Will new detector technologies enable new lidar applications in the near to mid-infrared?

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The near to mid-infrared region has been identified as a spectral region of high interest for Differential Absorption Lidar (DIAL) measurements [1], since this spectral range is a fingerprint region of many atmospheric pollutants and also greenhouse gases (GHGs) such as CO_2, CH_4 and N_2O [2]. Lidar applications, for example, range from industrial process monitoring [3] via pipeline monitoring [4] to the observation of GHGs from ground [5,6], air [7] or space [8]. However, lidar instruments are strongly dependent on available technology. Beyond adequate laser technology, the availability of high-quality detectors with adequate size and low noise properties is an essential prerequisite for practical infrared lidar applications. State-of-the-art ground-based DIAL systems suffer from long averaging times [5] and airborne or spaceborne lidar applications are currently restricted to deploying the Integral Path Differential Absorption (IPDA) lidar technology [2] that uses the much stronger return signals from hard targets such as the Earth`s surface at the expense of giving up the profiling capability to compensate for the deficient detector properties [7,8]. The availability of better infrared detectors with higher sensitivity and better noise performance will therefore enable range-resolved DIAL measurements and open up new prospects for future lidar applications. In this contribution we will report on recent progress and future prospects of two types of novel detector technologies: (1) HgCdTe avalanche photodiodes (MCT APD) and (2) upconversion detectors (UCD).

MCT APDs have opened a new horizon in low-light detection applications due to their exceptional performance in the near to mid infrared spectral range . MCT APDs are characterized by a close to deterministic avalanche gain which enables amplification of an optical signal. This characteristics, in combination with a high quantum efficiency, have motivated the development of MCT APD detectors in a large number of applications in which only a few number of photons can be detected, ranging from focal plane arrays for astronomy to fast single element applications for lidar and free-space laser communications [9,10]. Detector modules for atmospheric lidar have been developed in Europe, by Leonardo (Selex) and CEA-Leti [9], and in the US, by DRS [11,12]. The CEA-Leti detector module was developed for LMD, in collaboration with CNES, and has been used for ground based direct detection CO_2 DIAL measurements. The low noise of the detector, NEP = 25 fW/$\sqrt{Hz}$ at a gain of 80, allowed to reach high SNR at km distances using sub-second averaging times [13]. The quantitative exploration of the measured data was found to be limited by the low dynamic range, which reduced the SNR for long range signals, and by a slow response time tail, remanence, which was principally caused by a non-optimized optical detection set-up. This first development pointed to the potential of using MCT APDs in photon-starved high dynamic range applications, but also that the detector must be optimized to address the most challenging lidar applications. Such a detector is currently developed at CEA-Leti within the scope of the H2020 HOLDON project, in collaboration with DLR, LMD, AIRBUS, ALTER and IDquantique. The objective is to hybridize an optimized MCT APD detector onto a versatile Si CMOS amplifier to achieve 6 orders of magnitude of photon noise limited dynamic range, down to single photon detection, associated with variable temporal resolution and a strongly reduced remanence. The impact of the expected performance for lidar will be discussed in this presentation.

Instead of using direct infrared detectors, another promising approach is to use an upconversion detector (UCD) – a combination of an optical upconverter that efficiently translates infrared signals to the visible region in accordance with the energy conservation relation $1/\lambda_{VIS} = 1/\lambda_{IR} + 1/\lambda_{pump}$, and a visible detector that has high detectivity. In two recent studies, this approach was successfully demonstrated for differential absorption lidar measurements of CO_2 [14] and CH_4 [15]. Here, the upconversion modules were built as compact and portable units consisting of heated and temperature-stabilized periodically poled $LiNbO_3$ (PPLN) crystals in a highly reflecting Nd:YVO_4 laser cavity. The laser crystals were pumped by means of diode lasers and the finesse of the cavity enabled high intracavity fluxes to increase the upconversion efficiency. With a pump wavelength (λ_{pump}) of 1064 nm, infrared signal wavelengths (λ_{IR}) of 1572 nm (for CO_2) and 1645 nm (for CH_4), were converted to λ_{vis} at 635 nm and 646 nm, respectively, and detected either by means of a standard photomultiplier. During first experiments this concept was tested using CHARM-F [6], the airborne lidar demonstrator for the French/German MERLIN mission [7]. Preliminary experiments [14] demonstrated the potential of this approach. In a subsequent study [15] the UCD performance was enhanced, mainly with respect to higher upconversion efficiency and larger acceptance angles, such that the improved UCD did outperform the standard InGaAs APD detector of CHARM-F. On that basis and for the first time, range resolved measurements of methane using a UCD could be demonstrated. That system had the ability to measure the methane differential absorption optical depth (DAOD) between 3 and 9 km with relative errors smaller than 11%. Such UCD can easily be extended to other gas-sensing lidar applications working in the mid-infrared region (e.g. 2 μm to 5 μm) by simply changing the PPLN poling period, spectral filters, and a cavity optics to match the specific mid-infrared signal wavelength. Nevertheless, specific error sources such as upconverted spontaneous parametric downconversion noise need to be considered.

In our presentation we will discuss opportunities and limitations of these novel technologies for lidar applications.

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