AN AUTOMATED 60 GHz OPEN RESONATOR SYSTEM FOR PRECISION DIELECTRIC MEASUREMENT*

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ABSTRACT

An automated open resonator system is designed and constructed for precision measurement of loss tangent and dielectric permittivity of low absorbing materials at 60 GHz. The use of high Q hemispherical Fabry-Perot cavity together with highly stabilized synthesized phase locked Gunn oscillator sources and the super heterodyne receiver enabled us to measure loss tangent value as low as 10 micro-radians.

INTRODUCTION

At high microwave frequencies below 35 GHz, the open resonator technique has established itself as a powerful tool for measurement of permittivity and particularly loss tangent for low absorbing materials [1 - 7]. Until recently the measurement was limited to loss tangent value of about 300 micro-radians and to 35 GHz, because it was difficult to construct high Q Fabry-Perot cavity, low noise high power phase locked stable sources and sensitive receivers at high frequencies. Various theories and formulation were developed in the past decade to encounter beam conformation inside the Fabry-Perot open cavity. The scaler theory was used to develop the Gaussian beam theory for an open resonator until recently [4 -7]. For permittivity measurements, the newly developed vector theory provides much higher accuracy [7, 8].

At frequencies greater than 10 GHz, the closed cavity techniques run into several difficulties, mainly because of the small size requirement of the cavity and of the specimen for the fundamental mode and the decrease of the Q factor with decreasing wavelengths. The use of a large cavity with a large number of modes requirement desires an impractical large cavity at millimeter wavelength region [8,9]. In an open resonator technique the number of modes is proportional to the ratio of characteristic length of the resonator to the wavelength with the mode separation sufficient for a single mode operation. It is not too difficult to construct a high Q Fabry-Perot resonator. But a high Q cavity demands highly stable source frequency and extra sensitive receiver. Our newly constructed Fabry-Perot open resonator system utilizes a hemispherical cavity with a highly polished concave mirror and a flat mirror with optimized input and output coupling to provide high Q, a highly stable phase locked synthesized low-noise 60 GHz tunable Gunn oscillator source (stable to 10^9), another similar phase locked low noise 56 GHz Gunn oscillator acting as the local oscillator and the heterodyne extra sensitive 4 GHz receiver system.

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The system is automated via a precision lock-in amplifier, a V-band Hewlett-Packard spectrum analyzer and a Hewlett Packard Vectra computer system with analog to digital conversion accessories. The synthesizer allows the collection of data at very small steps over the complete Gaussian beam and together with a statistical fitting, the Q determination can be made very accurately.

OPEN RESONATOR THEORY

The Fabry-Perot open resonator configuration, utilizes two metal mirrors facing each other. Culshaw and Anderson [1] demonstrated such a cavity, with Q factors of the order of 30,000 made up with two flat parallel reflectors facing each other. The major disadvantage in such a cavity is the loss of energy at the edges due to diffraction. The use of two concave mirrors, or at least one concave spherical metal mirror generates Gaussian modes, where the field is focussed into a smaller volume, An analysis of Gaussian modes between spherical reflectors is given by Kogelnik and Li [10]. It is relatively easy to achieve the fundamental mode Q factor of the order of 100,000 for such a cavity in the 10 - 35 GHz region. The use of a single concave spherical mirror and a plane mirror , makes the design much simpler. A hemispherical resonator gives a very small beam diameter at the plane mirror, thus allowing to measure small specimens of the order of 50 mm / 60 mm in diameter.

Recently Yu and Cullen [8] used a variational formula to define the resonant frequency more accurately. The complex source point technique was used together with Maxwell's equations to derive the six Cartesian components of electromagnetic fields. This led to the more accurate determination of the real part of the dielectric permittivity value.

VARIOUS OPEN RESONATOR CONFIGURATIONS

As mentioned above, various types of Fabry-Perot open resonator configurations can be adapted, such as with two flat plane reflectors and two spherical full confocal reflectors facing each other. There are also other popular configurations such as semi confocal, the hemispherical and barrel resonators [6]. Both semi-confocal and hemispherical resonators use one concave and one plane mirror. In the semi-confocal configuration, the plane mirror is normally placed at approximately half the radius of the concave mirror. In the hemispherical configuration, the plane mirror is moved to a point close to the center of curvature of the concave mirror. Thus in a hemispherical resonator, it is possible to study small specimens because the diameter of the beam is very small at the

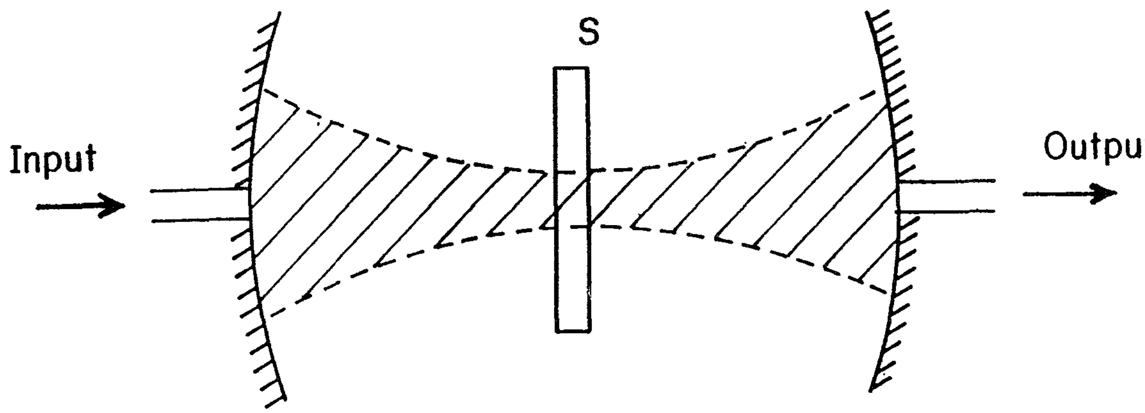

Figure 1 The full confocal Fabry-Perot Open Resonator with input and output coupling on each spherical mirror

plane mirror. It is also convenient to position the specimen in such a resonator. The flat parallel faced specimen can simply be placed on top of the plane mirror for the measurement. In a full confocal resonator the specimen needs to be placed at the center in between two concave mirrors with specimen faces perpendicular to the principal axis (Figure 1). One can also study liquid specimens in a hemispherical configuration, in which the liquid specimen simply rests on the plane mirror and forms a plane parallel layer above the plane mirror [7]

In designing hemispherical resonators, it is always important to consider the radius of the concave mirror, the mirror separation, and flatness and optical polishing of mirrors for specific frequency of operation. The other factor of consideration is the input and output coupling of energy into and out of the resonator. Various coupling through one or both mirrors and coupling via a beam splitter with input and output horns placed normal to the principal axis of the confocal mirrors and the beam splitter. It is convenient to make coupling hole or holes in the center of the concave mirror. The input and the output beams are coupled in and out of the cavity through separate mirrors in the confocal open resonator but coupled in and out through the same concave mirror in the hemispherical resonator.

Figure 2 shows a hemispherical configuration with waveguide coupling. At longer wavelength millimeter wave frequencies, the electromagnetic energy is commonly coupled in and out of the resonator by waveguide. For a confocal resonator a small coupling hole in each mirror is used to transmit the energy to and from input and output waveguide. In the hemispherical case the input and output coupling waveguides are attached to the same concave mirror. A Q value greater than 100,000 can easily be attained with very small coupling hole , which minimizes coupling perturbation.

THE 60 GHz OPEN RESONATOR SYSTEM

The block diagram of our complete automated precision 60 GHz measurement system can be seen in the Figure 3. Both Gunn oscillators are varacter tuned with output power of the order of about 30 milliwatts from each. The 60 GHz Gunn oscillator is tunable over the range ± 20 MHz. This is done by using a synthesized signal source. The 56 GHz Gunn oscillator acts as a local oscillator to provide superheterodyne detection at 4 GHz. All three frequency sources are phase locked to the same 10 MHz reference standard which is provided by the use of a specially prepared and housed Quartz crystal oscillator. The frequency is stable to one part in 10^9. The superheterodyne receiver includes the 4 GHz IF amplifier with built in isolator. A high precision lock-in amplifier with long time constant values minimizes the noise. The lock in amplifier output data is recorded in small steps of frequency via the computer over the full ± 20 MHz range around 60 GHz to provide information over the complete Gaussian profile. The recording of data at a very small step allows us to utilize a high degree of statistical fitting by means of a computer generated Gaussian profile.

We are now also using cavity length variation technique in addition to the frequency shift technique mentioned above. The flat mirror is mounted on an extra high precision non-rotating spindle large drum micrometer. The micrometer is coupled to a stepping motor capable of stepping at submicrometer lengths. A Gaussian beam beam can also be generated this way e.g. the recording of lock-in amplifier output as a function of cavity length variation. A number of Gaussian beam profile can now be recorded, while increasing or decreasing the cavity length. One can choose the Gaussian profile which gives the highest Q and process the data accordingly. With the advent of new electronicically controlled stepping motor, one can vary the cavity length to one tenth of a micrometer. This technique has an edge over the frequency shift technique. Additionally, it can provide much accurate information for the determination of the dielectric permittivity. We expect to provide at least a magnitude better in the reproducability of the real part of the complex dielectric permittivity values.

The loss tangent can now be measured very comfortably for low absorbing materials using any of the proceedure mentioned above. The use of the HP Vectra microcomputer with HPIB eases automatic control of the data acquisition, frequency sweep, cavity length variation and analysis and statistical fitting of the data. Our system is sensitive enough to measure very low value of loss tangent. The stability and phase reproducibility of the complete system, new frequency sweeping technique and cavity length variation technique together with the use of the new beam theory led us to measure highly reproducible value for the real part of the dielectric permittivity. Some preliminary results obtained on common low absorption loss window materials are shown in Table 1. These values at 60 GHz agree very well with data obtained using our dispersive broad-band technique [11-12]

TABLE I

Material	Loss tangent(micro-radians)	Permittivity(Real part)
Poly-4 Methyl Pentene-1(TPX)	785±50	2.022 ± 0.0004
High Density Polyethylene	1,144± 50	2.3989± 0.00005
Fused Silica	421± 50	3.9495± 0.00005
Alumina	1,521± 50	9.575 ± 0.00005

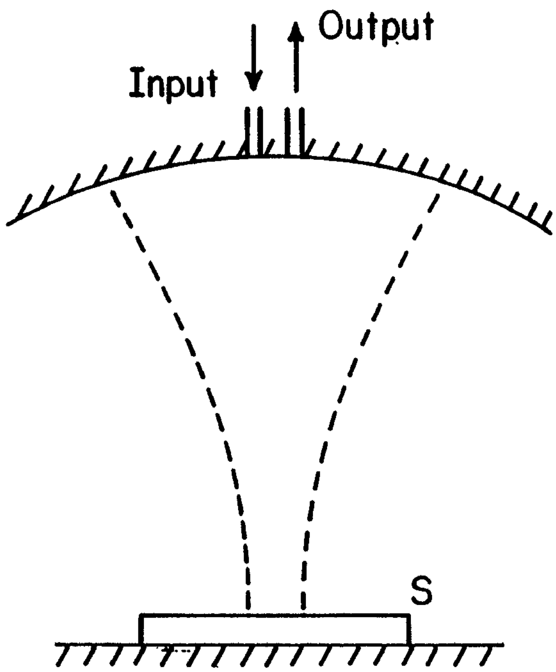

Figure 2. The hemispherical Fabry-Perot Open Resonator Cavity, The input and output coupling are made through the same spherical mirror

COCLUSIONS

The material processing and fabrication technology is developing very rapidly. For example single crystal silicon specimen is now available with resistivity as high as 16,000 ohm-cm. The loss tangent value of such a silicon specimen is very small e.g. 40 micro-radians at 140 GHz [13]. This is because of the absence of free carrier absorption in this highly pure and compensated material. The tail of the strong submillimeter wave lattice vibration band in a single crystal sapphire almost disappears at millimeter wavelength region at cryogenic temperatures. The measurement of such a small loss tangent value is very important in providing quality control of such special materials. It is not unlikely that such a material can regain its market in electronics industry, which is taken away by a larger gap semiconductor in recent years. Our precision dielectric permittivity and loss tangent measurement technique is described for low absorbing materials at millimeter wavelength region. The use of highly stable sources, sensitive detection system and high Q Fabry-Perot cavity enabled us to measure extremely low loss materials very reliably. The real part of the dielectric permittivity can now be measured with accuracy almost as high as dispersive Fourier transform spectroscopy. The next step perhaps will be the use of a super conducting cavity (cavity made with niobium titanium mirrors with lens input and output coupling and cooled by liquid helium), in which a Q of nearly a million can be achieved and an extension of present measurement system to several other millimeter wave atmospheric window frequencies such as 94 GHz, 144 GHz and 220 GHz .

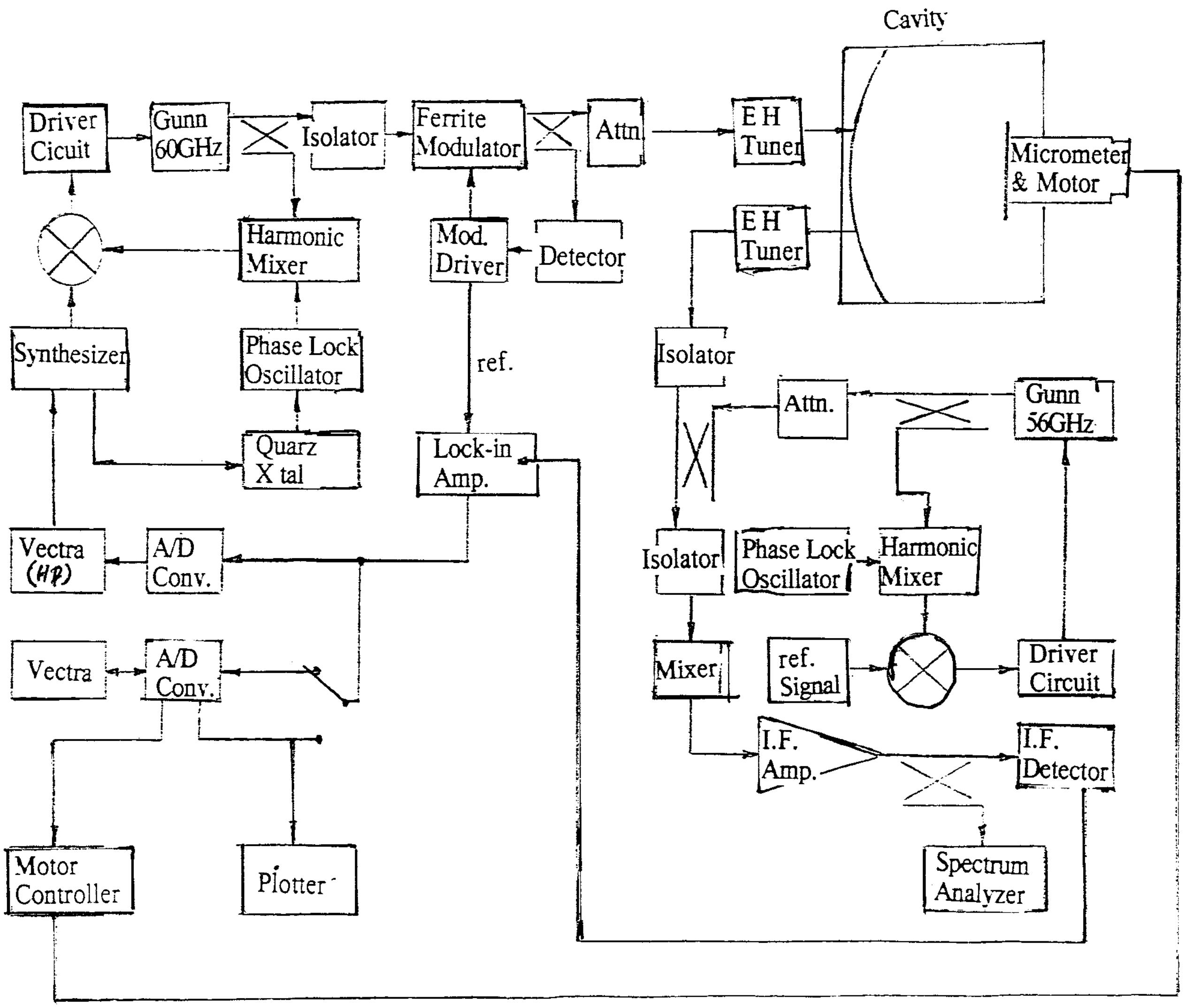

Figure 3. The block diagram of the Precision 60 GHz Open Resonator Dielectric Measurement Set up

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