the space industry, heavy and complex cryogenic devices are used, constituting a single point failure for which it is difficult to ensure redundancy [1]. Moreover, they can be source of microvibrations or limit the satellite lifetime due to the finite amount of coolant. Here, we report on a new hybrid technique for MIR spectroscopy using nonlinear optics in photon-counting regime. By shifting the MIR spectrum to the NIR domain by sum-frequency generation [2] (SFG) using a tunable pump laser, we can use sensors that have better signal-to-noise ratio than their thermal infrared counterparts.

2 Principle and experiment

We propose to analyze the spectrum of a thermal source emitting MIR radiation between 3 and 4 µm after shifting it to the NIR around 820 nm. The conversion process is performed in a Periodically Poled Lithium Niobate (PPLN) ridge waveguide [3], fed by continuous–wave

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monochromatic pump laser continuously tunable from 1000 nm to 1100 nm. The SFG process is driven by the energy conservation condition $\nu_{\text{converted}} = \nu_{\text{source}} + \nu_{\text{pump}}$ and the phase matching condition between the three interacting waves. For a given pump wavelength, a MIR spectral sample (spectral width $\Delta\nu_s$) is shifted to NIR domain while maintaining the spectral width $\Delta\nu_c = \Delta\nu_s$. By measuring the converted power in the NIR domain, it is possible to deduce the power of the original MIR spectral sample. On slight modification of the pump wavelength, the source and converted wavelengths change such that phase matching and energy conservation conditions are still satisfied. Hence by continuously tuning the pump wavelength and measuring the power in the NIR domain, the MIR source spectrum can be reconstructed. Our proof of concept experiment uses a filament heated around 750 °C as a MIR source, generating a blackbody radiation. The MIR radiation goes through a Michelson interferometer to create a modulated spectrum of period 1.66 THz by moving one of the mirrors of the interferometer by 90 μm from zero optical path difference. The goal is to retrieve this modulation period in NIR domain in order to validate our spectral analyser. To do so, the spectrally modulated MIR signal and pump wave are both coupled inside a 8.6×8 μm cross-section and 2 cm-long PPLN waveguide. The poling period of the PPLN is equal to 19.6 μm to satisfy the quasi phase-matching condition for the interacting waves. Moreover, the temperature of the waveguide is servo-controlled at 20 °C to obtain a stable nonlinear conversion process. At the output of the waveguide, the converted wave is collected by a single-mode fiber and sent to a filtering system to remove the pump wave. The converted NIR flux is then measured by a Si-APD photon-counter. Thereafter, the pump wavelength is continuously tuned between 1058 nm and 1078 nm, and the converted power in the NIR domain is measured. From this measurement, using the energy conservation and phase matching conditions, we are able to deduce the MIR spectrum from 3.2 μm to 3.7 μm. We measure a modulation period of 1.60 THz in MIR domain with a relative error of less than 5%. However, the resolution of the spectral analysis is currently limited by the spectral acceptance of the non linear waveguide $\Delta\nu_s$. At the present time, the spectral resolution of our setup in the MIR domain changes with the pump wavelength, and is typically around 36 nm ($\Delta\nu_s = 0.88$ THz). In the future, the spectral resolution will be improved by using a deconvolution process of the measured spectrum in the NIR domain taking into account the spectral acceptance of the waveguide.

3 Conclusion

We propose a new hybrid technique for MIR spectroscopy at room temperature using a nonlinear optic process in photon-counting regime. The MIR spectrum is transposed to the NIR domain by sum-frequency generation using a tunable pump laser. By scanning the pump wavelength between 1058 nm and 1078 nm, and measuring the power in the NIR domain, we were able to reconstruct the MIR spectrum from 3.2 μm to 3.7 μm. We retrieved the spectral modulation periodicity of a thermal source with a relative error of less than 5%.

References

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