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Towards Fully Integrated Mid-Infrared Heterodyne Detection Based on Quantum Cascade Technology

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Abstract *We present the current status of the development of a mid-infrared on-chip heterodyne interferometer, enabled by current advances in quantum cascade technology and plasmonics. We provide the demonstration of high-performance quantum cascade detectors at 9 µm and strategies for on-chip beam combiners onto InP substrates*

Introduction

Free-Space Optical (FSO) communication, also known as fibreless photonics, has become an important direction for optoelectronic technology applications, such as space and satellite communication, military data links, and ad-hoc mobile communications during crisis situations ("last mile" links) [1]. The main disadvantage of current commercial FSO systems is the high sensitivity to weather conditions, as they typically operate in the 780-850 nm and 1520-1600 nm range.

In contrast, the longwave infrared (LWIR, 8-12 µm) band hosts an important atmospheric window, that offers low sensitivity to turbulences and light scattering by aerosols. But the realization of FSO systems in this wavelength range is still limited due to the lack of suitable components in the mid-infrared spectral range including laser emitters, detectors, modulators, etc. While Quantum Cascade (QC) technology has triggered the rapid generation of compact, tunable, high-speed mid-Infrared (mid-IR) Lasers (QCLs) [2], MCTs detectors are still the commercial solution for the receiver part. They present high sensitivity operation, but are limited in their bandwidth to typically around 1 GHz, have low saturation thresholds, and show, under certain circumstances, limited chemical stability. Recent advances in the development of QC Detectors (QCDs) [3,4] offer a valid alternative. QC devices have been demonstrated with room temperature operation and intrinsic bandwidths over 100 GHz, limited only by the device RC constant [5,6]. This intrinsic speed, combined with the possibility to fabricate QCLs and QCDs with similar emission and detection wavelength from the same active region (QCLD) [7], can be the key to enabling on-chip room temperature LWIR heterodyne detection using Photonic Integrated Circuit (PIC) concepts.

Therefore, based on the recent progress in QC technology, it is possible to benefit from the GHz-modulation speed of these devices for developing a coherent on-chip LWIR heterodyne detector, with bandwidth exceeding the 1GHz range together with room temperature operation. Fig. 1 illustrates a schematic of the proposed heterodyne detection scheme.

However, the integration of all photonic components at this wavelength range is challenging. All building blocks still need to be demonstrated or further improved in the LWIR.

In this paper, we present the design and major steps in the realization of such compact PIC-based on-chip heterodyne spectrometers. This includes especially the first polymer-based waveguide for on-chip mode guiding and directing in the LWIR.

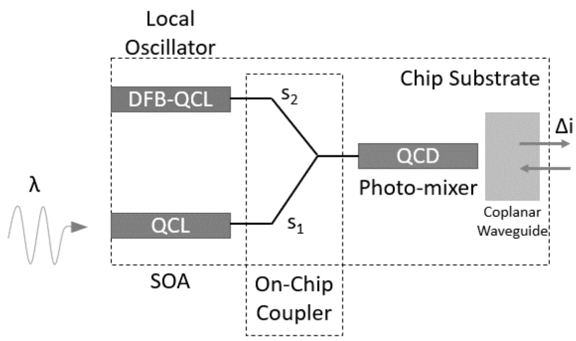

Fig. 1: On-chip heterodyne detector scheme

QCLD integration

Recent examples of QCD-QCL photonic micro-system are demonstrated in [8,9] for the 6-7 µm range, highlighting their highly compact monolithic integration on the same substrate, exploiting Dielectric Loaded Surface Plasmon Polariton Waveguides (DLSPPW) for compact biosensors. Based on the tunability of their spectral emission upon e.g., distributed feedback

(DFB) structures, they can typically be designed to address LWIR wavelengths. Therefore, the fabrication of QCL and QCD in ridge configuration allows the development of high-performance and densely integrated mid-IR PICs. However, before the full on-chip integration of all components, the separate building blocks of the system need to be designed, characterized, and optimized individually.

Plasmonic Waveguides and Couplers

Integration of III-V materials with typical LWIR integrated photonics based on Si-Ge structures or Chalcogenide glass can be quite challenging. In contrast, DLSPPWs pave a promising route to circumvent these limitations due to the full compatibility of the involved material systems. However, due to the low transparency of the commonly used dielectrics, only a limited number of materials are suitable for such an integration. Low-loss, broadband plasmonic waveguides based on Ge-Au structures have been recently demonstrated for the LWIR [10]. However, if they can offer mid-IR octave-spanning platforms for optical sensing, their guiding performance for low-loss, on-chip directing of optical signals can be quite low. Only recently, new processing protocols unlocked polyethylene as a new and very promising polymer material for mid-IR integrated optics [11].

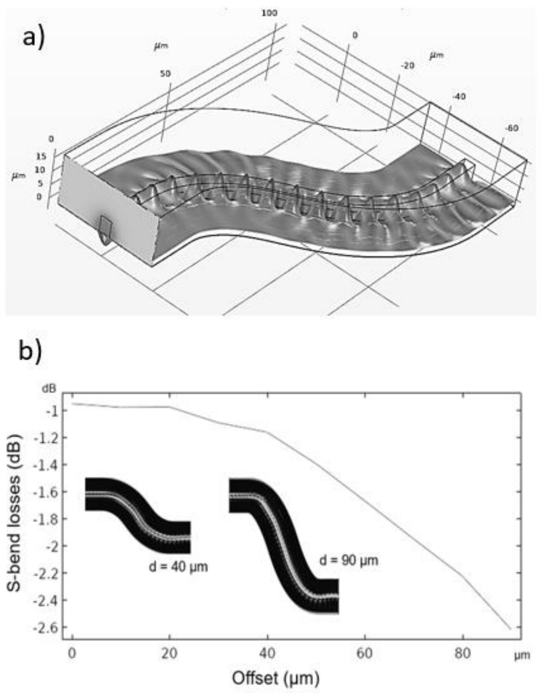

Fig. 2: a) 3D simulations of s-bend plasmon mode propagation and b) transmission performance of polyethylene-Au plasmonic waveguides at 9.1 µm for different S-bend offsets of 40 µm and 90 µm, respectively (for $n_{PE} = 1.5$ and $k_{PE} = 0$).

Its broad transparency combined with low refractive index (to reduce interference reflection) makes it a highly suitable candidate as core waveguiding material for the LWIR frequencies. Fig. 2a)+b) shows the simulations of a plasmonic beam combiner based on a polyethylene-gold waveguide, in an adiabatic Y-coupler configuration (so-called "s-bend"). Polyethylene coatings can be processed into ridge geometries with state-of-the-art cleanroom fabrication techniques, including the etching of the structures through the definition of a metallic hard mask. Fig. 3 shows a typical example of a fabricated polyethylene-on-gold waveguide. Measured losses extracted from the first experimental demonstration of such newly developed and fabricated s-bends waveguides show losses of 5.7 dB for a 120 µm section. This is in good agreement with the predictions from our simulations, after including the fabrication losses (due to scattering of light from surface roughness and waveguide imperfections) and the non-zero imaginary part of the refractive index.

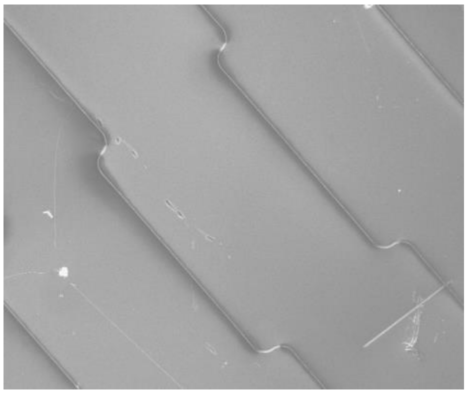

Fig. 3: SEM images of the s-band polyethylene ridges fabricated onto an Au layer

QC Detectors

The fast modulation capabilities of QCDs fabricated into mesa devices have recently been demonstrated at 9 µm resulting in 10 Gbit/s bitrate data transmission [6]. However, for on-chip integration of several multifunctional components, developing these devices into ridge configuration is not only necessary but also beneficial in terms of their performance. The main advantages are a higher responsivity, increased signal-to-noise ratio, and improved high-speed operation, as already demonstrated at telecom frequencies [12]. Moreover, single-period ridge QCDs have shown higher quantum efficiencies with 10 $pW/Hz^{1/2}$ noise equivalent power and corresponding detectivity of $7x10^7$ $cmHz^{1/2}/W$ at λ~ 4.1 µm and room temperature [13].

To realize suitable high-performance LWIR detectors, we developed λ~9.1 µm LWIR QCDs. We designed two devices shaped into ridge geometries with 15- and single-period active regions, and measured their figures-of-merit, including the responsivity, of R_P = 0.411 A/W (single-period) and R_P = 0.111 A/W (15-period), respectively. Their normalized spectral responsivity curves are shown in Fig.4).

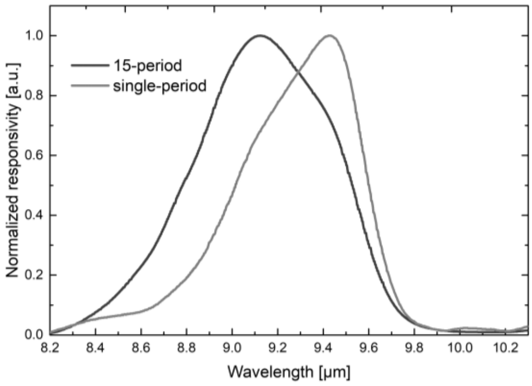

Fig. 4: Normalized spectral responsivity curves acquired at room temperature

Conclusion & Outlook

We have realized and improved the design, fabrication, and characterization of all necessary photonic building blocks for LWIR heterodyne detectors based on highly integrated PIC concepts. In the next step, the integration of all building blocks will be validated by implementing the individual components onto a QCLD substrate resulting in the first generation of fully integrated mid-IR/LWIR PICs for telecom applications.

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