ABSOLUTE LOSS MEASUREMENT OF HIGHLY REFLECTIVE SAMPLES BY USING A HIGH Q GAUSSIAN BEAM OPEN RESONATOR AT SHORT MILLIMETER WAVE FREQUENCIES

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ABSTRACT

A high Q Gaussian beam open resonator and a new arrangement of it are described as a new method for determing absolute loss due to surface resistance of highly reflective materials at short millimeter- and sub-millimeter wave frequencies. The Gaussian beam open resonator are consist of a pair of spherical mirrors with highly reflective partially transparent circular coupling regions and a plane mirror, where the palne mirror is the test sample. Application of this new method to reflection type measurement enabled simultaneous attainment of high Q factor and high signal-to-noise ratio, which would have been impossible using a conventional reflection-type open resonator with a small coupling hole. Moreover, the use of a pair of identical spherical mirrors enabled direct measurement of the Q of these mirrors, which is equal to Q_{others}, without changing the experimental conditions. Surface loss measurements of metal films are made at 100 GHz band. In the room temperature experiment, surface resistance of 110 mΩ was measured with an accuracy of ±7.6 %.

INTRODUCTION

Recently, microwave monolithic integrated circuits (MMIC) have become to be widely used in microwave techniques. The metal thickness of the striplines in MMICs might be of the order of the skin depth. The skin effect becomes an important issue for transmission loss in the planar microwave and millimeter wave circuits. In high-speed digital systems, since the rise time of digital pulses is reduced to the subnanosecond range, the quality of metal film is important for the high performance ULSI (or VLSI) circuits. Surface impedance measurement of low-conduction loss samples at high frequencies is important from the viewpoint of material study of metal films and their application to high-speed ULSI circuits, millimeter wave MMICs and terahertz technologies.

A. Conventional method & shortcomming

Surface impedance of high-T_c superconductor have recetly been measured by many researchers. Most of these measurements have been carried out using conventional closed cavities or thin film stripline resonators. In general, the total loss, α_t, is the sum of the conduction loss due to the sample, α_{sm}, and the loss due to other parts of the resonator, α_{others};

$$\alpha_t = \alpha_{sm} + \alpha_{others}. \qquad (1)$$

Using Q_L, Q_{sm} and Q_{others} which correspond to these losses, $1/Q_L=1/Q_{sm} + 1/Q_{others}$. The accuracy of surface resistance measurement increases as Q_{others} increased. α_{others} can be divided into the coupling loss, α_{coup}, and other internal losses, $\alpha_{other\text{-}int}$, as follows: $\alpha_{others} = \alpha_{coup} + \alpha_{other\text{-}int}$, where $\alpha_{other\text{-}int}$ depends on the type of resonator. Similarly using Q factors, $1/Q_L$ can be expressed by ,

$$1/Q_L=1/Q_{sm} + 1/Q_{coup} +1/Q_{other\text{-}int} \qquad (2)$$

Conventional methods below 50 GHz use undercoupling conditions ($\alpha_{coup} < \alpha_{sm} + \alpha_{other\text{-}int}$), however, the surface resistance of a sample is comparable to the sensitivity range of the closed cavity. Therefore, high-Q resonator measurement systems at higher frequencies are necessary to improve the sensitivity. Another problem is the method of deriving surface resistance. It can be derived from the difference between α_t and α_{others}, as is obvious from (1). However, no methods exist, so far, to measure α_{others}, directly. In most cases, with transmission-type resonators, the unloaded Q factor, Q_o, is first calculated from Q_L and the insertion loss at resonance. Some difference between the calculation and practical case might be caused due to the imperfections at the weak coupling region for high Q resonator.

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REFLECTION-TYPE OPEN RESONATORS

A. *Conventional open resonators*

Closed cavities become too small at millimter wave frequencies. It is impractical to fabricate a very small closed cavity with high Q factor. At these frequencies, a high Q factor is easily attained by using an open type resonator with one or two spherical mirrors. The use of mirrors with large apertures makes diffractive loss negligible small [1]. The mode of this type of resonator are well characterized by the scalar Gaussian beam theory [2].

At long millimeter-wave frequencies, the electromagnetic energy is usually coupled in and out of the resonator through a small hole in the mirror connected to the waveguide. In a resonator of this type, the diffraction effect at a coupling hole whose diameter is smaller than the wavelength is so strong that a major part of the signal power coupled through the hole is diffused over a wide angle inside the resonator and only a very small part can contribute to the resonant mode TEM_{ooq}. In this ordinary coupling method, attainment of high Q factors over 10^5, which corresponds to undercoupling condition, entails large insertion losses of the order of 25-30 dB [3]. In this case of the reflection-type high-Q open resonator using this coupling method, reflected power is insensitive to the resonance and a very shallow dip is observed. This is because the major part of the power coupled through the hole does not contribute to the interference.

B. *An open resonator with quasi-optical coupling*

For millimeter- and submillimeter-wave open resonators with spherical mirrors, fine coupling adjustment required to attain a high Q factor has always been a serious problem due to the difficulty of precise machining. However, this problem has been solved by quasi-optical coupling method [4]. In the new method, coupling region was designed to be almost the same as the spot size on the spherical mirror of a confocal symmetric resonator. The transmittance of the partially transparent circular region can be designed between the order of 10-3 and 10-5, depending on the grid parameters. Thus, by using a thin film technology, a highly reflective circular coupling region, as large as several wavelengths, can be realized to achieve weak coupling and high mode excitation efficiency for a high Q open resonator.

When applying this type mirrors to reflection-type measurement, reflected power is sensitive to resonace and a resonant curve with a high signal-to-noise ratio is observed. This reflection-type is convenient for precise measurement of highly reflective samples. Thanks to improvement of mode conversion efficiency, a large amount of energy can effectively be stored in a high Q resonator by a relatively small input power.

MEASUREMENT PRINCIPLE [5]

Fig.1(a) shows the half-symmetric resonator consisting of a spherical mirror and a plane mirror, where the plane mirror is the test sample. The sample is placed perpendicular to the optical axis. Resonators are designed to achieve negligible diffractive losses. Therefore, the loaded Q of this resonator is expressed by

$$Q_m = 2\pi D/\lambda \; (\alpha_{sp1}+\alpha_{sm}), \qquad (3)$$

where α_{sp1} is the sum of the conduction loss in the spherical mirror surface and the coupling loss. Here, α_{sp1} is equivalent to α_{others} . Therefore, α_{sm} is obtained directly if α_{sp1} can be measured. α_{sp1} is measured by using the following configuration. Fig.1(b) shows the symmetric resonator consisting of two identical spherical mirrors, which are configurated so that the optical axes coincide and the resonator length is exactly twice that of the half-symmetric resonator. The electromagnetic field distribution of each half of the confocal resonator is then the same as that of the half-symmetric resonator. Therefore, the loss due to the spherical mirror is the same in these resonators. State-of -the-art deposition and lithgrapy techniques enable fine control of the conducrion loss and the coupling loss in the spherical mirror. Therefore, it is possible to fabricate two identical spherical mirrors having the same reproducible properties. The loaded Q of the resonator shown in Fig.1(b) can be expressed by

$$Q_{sp}= 4\pi D/\lambda \; (\alpha_{sp1}+\alpha_{sp2}), \qquad (4)$$

where α_{sp2} is loss per reflection due to spherical mirror II. The pair of spherical mirrors should be fabricated under the same conditions in order to have the same properties. In the special case that α_{sp1} and α_{sp2} are exactly equal,

$$\alpha_{sm} = (2\pi D/\lambda) (1/Q_m - 1/Q_{sp}). \qquad (5)$$

For a metallic sample, classical theory gives

$$Z_s = R_s + j X_s = R_s + j R_s \qquad (6)$$

where $R_s/\zeta_0 << 1$ and ζ_0 is the intrinsic impedance (377

Ω). Then the surface resistance is related to the conduction loss by

$$R_s = (\zeta_0/4)\, \alpha_{sm} . \qquad (7)$$

This equation is also valid for superconductors when $X_s/\zeta_0 << 1$ are satisfied. The accuracy depends mainly on Q_{sm}/Q_{sp}. The smaller the ratio, the better is the accuracy obtained.

EXPERIMENTAL

Spherical mirrors were made with sputtered gold film on optically polished concave glass substrates. Film thickness was about 1.5 μm, which is over six skin depths at 100 GHz. This mirror is shown schematically in Fig.2. A fine stripe pattern was formed on a circular area in the center of the spherical mirror using a photolithograpic and dry-etching process. In our mirrors both the metal width, d', and the gap width , d, were 63 μm. The loss due to each spherical mirror was 3×10^{-3}, in which the coupling loss was about twice the conduction loss due to the gold film. The spherical mirror had a radius of curvature of 200 mm and a diameter of 80 mm. The Q factor, Q_{sp}, of a symmetric resonator consisting of two spherical mirrors was measured at room temperature and found to be 130,000 at 101.3 GHz and about 200 mm separation. The Q factor , Q_m, of a half-symmetric resonator with an Au thin film sample at the same frequency was 95000 at about 100 mm separation as described in the previous section. Fig.3 shows resonant curve for TEMooq of the half-symmetric resonator with an Au thin-film at 101.3 GHz. A deep resonat dip of over 60 % with a high signal-to-noise ratio is observed. The loss and surface resistance of the sample were calculated by substituting Q_m and Q_{sp} into (3). Results for various metal films are summarized in Table 1. The error and measurement sensitivity are calculated on the basis of Q factor measurement accuracy of ± 2 %.

CONCLUSION

We presented a new method to determine absolute loss due to surface resistance at short millimeter wave frequencies. Surface loss measurement was made at 101GHz. It can be the system for precision measurement of surface loss having the highest frequency and the highest Q value. Moreover, it is superior to other measurement methods in the point that it determines the loss at the mirror sample being measured after directly measuring the losses other than that of the mirror sample being measured. It was confirmed that the measurement of material surface characteristics using a high Q reflection-type open resonator constitutes an important, highly effective, new measurement method which can be used in furthering research into the anomalous skin effect of low-temperature metals and research of high-temperature superconductor.

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Sample	Thickness (μm)	Loss ($\times 10^{-3}$)	Surface resistance (mΩ)	Error (%)
gold film*	0.87	1.080	101.7	7.22
gold film*	0.40	0.998	93.99	7.70
copper film+	0.65	1.138	107.1	6.94
niobium film+	1.65	2.457	231.4	4.08
niobium film+	1.65	2.724	256.5	3.83

Table 1. Summary of loss measurement and surface resistance at 101.3 GHz (*Vacuum evaporation, +Spattering)

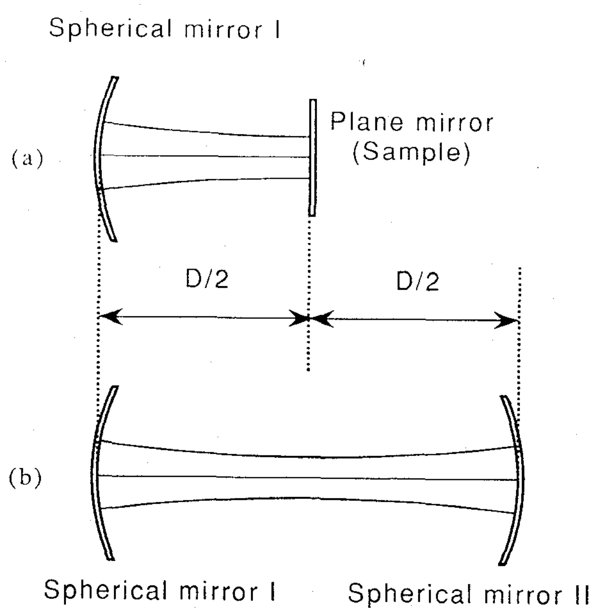

Fig.1. Determination method of surface resistance. (a) Half-symmetric resonator consisting of a spherical mirror and a plane mirror, where the plane mirror is sample. (b) Symmetric resonator consisting of two spherical mirrors. The resonator length is exactly twice that of the half-symmetric resonator.

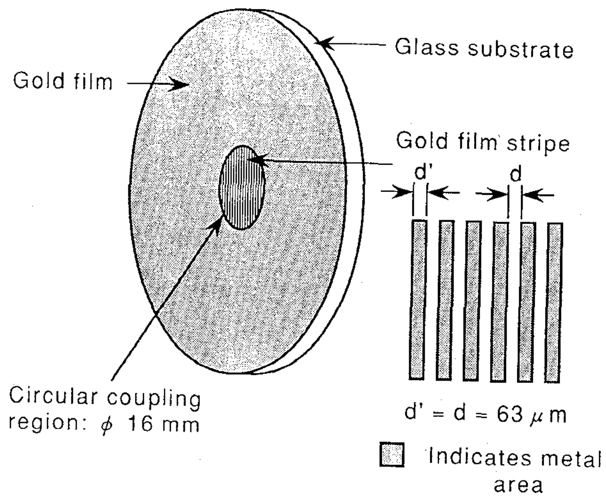

Fig.2. Schematic diagram of a fabricated spherical mirror with a highly reflective, partially transparent circular region. Mirror diameter is 80ϕ, Radius curvature is 200mm.

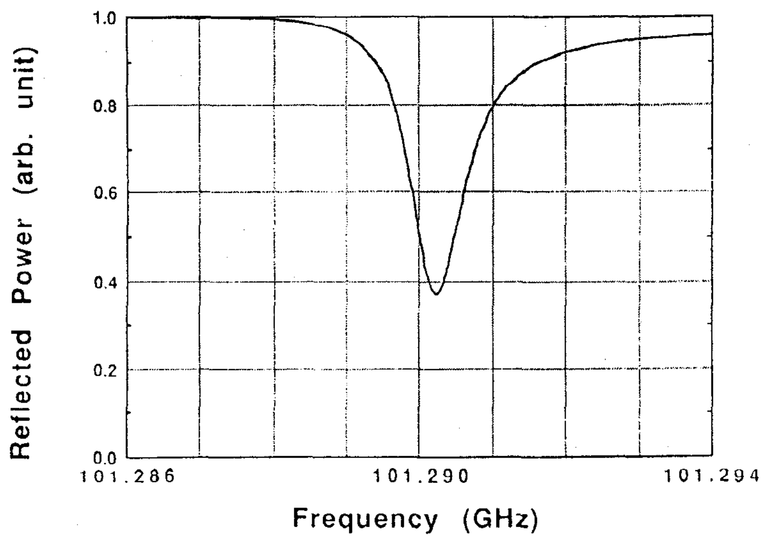

Fig.3. Resonant curve for TEM00q mode of the half-symmetric resonator with an gold film at 101.3 GHz. A deep resonant dip of over 60 % with a high signal-to-noise ratio is observed.