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Windowless and Brewster Window Resonant Spectrophones

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Many of the early papers on resonant spectrophones discussed multipass cell designs as a means of increasing the amount of power absorbed in the cell, and hence the sensitivity. A comparable increase in sensitivity can be achieved by placing the spectrophone inside the laser cavity, where it responds to the full intracavity power.

A principal problem in implementing such a seemingly desirable scheme is that for conventional resonant spectrophone designs, in which the beam passes through the windows at normal incidence, the window reflection losses impair operation of the laser. A further problem, not unique to intracavity spectrophones, is that if the beam enters and leaves the cell at points of high pressure amplitude for the mode being excited, as is the case when the beam passes directly down the center of the cell and a radial mode is excited, any window absorption can give rise to a spurious background signal due to window heating. The first problem can be alleviated by antireflection coating the windows, but single-layer AR coatings are usable over only a limited range of wavelengths. It would be more desirable to have the beam enter and leave at Brewster's angle, since for many commonly used optical materials such as fused silica or sodium chloride, the variation of refractive index with wavelength is small over a large range of wavelengths; furthermore, reflectivity varies quadratically as a function of angle or incidence in the neighborhood of Brewster's angle, so that the tolerance to variations in Brewster's angle is high. Reflectivity can be kept lower over a wider range of wavelengths than for even a wideband multilayer antireflection coating. The problem of window heating can be alleviated by placing the windows at nodes of the mode being excited. Somewhere inside the cell, however, the beam must pass through a region where the mode has a high amplitude in order to excite that mode efficiently.

For a spectrophone to be used for monitoring ambient air, it would be desirable to eliminate the windows altogether. This would permit continuous sampling by inducing a slow flow of air through the cell. Absence of windows certainly solves the optical insertion loss problem, yet it can greatly degrade the Q of the acoustical cavity resonance. Again, the solution is to let the beam enter and leave the cell at pressure nodes, where the holes will constitute a minimal perturbation.

We present here a spectrophone design based on the above considerations. Our cell is cylindrical with flat end walls and we excite the first radial mode. The beam enters through a window mounted virtually flush with the flat wall, located at $r=0.6276R$, $\phi=0$, $z=0$; it then passes diagonally through the center of the cell and exits through another window at $r=0.6276R$, $\phi=180°$, $z=L$. (Here r, ϕ, and z are the conventional cylindrical coordinates, and R and L are the cell radius and length, respectively.) The value of r at entry and exit is chosen to lie on a node of the first radial mode. In order for the beam to pass through the windows at Brewster's angle, the ratio of cell radius to length must be $R/L = 0.7967n$, where n is the refractive index of the window material. For $n=1.5$, $R/L=1.19$.

The microphone is centered directly on the cell axis ($r=0$). This has two advantages. First, the flat microphone face mounts approximately flush with the flat end wall of the cylinder, and does not spoil the cavity Q significantly. Second, the microphone is now at the absolute maximum of the first radial mode, where the pressure amplitude is 2 1/2 time larger than at $r=R$, the usual microphone location. This latter advantage is partially offset by the fact that the first radial mode is now only about 2/3 as strongly excited as it would be if the beam were passing directly down the center axis of the cell.

A gas filling port was also located on a pressure node at $r=0.6276\ R$, again to avoid spoiling the Q.

The same design is applicable to windowless operation. However, there is no longer a constraint on the ratio R/L, and it is therefore desirable to make the ratio smaller so that smaller beam entrance holes can be used without aperturing the beam. This can also help to reduce the importance of viscous losses on the end surfaces.

We built a single cell having the R/L ratio quoted above, and tested it both with and without windows. We placed it inside the cavity of a current-modulated CO_2 laser tuned to the P(14) line in the 10 μm band. We filled the cell with a 54 ppm mixture of ethylene in nitrogen, or in the case of windowless operation, allowed the mixture to flow continuously into the fill port and out through the window holes. With windows we observed a Q of 560, while without windows the Q was 509. With windows, with an intracavity power of about 11 W, we could detect 54 ppm of ethylene with a signal to noise ratio of 2×10^6 with a 1 Hz bandwidth, giving a noise-equivalent concentration of 25 parts per trillion. Without windows the noise was equivalent to about 1 part per billion. Using published values of the ethylene absorption coefficient, we estimate noise-equivalent absorption coefficients of $7.5 \times 10^{-10}\ \mathrm{cm}^{-1}$ and $3 \times 10^{-8}\ \mathrm{cm}^{-1}$ for Brewster window and windowless operation, respectively.

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