# A Chaotic Optical Cavity Combined With a Quantum Cascade Laser for Chemical Vapor Sensing

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**Abstract:** A novel multi-pass optical cavity with partially-chaotic ray dynamics has been combined with a Quantum Cascade laser for sensing of ethanol. The 4-cm diameter cavity shows an optical path length in the mid-infrared of ~4.5-m.

OCIS Codes: (140.4780) Optical resonators, (140.1540) Chaos

## 1. Introduction

Sensitive mid-infrared laser absorption spectroscopy often involves overlapping the gas sample under test with the probing laser light in a multiple-pass optical cavity. Such an arrangement increases the effective path-length of the light in the cavity and, hence, in Beer's law maximizes the overall absorption. Commercially available and often-used optical multi-pass cells are the so-called White or Herriott cells.[1] While conveniently available, they are still rather bulky and prone to misalignment, as they typically consist of two separate, opposed mirrors. We recently proposed a novel, quasi-chaotic optical cavity for multi-pass measurements.[2] A single hollow body is formed with a quadrupolar shape and coated for high reflectivity. The particular shape of the inner surface allows for a ray dynamics that repeatedly refocuses the incident beam for a range of incident angles and hence allows long path-lengths over a small volume. The advantages of this type of multi-pass resonator are its small size and volume, a few cm size cavity results in a few meters of path-length in the experiment, its single surface shape, resulting in less sensitivity towards optical misalignment, and a potential for low-cost manufacturing.

Here, we present experimental results for such a multi-pass optical cavity used in combination with a $\lambda \sim 8$ µm Quantum Cascade (QC) laser; a first demonstration of sensing of ethanol vapor is also presented.

## 2. Experimental Setup

Our multi-pass cavity has the shape of a three-dimensional quadrupole, defined in terms of its average radius $R_0$ and the deformation parameter $\varepsilon$ as $R(\theta) = R_0(1+\varepsilon\cos(2\theta))$ in the standard spherical coordinates (R, θ, φ), and with $R_0$ = 2.54 cm, and $\varepsilon$ = 0.16. It is rotational symmetric around a major axis. The cavity has been fabricated from two halves of an acrylic plastic shell by diamond-turning, and gold is uniformly deposited inside the cavity. A circular aperture 2 mm in diameter is drilled along the line $\varphi = 54.4^0$ at one point in the cavity. Light from a $\lambda \sim 8$ µm QC laser is coupled into the cavity using a telescope of Ge lenses. Light coupled out of the cavity is focused through a

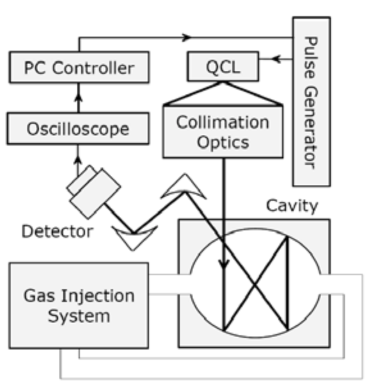


Fig. 1. Schematic of the experimental setup; QCL stands for Quantum Cascade laser.

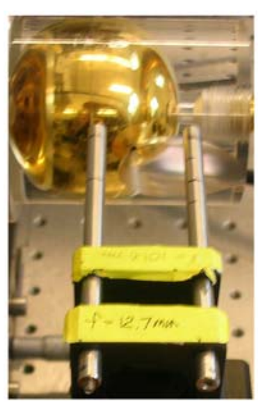

Fig. 2. Photograph of the optical cavity (back) and the collimating lenses for the QC laser (front). The cavity is made from a hollow acrylic body coated inside with gold. Refraction on the acrylic makes the cavity appear more spherical than it is in reality.

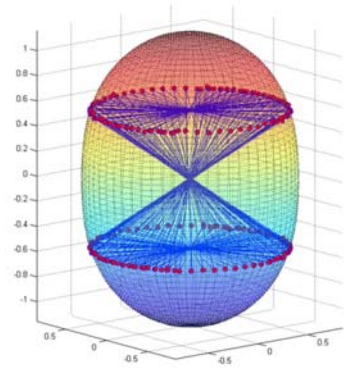

Fig. 3. Schematic of the ray dynamics inside the quasi-chaotic cavity. A multi-pass beam (blue line) is bouncing repeatedly inside the cavity; the bounce points are indicated by the red dots.

pair of off-axis parabolas, detected by a high-speed photo-voltaic HgCdTe detector, and analyzed using a digital oscilloscope. The ray-dynamics of the cavity is such that the light injected along the desired rotating bow-tie pattern never reaches the poles of the cavity. Therefore, the gas inlet and outlet ports are placed there. Figures 1-3 show the schematic of the experimental set-up as well as a photograph of the cavity and a calculation of the ray-dynamics of the cavity.

We determine the optical path-length, which is determined by the initial incidence angle of the ray into the cavity through run-time measurements. By injecting short, few 10 ns, light pulses, and comparing the pulse delay of the light exiting the cavity, we estimate the path-length. At a set path-length, we then compare pulse intensities of the out-coupled laser beam with the cavity purged with dry nitrogen or ethanol vapor, which is prepared by bubbling nitrogen through liquid ethanol held at room temperature.

## 3. Results and Analysis

Figure 4 shows the results of the optical path-length measurement. A pulse-delay of 15 ns can easily be measured, which corresponds to a total optical path-length difference between the single- and multi-pass beam alignments of about 4.5 m. This path-length can be interpreted as an approximate 100-fold increase in path-length over the physical diameter (~ 4 cm) of the cavity. Currently, this path-length is limited in the experiment by the beam spreading in the direction of axial symmetry, and the ensuing temporal overlap of partial pulses exiting the cavity after successive roundtrips. In future designs of the optical cavity this can be mitigated by reducing the symmetry also in axial direction and by introducing a focusing shape along this direction of beam motion.

Nevertheless, we used the current cavity to provide a first demonstration of chemical vapor sensing using this novel approach. Figure 5 shows the result of this experiment. With the path-length kept constant at an intermediate length (to allow for sufficient signal strength of the outcoupling beam), dry nitrogen and a nitrogen/ethanol vapor mixture are subsequently fed through the cavity; ethanol is strongly absorbing at the $\lambda \sim 8$ μm emission wavelength of the QC laser. A clearly noticeable, larger than a factor of two, drop in detected intensity indicates the presence of the ethanol vapor. While this is only a first demonstration, future experiments will focus on the quantitative detection of chemical vapors, an improved cavity design, and the sensitivity limits of this novel multi-pass cavity approach.

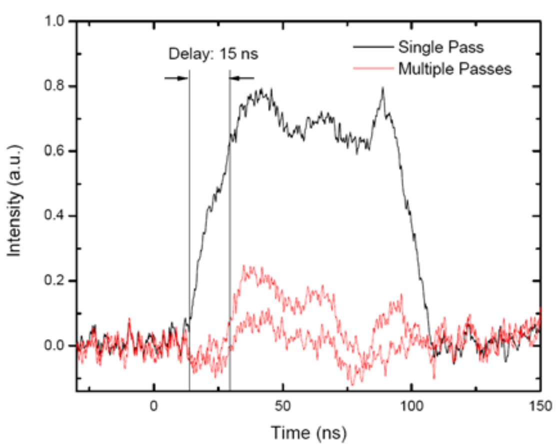


Fig. 4. Laser pulses as monitored by a fast detector and digital oscilloscope; the black line shows the laser pulse after one round trip (one "bow-tie") in the cavity; red lines are for multiple passes, the ~ 15 ns pulse delay indicates a path length of about 4.5 m.

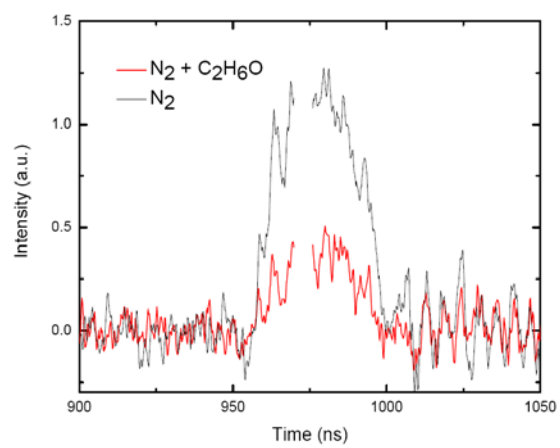


Fig. 5. Laser pulse as monitored by a fast detector and digital oscilloscope. The black line shows the laser pulse with the cavity purged by dry nitrogen; the red line shows the same optical path of the $\lambda \sim 8$ μm QC laser pulse with the cavity filled with ethanol vapor. The difference in signal indicates the ethanol absorption. The gap in the data is the result of a read/write error on the digital scope.

## 5. Acknowledgements

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