Mid-IR Optoelectronics: Materials and Devices
Room Lecture Hall, Nielsen Hall - Session MIOMD-MoA2

Quantum and Interband Cascade Lasers
Moderator: Benjamin S. Williams, University of California Los Angeles

3:40pm **MIOMD-MoA2-14 Low Threshold Long Wavelength Interband Cascade Lasers***, **Jeremy Massengale**, Y. Shen, R. Yang,* University of Oklahoma*; S. Hawkins, A. Muhowski,* Sandia National Laboratories, USA

Interband cascade lasers (ICLs) [1-2] employ type-II quantum wells (QWs) as the active region and can cover a wide range of mid-IR spectrum with high performance especially in wavelength range from 3 µm to about 6 µm [2-4]. In this work, we report significantimprovements in long wavelength ICLs in terms of reduced threshold current density J_{th} and voltage V_{th} compared to previous ICLs [5]. For example, in cw operation, the J_{th} at 80 K is below 9 A/cm^2 with output power exceeding 100 mW/facet and with a lasing wavelength near 10.7 µm close to 140 K. Such a low J_{th} indicates a weak SRH recombination, suggesting a good material quality. The threshold voltage V_{th} at 80K is 3.61 V with a voltage efficiency of 73%, which is quite high considering that the photon energy (126meV) is low at such a long wavelength (9.83 µm at 80 K). ICLs from another wafer EB7910 lased at a longer wavelength in cw mode near 11.4 µm at 80 K with a J_{th} of 24.9 A/cm^2 and V_{th} of 3.95 V, corresponding a voltage efficiency of about 55%. These ICLs were able to operate at wavelengths exceeding 12 µm in pulsed mode at 135 K, the longest ever reported for ICLs with standard W-shape QW active regions. Detailed results will be presented at the conference.

4:00pm **MIOMD-MoA2-16 Progress in Terahertz Quantum Cascade Lasers Supporting Clean N-Level Systems***, **Asaf Albo**,* Bar-Ilan University, Israel

Although Terahertz Quantum Cascade Lasers (THz-QCLs) have a lot of potential, since they were first demonstrated in 2002, their use has been restricted due to lack of portability due to the requirements of cooling machinery. Therefore, raising the T_{max} is the main goal in the field. In 2021, a new T_{max} of ~250 K was achieved and demonstrated [1], enabling the launch of the first high-power portable THz-QCL. Although portable, this device, still required thermoelectric cooling, and the T_{max} was reached in pulsed operation. Moreover, up to date, other groups did not report similar T_{max} values, indicating how big of a challenge this represents.

The design that reached the T_{max} of ~250 K [1] is a two-well (TW) design supporting a clean three-level system (meaning the electron transport occurs only within the laser´s active subbands and all thermally activated leakage paths for electrons were suppressed). This design is like the design demonstrated beforehand with small variations (Design HB2 in Ref. [2]), and it is not the only design with a clean n-level system. Other designs that showed to have successfully suppressed thermally activated leakage channels are a resonant-phonon design presented in 2016 [3], and a split-well direct-phonon (SWDP) proposed in 2019 [4]. However, it is not clear why designs with very similar characteristics show very different T_{max} values, hence, the investigation is still ongoing.

Within our study, we suggest two other novel designs with clean n-level system. The first one is a highly diagonal split-well resonant-phonon (SWRP) scheme [5] and the second is a two-well injector direct-phonon (TWI-DP) scheme. Just as the structures mentioned earlier, both these new designs support clean 4-level systems.

The focus of the research we are presenting is on investigating these designs and comparing their device performance with other designs supporting clean n-level systems. Considering that THz-QCL designs supporting clean n-level systems are not limited by thermal leakage, a detailed comparison of their temperature performance should be the key for improvements beyond the state-of-the-art.

4:20pm **MIOMD-MoA2-18 Improving Transverse Mode Quality of QCLs with Novel Waveguides***, **Matthew Suttinger**, R. Go, A. Lu,* Air Force Research Laboratory

Quantum Cascade Lasers (QCLs) are reaching a level of commercial maturity. With multiple watts of CW power available from a single QCL source with near transform limited ("fundamental mode-like") beam quality. This beam quality is achievable due to the standard configuration of the QCL waveguide, with an laser core having transverse dimensions of 1-2 µm X 8-12 µm relative to the 4-5 µm wavelengths produced by higher power Midwave infrared (MWIR) devices. However, remaining with this form factor will limit the amount of available power produced by the laser, as the longitudinal extent of the waveguide cannot be indefinitely extended without issue. Multiple geometries have been explored to expand the total achievable power of single emitter beyond that of the narrow Fabry-Perot cavity, most immediately available being the broad area QCL. In this presentation, results of novel QCL waveguides fabricated at Air Force Research Laboratory are discussed.

In the "ultrawide" Fabry-Perot waveguide, extremely wide laser cores exceeding the standard configuration width by an order of magnitude allow for the scaling of average power, but with severely reduced and divergent beam quality. Through a modification of waveguide to bring the waveguide mode closer to the electrical contact, and splitting said contact into a Dual Contact Strip, the mode quality can be rectified to fundamental-like behavior.

Another approach to improving mode quality relative to the Fabry-Perot geometry is through an angled cavity waveguide. On its own, an angled cavity with a severe enough tilt may induce improved transverse mode quality, but at the expense of overall power potential through losses induced by sidewall interaction. A similar effect may be achieved by using a less pronounced angle and interrupting the waveguide with "notches" etched out of areas far from the internal beam path of the fundamental mode. This allows losses to preferentially disrupt higher order modes. Power can then be scaled by overlapping multiple angled cavities to produce a coherent array with an output beam envelope reflected by that of the output of its components in isolation.

4:40pm **MIOMD-MoA2-20 Broadly Tunable Single Spatial Mode Quantum Cascade Lasers in an External Cavity***, **B. Knipfer**, D. Ruiz, S. Ruder, K. Oresick, M. Klaus, M. Dwyer, C. Galstad, T. Earles,* DRS Daylight Solutions

Broadly tunable laser sources spanning mid- to long-wave IR are highly sought after for their ability to characterize materials with non-destructive spectroscopy techniques. The wavelengths of interest typically span 3-13 µm, or approximately 2500 cm^{-1}. Given such a large spectrum window finding materials adequately suited can be a challenge, however, given the scalability of MOCVD growth, and the wavelength agility of quantum cascade lasers, MOCVD-grown QCLs fill this niche perfectly.

Previous work has shown heterogeneous quantum cascade lasers emitting in the LWIR that span, up to 760 cm^{-1}, however, at relatively low pulsed powers and in a double-channel ridge configuration [1]. We have previously reported on tuning capabilities within an external cavity in the 4.0-4.8 µm regime [2] and here we push wavelengths across the MW- to LWIR while optimizing CW and pulsed powers with superb beam pointing stability.

This work shows advances in the tuning capabilities of single-core and heterogeneous quantum cascade structures within an external cavity. Previous state-of-the-art products would use four QCL chips to cover 1000 cm^{-1}, but here we are able to further expand the tuning range of individual chips such that the same range can be covered by only three QCLs, shown in Figure 1. Typically, the expansion of tuning range is achieved by broadening the spectral gain through either broadening of a single core, the introduction of additional cores supporting different wavelengths, or both. These different methods typically correspond to a decrease in output power; however, we show this expansion is achieved while maintaining high single mode powers. Through optimization of the active region, a relatively flat modal gain can be achieved across the desired emission range.

These devices exemplify the ability of QCLs to span significant wavenumbers, at high pulsed and CW power levels while maintaining strong single spatial mode operation which has been verified through pointing stability measurements. Beam measurements show deviations of less than 100 µrad over the range of tuning under CW and pulsed operation.

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