Quiet Cascade: Measuring QCL Intrinsic Linewidth

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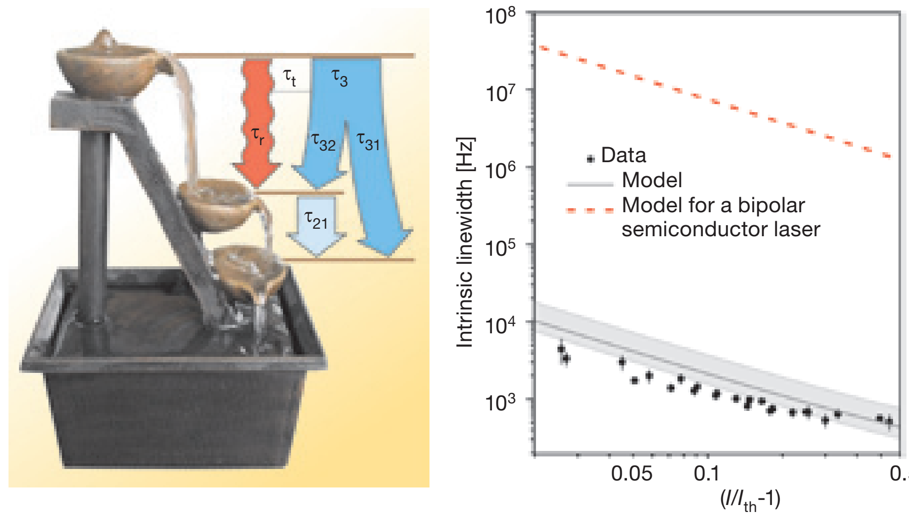
Dramatic narrowing of light frequency spread is a signature of lasing. Quantum noise—i.e., the phase and amplitude noise of the photon field—determines the laser intrinsic linewidth, and is the ultimate limiting factor for sensitivity, resolution and precision in any laser measurement. In our investigation 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.

To test the prediction, we tuned a 4.33-µm-emitting QCL half-way down



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.

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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