# Quiet Cascade: Measuring QCL Intrinsic Linewidth

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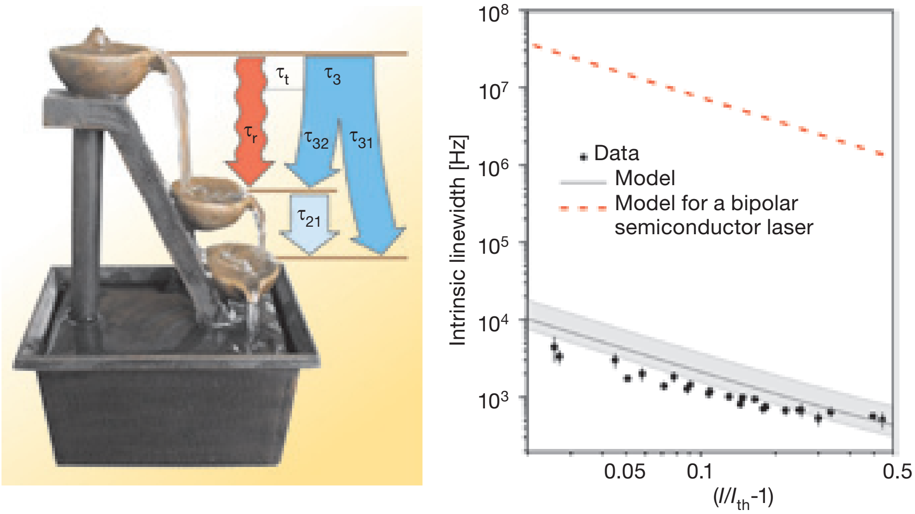
Dramatic narrowing of light frequency spread is a signature of lasing. Quantum noise—i.e., the phase and amplitude noise of the photon field—determines the laser intrinsic linewidth, and is the ultimate limiting factor for sensitivity, resolution and precision in any laser measurement. In our investigation of the frequency-noise spectral density of a free-running mid-infrared (IR) quantum-cascade laser (QCL), we have provided direct evidence of an intrinsic linewidth of a few hundred hertz for these sources.

Among the most recent semiconductor lasers, QCLs[1] can be tailored to emit throughout most of the IR spectrum. Therefore, they are key photonic tools for an expanding range of applications. Unlike conventional semiconductor lasers, where lasing is a result of recombination of electron-hole pairs across the band gap, they operate through intersubband transitions in a stack of quantum wells. Since their demonstration, QCLs had been thought to exhibit a very narrow intrinsic linewidth, considerably smaller than that of bipolar semiconductor lasers; however, a clear estimation proved to be elusive.

In 1958, Arthur Schawlow and Charles Townes deduced that the laser linewidth is fundamentally limited by unavoidable spontaneous emission.[2] In 2008, a model by Yamanishi and coworkers at Hamamatsu Photonics proposed that nonradiative transitions in QCLs strongly suppress the effects of spontaneous emission. This led to a reformulation of the Schawlow-Townes formula in terms of measurable physical characteristics of QCLs.[3] In 2010, using state-of-the-art instrumentation with unprecedented low noise, we measured a QCL intrinsic linewidth,[4] confirming Yamanishi's model.



In a QCL, the nonradiative decay mechanisms (blue arrows) compete with the spontaneous emission (red arrow), contributing to their peculiar "quiet cascade"—i.e., their extremely small intrinsic linewidth. The graph shows the QCL intrinsic linewidth vs. different ratios of the driving current $I$ to the threshold current $I_{th}$ (black dots). The data are in good agreement with the theoretical model (dark gray curve), especially when the uncertainty on the QCL parameters is taken into account (light gray area). The dashed red line represents the Schawlow-Townes formula.

To test the prediction, we tuned a 4.33-µm-emitting QCL half-way down a carbon dioxide absorption peak. Thanks to the steep slope of the absorption curve, frequency fluctuations were converted into detectable intensity variations. That technique enabled us to measure the noise spectrum over seven frequency decades and to extract the intrinsic QCL linewidths for several pump currents.[4] The obtained widths, in the range of hundreds of Hz, agree well with the new theory and are three orders of magnitude smaller than those of bipolar semiconductor lasers with the same emitted power.

The demonstration that QCLs have peculiar noise features provides experimental evidence of a linewidth narrowing beyond the limit set by the spontaneous emission rate, which was thought to be a fundamental limit for lasers. These measurements pave the way to a deeper understanding of QCLs and to improved designs of their quantum-well structure. Moreover, the measured intrinsic linewidths are comparable with the natural linewidth of molecular IR ro-vibrational transitions. Therefore, similar to what visible/near-IR-emitting diode lasers have represented in the past 20 years for the progress of atomic physics, mid-IR QCLs are candidates to become unique tools for investigating and harnessing molecules with unprecedented sensitivity and precision levels. ▲

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# Random Distributed Feedback Fiber Laser

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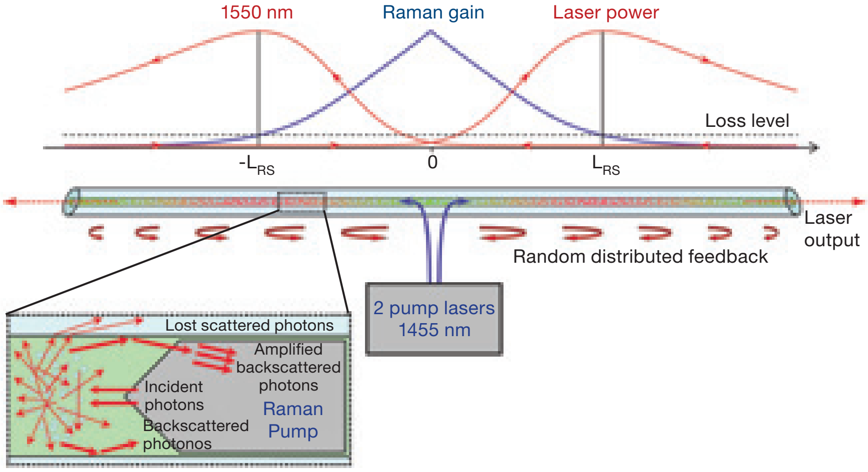
A basic laser scheme normally requires two key elements: A gain material that provides amplification and an optical cavity that traps the light, creating positive feedback. Lasing occurs when the total gain in the cavity overcomes the total cavity loss. Operational characteristics of conventional lasers are determined both by the distinctive features of the gain medium and by the cavity design that defines the structure of laser modes.

In random lasers with no cavity (or with an open cavity),[1,2] the output characteristics are determined by the buildup of radiation due to multiple scattering in the gain medium, resulting in randomly embedded local spatial modes that may coexist with non-localized extended modes.[3] Random lasers have advantages, such as simple technology that does not require a precise microcavity, and low production cost. However, the properties of their output radiation are rather special in comparison to those of conventional lasers, and they are usually characterized by complex features in the spatial, spectral and time domains.

We demonstrated a new type of one-dimensional laser with random distributed feedback based on Rayleigh scattering (RS), which is present in any transparent glass medium due to natural inhomogeneities of refractive index.[4] The cylindrical fiber waveguide geometry provides transverse confinement, while the cavity is open in the longitudinal direction and does not include any regular point-action reflectors.

Though Rayleigh backscattering is extremely weak, the effect may be accumulated and amplified in the long fiber. Using stimulated Raman scattering to provide distributed amplification, we demonstrate random lasing in low-cost, open-cavity standard transmission fiber with stationary narrowband output power of about 300 mW from two fiber ends. The weakness of the RS-based random distributed feedback makes the operation and properties of the demonstrated lasers profoundly different from those of both traditional random lasers and conventional fiber lasers.



Principle of random distributed feedback fiber laser operation. Photons propagating in a long fiber are coherently scattered in a 83-km fiber by random refractive-index inhomogeneities complying with Rayleigh's law. Most of the scattered photons leak out of the fiber core. Only $Q$~$10^{-3}$ of them are backscattered and guided by the fiber. Two pump waves coupled at $z$=0 provide distributed Raman gain along the fiber. The backscattered guided photons can be amplified if total gain is larger than the loss level, which is fulfilled for all points $|z|<L_{RS}$. As a result, two forward and backward propagating waves are generated. The numerically calculated laser power distribution (red) and Raman gain (blue) are shown.

Note that RS might also have a critical impact on performances of conventional (with point reflectors) fiber lasers with a long cavity. In particular, the mode structure of Raman fiber lasers with linear cavity formed by highly reflecting mirrors/gratings is washed out at a resonator length of about 300 km.[5]

In conclusion, the lasing provided by weak random distributed feedback in an amplifying fiber waveguide medium constitutes a new class of laser—the random distributed feedback fiber laser. We believe that new fundamental science as well as new applications and technologies, in particular, for telecommunications and sensing, will emerge as a result of our development. ◭

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