

## Quantum and Interband Cascade Lasers

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Over 16 years have passed since the Bell Labs group headed by Federico Capasso first demonstrated the quantum cascade laser (QCL). The intervening interval has seen the QCL evolve from a barely functional scientific curiosity into a powerful technology poised to offer new capabilities to a broad spectrum of real-world applications. In assembling this special section of *Optical Engineering*, our dual goals have been to provide a snapshot of the cascade laser field in its adolescence, and to familiarize a wider audience of optical engineers with the far-reaching practical potential of these unique IR sources.

The remarkable advance of the QCL technology has been both pulled on the end-user side by the prior lack of any noncryogenic semiconductor lasers emitting beyond  $3\ \mu\text{m}$ , and pushed on the scientific side by the compelling notion that applying quantum principles to layered semiconductor heterostructures can open pathways to novel functionalities extending far beyond those offered by the parent materials. The applications are driven, for example, by military and industrial needs for compact, powerful, and efficient IR sources, as well as by the spectroscopic community's desire for low-cost and field-friendly narrow-line lasers capable of enhancing molecular detection sensitivities by orders of magnitude. Scientifically, it was realized that the shift to intersubband active transitions finally unbinds the emission wavelength from its slave-like coupling to the energy gap that was unavoidable in conventional diodes. Introduction of the cascade geometry, whereby a single electron traverses multiple gain regions and potentially emits an additional photon at every step, provided the masterstroke that made lasing possible despite the competition with parasitic nonradiative processes occurring on a picosecond time scale. Cascading can rapidly empty the lower lasing level via a combination of phonon emission and subsequent "miniband" transport, while minimizing the impact of series resistance by trading a higher voltage (proportional to the number of stages) for much lower threshold current density (corresponding to  $<10^{10}\ \text{cm}^{-2}$  electrons injected into each stage to reach population inversion). Also essential has been a careful iterative optimization of the epitaxial growth by molecular beam epitaxy and metalorganic chemical vapor deposition, to produce high-quality structures with sharp interfaces and reduced transition linewidths. These and other advances have enabled QCLs to cover an astonishing  $2\frac{1}{2}$  orders of magnitude in emission wavelength ( $2.6\text{--}750\ \mu\text{m}$ ). Mid-IR devices operating at room temperature can now generate several watts of continuous wave (CW) power, with wall-plug efficiencies well over 10%.

Soon after the first QCL demonstration, Rui Yang (then at the University of Toronto) recognized that interband lasers

can also profit when a cascade geometry is adopted. This is because cascading again reduces the threshold power density by lowering the series voltage drop. Furthermore, the versatile antimonide material family provides a type-II band overlap that enables recycling from the valence band back to the conduction band, and also eliminates the need for lossy  $p$ -doped optical cladding layers. Even though the so-called interband cascade laser developed less rapidly, due in part to its dependence on less mature antimonide materials, ICLs now generate  $>10\ \text{mW}$  CW in a single spectral mode at temperatures above ambient. The preferred QCL wavelength range beginning around  $4\ \mu\text{m}$  is complemented by the ICLs that work best at  $\lambda \approx 3\text{--}4.2\ \mu\text{m}$ . While the maximum CW output powers demonstrated to date do not approach the multi-Watt levels of recent QCLs, ICLs require roughly an order of magnitude less input power to reach threshold due to their fewer number of stages and lower threshold current densities. This will substantially extend the battery lifetimes in fielded systems limited by power consumption.

This special section presents an invited review paper by a founder and guiding force of the cascade laser field, Federico Capasso, along with 25 contributed papers. Topics covered include high-performance QCLs operating in the mid-IR and longer wavelengths, a new theoretical description of the transport and gain in a QCL, approaches to scaling the QCL output power, heat transport in THz QCLs, recent advances in ICL performance, and applications of both QCLs and ICLs to sensing such trace gases as methane, water vapor, nitrogen oxide, carbon dioxide, and ozone, as well as explosives. We thank all the authors for assembling their valuable contributions to this collection on a compressed publication schedule. We also greatly appreciate the efforts of the numerous peer reviewers who ensured high standards of the published versions, the SPIE staff who shepherded the papers through the entire process, and of the editor of *Optical Engineering*, Ron Driggers, whose original suggestion led to this special section.



**Jerry R. Meyer** completed his PhD in physics at Brown University in 1977. Since then he has carried out basic and applied research at the Naval Research Laboratory in Washington DC, where he is head of the Quantum Optoelectronics Section and a senior scientist for Quantum Electronics (ST). His investigations have focused on semiconductor optoelectronic materials and devices, such as the development of new classes of semiconductor lasers and detectors for the infrared. He is a Fellow of the Optical Society of America, the American Physical Society, the Institute of Electrical and Electronics

Engineers, and the Institute of Physics. He has coauthored over 320 refereed journal articles which have been cited more than 7200 times (H-Index 36), 13 book chapters, 22 patents awarded and pending, and over 110 invited conference presentations.



**Igor Vurgaftman** received his BS degree *summa cum laude* in computer engineering from Boston University in 1991, and his MS and PhD degrees in electrical engineering from the University of Michigan in 1993 and 1995, respectively. Since 1995, he has been with the Optical Sciences Division of the Naval Research Laboratory (NRL) in Washington, DC. At NRL, he has investigated midinfrared lasers based on interband and intersubband transitions, methods of main-

taining optical coherence in large-area semiconductor lasers, type-II superlattice photodetectors, coherent sources of surface plasmons, and spintronic optical and electronic devices, among other topics. He is the author of more than 200 refereed articles in technical journals, numerous contributed and invited talks at professional conferences, as well as 12 patents.