Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-MoM1

Frequency Combs

Moderator: David Burghoff, University of Notre Dame

8:20am **MIOMD-MoM1-1 Welcome and Opening Remarks***,*

8:30am **MIOMD-MoM1-2 Mid-Infrared Semiconductor Laser Frequency Combs: From FM-Combs to Nozaki-Bekki Solitons***, N. Opacak,* TU Wien, Austria*; D. Kazakov,* Harvard University*; L. Columbo,* Politecnico di Torino, Italy*; S. Dal Cin, M. Beiser, F. Pilat,* TU Wien, Austria*; T. Letsou,* Harvard University*; M. Brambilla,* Universit`a e Politecnico di Bari, Italy*; F. Prati,* Universit`a dell'Insubria, Italy*; M. Piccardo,* Universidade de Lisboa, Portugal*; F. Capasso,* Harvard University*; **Benedikt Schwarz**,* TU Wien, Austria **INVITED**

Optical frequency combs (OFCs) stand as the cornerstone of modern optics, with applications ranging from fundamental science to sensing and spectroscopy. Generation of short optical soliton pulses in passive media such as optical fibers and microresonators has been an established technique for stable OFC formation with a broad optical spectrum – however these platforms are driven by an external optical signal and often rely on additional bulky elements that increase the complexity of the system.

Here, we aim to overcome these difficulties by direct OFC generation in mid-infrared semiconductor lasers, such as quantum and interband cascade lasers. After a general introduction to such combs and their nonlinear dynamics, the soliton concept from microresonator Kerr combs will be generalized to active media that are electrically-driven and a new type of solitons in free-running semiconductor laser integrated on a chip will be demonstrated.

9:00am **MIOMD-MoM1-5 Temporal Solitons in Coherently-Driven Ring Lasers***, **Theodore Letsou**, D. Kazakov,* Harvard University*; M. Piccardo,* Universidade de Lisboa, Portugal*; L. Columbo,* Politecnico di Torino, Italy*; M. Brambilla,* Politecnico di Bari, Italy*; F. Prati,* Università dell'Insubria, Italy*; S. Dal Cin, M. Beiser, N. Opačak,* TU Wien, Austria*; M. Pushkarsky, D. Caffey, T. Day,* DRS Daylight Solutions*; L. Lugiato,* Università dell'Insubria, Italy*; B. Schwarz,* TU Wien, Austria*; F. Capasso,* Harvard University

Pulsed lasers have been the workhorse of ultrafast optics since their advent and rapid development throughout the 20th century, revolutionizing a wide variety of fields from spectroscopy to tattoo removal. Over the past twenty years, pulsed laser sources have shrunk from tabletop laboratory setups down to micron-sized chips, making them ideal components for integrated photonic devices. Despite this miniaturization, chip-scale pulsed laser sources have eluded the mid infrared (IR) spectral region. Active mode-locking of mid IR semiconductor lasers—such as quantum cascade lasers (QCLs)—has produced pulse widths on the order of 6 picoseconds [1]. Pulse compression techniques can be utilized to shrink these pulses to hundreds of femtoseconds [2], but rely on large optical setups that cannot be scaled down. Here, we present a fundamentally new way to produce bright pulses of mid IR light by optically pumping ring QCLs. This technique unifies the physics of passive, Kerr microresonator combs and ring QCLs [3]. Using a modified racetrack QCL with an integrated directional coupler, we injection-lock the unidirectional laser field circulating in the racetrack to a commercial external cavity QCL. Much like in Kerr microresonator combs, when the injection-locked field is detuned from its natural cavity resonance, the resonance becomes bistable, with its unstable branch supporting bright solitons with pulse widths of ~1 picosecond at a center wavelength of 8 µm. This method of pulse formation is well-suited for lasers with fast gain dynamics, which encompasses the entire family of QCLs, spanning from 3 µm to 300 µm. Furthermore, the optical drive can, in principle, be integrated with the racetrack, providing a route for on-chip, ultrashort pulse formation throughout the entire mid-IR.

[1] J. Hillbrand, *et. al.*, Nat. Commun. **11**, 5788(2020).

[2] P. Täschler, *et. al.*, Nat. Photon. **15**, 919-924(2021).

[3] L. Columbo, M. Piccardo, *et. al.*, Phys. Rev. Lett. **126**, 173903(2021).

9:20am **MIOMD-MoM1-7 Full-Band Modeling of AM and FM Interband Cascade Laser Frequency Combs***, **Michael Povolotskyi**,* Jacobs*; I. Vurgaftman,* Naval Research Laboratory, USA

Compact and efficient mid-infrared (MIR) frequency combs are expected to find widespread use in chemical sensing applications, such as on-chip spectroscopy of toxic substances. While most of the experimental MIR laser comb work has involved quantum cascade lasers (QCLs), interband cascade lasers (ICLs) operate cw at room temperature in the 3-4 mm spectral range, which remains difficult for QCLs, and also promise significant reductions in the operating power throughout the MIR spectral range. Furthermore, owing to the long carrier lifetime in an ICL, both passive mode-locking with short pulses (AM) and quasi-cw (FM) comb generation should be possible.

In spite of these promising characteristics, only FM combs based on ICLs have been demonstrated to date. In order to clarify the physical requirements for both AM and FM operation, we have developed a multiscale numerical model that efficiently solves the Maxwell-Bloch equations for the full subband dispersion in the ICL's active type-II wells over a time period of µs. We compare the results of this model to those derived from the two-level approximation relevant to QCLs, and evaluate the importance of such parameters as the second-order and higher-order group velocity dispersions, saturable absorber length and recovery time, ambipolar diffusion coefficient, and polarization relaxation time (homogeneous gain broadening linewidth). We determine the optimal design parameters for experimentally demonstrating both passively mode-locked and FM ICL combs, and outline how they can be realized in practice.

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