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SPOTLIGHT

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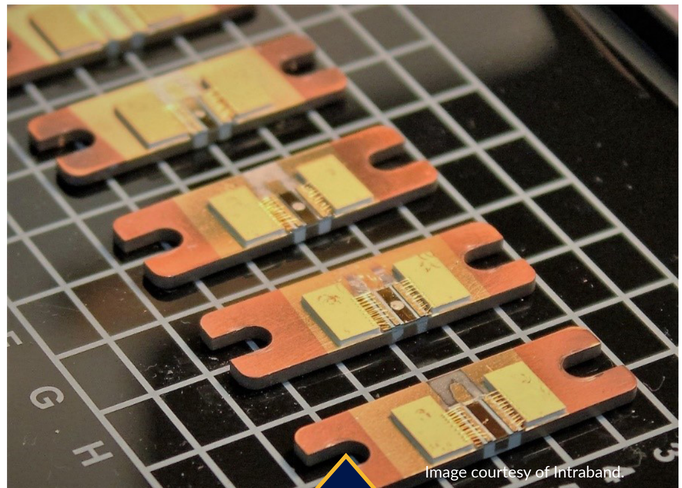
Turning research into defense innovation: Intraband and UW-Madison's quantum cascade laser breakthrough

The Department of the Navy's (DoN) Small Business Technology Transfer (STTR) program funds collaboration between small businesses and research institutions to translate academic research into products and services that benefit the warfighter. In a recent STTR-funded project, Intraband, LLC, in partnership with the University of Wisconsin-Madison (UW-Madison), made a breakthrough in the development and understanding of high-power and high-efficiency mid-infrared (IR) quantum cascade lasers (QCLs), which could improve the directional infrared countermeasures (DIRCM) used in many defense systems.

Through this project, Intraband was able to design a device that demonstrated record-high power and efficiency values. "It's one of the best QCLs out there," said Suraj Suri, a research engineer at Intraband.

Addressing key challenges in high-power mid-IR QCL development

QCLs are semiconductor lasers that emit in the mid-IR range (3 to 5 μm) used by the Navy's Large Aircraft Infrared Countermeasures (LAIRCM) and other defense DIRCM systems to defeat IR-guided missiles. While current QCLs enable emissions in this range, they are four times less efficient than near-IR (0.8 to 2.5 μm) lasers, requiring significantly more space, electrical power, and liquid cooling to operate.



Intraband's QCL device

Intraband's STTR project aimed to improve QCL optical power and wall-plug efficiency (WPE), which would reduce the size, weight, and electrical power (SWaP) requirements of existing and future DIRCM systems.

Developing mid-IR emitting QCLs for high-power applications is a multifaceted research and development challenge requiring advancements in active-region (AR), waveguide and packaging designs. By the end of the STTR Phase I, Intraband had developed a 5.1 μm-emitting, high-power, high-efficiency QCL that achieved 14% front-facet WPE in pulsed operation, and 2.6 watts (W) power in continuous-wave (CW) operation. These results represented the best performance published at that time from QCLs grown by metal-organic chemical vapor deposition (MOCVD). This method of

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growing crystalline layers for the fabrication of semiconductor devices is preferred by industry because it is cost-effective, enabling production on an industrial scale.

During Phase II, the team at Intraband and UW-Madison initially developed the first comprehensive carrier-leakage formalism for QCLs, which identified interface-roughness scattering as the main cause of carrier leakage in high-power QCLs, and, in the process, bridged the gap between theoretical and experimental internal-efficiency values, a critical device performance metric.

Intraband and UW-Madison also collaborated with nextnano Lab in Corenc, France, to introduce advanced device modeling techniques to the design of the AR, the key device region that generates light. This collaboration focused on understanding the role of graded interfaces and carrier-leakage mechanisms to enable high-power operation. By modeling and designing high-performance AR superlattice structures, the team identified novel device-physics mechanisms, which led to filing a patent application with the U.S. Patent and Trademark Office.

Building on the deeper understanding of carrier dynamics reached during Phase II, Intraband demonstrated a QCL emitting at 4.6 µm with pulsed, front-facet WPE of 19.1%, the highest such value for MOCVD-grown devices and the second-highest WPE value for any type of QCL. Under CW-operating conditions, the device achieved a pure diffraction-limited beam pattern with 1.3 W of power, marking one of the highest single-spatial-mode CW power reported from mid-IR QCLs.

By further optimizing the AR design for substantial carrier-leakage suppression, Intraband expects to be able to increase the WPE value to about 25% using current MOCVD-growth conditions, and to about 37% with optimized crystal-growth conditions for high-quality superlattice interfaces. Computer simulations suggest that the Navy's ultimate goal of 40% efficiency in CW operation is achievable with optimizations in AR design, interface quality and packaging.

A decade-long challenge

The Navy and other DoD organizations have been working to develop high-efficiency mid-IR lasers for over a decade. Suri explained, "It's been a struggle to achieve high efficiency QCLs at these wavelengths. With increasing geopolitical tensions, the Navy, Air Force and Army are all looking toward high-power laser technologies, especially in the mid-IR range, to meet emerging defense needs."

In 2011, researchers at Northwestern University developed a QCL emitting at 4.9 µm with high power and a record-high efficiency of 27% in pulsed and 21% in CW operation. However, the physics behind these results remained unclear. Suri noted, "Once the device was made public, nobody understood how it was able to achieve these record performance numbers for power and efficiency."

Unraveling the physics behind high-performance QCLs

Based on the research conducted during the 2020 STTR project, Suri and other researchers from Intraband and UW-Madison published a paper in January 2024 in the journal Nanophotonics that answered these questions. "Through this Navy funding we were able to understand what was going on in this record-performance device," he explained. "Finally, we were able to explain exactly how the device works and why it was able to achieve those high efficiency values. In the same paper, we also published experimental data from the device we developed in our lab that applied the newly discovered physics."

Bridging academia and defense innovation

Suri became involved with Intraband's STTR project while working toward his PhD in electrical engineering at UW-Madison. The company and the university are closely connected. Intraband is based at the University Research Park and Suri's PhD advisors, professors Dan Botez and Luke Mawst, are part of the company's leadership team.

A key feature of the STTR program that differentiates it from the Small Business Innovative Research (SBIR) program is its requirement for collaboration with research institutions. While the partnering small business is the official awardee and manages the project, the partnering research institution can receive up to 60% of total award funding. STTR guidelines require the small business to perform at least 40% of the work on the project with a minimum of 30% of the work subcontracted to the partnering research institution. The remaining 30% can be allocated to either the research institution or another R&D subcontractor.

"My research was funded through that project that Intraband subcontracted to UW-Madison," Suri said.

After completing his PhD in 2023, Suri joined the staff of Intraband, where he continues to develop high-power mid-IR QCLs for defense applications including DIRCM systems and free-space communications. In 2024, he attended Sea-Air-Space to support another Intraband technology that was featured in the Navy SBIR Transition Program Showcase.

Seeing first-hand the real-world defense applications for his academic research was a revelation, Suri recalled. "At academic conferences we talk a lot about basic sciences. We don't talk about the larger scheme of things—why something is being developed or researched. At Sea-Air-Space, I was able to see where those technologies end up. That was quite exciting. It was a completely different experience, and I loved it because it gives a clear perspective of how our research is used in defense."

Future applications for QCL technology

Intraband's QCL technologies support the advancement of defense DIRCM systems and covert communications. Further applications include lasers for research and development, industrial lasers, sensor systems, and medical applications. The company has achieved state-of-the-art multi-watt CW and peak-pulsed powers from MOCVD-grown QCL single edge emitters. It also develops surface emitting and coherent arrayed QCLs.

For more information, visit www.intraband.us.

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