Progress In Electromagnetics Research Letters, Vol. 4, 139–148, 2008

MEASUREMENT OF RF PCB DIELECTRIC PROPERTIES AND LOSSES

Y.-H. Chou †

Department of Electronic Engineering
St. John's University
499, Sec. 4, Tam King Road, Tamsui
Taipei County, Taiwan 25137, R.O.C.

M.-J. Jeng

Department of Electronic Engineering
Chang Gung University
259 Wen-Hwa 1st Road, Tao-Yuan
Kweishan-Taoyuan, 333, Taiwan, R.O.C.

Y.-H. Lee and Y.-G. Jan

Department of Electronic Engineering
St. John's University
499, Sec. 4, Tam King Road, Tamsui
Taipei County, Taiwan 25137, R.O.C.

Abstract—This paper presents the calculations of transmission line loss factor by extracting from the Q-factor measurement of the quarter-wavelength open stub resonators over the designed frequency and other resonant frequencies. A comparison of the loss factor of the design frequency with other resonant frequencies of each of the stub's quarter-wave resonances is provided in this paper. The radiation and discontinuity losses are undesirably included in the unloaded Q-factor measurement and it shows that the unloaded Q-factor is not repeatable at different designed frequency. The implementation of the loss factor measurement by quarter-wavelength open stub resonators is becoming more and more important to be considered with the increase of using the electronic circuits operating at high frequencies.

† This author is also with Department of Electronic Engineering, Tam Kang University, 151 Ying-chuan Road, Tamsui, Taipei County, Taiwan 25137, R.O.C.

1. INTRODUCTION

Since the clock frequencies of computers are ever increasing to higher levels for high speed signal transmission, it is necessary to evaluate the dielectric constant and loss factor of the constituent printed circuit board (PCB) substrates at radio frequencies. The dielectric constant and loss factor are two of the most significant parameters that affect the performance of the circuits. Impedance matching is an indispensable methodology in the high speed circuit design. If we want to precisely determine the intrinsic impedance value, the accurate measurement of dielectric constant would be one of the most significant requirements. However, several measurement techniques such as parallel plate method, coaxial line method and resonator method are available for the determination of dielectric properties [1–7]. It is some what difficult to theoretically determine the characteristics of the transmission line attenuation, but they can be easily measured. The proposed new technique to measure transmission line attenuation is to find the Q-factor of quarter-wavelength open stub resonators [8]. Typically, the insertion loss S21 of quarter-wavelength open stub resonators around resonance is used to determine the transmission line's attenuation. The implementation by using quarter-wavelength open stub resonator is more accurate than other methods of attenuation measurement in the characterization of planar transmission lines.

In this paper, the quarter-wavelength open stub resonators method of measuring dielectric constant and loss factor are performed. The test structure is shown in Figure 1 with 10 cm through line. From the measurement and calibrations, we make comparisons in the characterizing of the loss factors and dielectric constants of the microstrip line. It concludes that the loss factor of the design frequency is accurate but it deviates from their theoretical values over each of the stub's quarter-wave resonant frequencies.

2. QUARTER-WAVELENGTH OPEN STUB RESONATOR MEASUREMENT METHOD

In this paper, we exploit quarter-wavelength open stub resonators measurement in combining with theoretical considerations to evaluate the dielectric constants and loss factor. First we locate the frequencies f_l and f_h of the 3 dB insertion loss at each resonant frequencies and substitute them with the quarter-wavelength open stub length l into the following formula (1) to get the effective dielectric constant ε_{eff} of

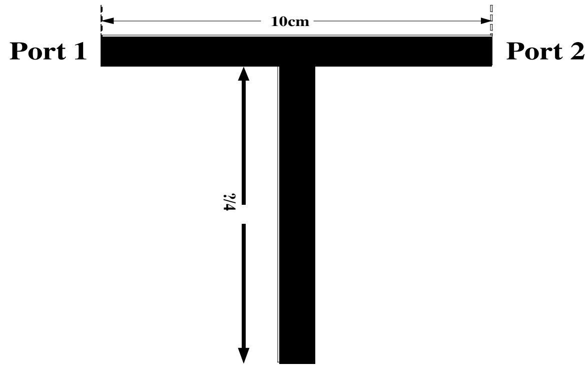


Figure 1. Quarter-wavelength open stub resonator structure.

the transmission line [9],

$$\varepsilon_{\mathit{eff}} = \left(\frac{n \cdot C}{4 f_o (l + l_a)}\right)^2, \quad n = 1, 3, 5, \ldots \tag{1}$$

where

$f_o\ = \frac{f_l + f_h}{2}$
f_1 : the lower frequency of the 3-dB insertion loss
f_h : the upper frequency of the 3-dB insertion loss
C : the speed of light in free space
l_a : adjusted length to be determined from empirical formula [10].

The loss factor of the transmission line, α_0 in dB/length, can be determined at each resonant frequency f_0 from the following formula, Eq. (4), via the loaded and unload loss factors Q_L and Q_0 respectively.

$$Q_L \equiv \frac{f_0}{BW} \tag{2}$$

$$Q_0 = \frac{Q_L}{\sqrt{1 - 2 \cdot 10^{-(L_A/10)}}} \tag{3}$$

$$\alpha_0 = \frac{8.686 \pi f_0 \sqrt{\varepsilon_{\mathit{eff}}}}{C Q_0} \tag{4}$$

where

$\varepsilon_{\mathit{eff}}$: effective dielectric constant
$BW = f_h - f_1$
C : the speed of light

L_A : the insertion loss at the resonant frequency

Realistically it is not easy to formulate the relation between the effective dielectric constant and the theoretical dielectric constant from measured microstrip characteristics. In fact, the relations we derived are rather complicated, and it is suggested that the empirical formula (5) is used instead.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-\frac{1}{2}} \tag{5}$$

where

h : thickness of the medium material

W : width of the microstrip line

ε_{eff} : the effective dielectric constant

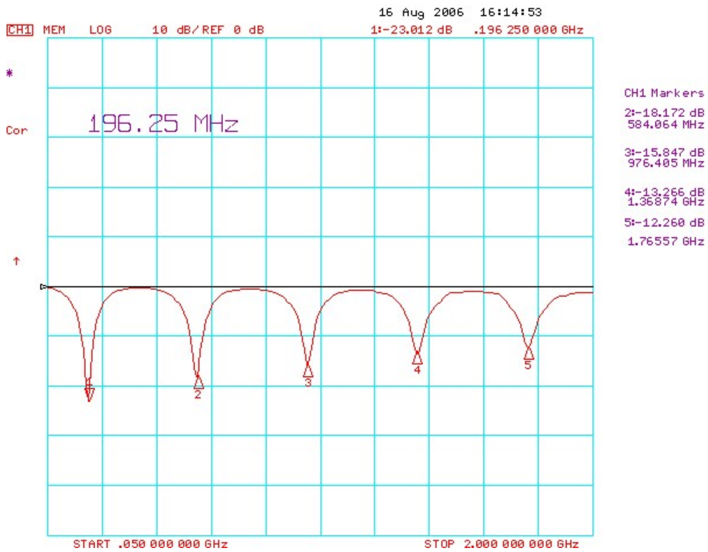
ε_r : the dielectric constant

The most important requirement of this experiment is to accurately measure the frequency, the resonators are first measured by sweeping over a broad frequency range to determine the location of resonant frequency, and then a set of narrow frequency are swept to measure around each resonant frequency to ensure low measurement error. The insertion loss S_{21} of resonators over 0–3 GHz for the quarter-wave length open stub resonators is shown in Figure 2(a) and the expanded view of one resonance is shown in Figure 2(b). All Q-factors are measured at no more than 0.2 GHz frequency steps in order to keep the measurement error less than $\pm 3\%$ for the Q-factors lower than 100, while the measurement error is less than $\pm 6\%$ for the other higher Q-factors [11].

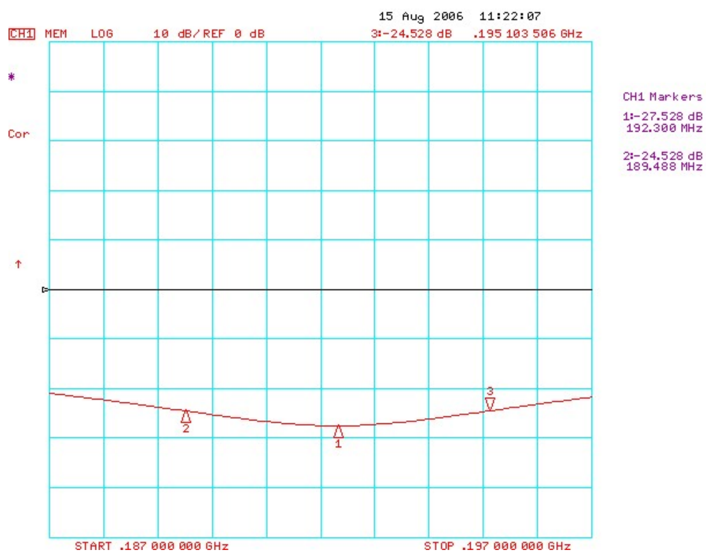
3. EXPERIMENTAL RESULTS AND DISCUSSION

In this paper, we select the FR4 substrate ($\varepsilon_r = 4.5$, $H = 0.76\,\text{mm}$, $t = 0.02\,\text{mm}$) as the measurement material and implementing the quarter-wavelength open stub resonators as the measurement method. As shown in Figure 3 is a 600 MHz quarter wavelength open stub resonator for a PCB's 50 Ω transmission line. The measured dielectric constant has results shown in Table 1, which reveals that when the resonant frequency is getting higher, the associated dielectric constant (ε_r) of the medium material is becoming lower.

The measured results of the loss factor (α) of the designed resonant frequency are listed in Table 2. As shown in Figure 3, it appears that when the designed resonant frequency is higher, its associated



(a)



(b)

Figure 2. (a) Measured S_{21} of the quarter-wavelength open stub resonator at 193 MHz. (b) Expanded scale of the measured S_{21} of the quarter-wavelength open stub resonator at 193 MHz.

Table 1. Statistics of the dielectric constant (ε_r).

Resonant Frequency (GHz)	ε_{eff}	ε_r
0.1923	3.5725	4.7611
0.3847	3.5715	4.7597
0.582	3.5122	4.6673
0.995	3.3965	4.5038
2.0075	3.3154	4.3852

Table 2. Statistics of the loss factor of each of the 200 MHz, 400 MHz and 600 MHz harmonic resonant frequencies.

Resonant Frequency (MHz)	load Q	unload Q	Attenuation dB/m
The First Resonant Frequency by 200MHz Quarter-wavelength Resonator	34.2476	34.3082	0.9636
The Third Resonant Frequency by 200MHz Quarter-wavelength Resonator	39.803	40.2349	2.4651
The Fifth Resonant Frequency by 200MHz Quarter-wavelength Resonator	42.5564	43.6388	3.788
The Seventh Resonant Frequency by 200MHz Quarter-wavelength Resonator	43.5178	45.4185	5.0954
The Ninth Resonant Frequency by 200MHz Quarter-wavelength Resonator	44.5599	47.3726	6.281
The First Resonant Frequency by 400MHz Quarter-wavelength Resonator	36.1764	36.2415	1.8247
The Third Resonant Frequency by 400MHz Quarter-wavelength Resonator	39.9465	40.4413	4.9056
The Fifth Resonant Frequency by 400MHz Quarter-wavelength Resonator	41.5511	42.3743	7.8031
The First Resonant Frequency by 600MHz Quarter-wavelength Resonator	36.3818	36.2415	1.8247
The Third Resonant Frequency by 600MHz Quarter-wavelength Resonator	39.9465	40.4413	7.0465

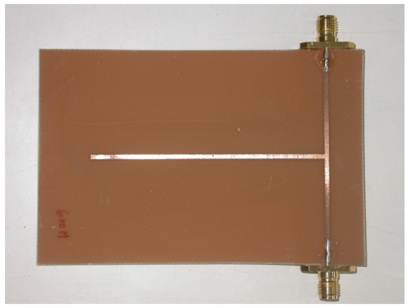


Figure 3. A 600 MHz quarter wavelength open stub resonator.

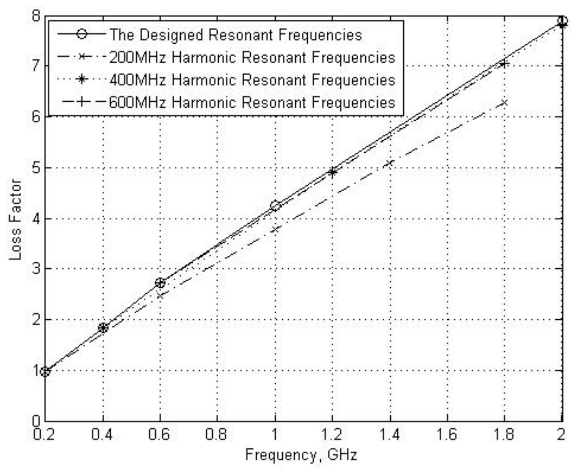


Figure 4. Loss factor (α) of the designed resonant frequencies, 200 MHz harmonic resonant frequencies, 400 MHz harmonic resonant frequencies and 600 MHz harmonic resonant frequencies.

loss factor α is getting larger. On the other hand, due to most of the radiation and discontinuity losses are undesirably included in the measuring of unloaded Q-factor and it depicts that the unloaded Q-factor is not repeatable for measuring at different designed frequency. Theoretically, when measuring at certain designed resonant frequency, we can also get data at the third harmonic, the fifth harmonic, the seventh harmonic and even higher harmonic resonant frequencies. Consequently, we can have simultaneously the statistics loss factor and dielectric constant of resonant frequencies as shown in Table 2. However, from the measured results the loss factor of other frequency of each of the stub's quarter-wave resonances, as shown in Figure 4, is

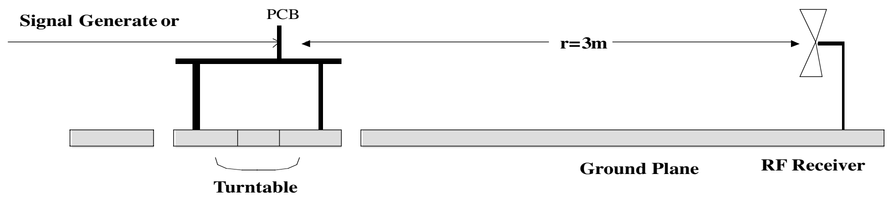


Figure 5. Test setup in a semi-anechoic room for the measurement of the overall maximum radiated field of a parallel-plane structure.

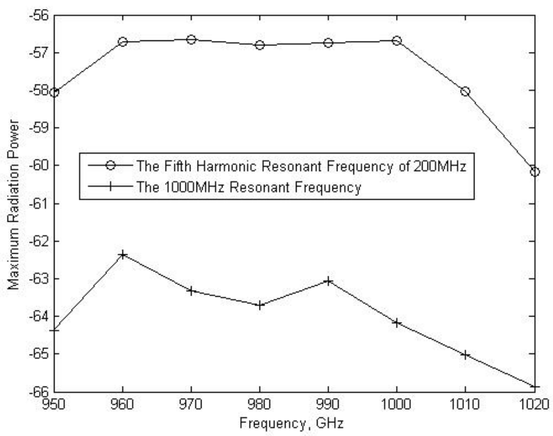


Figure 6. The maximum radiation field strengths of the fifth harmonic of the designed 200 MHz resonant quarter-wavelength resonator and the designed 1 GHz resonant quarter-wavelength resonator.

lower than theoretically expected. It is primarily due to the radiation loss that affects the characterizing of the loss factor of the quarter-wavelength open stub resonator [12–18].

As shown in Figure 5, a parallel-plane structure is placed in a $9\,\mathrm{m} \times 6\,\mathrm{m} \times 6\,\mathrm{m}$ Semi-Anechoic Chamber for measuring its overall maximum radiation field. The test board is placed on a wooden table and is excited by the signal generated from the measuring receiver through an SMA jack that is soldered to the PCB. The maximum field strength is measured at each frequency when the receiver antenna is positioned in parallel or perpendicular to the plane of the table or when the receiver antenna is in the horizontal or vertical polarization. As shown in Figure 6 is the maximum radiation field strengths measured at distance $r = 3\,\mathrm{m}$ for the designed 1 GHz resonant quarter-wavelength resonator and for the fifth harmonic of the designed 200 MHz resonant quarter-wavelength resonator. From the figure it reveals that the maximal radiation field of the fifth harmonic of the 200 MHz resonant resonator is larger than that of the designed 1 GHz resonant quarter-wavelength resonator consequently the loss factor of the fifth harmonic of the designed 200 MHz resonant quarter-wavelength resonator is lower than the 1 GHz resonator.

4. CONCLUSIONS

The characterization of transmission line loss factor by extracting from the measured Q-factor of quarter-wavelength open stub resonators at the designed frequency and other higher harmonic resonant frequencies is experimented and demonstrated in this paper. Most of the radiation and discontinuity losses are undesirably including the measuring of the unloaded Q-factor and it consequently shows that the unloaded Q-factor measurement is not repeatable for other different designed frequency. Thus, only the loss factor at the designed frequency that is extracted from the measured Q-factor of the quarter-wavelength open stub resonators method is reliable, although the loss factors of other higher harmonic resonant frequencies of each of the stub's quarter-wave resonances are obtainable simultaneously.

REFERENCES

1. Edwards, C. L., M. L. Edwards, and S. Cheng, "A simplified analytic CAD model for linearly tapered microstrip lines including losses," *IEEE Trans. on Microwave Theory and Tech.*, Vol. 52, No. 3, 2004.
2. Afsar, M. N., J. R. Birch, and R. N. Clarke, "The measurement of the properties of materials," *Proc. IEEE*, Vol. 74, No. 1, 183–199, 1986.
3. Yamacli, S., C. Ozdemir, and A. Akdagli, "A method for determining the dielectric constant of microwave PCB substrates," *International Journal of Infrared and Millimeter Waves*, Vol. 29, No. 2, 207–216, 2008.
4. Kumar, A. and G. Singh, "Measurement of dielectric constant and loss factor of the dielectric material at microwave frequencies," *Progress In Electromagnetics Research*, PIER 69, 47–54, 2007.
5. Qian, C. and W. B. Dou, "A new approach for measuring permittivity of dielectric materials," *Journal of Electromagnetic Waves and Applications*, Vol. 19, 795–810, 2005.
6. Bogle, A., M. Havrilla, D. Nyquis, L. Kempel, and E. Rothwell, "Electromagnetic material characterization using a partially filled

rectangular waveguide," *Journal of Electromagnetic Waves and Applications*, Vol. 19, 1291–1306, 2005.

7. Roumeliotis, J. A., "Resonant frequencies in an electromagnetic rectangular/cylindrical/spherical cavity with an inner-off-axis smalldielectric sphere," *Journal of Electromagnetic Waves and Applications*, Vol. 11, 185–195, 1997.
8. Carroll, J., M. Li, and K. Chang, "New technique to measure transmission line attenuation," *IEEE Trans. on Microwave Theory and Tech.*, Vol. 43, No. 1, 219–222, 1995.
9. Edwards, T. C., *Foundations for Microstrip Circuit Design*, 2nd edition, 254–255, John Willy & Sons, New York, 1992.
10. Kirschning, M., R. H. Jansen, and N. H. L. Koster, "Accurate model for open end effect of microstrip lines," *Electron Lett.*, Vol. 17, No. 3, 123–125, Feb. 1981.
11. Goldfarb, M. and A. Platzker, "Losses in GaAs microstrip," *IEEE Trans. on Microwave Theory and Tech.*, Vol. 38, No. 12, 1957–1963, Dec. 1990.
12. Leone, M., "The radiation of a rectangular power-bus structure at multiple cavity-mode resonances," *IEEE Trans. Electromagn. Compat.*, Vol. 45, No. 3, 486–492, Aug. 2003.
13. Chen, R. L., J. Chen, T. H. Hubing, and W. Shi, "Analytical model for the rectangular power-ground structure including radiation loss," *IEEE Trans. Electromagn. Compat.*, Vol. 47, No. 1, 10–16, Feb. 2005.
14. Ranjkesh N. and M. Shahabadi, "Loss mechanisms in SIW and MSIW," *Progress In Electromagnetics Research B*, Vol. 4, 299–309, 2008.
15. Mondal, M. and A. Chakrabarty, "Resonant length calculation and radiation pattern synthesis of longitudinal slot antenna in rectangular waveguide," *Progress In Electromagnetics Research Letters*, Vol. 3, 187–195, 2008.
16. Hussein, K. A., "Efficient near-field computation for radiation and scattering from conducting surfaces of arbitrary shape," *Progress In Electromagnetics Research*, PIER 69, 267–285, 2007.
17. Valagiannopoulos, C. A., "Single-series solution to the radiation of loop antenna in the presence of a conducting sphere," *Progress In Electromagnetics Research*, PIER 71, 277–294, 2007.
18. Shin, D. H. and T. Itoh , "A note on radiation loss of zeroth order resonators," *Progress In Electromagnetics Research C*, Vol. 2, 109–116, 2008.