A CPW T-Resonator Technique for Electrical Characterization of Microwave Substrates

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***Abstract*—An impedance independent method is proposed using a finite ground coplanar waveguide (CPW) T-resonator to electrically characterize microwave materials. Silicon-based CPW T-resonators are designed and measured, with calibrated data agreeing well with other methods up to 30 GHz. Uncalibrated measurements produce dielectric constant and attenuation results within 3.7% and 25%, respectively, of those obtained with calibration. Hence, the CPW T-resonator can be used to provide rapid and accurate characterization of microwave substrates with unknown dielectric properties.**

***Index Terms*—Coplanar waveguide, dielectric constant, resonators, semiconductor material measurements.**

I. Introduction

THE MICROSTRIP T-resonator technique [1] allows quick and accurate electrical characterization of microwave substrates up to 20 GHz [2]. The primary advantages of this technique over others are a) easy implementation and testing, b) broadband results, and c) calibration independence of data.

Two important factors, however, limit the applicability of the microstrip T-resonator to novel substrates. First, effective dielectric constant (ε_{eff}) is a strong function of line impedance and thus of line dimensions and substrate height. Hence, its use is hindered on substrates with unknown dielectric constant. Second, the microstrip configuration cannot be easily implemented on all substrates since via holes may be necessary to transfer ground signals to the lower substrate surface. This is particularly true in assessment of novel materials such as porous silicon [3], [4] that form an integrated layer on the host substrate, silicon. A coplanar waveguide (CPW) T-resonator approach can be used to overcome both of these issues since the effective dielectric constant has weak impedance dependence and all conductors are printed on one surface.

II. Design and Fabrication

At odd quarter-wavelengths, a standing wave distribution exists along the open-circuited T-resonator stub (see Fig. 1) and presents well-defined resonances. Under low loss conditions, the resonant frequency (f_n) and 3 dB bandwidth (BW_n) around each resonance point can be used to extract effective dielectric constant $(\varepsilon_{eff,n})$ and total attenuation $(\alpha_{tot,n})$, according to

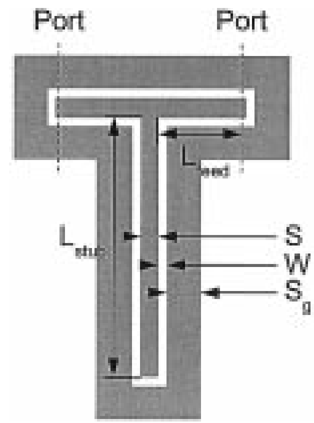

Fig. 1. Layout of a CPW T-resonator (not to scale).

$$\varepsilon_{eff,n} = \left(\frac{n \cdot c}{4 \cdot L_{stub} \cdot f_n}\right)^2 \quad (1)$$

$$\alpha_{tot,n} = 8.686 \cdot \frac{\pi \cdot n \cdot BW_n}{4 \cdot L_{stub} \cdot f_n} \left[\frac{\text{dB}}{length}\right] \quad (2)$$

where n is the resonance index ($n = 1, 3, 5, ...$), c is the speed of light in vacuum and L_{stub} is the effective physical length of the resonating stub.

Using Hoffman's equations [5] and finite ground coplanar waveguide techniques [6], 50 Ω test circuits are designed with signal line (S), gap (W), and ground plane (S_g) widths of 94, 53, and 400 μm, respectively, on silicon ($\varepsilon_{r,\text{Si}} = 11.7$). Gap spacing at the stub open end and feed line ends is also 53 μm. The T-resonator layout, shown in Fig. 1, has stub (L_{stub}) and feed lengths (L_{feed}) of 1.0 cm and 0.2 cm, respectively. All circuits are printed on high resistivity silicon wafers [n-type (100), >2000 Ω-cm, 525 μm thick] with an evaporated Ti/Au (400/1500 Å) layer that is gold electroplated to 4 μm.

III. Experimental Results

Scattering parameter data are measured on an HP8510C automatic network analyzer using a Cascade Microtech/Alessi RF1 microwave probe station with Cascade Microtech GSG150 probes. In this work, a probe-tip calibration, based on the LRM (Line–Reflect–Match) technique, is performed on an ISS alumina substrate.

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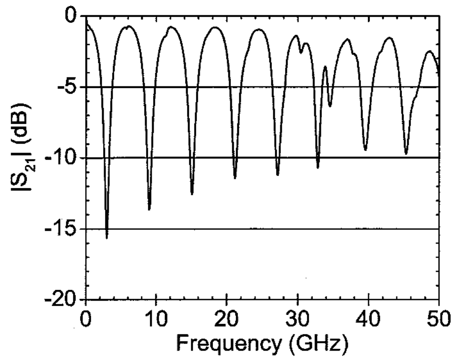


Fig. 2. Magnitude S_{21} response of a wire bonded CPW T-resonator with S–W–S_g = 94–53–400 μm, measured with an LRM calibration.

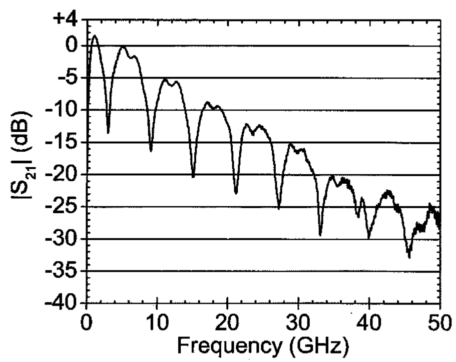


Fig. 3. Magnitude S_{21} response of a wire bonded CPW T-resonator with S–W–S_g = 94–53–400 μm, measured with no calibration.

A. Odd Mode Suppression for CPW T-Resonators

Coplanar waveguide structures can support both the desired even as well as the undesired odd mode. Unfortunately, discontinuities like the CPW T-junction increase the excitation of the latter mode [7], requiring wire bonds to short opposing ground planes at the junction for odd mode suppression.

Before bonding, only the first three resonance points are easily identifiable. Above 20 GHz, parasitic modes obscure the resonant behavior. S-parameter data measured after gold wire bonding are plotted in Fig. 2. The response is noticeably improved, with visible resonance values through 50 GHz (the anomaly around 34 GHz shows response sensitivity to other modes induced or uncompensated by the wire bonds). The resonant frequencies in both cases agree within 2.8%, indicating that the wire bonds suppress parasitic modes up to 30 GHz without significantly changing the resonator response.

B. Calibration Independence

For comparison, the uncalibrated response of the same wire bonded T-resonator is shown in Fig. 3. When resonance values are extracted from S_{21} data using an ANSI C program, the LRM and uncalibrated resonant frequencies agree within 1.8% and the bandwidths within 23% across the entire frequency band. Corresponding percentage errors in the calculated effective dielectric constant and attenuation are 3.7% and 25%, respectively. Thus, the T-resonator supplies reliable electrical property data regardless of the presence or quality of calibration.

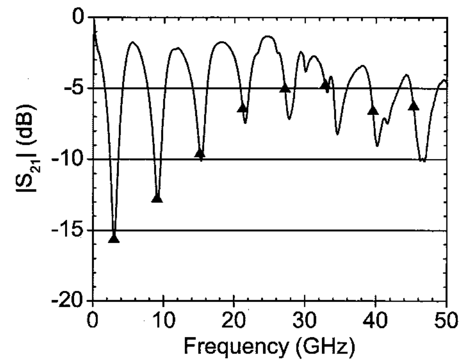


Fig. 4. Magnitude S_{21} of a wire bonded CPW T-resonator with 0.84 AR (solid line) measured with an LRM calibration. The solid triangles (▲) indicate resonant frequency locations for a wire bonded 0.47 AR CPW T-resonator (see Fig. 2 for complete response).

C. Impedance Independence

Effective dielectric constant (ε_{eff}) is a function of CPW aspect ratio (AR $\equiv S/(S+2W)$) and is computed using a two-dimensional simulation[1] of the transmission line cross section. The observed variation in ε_{eff} is less than 5% from its peak value (at 50 Ω) for AR between 0.04 and 0.93.

The measured S_{21} response of wire bonded T-resonators is plotted in Fig. 4 for aspect ratios of 0.47 and 0.84 with corresponding line dimensions (S–W–S_g) of 94–53–400 and 167–17–400 μm, respectively. Note that only resonant frequency points are indicated for the 0.47 AR design since full data is presented in Fig. 2. Resonant frequencies agree within 3.4% across the band and 3 dB bandwidths agree within a factor of 2.4. This is excellent agreement given the large difference in characteristic impedance values. Simulated impedances for the 0.47 and 0.84 AR lines are 48 and 29 Ω with effective dielectric constants of 6.16 and 6.04, respectively. The lower effective dielectric constant of the 29 Ω T-resonator causes the resonant frequency spacing to broaden slightly, as can be seen in Fig. 4.

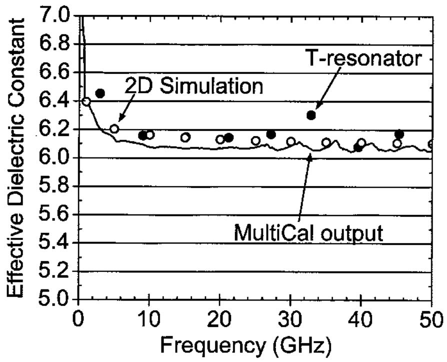
D. Extracted Electrical Properties

Using equations (1) and (2), the electrical properties of the 48 Ω sample can be calculated. The value of ε_{eff} (excluding the lowest frequency point) is 6.19 $\pm$ 0.11 and attenuation (α_{tot}) is 1.84 dB/cm at 27.2 GHz. In Fig. 5, T-resonator results are compared with simulated values as shown in footnote 1 and measured data from the through-line-reflect (TRL) calibration software MultiCal[2] [8] for identically dimensioned calibration standards on the same substrate.

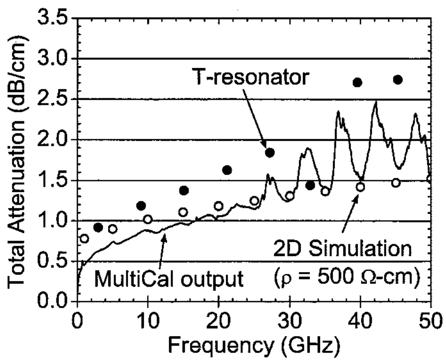
Below 30 GHz, the T-resonator results agree well with the other methods. Above this frequency, the measured resonator attenuation increases sharply and ε_{eff} begins to exhibit perturbed behavior, indicating that the T-junction no longer supports single-mode propagation. These perturbations can be suppressed by using higher quality bonds (e.g., airbridges [7]) to extend the frequency band.

[1]Maxwell 2D Extractor, version 2.0.63 (1999). Pittsburgh, PA: Ansoft Corporation.

[2]R. B. Marks and D. F. Williams, Program MultiCal revision 1.00 (Aug. 1995). Boulder, CO: National Institute of Standards and Technology (NIST).



(a)



(b)

Fig. 5. (a) Effective dielectric constant and (b) total attenuation in dB/cm as a function of frequency. The wire bonded CPW T-resonator has S–W–S_g = 94–53–400 μm and is measured using an LRM calibration.

IV. Conclusion

The CPW T-resonator has been shown to provide accurate electrical characterization of microwave materials. The resonator is easy to implement, can provide correct data on substrates of unknown dielectric constant, and is calibration and largely impedance independent up to 30 GHz with simple wire bonds. The application of the CPW configuration to the T-resonator technique offers a quick and effective method to characterize novel laminates, thin films, ceramics, and semiconductor substrates for microwave circuit applications.

Acknowledgment

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References

[1] D. I. Amey and J. P. Curilla, "Microwave properties of ceramic materials," in *Proc. 41st Electron. Comput. Technol. Conf. (ECTC 91)*, 1991, pp. 267–272.

[2] D. I. Amey and S. J. Horowitz, "Tests characterize high-frequency material properties," *Microwaves RF*, pp. 68–80, Aug. 1997.

[3] C.-M. Nam and Y.-S. Kwon, "Coplanar waveguides on silicon substrate with thick oxidized porous silicon (OPS) layer," *IEEE Microwave Guided Wave Lett.*, vol. 8, pp. 369–371, Nov. 1998.

[4] R. L. Peterson and R. F. Drayton, "Dielectric properties of oxidized porous silicon in a low resistivity substrate," in *IEEE Int. Microwave Symp. Dig.*, May 2001, pp. 767–770.

[5] R. K. Hoffman, *Handbook of Microwave Integrated Circuits*. Norwood, MA: Artech House, 1987, pp. 338–339 and 351–362.

[6] K. J. Herrick, "W-band three-dimensional integrated circuits utilizing silicon micromachining," Ph.D. dissertation, Dept. Elect. Eng. Comput. Sci., Univ. Michigan, Ann Arbor, chs. 1–2, 2000.

[7] R. Kulke, M. Rittweger, W. Simon, A. Wien, and I. Wolff, "High resolution coplanar structures on multilayer LTCC for applications up to 40 GHz," in *Int. Symp. Microelectron. (IMAPS) Dig.*, Oct. 1999, pp. 79–83.

[8] R. Marks, "A multiline method of network analyzer calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1205–1215, July 1991.