Design a tunable cavity resonator for complex permittivity measurement of low-loss material at L band

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The value of loss tangent (\(\tan \delta\)) of the low loss material is of the order of \(10^{-4}\). There are different methods used to measure loss tangent as well as complex permittivity. Out of different methods, Cavity Resonator method is the best method for the measurement of complex permittivity of low loss materials i.e. teflon, duroid, polystyrene and stycast. In this present paper, a cylindrical cavity resonator is designed and fabricated in the frequency range 2.2-2.3 GHz and the complex permittivity of low loss material teflon using cavity resonator method has been measured.

Keywords: Cavity resonator, Complex permittivity, Dominant mode, Low-loss materials

1 Introduction

To design a tunable cavity resonator at desired frequency range, two parameters i.e. diameter and length of cavity, have been calculated on the basis of the cut-off frequency and the dominant mode for the desired range. The information about the dominant mode and the relationship between length and diameter of the cavity resonator are obtained with the help of mode chart and mode equation, which is a linear equation that provides the relationship among the dominant mode, diameter and the length of the cavity. This tunable cavity resonator is used for the measurement of complex permittivity for low loss materials like teflon, duroid, polystyrene and stycast. A specimen disc of low loss material with appropriate thickness was inserted inside the resonator and the resonant length and the quality factor of the resonator were measured. Both the measurements were done with and without the specimen disc. The resonant length measurement provides the relative dielectric constant of the material. The Panoramic display method is applied for the measurement of the quality factor (\(Q\)). The quality factor (\(Q\)) is used for the measurement of loss tangent of the materials. In this way, the complex permittivity for the low loss materials can be measured with cavity resonator method with very small error. The electromagnetic characteristics of all materials are represented by conductivity (\(\sigma\)), permittivity (\(\varepsilon\)) and permeability (\(\mu\)). In the loss less materials, the conductivity is near zero, i.e. the material is a poor conductor of electricity and the material is called dielectric material. An important property of dielectric material is its ability to support an electrostatic field while dissipating minimal energy in the form of heat, thus, shows the energy storage capability of a material. The lower the...
dielectric loss (less is the proportion of energy lost by heat), the more effective is a dielectric material. Dielectric constant of a material is complex in nature, known as complex permittivity\(^1,2\), that is expressed as:

\[
\varepsilon = \varepsilon' - j\varepsilon'' \quad \ldots (1)
\]

where,

\[
\varepsilon' = \text{Re}\left(\frac{\varepsilon}{\varepsilon_0}\right) \quad \ldots (2)
\]

\[
\varepsilon'' = -\text{Im}\left(\frac{\varepsilon}{\varepsilon_0}\right) \quad \ldots (3)
\]

Real part is known as storage factor whereas imaginary part is known as loss factor. In order to explain the dielectric losses more clearly, a ratio of real and imaginary part of complex permittivity is defined known as loss tangent or dissipation factor. It is defined as:

\[
\tan \delta = [-\text{Im}(\varepsilon)/\text{Re}(\varepsilon)] = \frac{\varepsilon''}{\varepsilon'} \quad \ldots (4)
\]

It is proportional to the ratio of the power lost in the heat (by means of dielectric losses) to the energy stored per cycle, and therefore is a good measure of how lossy a dielectric material is. Dielectric constant/complex permittivity can be measured by various methods\(^3\) but all these methods show their limitations while measuring the dielectric constant for the low loss material. Thus, in this present study, a tunable cavity resonator is designed and the cavity resonator method is employed for the measurement of dielectric constant for the low loss material i.e. teflon at different microwave frequencies in L band.

2 Methodology

Complex permittivity\(^4,5\) is measured using resonant cavity. First, the cavity is calibrated before measuring \(\varepsilon'\) and \(\varepsilon''\). The \(\varepsilon'\) is found out using the measured resonant length of the air filled cavity and dielectric filled cavity, respectively. The \(\varepsilon''\) is obtained by measuring the \(Q\) of the cavity when it is air filled and for dielectric filled along with the resonant length of the cavity for air filled and with dielectric filled. For very low loss materials having tan\(\delta\) of the order of \(10^{-4}\), the \(\varepsilon''\) will also be of the order of \(10^{-4}\).

The method of measurement of \(Q\) using panoramic display method is used. The resonance curve is obtained on the oscilloscope. For this the function generator giving triangular wave is used to frequency modulate the klystron source. From the resonance curve, the resonance frequency \(f_0\) and the frequency \(f_{01}\) at 3 dB points are obtained and \(Q\) is calculated.

The storage factor (\(\varepsilon'\)) is obtained using the resonant lengths of air-filled cavity and the cavity with dielectric material. The \(\varepsilon'\) is calculated using the formula\(^4\) which is given by:

\[
k = \frac{\varepsilon'}{\varepsilon_0} = \frac{\beta_1^2 + \kappa_\varepsilon^2}{\beta_0^2 + \kappa_\varepsilon^2} \quad \ldots (5)
\]

where \(k_\varepsilon = 3.832/a\) [First root of Bessel function \(J_0\) \((k_\varepsilon a) = 0 = k_\varepsilon a = 3.832\)], \(a\) is the radius of the cavity \(\beta_0 = \frac{\pi}{l_0}\), is the phase constant for air filled cavity and \(l_0\) is the resonant length of air filled cavity, and \(\beta_1 = \) is phase constant for cavity filled with dielectric material, which can be calculated from the Eq. (6).

\[
\tan \beta_0 b = \frac{l_r - b \tan \beta_0 (l_r - b)}{b} \quad \beta_0 = \frac{l_r - b}{b} \quad \ldots (6)
\]

where \(l_r\) is the resonant length of the cavity filled with dielectric material and \(b\) is the thickness of the specimen. Similarly, the loss factor\(^5\) (\(\varepsilon''\)) is calculated using Eq. (7):

\[
\varepsilon'' = 0.539 \times \frac{V_0}{V_1} \delta \left(\frac{1}{2Q}\right) \quad \ldots (7)
\]

where \(V_0 = \) volume of air-filled cavity = \(\pi r^2 l_0\), \(V_1 = \) Volume of the specimen = \(\pi r^2 b\) \(b = \) thickness of the specimen:

\[
\delta = \left(\frac{1}{2Q}\right) = \frac{1}{2} \left(\frac{1}{Q_1} - \frac{1}{Q_0}\right) \quad \ldots (8)
\]

where \(Q_1\) is the quality factor of the cavity filled with specimen and \(Q_0\) is the quality factor of the air filled cavity.

The \(Q\) factor is obtained from Eq. (9):

\[
Q = \frac{f_0}{\Delta f} = \frac{f_0}{(2|f_0 - f_1|)} \quad \ldots (9)
\]

where \(f_0 = \) resonant frequency at maximum power; \(f_1 = \) resonant frequency at half power.
The loss tangent is the ratio of loss factor and the storage factor and is given by Eq. (10):
\[ \tan \delta = \frac{\varepsilon''}{\varepsilon'} \quad \ldots \quad (10) \]

3 Design of Tunable Cavity Resonator

A tunable cylindrical cavity to sustain the proper mode \((H_{011})\) with minimized effects of the unwanted modes is designed and fabricated at frequency range 2.2 - 2.3 GHz in L band. The design specifications are given below.

**Design specification**
- Range = 2.2 - 2.3 GHz
- Safety figure = 20%
- Cut-off frequency = 1.76 GHz
- External diameter of cavity = 21.207 cm
- Diameter of the plunger = 20.472 cm
- Internal diameter of cavity = 20.789 cm
- Limit of mechanical motion = 0.553 cm
- Diameter of iris = 2.687 cm
- Rectangular waveguide = WR-430 (standard)
- Length of tube = 29.448 cm
- Material used = Brass
- Micrometer used = 150mm (standard)

**Material used for Cavity fabrication**

Generally brass is taken for the fabrication of the cavity. Other metals like aluminum can also be used. The material is chosen on the basis of conductivity and density. Low density metal or alloy is taken to reduce the weight of the cavity, and high conductive metal is used to reduce the penetration depth. In general cases the internal surface of the cavity is coated with silver to reduce skin effect.

4 Measurement Procedure

The measurements are done at 2.2, 2.25 and 2.3 GHz frequencies. The different parts of the designed cavity are shown in Fig 1 and block diagram in Fig 2. Fig 3 shows the experimental set-up of panoramic display method. The following procedures are used for measurement of dielectric constant.

**Calibration of Cavity**

The components are assembled as shown in Figs 2 and 3. Then slotted section and probe are properly adjusted to get the stable operation and maximum power. Then the frequency meter is tuned to see maximum dip on the CRO and noted down the frequency from the frequency meter. By detuning the frequency meter, the micrometer of the cavity is adjusted and checked the resonance using the CRO. The micrometer reading which indicates the resonant length of the cavity for that particular frequency is noted down. Then same procedures are followed by changing the frequency of the source. As the cavity is designed for a particular frequency range, we need to know the resonant lengths of the cavity for each frequency point. Therefore same steps are repeated for all the possible frequency points and their corresponding resonant lengths are noted. The calibration curve is drawn by taking frequency on X axis and micrometer reading on Y axis. The above procedure is performed and the calibration curve is shown in Fig. 4 which is obtained for the cavity for frequency of operation between 2.2 to 2.3 GHz.

**Measurement of \( \varepsilon' \) and \( \varepsilon'' \)**

Using same experimental set-up as shown in Fig. 3 the resonance point \((l_0)\) is noted down from micrometer where resonance occurs due to the air filled cavity. Then, the cavity is detuned to get the 3dB point on the resonance curve and noted down the micrometer reading \((l_{01})\). Then, the sample of required size and thickness of the test material is put in the cavity and tuned the cavity to get the resonance and then noted down the micrometer reading \((l_r)\) where resonance occurs due to the dielectric-filled cavity.
Similarly, the micrometer reading ($l_{11}$) is noted down to get 3dB point on the resonance curve by adjusting the micrometer when it is filled with dielectric. The corresponding frequency is noted down from the calibration curve. Then putting these values in Eqs (5-9), $\varepsilon'$ and $\varepsilon''$ are obtained. The resonance curves are shown in Figs 5 - 9.

5 Results and Discussion

The measurements of $\varepsilon'$ and $\varepsilon''$ of teflon are done at frequencies 2.2, 2.25 and 2.3GHz. The results are given in Table 1.

Figs 10 and 11 show the variation in storage factor and loss factor with frequency, respectively. It is observed that the loss factor of teflon is slightly increasing with the increase in frequency compared to the storage factor.
6 Conclusion

In this paper, the complex permittivity of dielectric material of teflon, is measured at different microwave frequencies i.e. 2.2, 2.25 and 2.3 GHz using cavity method. The results are given in Table 1. From the results, it is observed that the values of $\varepsilon'$ for teflon is found around 1.98 to 2.05. The value of $\varepsilon''$ for teflon is around $4.3 \times 10^{-4}$ to $5.11 \times 10^{-4}$. It is also observed that the value of loss factor of teflon is increasing with the increase of frequency in comparison to the storage factor.

The Cavity Resonator method shows its importance for the measurement of complex permittivity for low loss materials by providing better results than the other methods\(^3\). The low loss materials show very small loss of energy in the form of dielectric losses. Teflon, duroid, polystyrene and stycast and other low-loss materials which are used for radome applications which have the value of loss tangent in the order of $10^{-4}$.

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