Quantum cascade laser (QCL) critical component for standoff detection of chemical warfare agents

The quantum cascade laser is a special kind of semiconductor laser, usually emitting mid-infrared light. Such a laser operates on laser transitions not between different electronic bands but on intersubband transitions of a semiconductor structure.

The most important applications for quantum cascade lasers is in the area of spectroscopy of trace gases, e.g. for detecting very small concentrations of pollutants in air. Quantum cascade lasers (QCLs) are increasingly being used to detect, identify, and measure levels of trace gases in the air. Such systems measure the unique infrared absorption "fingerprints" of chemicals to provide high detection sensitivity and identification confidence, and are particularly useful for field-portable sensing.

Applications include detecting chemical warfare agents and toxic industrial chemicals, monitoring building air quality, measuring greenhouse gases for atmospheric research, monitoring and controlling industrial processes, analyzing chemicals in exhaled breath for medical diagnostics, and many more. Compact, portable trace gas sensors enable operation in a wide range of platforms, including handheld units for use by first responders, fixed installations for monitoring air quality, and lightweight sensors for deployment in unmanned aerial vehicles (UAVs).

This property is also useful to intelligence agencies for detecting chemical warfare agents. For battlefield as well as many civilian applications it is not possible to locate the sensor in the near vicinity of the dangerous source. “Standoff detection of trace chemicals, such as explosive residues, chemical warfare agents and toxic industrial materials, is a critical unmet need within the Intelligence Community, Department of Defense, and Department of Homeland Security,” commented Dr. Anish Goyal, Block’s VP of Technology.

Quantum cascade laser (QCL) systems also support military applications such as Infrared Countermeasures (IRCM) and targeting. The demanding product requirements for aircraft platforms that include reduced size, weight, power consumption and cost (SWaP-C) extends to portable, battery powered handheld products.

Most quantum cascade lasers emit mid-infrared light. However, quantum cascade lasers can also be made for generating terahertz waves. Such devices constitute very compact and simple sources of terahertz radiation. Recently, even room temperature terahertz generation has been achieved via internal difference frequency generation.

Military and Security Applications

The spectral region from ~2 µm to >12 µm has been extensively explored for a broad range of laser sources because of the importance of the MWIR and the LWIR regions for spectroscopy, air pollution detection, detection of chemical warfare agents (CWAs), toxic industrial chemicals (TICs) and explosives, protection of aircraft from shoulder-fired missiles (MANPADS), target illuminators and designators and IFF beacons.

QCL technology operates throughout the mid-wave (MWIR) and long-wave (LWIR) infrared to provide new capabilities that leverage existing thermal imaging cameras. In addition to their suitability for aircraft platforms, QCL products are a natural fit to meet operator demands for small, lightweight pointer and beacon capabilities. Field-testing of high power, lightweight, battery operated devices has demonstrated their utility across a range of air and ground applications.

A key application for QCLs is stand-off explosives detection. In this developing field researchers have set the ambitious goal of detecting and discriminating nanogram quantities of various explosives at distances up to 50 m with eye-safe lasers.

There are a number of tactics being employed, one approach being Thermal Imaging. When a compound absorbs infrared light, it re-emits most of the absorbed light isotropically as heat which can be imaged by infrared cameras. Since each analyte has a unique absorption spectrum, each will heat selectively as the IR source is tuned through these absorptions and may be identified unambiguously by analysis of the multi-spectral or hyperspectral data cube produced.

While QCLs serve as the engines for new techniques in spectroscopy in the mid-IR, they also can provide raw power at new performance levels. Powers exceeding 5 W have been demonstrated from single room-temperature devices. Combining performance such as this with ruggedized packaging has enabled a new generation of Infrared Countermeasure (IRCM) devices. For IRCM applications, one needs a multiple wavelength illumination source to disable the tracking sensor in MANPADS.

High-power, solid-state lasers that operate in mid-infrared “atmospheric windows” can be used by pointer-trackers to disable the heat seeking mechanism employed on surface-to-air missiles, thus safeguarding soldiers in battlefield situations. Multiple “socket” QCL-based laser systems have been militarily hardened and have completed helicopter flight testing.

IARPA’s Standoff Illuminator for Measuring Absorbance and Reflectance Infrared Light Signatures (SILMARILS)

Block MEMS, the Massachusetts company specializing in photonics-based threat detection technologies, has been awarded $10.7 million under the US Intelligence Advanced Research Programs Activity (IARPA) developmental funding scheme. The Marlborough-based firm, which has been nominated for a Prism Award at the forthcoming SPIE Photonics West event, says that the “Phase II” backing follows its successful stand-off detection of trace quantities of explosives using a benchtop system based around quantum cascade lasers (QCLs).

“Under Phase I, Block successfully demonstrated the ability to detect trace quantities of explosives and other threats on multiple surfaces at 1 and 5 meter standoff distances in a few seconds,” it stated, adding that the Phase II selection was made in a competitive down-selection process. That Phase I award was made in July 2016.

It has won the funding under IARPA’s “Standoff Illuminator for Measuring Absorbance and Reflectance Infrared Light Signatures” (SILMARILS) program, which is managed by Kristy DeWitt and the US Air Force Research Laboratory at Wright-Patterson Air Force Base in Ohio.

30 meter stand-off target

The ultimate aim of the SILMARILS program is to develop a portable system for real-time stand-off detection and identification of trace chemical residues on surfaces using active infrared spectroscopy, at a range of 30 meters.

In combination with what Block MEMS calls its “innovative chemical detection algorithm”, the QCL is able to probe for tell-tale spectroscopic transitions in the mid-infrared part of the spectrum that are characteristic of specific molecules. “The algorithm combines powerful data processing techniques, simulations of light/material interactions, and modeling of anticipated detected signatures in order to eliminate the effect of clutter, reduce false alarm rates, and improve limits of detection,” says the firm.

Specific applications envisaged for the developed technology include airport scanning of hands and clothes for signs of narcotics or explosives, or forensic analysis of the pavement around the area of a chemical release. Other contractors to have been involved in the program include Leidos, LGS Innovations, Physical Sciences, Inc., and Spectrum Photon

Under this contract, Block will develop a new class of widely tunable, high-pulse energy Quantum Cascade Lasers and also next-generation detection algorithms to detect and identify hundreds of chemicals on a wide range of surfaces. In addition to the suitable wavelength range, QCLs usually feature a relatively narrow linewidth and good wavelength tunability, making them very suitable sensor to detect a broad range of CWAs, TICs and explosives.

Standoff chemical detection is a ubiquitous need across the Intelligence Community (IC) for applications ranging from forensic crime scene analysis to border and facility protection to stockpile and production monitoring. However, current systems do not provide the sensitivity, specificity, and low false-alarm rates that are needed to enable effective use in a cluttered, realworld environment.

The SILMARILS program aims to develop a portable system for realtime standoff detection and identification of trace chemical residues on surfaces using active infrared spectroscopy at a 30 meter range. Program goals include: high chemical sensitivity and specificity across a broad range of target classes; effective operation in a real-world environment accounting for issues such as gas phase and surface-adsorbed clutter, varying substrates, temperature, humidity, indoor/outdoor background light; a system that is eye-safe and has a visually unobservable illumination beam; human-portable size and power draw commensurate with limited-duration battery operation; and a rapid scan rate.

Primary chemical classes and specific representative examples that are of interest in the SILMARILS program include, but are not limited to:

- **Explosives:** Nitro-based compounds such as TNT and RDX, newer formulations such as acetone peroxide, and home-made explosives such as fertilizer bombs.
- **Chemical weapons and poisonous or toxic chemicals:** Chemical weapons such as sarin or tabun, newer non-traditional agents, and toxic chemicals that may be intentionally or unintentionally released such as hydrogen cyanide or ammonia gas.
- **Narcotics:** Illicit drugs such as cocaine, heroin, or methamphetamine, or legal but abused· drugs such as Vicodin or hydrocodone.

“This machine would use infrared lasers to measure the signature of chemical agents and different molecules so that it’s much safer, practical way of interrogating a surface, like the bottom of someone’s shoe, footprints and those kinds of things,” said Kevin Kelly, chief executive officer of LGS Innovations, which could earn as much as $11 million over four years through SILMARILS.

Key goals for SILMARILS indicate the device must produce a steerable “eye-safe, visually unobservable illumination beam,” and must be of “human-portable size,” while drawing power at low enough levels to be battery operated.

“There are also many commercial applications for sensitive, standoff chemical detection. Block’s QCL technology combined with advanced data analytics makes it possible to meet the challenging performance goals of the SILMARILS Program.

Scientists create most efficient quantum cascade laser ever

A team of UCF researchers has produced the most efficient quantum cascade laser ever designed — and done it in a way that makes the lasers easier to manufacture.

Quantum cascade lasers, or QCLs, are tiny — smaller than a grain of rice — but they pack a punch. Compared to traditional lasers, QCLs offer higher power output and can be tuned to a wide range of infrared wavelengths. They can also be used at room temperature without the need for bulky cooling systems. But because they’re difficult and costly to produce, QCLs aren’t used much outside the Department of Defense.

A University of Central Florida team led by Assistant Professor Arkadiy Lyakh has developed a simpler process for creating such lasers, with comparable performance and better efficiency. The results were published recently in the scientific journal Applied Physics Letters.

“The previous record was achieved using a design that’s a little exotic, that’s somewhat difficult to reproduce in real life,” Lyakh said. “We improved on that record, but what’s really important is that we did it in such a way that it’s easier to transition this technology to production. From a practical standpoint, it’s an important result.”

That could lead to greater usage in spectroscopy, such as using the infrared lasers as remote sensors to detect gases and toxins in the atmosphere. Lyakh, who has joint appointments with UCF’s NanoScience Technology Center and the College of Optics and Photonics, envisions portable health devices. For instance, a small QCL-embedded device could be plugged into a smartphone and used to diagnose health problems by simply analyzing one’s exhaled breath.

“But for a handheld device, it has to be as efficient as possible so it doesn’t drain your battery and it won’t generate a lot of heat,” Lyakh said.

The method that previously produced the highest efficiency called for the QCL atop a substrate made up of more than 1,000 layers, each one barely thicker than a single atom. Each layer was composed of one of five different materials, making production challenging.

The new method developed at UCF uses only two different materials — a simpler design from a production standpoint.

Quantum Cascade Lasers Market Growth

The quantum cascade lasers market is expected to be worth USD 374.8 million by 2022, growing at a CAGR of 3.9% between 2017 and 2022. The growth of the QCL market can be attributed to the growing application of QCL in gas sensing and chemical detection in industries and the increasing adoption of non-invasive diagnostic tools in the medical industry. The high cost of QCLs is the main restraining factor for the QCL market.

The market for HHL & VHL packaged QCLs is expected witness the highest growth during the forecast period because of the high-power applications in the military and defense sector. HHL & VHL packaged QCLs are used in high-power applications in the military and defense sector for infrared countermeasures (IRCM).

The industrial sector held the largest share of the QCL market among industries such as medical, telecommunication, and military and defense. Gas sensing and chemical detection is the main application of QCLs. These techniques are adopted in various industries to detect hazardous gases such as CO, CO_2, and NH_3.

QCL operation

The quantum cascade laser is a special kind of semiconductor laser, usually emitting mid-infrared light. Such a laser operates on laser transitions not between different electronic bands but on intersubband transitions of a semiconductor structure.

Epitaxially grown semiconductor structures provide periodically repeated stacks of quantum well heterostructures (for example, semiconductor superlattices) allowing for discrete intersubband transition of electrons injected within the conduction band of such devices

The injected electrons are sequentially transiting via appropriately cascaded potential barriers, ideally emitting a photon upon relaxation into a lower energy quantum well. Multiplication of these quantum heterostructures leads to a cascade effect with each electron responsible for the emission of multiple photons, thereby achieving higher quantum efficiencies than conventional laser diodes

The higher optical gain is obtained at the expense of a higher required electrical voltage. The operation voltage can easily be of the order of 10 V, whereas few volts are sufficient for ordinary laser diodes.

As the transition energies are defined not by fixed material properties but rather by design parameters (particularly by layer thickness values of quantum wells), quantum cascade lasers can be designed for operating wavelengths ranging from a few microns to well above 10 μm, or even in the terahertz region. By careful design of the quantum wells, lasing from 2.75 μm to 161 μm (1.9 THz) has been observed.

The longer wavelength devices still require cryogenic cooling, but room temperature operation is possible to at least 16 μm. Commercial availability has concentrated in the mid-infrared (3.5 – 13 μm).

In a quantum cascade laser, the mentioned quantum well structure is embedded in a waveguide, and the laser resonator is mostly of DBR or DFB type. There are also external-cavity lasers, where a wavelength tuning element such as a diffraction grating is part of the resonator.

Whereas continuously operating room-temperature devices are normally limited to moderate output power levels in the milliwatt region (although more than a watt is possible), multiple watts are easily possible with liquid-nitrogen cooling. Even at room temperature, watt-level peak powers are possible when using short pump pulses.

The power conversion efficiency of quantum cascade lasers is typically of the order of a few tens of percent. Recently, however, devices with efficiencies around 50% have been demonstrated, although only for cryogenic operation conditions.

New designs of high power, continuous wave/room temperature (CW/RT) QCLs in the MWIR and LWIR regions have been demonstrated. At present, the highest power that has been reported in the MWIR region is about 5 W with device electrical power input to optical power output conversion efficiency (wall plug efficiency, WPE) of about 20% for TEC cooled devices with operation at ~ 20°C. Under similar operating conditions, CW/RT power outputs in excess of 1.4 W and WPE of 10% have been achieved at a wavelength of ~7.2 μm.

Maxion Technologies is developing high-performance quantum-cascade (QC) lasers in the mid-IR spectral region for Army and other DoD and DHS infrared countermeasure (IRCM) applications.

The objectives are to: (1) develop and demonstrate a Band-IV (around 4.8-micron wavelength) QC laser operating quasi-cw (at 25% duty cycle) near room temperature with a peak output power in excess of 2 W (average power of 0.5 W), and

(2) Illustrate the feasibility of power-scaling techniques for IRCM applications using QC laser technology by demonstrating a suitable laser-beam combining scheme with these lasers.

References and resources also include:

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