Research Article

Uncertainty analysis of Q-factor measurement in cavity resonator method by electromagnetic simulation

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Abstract
Effects of cavity material on the Q-factor measurement of microwave dielectric materials were studied by HFSS simulation and the measurements using metal cavity. $TE_{01\delta}$ mode resonant frequency was determined from the electric and magnetic field patterns and the Q-factor was calculated from the 3 dB bandwidth of resonant peak at the scattering matrix S_{21} spectrum. In the cavity resonator method, Cu metal cavity has been generally used. However, the oxidized surface of Cu cavity could generate errors in Q-factor measurements. From the simulation, it is observed that the Q-factor significantly decreased with decreasing conductivity of cavity metal. When the conductivity of the oxidized Cu is assumed as 1000 Ω^{-1} m^{-1}, the Q-factor could be decreased by 80% compared to pure Cu.

Keywords Microwave · Cavity · Dielectric materials · Q-factor · Simulation

1 Introduction

High-Q dielectric materials have been widely studied and used for the microwave passive devices such as resonators and filters. Recently, the miniaturization of microwave components and circuits strongly requires high-permittivity low-loss dielectrics with good temperature stability. Considering the RF frequency range used in microwave telecommunication system (0.3–30 GHz) and the desirable chip sizes in the current packaging technologies (1–10 mm), the dielectric compositions having the permittivity of 20–100 and the Q-factor of hundreds-thousands are required [1–3]. Generally, high-Q dielectric materials are based on TiO_2 composition such as (Zr, Sn) TiO_4, $BaO–TiO_2–WO_3$, $MgTiO_3–CaTiO_3$, $BaTi_4O_9$, and the $ZnNb_2O_6–TiO_2$ system.

In the development of high-Q microwave dielectrics, it is essential to measure the quality factor and the permittivity of the dielectrics. There are several methods of determining the dielectric permittivity and the quality factor of microwave dielectrics [3, 4]. Among them, transmission-mode cavity resonator method is very useful for the measurement of quality factor of the dielectrics. In this method, disk-type dielectric sample is located in the center of metal cavity and the Q-factor can be calculated from the resonant characteristics of the dielectric disk. However, there could be some error factors in determining Q-factor measurement. Firstly, there could be geometric and/or microstructural imperfections in dielectric resonator. Measured Q-factor could be decreased with the pores and the other phases in the dielectrics [5]. Sintered dielectric bodies have not only a main phase but also some other phases which show different dielectric properties. Also, the imperfections of the metal cavity could also lower the measured Q-factor.

In the cavity resonator method, Cu metal cavity has been generally used as it has excellent conductivity and machinability. However, by chance, we found that the measured Q-factor with old Cu cavity is lower than that with new one. This phenomena could be attributed to the surface

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oxidation of the cavity metal and the decrease of conductivity. In this study, we are to study the effects of cavity materials on the Q-factor measurements by computer simulation and realistic measurement.

2 Experimental

2.1 Q-factor measurement by the cavity resonator method

The cavity resonator method has been used for the Q-factor measurement of low-loss dielectric materials. Figure 1 shows the schematic diagram of cavity resonator method. By measuring RF power from port 1 and port 2 of the metal cavity, scattering matrix S_{21} can be determined with frequency scan. S_{21} is the ratio of the voltage measured at port2 compared to the voltage generated at port1. In this study, a 40 GHz RF network analyzer (N5230A, Agilent) was used for S-parameter measurement. From the plot of S_{21} in frequency domain, the unloaded quality factor can be determined by calculating the half-power bandwidth of the peak which appears at dominant resonant frequency.

$$Q_{loaded} = \frac{f_0}{\Delta f(3\,dB)} \quad (1)$$

Unloaded Q-factor can be calculated by the following equation. α is the insertion loss at the resonant frequency in decibels. Since S_{21} is always smaller than unity, the unloaded Q-factor is always larger than loaded Q.

$$Q_{unloaded} = \frac{Q_{loaded}}{1 - S_{21}(3\,dB)},\ S_{21}(f_0) = 10^{\frac{\alpha}{20}} \quad (2)$$

2.2 HFSS and simulation setup

FEM principle is a convenient method in the analysis of complicated structure and anisotropic materials. Most commercially available 3-dimensional full wave electromagnetic simulators are based on FEM algorithm. In this study, HFSS (High Frequency Structure Simulator, V7.0, Ansoft Co., USA) was used for the electromagnetic simulation. HFSS brings the power of the FEM to the engineer's desktop by leveraging advanced techniques such as automatic adaptive mesh generation and refinement, tangential vector finite elements, and Adaptive Lanczos Pade Sweep (ALPS). HFSS can solve any 3D electromagnetic problem and calculate S-parameters between two ports [6]. Thus, we set up a simulation model of cavity resonator method as shown in Fig. 1c and calculated the unloaded Q-factor of the sample object in the HFSS modeling.

Fig. 1 **a** Measurement setup cavity resonator method. **b** Metal cavity. **c** HFSS simulation model of cavity resonator
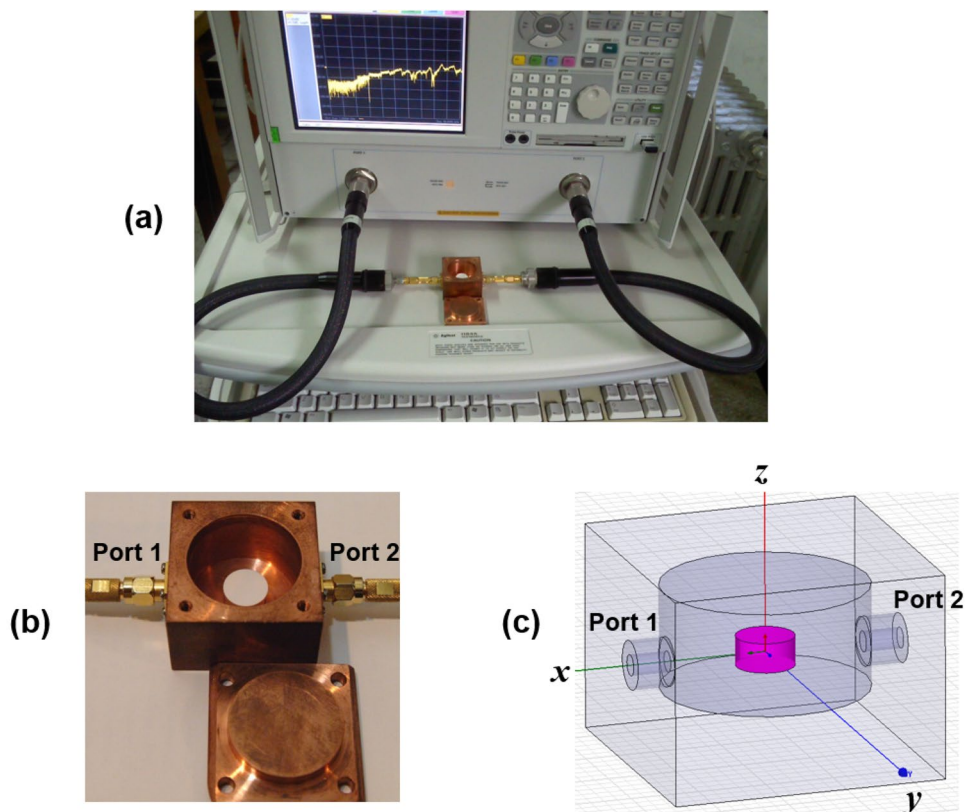
The Q-factor measured in the cavity is contributed by both dielectric disk and metal cavity as shown in Eq. (3). Metal cavity is introduced to prevent field radiation. However, as we observed, the cavity wall could be oxidized and hence the conductivity could be decreased. Then the oxidized metal cavity could lower the total Q-factor. As shown in Fig. 1b, dark luster is observed at the surface of Cu metal which indicates the oxidation of Cu.

$$\frac{1}{Q_{total}} = \frac{1}{Q_{(dielectric)}} + \frac{1}{Q_{(cavity)}} \tag{3}$$

In the HFSS simulation, we set up the cavity materials as listed in Table 1. From the reference, it is expected that the conductivity of CuO or Cu_2O could be lowered below 1000 Ω^{-1} m^{-1} [7]. Thus, we set up the conductivity of the oxidized Cu as 1000–100,000 Ω^{-1} m^{-1}.

2.3 Sample preparation

In this study, a disk sample of $0.8ZnNb_2O_6$–$0.2TiO_2$ composition was used to compare the simulated results with measured values with RF network analyzer. The starting raw materials were powders of ZnO, Nb_2O_5, and TiO_2. By using solid state sintering method, the disk was fabricated at sintering temperature of 900 °C for 2 h in air. Details of sample preparation is described elsewhere [8].

3 Results and discussion

Figure 2 shows the scattering parameter S_{21} spectrum for the sample by using RF network analyzer. Frequency scan range was 5–20 GHz and $TE_{01\delta}$ mode was appeared at 9.83 GHz. From the center frequency (f_0) of 9.83 GHz and the 3 dB bandwidth of 0.008 GHz, the loaded Q is calculated as about 1230. Insertion loss at the resonant frequency was − 33 dB and the unloaded Q is calculated as 1260 by using Eq. (2). The Q×f value of ca. 12,000 in this study is quite similar with the values in the Ref. [8]. In
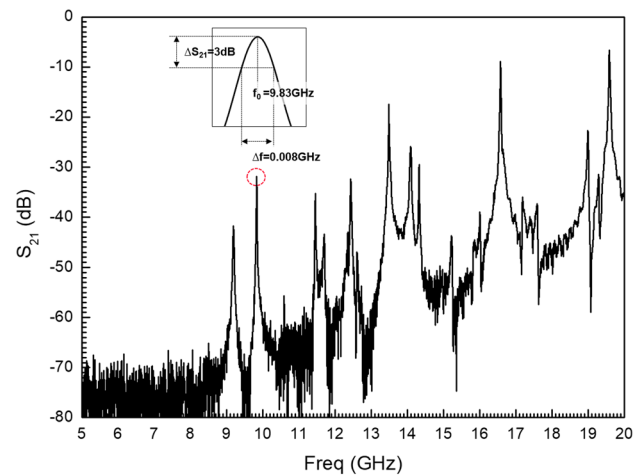

Fig. 2 Scattering parameter S_{21} spectrum for the dielectric sample obtained by using RF network analyzer

the realistic measurement, there are a number of spurious peaks especially in low frequency range. These peaks could be attributed the geometric/compositional imperfections in the metal cavity, dielectric resonator, and the transmission line.

Figure 3 shows the scattering parameter S_{21} spectra for the simulation object by using HFSS simulation. Used HFSS materials setup were #1 and #7 in Table 1. Ansoft HFSS provides several options for calculating the frequency response. Figure 3a shows the fast sweep and Fig. 3b shows interpolating sweep. In "fast sweep", an Adaptive Lanczos-Pade Sweep (ALPS) solver is used to extrapolate an entire bandwidth of solution information from the center frequency. In "interpolating sweep", HFSS solves at discrete frequency points that are fit by interpolating. Although the S_{21} spectra are different to each other especially at higher frequencies above 10 GHz, the same $TE_{01\delta}$ mode frequency of 9.72 GHz was identified.

There are a lot of resonant peaks at Fig. 3. By plotting the electric field and magnetic field inside the dielectric resonator, the $TE_{01\delta}$ mode frequency could be easily

Table 1 Materials setup for HFSS simulation

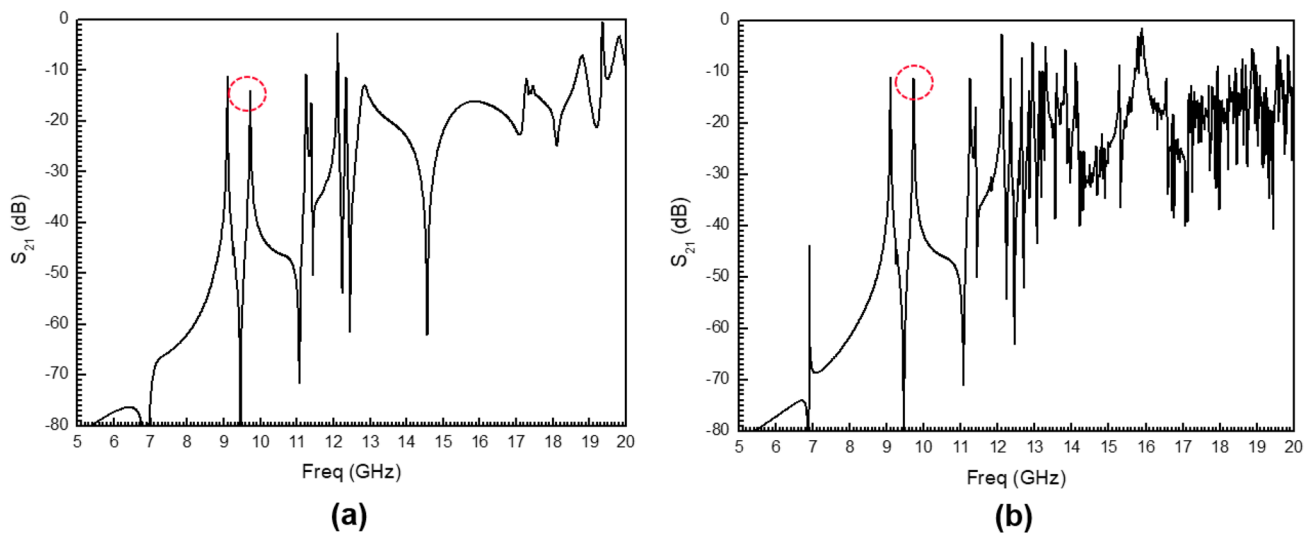| Setup #	Object	Material	Conductivity (Ω^{-1} m^{-1})	Relative permittivity	Dielectric loss	Relative permeability
1	Metal cavity	Cu	58,000,000	1.0	–	0.999991
2		Oxidized Cu	100,000	1.0	–	0.999991
3			10,000	1.0	–	
4			1000	1.0	–	
5		Au	41,000,000	1.0	–	0.999991
6		SUS	1,100,000	1.0	–	0.999991
7	DR	K20	–	20.0	0.001	1.0

Fig. 3 Scattering parameter S_{21} spectra for the simulation object obtained by using HFSS simulation

determined. This is a strong merit of electromagnetic simulation. Figure 4 shows the E-field and H-field vector distribution inside the resonator disk. From the circular E-field pattern along the diameter of the disk and the rotating H-field pattern along the E-field revealed at 9.72 GHz, it is concluded that the $TE_{01\delta}$ mode frequency is 9.72 GHz. The frequencies of 9.10 GHz and 11.50 GHz are other modes of resonance.

Figure 5 shows the effects of cavity materials on the scattering parameter S_{21} spectra for the simulation object

by using HFSS simulation. As mentioned earlier, the cavity wall could be oxidized and hence the conductivity could be decreased. Then the measured Q-factor could be decreased according to the energy loss inside the metal. As the microwave skin depth at the frequency range of 1–10 GHz is about 1 μm, slight oxidation at metal surface could significantly lower the Q-factor. In Fig. 5, we can see that the bandwidth of the $TE_{01\delta}$ mode resonant peaks increases with decreasing conductivity of the metal cavity. This could be attributed to the larger electromagnetic

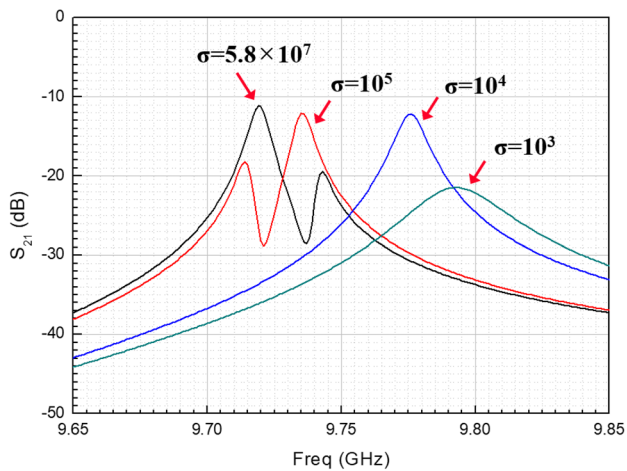**Fig. 4** E-field and H-field vector distribution inside the resonator disk at selected frequencies
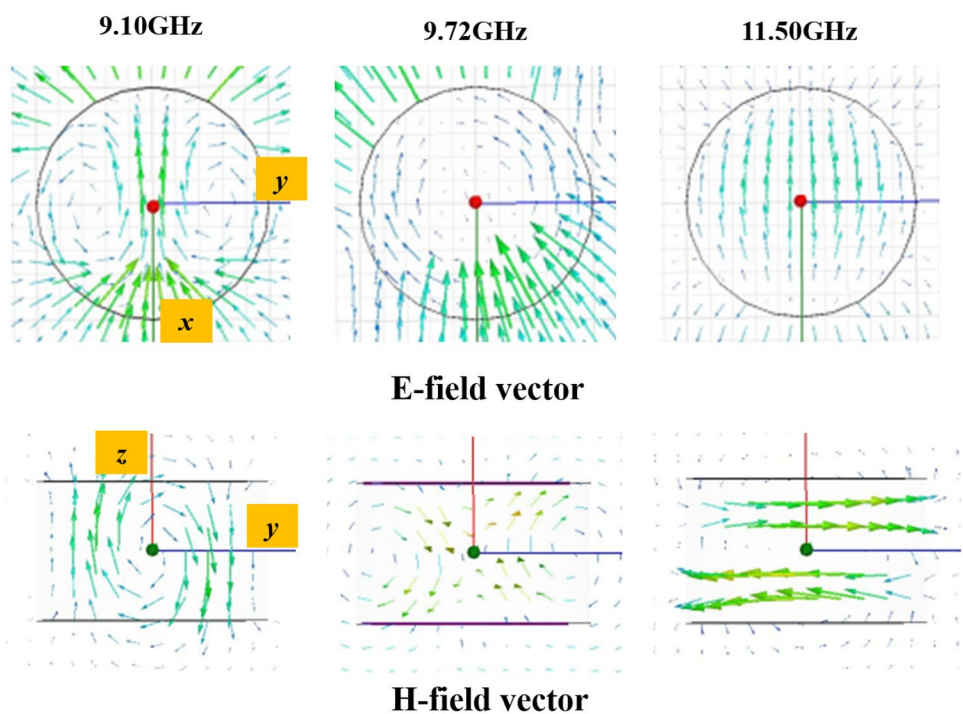
Fig. 5 Effects of cavity materials on the scattering parameter S_{21} spectra for the simulation object by using HFSS simulation

Table 2 HFSS simulation setup and simulated Q-factor

Cavity material	Conductivity (Ω^{-1} m^{-1})	f_0 (GHz)	Δf (GHz)	Simulated unloaded Q
Cu	58,000,000	9.72	0.007	1800
Oxidized Cu	100,000	9.74	0.008	1600
	10,000	9.78	0.012	1100
	1000	9.79	0.033	350
Au	41,000,000	9.72	0.007	1800
SUS	1,100,000	9.72	0.007	1750

energy dissipation inside the lossy conductor. The calculated unloaded Q-factors with various metal conductivity were summarized at Table 2.

From the simulated data at Table 2, it is clear that the Q-factor could be significantly decreased with decreasing conductivity of cavity metal. When the conductivity of the oxidized Cu is assumed as 1000 Ω^{-1} m^{-1}, the Q-factor could be decreased by 80% compared to its native value. It should be noted that the dielectric loss setup for the sample is fixed as 0.001 at every conductivity setup in Table 2. This results clearly show that the measured Q-factor could be decreased far below the dielectric Q-factor when the metal cavity is lossy.

Figure 6 shows the E-field intensity inside the metal cavity simulated by HFSS. When the conductivity of metal cavity was 58,000,000 Ω^{-1} m^{-1}, the electric field intensity inside the cavity was 2×10^{-7} V/m. However, When the conductivity was 1000 Ω^{-1} m^{-1}, the electric field intensity inside the cavity increased up to 3×10^{-2} V/m. This implies that electromagnetic energy loss increases with decreasing metal conductivity.

Table 3 summarizes the measured unloaded Q-factor of the sample by using various metal cavities in our laboratory. When the newly machined Cu cavity, the measured Q-factor was 1260. However, when the old Cu cavity (5 years after machining), the measured Q-factor was decreased significantly. Thus, we can conclude that we should not trust old Cu cavity made several years or months earlier. The measured Q-factor using SUS cavity
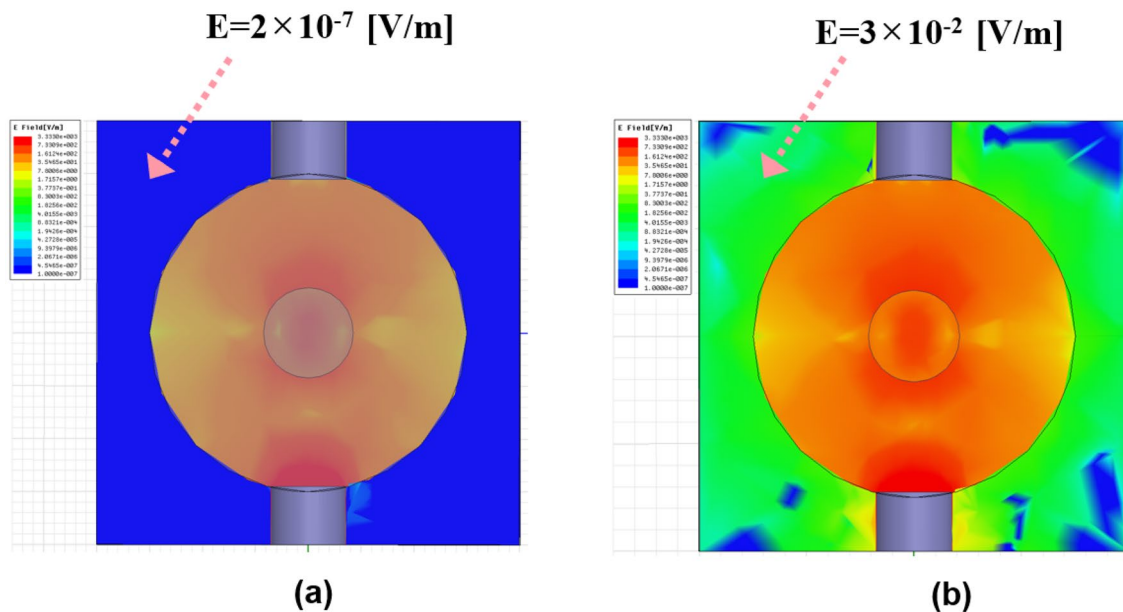

Fig. 6 E-field intensity inside the metal cavity. **a** When σ = 58,000,000 Ω^{-1} m^{-1}. **b** When σ = 1000 Ω^{-1} m^{-1}

Table 3 Effect of cavity on the measured Q-factor by RF network analyzer

Cavity	Measured unloaded Q
Cu cavity (as machined)	1260
Cu cavity (5 years)	450
SUS cavity (5 years)	600

was also lower than that using as-machined Cu cavity. This implied that there could be some lossy films at the surface of the SUS materials.

4 Summary and conclusions

Effects of cavity material on the Q-factor measurement of microwave dielectric materials were studied by HFSS simulation and the measurements using metal cavity. From the simulation, it is observed that the Q-factor significantly decreased with decreasing conductivity of cavity metal. When the conductivity of the oxidized Cu is assumed as $1000\,\Omega^{-1}\,m^{-1}$, the Q-factor could be decreased by 80% compared to pure Cu. Thus, it is concluded that we should not trust old Cu cavity made several years or months earlier.

All the realistic measurements by RF network analyzer showed consistent results with HFSS simulation.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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