Widely Tunable Mode-Hop-Free External-Cavity Quantum Cascade Laser

This technology is suitable for spectroscopic applications, multi-species trace-gas detection, and measurements of broadband absorbers.

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The external-cavity quantum cascade laser (EC-QCL) system is based on an optical configuration of the Littrow type. It is a room-temperature, continuous-wave, widely tunable, mode-hop-free, mid-infrared, EC-QCL spectroscopic source. It has a single-mode tuning range of 155 cm^{-1} (≈8% of the center wavelength) with a maximum power of 11.1 mW and 182 cm^{-1} (≈15% of the center wavelength), and a maximum power of 50 mW as demonstrated for 5.3 micron and 8.4 micron EC-QCLs, respectively. This technology is particularly suitable for high-resolution spectroscopic applications, multi-species trace-gas detection, and spectroscopic measurements of broadband absorbers.

Wavelength tuning of EC-QCL spectroscopic source can be implemented by varying three independent parameters of the laser: (1) the optical length of the gain medium (which, in this case, is equivalent to QCL injection current modulation), (2) the length of the EC (which can be independently varied in the Rice EC-QCL setup), and (3) the angle of beam incidence at the diffraction grating (frequency tuning related directly to angular dispersion of the grating). All three mechanisms of frequency tuning have been demonstrated and are required to obtain a true mode-hop-free laser frequency tuning.

The precise frequency tuning characteristics of the EC-QCL output have been characterized using a variety of diagnostic tools available at Rice University (e.g., a monochromator, FTIR spectrometer, and a Fabry-Perot spectrometer). Spectroscopic results were compared with available databases (such as HITRAN, PNNL, EPA, and NIST). These enable precision verification of complete spectral parameters of the EC-QCL, such as wavelength, tuning range, tuning characteristics, and line width.

The output power of the EC-QCL is determined by the performance of the QC laser chip, its operating conditions, and parameters of the QC laser cavity such as mirror reflectivity or intracavity losses. In order to maximize the output power, an analysis and optimization of the EC laser parameters has been performed. The parameters of the beam emitted from the gain medium, such as divergence angle, beam profile, and astigmatism, have been investigated. The gain medium has been fully characterized before and after each stage of modification. The main modification steps are coating one facet of the gain chip with a high reflectivity mirror and the other facet with an anti-reflection layer. Then the chip is mounted in the EC-QCL. The optomechanical design has been reviewed and improved to provide for precise collimation of the strongly divergent beam of the QCL and the tuning diffraction grating.

This work was done by Gerard Wysocki, Robert F. Curl, and Frank K. Tittel of Rice University for Johnson Space Center. Further information is contained in a TSP (see page 1).

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to:

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Refer to MSC-24486-1, volume and number of this NASA Tech Briefs *issue, and the page number.*

Non-Geiger-Mode Single-Photon Avalanche Detector With Low Excess Noise

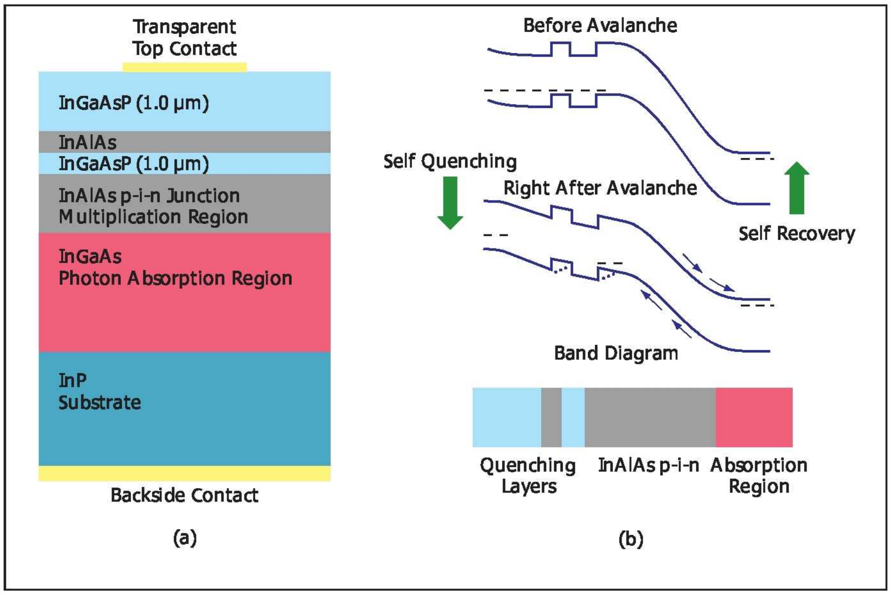
Applications include quantum key distribution for the financial industry and photon-starved optical communications needs.

NASA's Jet Propulsion Laboratory, Pasadena, California

This design constitutes a self-resetting (gain quenching), room-temperature operational semiconductor single-photon-sensitive detector that is sensitive to telecommunications optical wavelengths and is scalable to large areas (millimeter diameter) with high bandwidth and efficiencies.

The device can detect single photons at a 1,550-nm wavelength at a gain of 1×10^6. Unlike conventional single photon avalanche detectors (SPADs), where gain is an extremely sensitive function to the bias voltage, the multiplication gain of this device is stable at 1×10^6 over a wide range of bias from 30.2 to 30.9 V. Here, the multiplication gain is defined as the total number of charge carriers contained in one output pulse that is triggered by the absorption of a single photon. The statistics of magnitude of output signals also shows that the device has a very narrow pulse height distribution, which demonstrates a greatly suppressed gain fluctuation. From the histograms of both pulse height and pulse charge, the equivalent gain variance (excess noise) is between 1.001 and 1.007 at a gain of 1×10^6. With these advantages, the device holds promise to function as a PMT-like photon counter at a 1,550-nm wavelength.

The epitaxial layer structure of the device allows photons to be absorbed in the InGaAs layer, generating electron/hole (e-h) pairs. Driven by an electrical field in InGaAs, electrons are coll'ected at the anode while holes reach the multiplication region (InAlAs p-i-n structure) and trigger the avalanche process. As a result, a large number of e-h pairs are created, and the holes move toward



The schematic diagram of the **InGaAs-InAsAs SPAD Layer Structure** (a) and (b) the **Concept of Operation** for the structure showing the self-quenching and self-recovery processes.

the cathode. Holes created by the avalanche process gain large kinetic energy through the electric field, and are considered "hot". These hot holes are cooled as they travel across a p-InAlAs low field region, and are eventually blocked by energy barriers formed by the InGaAsP/InAlAs heterojunctions.

The composition of the InGaAsP alloy was chosen to have an 80 meV valance band offset with InAlAs, which is high enough to hinder the transport of the already cooled holes. Being stopped by the energy barrier, holes are accumulated at the junctions to shield the electric field, resulting in a decrease of the electric field in the multiplication region. Because the impact ionization rate is extremely sensitive to the magnitude of the electric field, the field-screening effect drastically reduces the impact ionization rate and quenches the output signals.

After the avalanche pulse signal is self-quenched, the accumulated holes at the InGaAsP/InAlAs interface escape the energy barrier through thermal excitation and tunneling and finally leave the device. The device is thus reset and ready for subsequent photon detection. This recovery time is controlled by the height of the energy barrier and the hole-cooling rate.

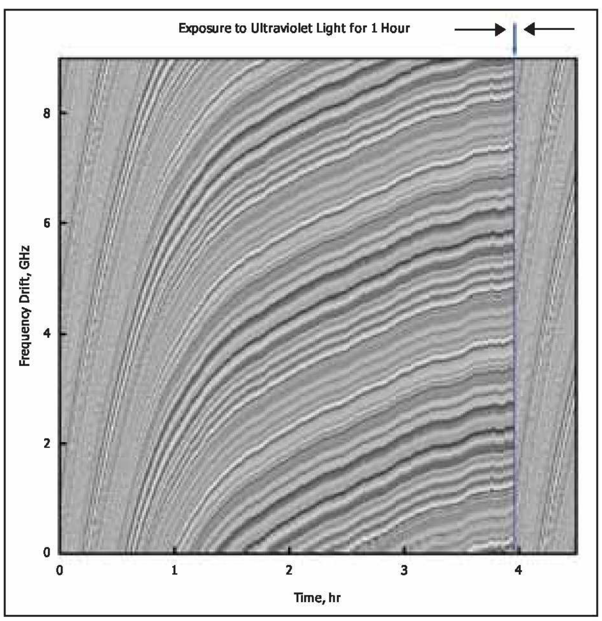
This work was done by Kai Zhao and Yu-Hwa Lo of the University of California San Diego and William Farr of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-45801

Using Whispering-Gallery-Mode Resonators for Refractometry

Refractive and absorptive properties are inferred by correlating predictions with measurements.

NASA's Jet Propulsion Laboratory, Pasadena, California

A method of determining the refractive and absorptive properties of optically transparent materials involves a combination of theoretical and experimental analysis of electromagnetic responses of whispering-gallery-mode (WGM) resonator disks made of those materials. The method was conceived especially for use in studying transparent photorefractive materials, for which purpose this method affords unprecedented levels of sensitivity and accuracy. The method is expected to be particularly useful for measuring temporally varying refractive and absorptive properties of photorefractive materials at infrared wavelengths. Still more particularly, the method is expected to be useful for measuring drifts in these properties that are so slow that, heretofore, the properties were assumed to be constant.



This **Time-vs.-Frequency Plot** shows a saturating drift of the spectrum of a WGM resonator made of a photorefractive material exposed to light. The discontinuity just before the 4-hour mark represents a 1-hour exposure to ultraviolet light, after which the drift of the spectrum recommenced.

The basic idea of the method is to attempt to infer values of the photorefractive properties of a material by seeking to match (1) theoretical predictions of the spectral responses (or selected features thereof) of a WGM of known dimensions made of the material with (2) the actual spectral responses (or selected features thereof). Spectral features that are useful for this purpose include resonance frequencies, free spectral ranges (differences between resonance frequencies of adjacently numbered modes), and resonance quality factors (Q values).

The method has been demonstrated in several experiments, one of which was performed on a WGM resonator made from a disk of $LiNbO_3$ doped with 5 percent of MgO. The free spectral range of the resonator was ≈3.42