Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-MoA1

THz Sources and Detectors
Moderator: Daniel Wasserman, University of Texas at Austin

1:30pm **MIOMD-MoA1-1 Stabilization of Terahertz Quantum-Cascade VECSELs***, C. Curwen, J. Kawamura, D. Hayton,* Jet Propulsion Laboratory, California Institute of Technology*; S. Addamane, J. Reno,* Center for Integrated Nanotechnologies at Sandia National Laboratories*; B. Karasik,* Jet Propulsion Laboratory, California Institute of Technology*; **Benjamin S. Williams,*** University of California Los Angeles

Terahertz metasurface quantum-cascade (QC) vertical external cavity surface emitting lasers (VECSELs) are excellent candidates for frequency agile local oscillators and spectroscopic sources, that emit milliwatts to tens-of-milliwatts continuous-wave power with excellent beam power. We present the first high resolution studies of the free-running laser behavior of QC-VECSELs at 2.5 THz and 3.4 THz, and demonstrate phase-locking to a microwave reference, by using subharmonic Schottky-diode mixer instrumentation to downconvert the THz signal to a GHz intermediate frequency (IF). Feedback from reflections at the mixer are observed to have a strong influence on the free-running QC-VECSEL frequency stability as a result of efficient coupling to free-space compared to more typical ridge waveguide lasers. Instabilities in feedback result in free-running linewidths of tens of MHz. The QC-VECSEL IF signal is phase locked to a 100 MHz reference using the bias on the device as a means of error correction. Between 90-95% of the QC-VECSEL signal is locked within 2 Hz of the multiplied RF reference, and amplitude fluctuations on the order of 1-10% are observed, depending on the bias point of the QC-VECSEL. The bandwidth of the locking loop is ~1 MHz. Many noise peaks in the IF signal corresponding to mechanical resonances in the 10 Hz-10 kHz range are observed. These peaks are generally -30 to -60 dB below the main tone, and are below the phase noise level of the multiplied RF reference which ultimately limits the phase noise of the locked QC-VECSEL.

2:10pm **MIOMD-MoA1-5 RF Injection Locking of THz Metasurface Quantum-Cascade-VECSEL: Effect of Cavity Length Variation***, **Yu Wu,*** University of California, Los Angeles*; C. Curwen,* Jet Propulsion Laboratory*; J. Reno,* Sandia National Laboratories*; B. Williams,* University of California, Los Angeles

Quantum-cascade (QC) lasers are ideally suited for high-resolution, high speed spectroscopy techniques in terahertz (THz) spectral region. Their inherently high optical nonlinearity promotes the generation of spontaneous frequency combs via four-wave mixing in Fabry-Pérot or ring QC-lasers, based on which THz dual-comb spectroscopy has been demonstrated. Besides that, THz QC-laser has recently been implemented in the vertical-external-cavity surface-emitting laser (VECSEL) architecture, which is considered as a great candidate for THz frequency comb or mode-locking operations.

Here, we demonstrate RF injection locking in THz metasurface QC-VECSEL for the first time. An intra-cryostat focusing VECSEL cavity design is applied to reduce the intra-cavity diffraction loss and enable continuous wave lasing at 3.4 THz in an external cavity length over 30 mm (Fig. 1(a)). RF current modulation is applied to the QC-metasurface at a frequency close to the cavity round-trip frequency. Under weak RF power, pulling and locking of the round-trip frequency to the injected RF signal has been observed with locking bandwidth characterized using Adler's equation; Under strong RF power, broadening of the lasing spectrum with a maximum observable bandwidth around 110 GHz has been demonstrated under an injected RF power of 20 dBm (Fig. 1(b)). Injection locking phenomenon using metasurfaces with different gain/dispersion and tunable external cavity lengths has also been explored, taking the advantage of design flexibility of the VECSEL configuration. This experimental setup is suitable for further exploration of active mode-locking in THz QC-VECSELs.

2:30pm **MIOMD-MoA1-7 THz Quantum Photodetector Based on LO-Phonon Scattering-Assisted Extraction***, **Joel Pérez Urquizo,*** Laboratoire de Physique de l'École Normale Supérieure, France

The use of the LO-phonon scattering mechanism has proven effective to enhance electron transfer between quantum wells in diverse intersubband devices, such as Mid IR QCDs [1] and THz QCLs [2,3]. In this work we present a THz quantum detector based on $GaAs/Al_{0.25}Ga_{0.75}As$ heterostructure which is designed to exploit LO phonon scattering as an extraction mechanism for photoexcited electrons. The absorbing quantum well has an intersubband transition of 15.5 meV. When an electric field is applied a miniband is formed in the subsequent quantum wells, the edge of which is aligned resonantly with the first subband of the next period's absorbing quantum well, exhibiting a transition at roughly the LO phonon energy in GaAs E_{LO}= 37 meV. Spectral-resolved measurements were performed on samples processed into arrays of patch microcavities [4]. Measurements show detection in the THz with a peak responsivity of 80 mA/W at 3.5 THz at 20 K. This type of quantum detectors allows exploiting the degrees of freedom of quantum confinement for a constant Al content.

[1] F. R. Giorgetta, et al. IEEE Journal of Quantum Electronics, vol. 45, no. 8, pp. 1039-1052. 2009.

[2] B.S. Williams, et al. Appl. Phys. Lett. 82, 1015-1017 (2003).

[3] G. Scalari, et al. Appl. Phys. Lett. 86, 181101 (2005).

[4] Y. Todorov et al. Opt. Express 18, 13886-13907 (2010).

2:50pm **MIOMD-MoA1-9 Multi-Octave THz Wave Generation in PNPA crystal at MHz Repetition Rates***, **Lukasz Sterczewski**, J. Mnich, J. Sotor,* Wroclaw University of Science and Technology, Poland

Terahertz (THz) wave generation using organic nonlinear optical (NLO) crystals has received considerable attention in the past decades as a viable method to convert broadband near-infrared radiation to the far-infrared region. Nowadays, the rapid development of fiber laser oscillators at telecom wavelengths creates a demand for novel NLO crystals optimized for longer-wavelength excitation and lower pulse energy compared to conventional solutions optimized for millijoule-level pulses with kHz repetition rates at near-visible wavelengths. This requirement is partially addressed by well-established NLO materials like DAST, DSTMS, or OH-1. However, further improvements in terms of conversion efficiency are still desired. Very recently, PNPA ((E)-4-((4-nitrobenzylidene)amino)-*N*-phenylaniline) has been identified as a potential candidate to address this need. Spectra in the 0.2–5 THz range have been obtained using mJ-level 100 fs long pump pulses with kHz repetition rates, yet lower-energy MHz-rate excitation has not been tested to date. In this work, we demonstrate multi-octave THz generation from PNPA pumped by a simple all-fiber femtosecond laser providing 17 fs pulses at a 1550 nm wavelength with 50 MHz repetition rate (4 nJ pulse energy). Increasing the repetition rate 5×10^4 times accompanied by a 5-fold decrease in the pulse duration grants us access to the longwave infrared and THz region from 10 µm of wavelength (30 THz) to 300 µm (1 THz). Using the THz-induced lensing technique we optically sample the emitted field as shown in Fig. 1a. Without purging the measurement chamber, persistent oscillations of water molecules persist over tens of picoseconds, which appear as sharp absorption dips in the spectrum (Fig. 1b). We will discuss the time-frequency characteristics of the waveform and compare them with other well-established THz emitters like DSTMS.

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