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APPLICATION OF MICROWAVE FABRY-PEROT RESONATORS IN INSTRUMENTATION FOR AIR POLLUTION RESEARCH

H. T. Buscher, B. Leskovar, and W. F. Kolbe

February 16, 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
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LBL-4469

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy $4.50; Microfiche $2.25

LBL 4469

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[*] This report was done with support from the United States Energy Research and Development Administration. Any conclusions or opinions expressed in this report represent solely those of the authors and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the United States Energy Research and Development Administration.

Abstract

The usefulness of the Fabry-Perot resonator as a sample cell in microwave spectrometer-type gaseous pollution detectors is discussed. The design of a new 70-GHz semiconfocal resonator with variable microwave coupling and wide-range piezoelectric tuning is presented. Experimental data were taken on cavity tuning performance and on the behavior of the variable microwave coupling structure. Theoretically obtained value for the cavity Q-factor is compared with experimental data.

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Introduction

There has been a strong interest for many decades in the use of microwave absorption spectrometry as a research tool in studies of the structure of molecules.[1] More recently, the techniques of microwave spectroscopy have been applied in instrumentation associated with research on chemical species broadly classed as gaseous pollutants.[2] One of the applications that has very recently been shown to have practical utility is the detection of trace quantities of gaseous pollutants by means of their characteristic microwave absorption line spectra. At least one portable 35 GHz formaldehyde monitor has been reported based on microwave absorption,[3] and the present authors have reported data on sulfur dioxide taken in the course of developing a 70 GHz microwave pollution monitor.[4]

Because the design objectives for classical research spectrometers have not usually included both portability and extreme sensitivity, only limited knowledge is available concerning the optimizing of such instruments for these characteristics.[5,6] It has been recently demonstrated, however, that both portability and sensitivity can be enhanced by replacing the conventional microwave spectrometer's wave-guide gas sample cell with a Fabry-Perot cavity resonator based on the classical optical interferometer design.[3]

While microwave spectrometers have employed cavity-type sample cells in the past, few have taken full advantage of the very high Q factors achievable using Fabry-Perot cavities. Because a spectrometer's ultimate detection sensitivity increases with cavity Q, it can be desirable to maximize it. This is especially true for devices operating above 20 GHz, where the difficulty of building conventional wave-guide cavities with low losses begins to make the mechanical simplicity of the open resonator quite attractive. When the cavity size is not a limiting factor, open resonators of Fabry-Perot geometry, having loaded Q's of over 100,000, are practical in the millimeter region of the microwave spectrum, providing remarkable selectivity and detection sensitivity.[6]

In this paper, we report the design of a 70 GHz Fabry-Perot sample cell for use in a high-sensitivity microwave spectrometer. Microwave coupling to the resonator and electrical tuning of the device, as well as optimization criteria, are also discussed.

Fabry-Perot Cavity Design

Of the several possible configurations which fall under the category of Fabry-Perot resonators, the most attractive for stable, high-Q microwave operation is the semiconfocal geometry. This consists of a flat mirror facing a concave one, spaced as shown in Fig. 1. (The radius of curvature of the concave mirror is exactly twice the mirror spacing.) This geometry has the advantage that it is noncritical in alignment, is compact, and exhibits high Q. Resonances occur according to the relation

$$\frac{4d}{\lambda} = 2q + 1/2, \quad (q = 1,2,3\ldots)$$

where d is the mirror spacing, λ is the wave length of the radiation in the cavity, and q is the number of half-standing waves between the mirrors.[7]

The Q of such a cavity is determined by reflection and diffraction losses as well as perturbations to the field structure due to coupling energy into and out of the resonator. The primary design criterion is to generally minimize all losses. This policy was applied to the design described below, within limits imposed by other system constraints.

The cavity desired was expected to be part of a working prototype high sensitivity spectrometer which eventually would be packaged as a portable air pollution detector. Therefore, the physical size of the entire spectrometer as well as the cavity size was limited. Mirrors were chosen primarily on the basis of compactness, having 5.08 cm diameters and a spacing of 7.43 cm. The spacing was such that diffraction losses could be assumed negligible compared to reflection losses.

To maximize the stability of the mirror surfaces, type 316 stainless steel 1.25 cm thick was used for the blanks. Optical quality grinding techniques produced surfaces true to a few wave lengths of sodium light on both mirrors. In order to provide high surface conductivity at microwave frequencies, 75μ of silver was plated onto each mirror, followed by 1.5μ of gold as a corrosion inhibitor. It was expected that the gold would be essentially transparent to 70 GHz microwave radiation, with the mirror surface exhibiting a conductivity characteristic of pure silver.

In order to couple energy in and out of the cavity, two small holes were drilled in the surface of the plane mirror, and larger holes were bored from the rear to allow V-band wave guides to be positioned behind the small coupling holes as shown in Fig. 1.[8] The positions of the input and output wave guides were made adjustable with respect to the irises, in a manner similar to that of Frenkel and Woods,[9] in order to allow the energy coupling to the cavity to be as varied as desired. To minimize microwave losses in the coupling structure, the irises should be as thin as practicable. For the value of 0.13 mm thickness chosen, adequate coupling was obtained with a hole diameter of 0.64 mm. The separation between the input and output coupling holes was 6.2 mm. Under these conditions a measured (loaded) Q of 42,000 and a minimum transmission loss of 22 dB were obtained.

The variable transmission loss of the cavity and coupling network is shown in Fig. 2 as a function of the distance (d_2 in Fig. 1) between the output wave guide and the rear surface of the coupling iris. In obtaining this data, the input guide was positioned for maximum coupling. The quality factor, Q, of the cavity as measured at the output wave guide was nearly constant over the data range of Fig. 2.

The mirrors were mounted in a fixture which allowed their spacing to be adjusted while enclosed in a vacuum chamber. For fine adjustment of spacing, a cylindrical piezoelectric transducer 7.62 cm long and coated with a low vapor pressure epoxy was used as the mount for the concave mirror. The transducer was designed to provide about 10μ of electrically-controlled tuning as compensation for thermal changes in the cavity and to allow it to track a frequency-swept and/or modulated microwave input. Experimental data demonstrating the slow-speed (thermal compensation) performance of the transducers and also their high-frequency response are shown in Figs. 3 and 4, respectively.

Discussion of Design

The tuning behavior of the cavity, while reflecting mechanical resonances of the transducer-mirror structure, still represents expected behavior. On the other hand, the cavity Q appears to be somewhat lower than predicted. (Q was estimated from theory to be on the order of 71,000 for critical coupling.) This reduction in measured Q was due to three factors: reduced conductivity of the plated silver mirror surfaces, diffraction and conductivity losses associated with the coupling holes themselves, and conductivity losses in the (unplated) regions behind the coupling irises.

The mirror surface plating appeared smooth to the eye, although no confirmation of its conductivity was made. The silver plating was not extended, however, through the coupling holes and into the region between the ends of the wave guides and the rears of the coupling holes. The losses there, associated with microwave currents flowing in stainless steel, could have been substantial. The small variation in Q found over a wide range of transmission losses supports the theory that the stainless steel input and output coupling regions were very lossy and that little variation of the coupling strength to the Fabry-Perot itself was occurring when the guide was moved in the coupling structure. It was also noted that when the Fabry-Perot was tuned off resonance, and negligible input power was entering the cavity, about 90% of the power entering the input guide was absorbed by the input coupling cavity bored in the flat mirror. Its losses when the Fabry-Perot was on resonance were probably comparable.

Conclusions

The use of a Fabry-Perot type resonant cavity in high-sensitivity microwave absorption spectrometers is discussed. The high-Q potential of the resonators is an attractive feature contributing to the ultimate detection sensitivity of a spectrometer used as a pollutant monitor. The observed discrepancy between the calculated Q-factor and that obtained experimentally has been attributed primarily to losses in the coupling structures and to a degradation of the surface conductivity of the mirrors relative to that predicted for pure bulk silver. The performance of the piezoelectric tuning mechanism has been described and will allow stabilization and tuning of the cavity to be accomplished.

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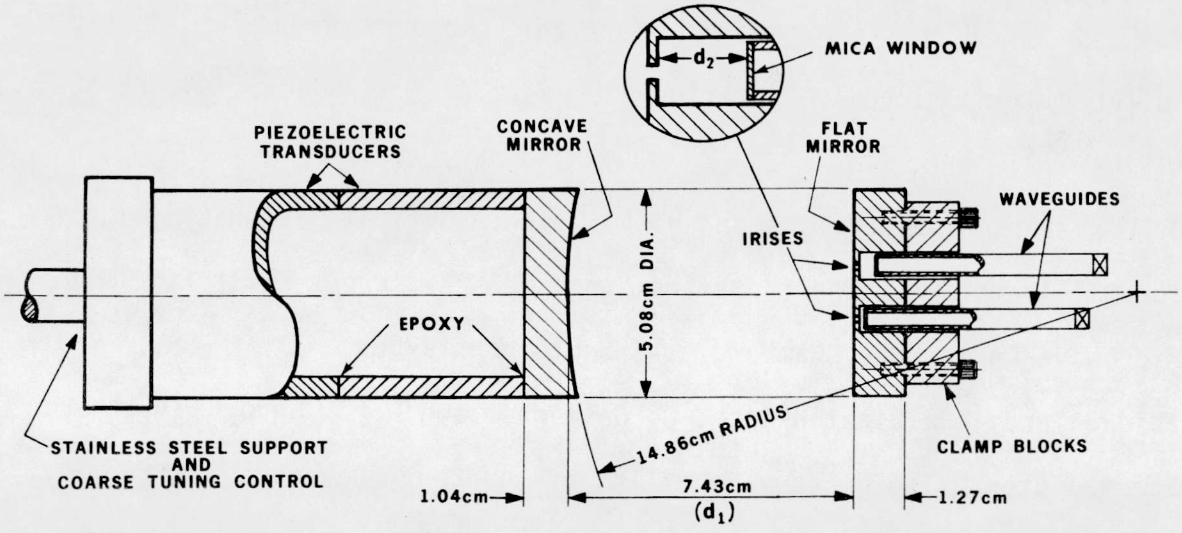

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Fig. 1. Schematic view of Fabry-Perot cavity, showing detail of variable coupling mechanism.

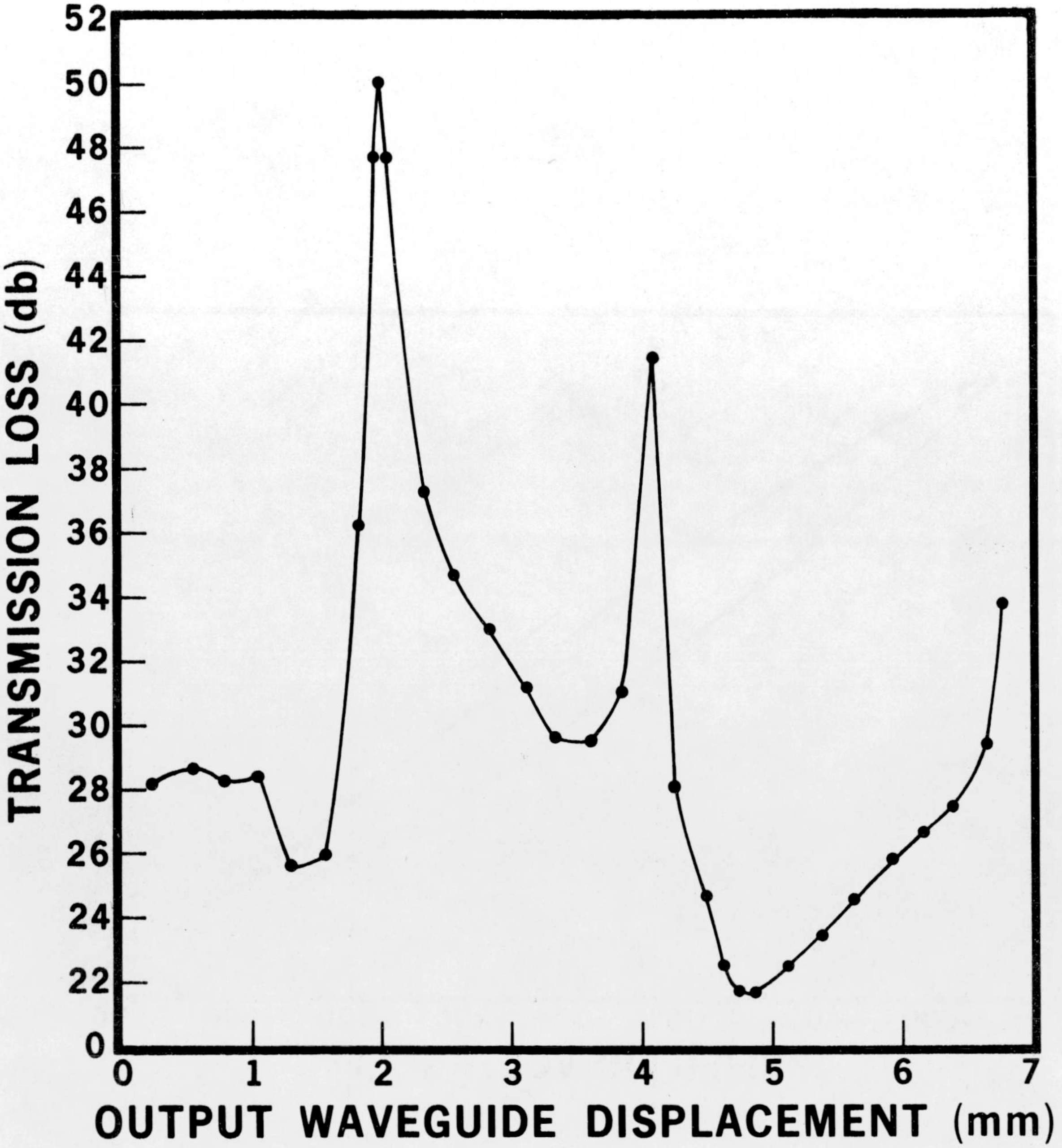

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Fig. 2. Transmission loss of cavity as a function of output wave guide displacement.

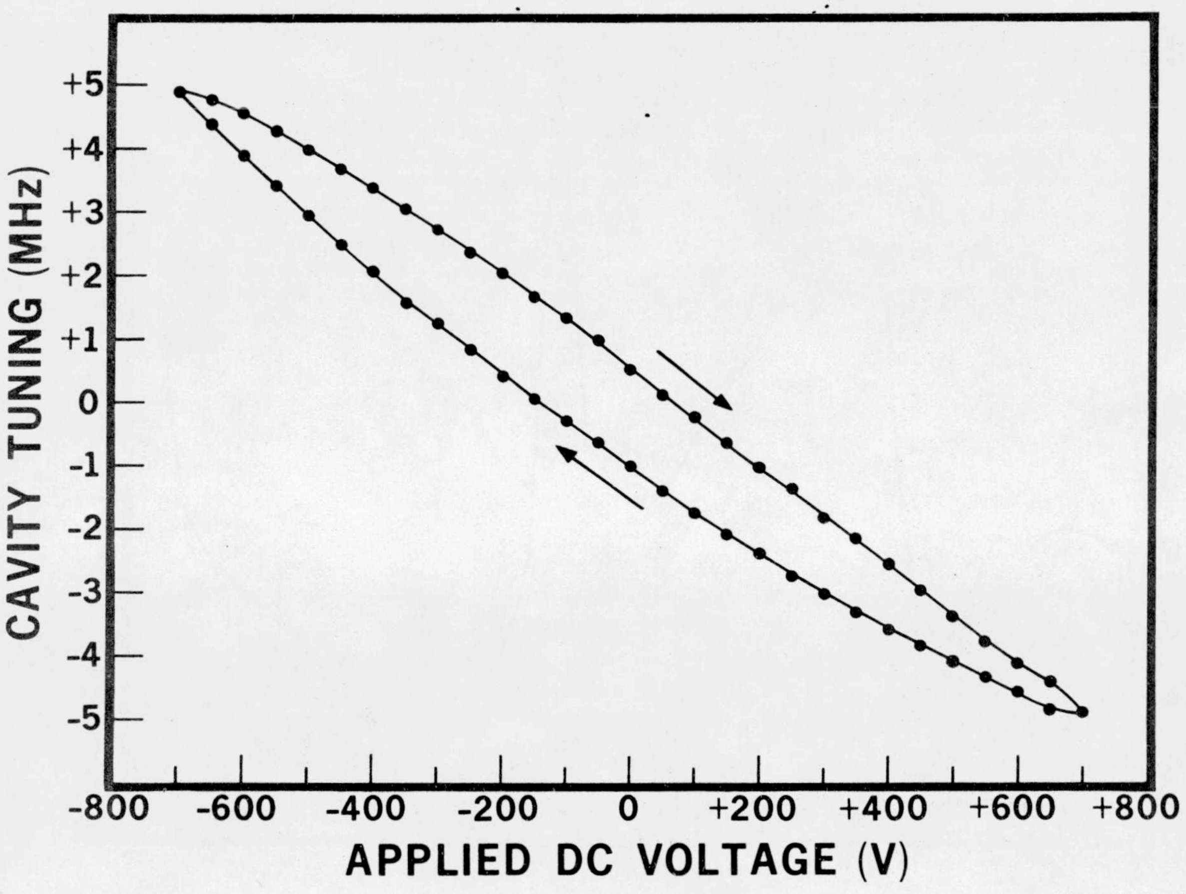

Fig. 3. Piezoelectric tuning characteristics of cavity system. For the mirror separation given in Fig. 1, 1 MHz corresponds to a displacement of approximately 1.07 microns.

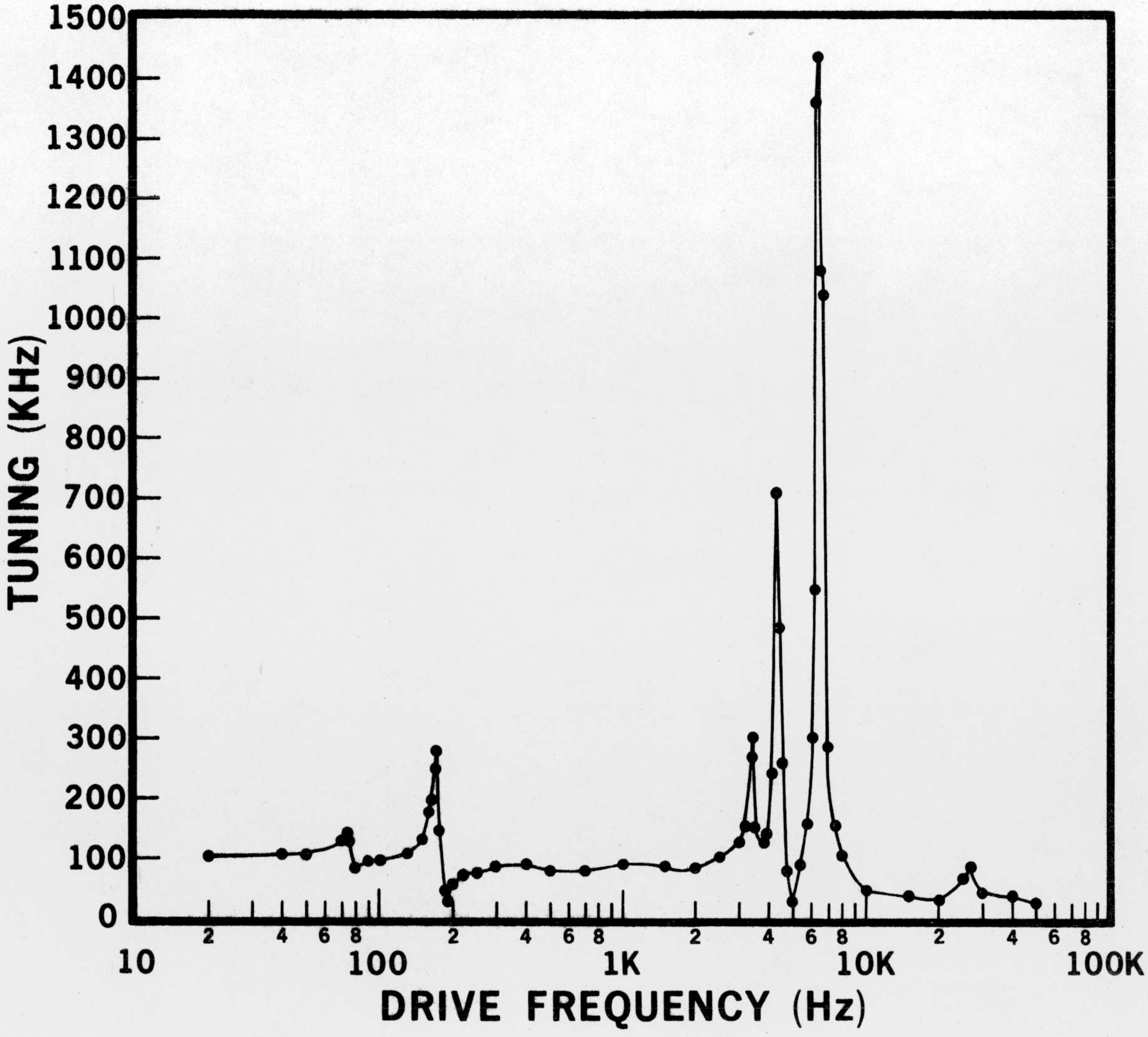

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Fig. 4. Fabry-Perot cavity tuning in kHz peak-to-peak as a function of frequency of applied drive voltage. The drive voltage was maintained at a constant 10 V rms.

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