Ring-Resonator Method—Effective Procedure for Investigation of Microstrip Line

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***Abstract*—In addition to the traditional application of the ring-resonator method for determination of the microstrip line effective permittivity, measurements of the insertion losses and equivalent substrate permittivity are proposed. The obtained data for a number of isotropic and anisotropic substrate materials are in good agreement with the results predicted theoretically.**

***Index Terms*—Attenuation coefficient, effective permittivity, microstrip line, ring resonator, substrate anisotropy, substrate permittivity.**

I. Introduction

THE ring-resonator method proposed by Troughton [1] is one of the successful experimental procedures for evaluation of the effective permittivity in a wide frequency range. First this method was used in the case of microstrip line, and afterwards was applied to different planar transmission lines: suspended and inverted microstrip line, coplanar lines, coupled lines etc. [2], [3]. The ring-resonator method is simple in realization and easy to use. In comparison with the linear resonator method [3, pp. 189–191], where the influence of edge effects must be taken into account properly, the ring-resonator method is more accurate, wideband and compact if a resonator with large enough diameter is used. In addition to the traditional application, two novel implementations of microstrip ring resonators are proposed. The first approach is a procedure for determination of the attenuation coefficient through measurement of the unloaded quality factor of the ring resonator. The second approach is related to determination of the "equivalent substrate permittivity." This parameter is calculated by the Kirschning and Jansen formulae [4], applied for solving the reverse problem—determination of the substrate permittivity through the measured values of the effective permittivity. Applicability of the described procedures is demonstrated for microstrip line realized on different microwave substrate materials. In particular, measured data for equivalent permittivity of reinforced laminate substrates are presented. These data could be used as a supplement to the reference permittivity values offered by manufacturers for microstrip application of reinforced materials.

II. Description of the Measuring Procedure

In [1] the application of the ring-resonator method was demonstrated in the frequency range 2–18 GHz for the case of a microstrip line. The method is based on the relation $\pi.D = n.\lambda_g$, where D is the medium diameter of the ring and n is number of wavelengths λ_g along the ring circumference. The correct application of the ring-resonator method supposes several requirements [3, p. 186]: weak influence of curvature effect; small local distortions of the field in the vicinity of coupling gap; low field interaction across the ring and good reproducibility of microstrip parameters (strip width W, substrate thickness h and permittivity ε_r) along the ring circumference. In addition, one can point conditions for the existence of "quasi TEM" approximation, which can be formulated as $W \ll \lambda_g$ and $h \ll \lambda_g$. The satisfaction of the above-mentioned demands could be fulfilled by the following assumptions:

- microstrip line on thin enough substrates and moderate values of the strip width (for instance corresponding to the impedance values 30–80 Ω) should be used to prevent radiation effects and excitation of higher modes;
- ring-resonator diameter larger than the wavelength, corresponding to the lowest frequency used $(n > 3)$ is necessary to ensure proper determination of the resonator length;
- gap between the exciting microstrip lines and the ring resonator must cause small coupling (e.g. when the resonance values of the transmission coefficient are below -30 dB).

At these conditions the application of the microstrip ring resonator seems to be quite reasonable and the effective permittivity can be determined by the expression

$$\varepsilon_{eff}(f) = \left(\frac{95.449}{D}.\frac{n}{f_n}\right)^2 \quad (1)$$

where f_n is the measured resonance frequency in GHz and ring diameter D is in mm. The ring resonator could be tested either in transmission [2] or reflection mode [3]. The used measurement set-up consists of a scalar network analyzer (e.g. Hp 8757S) for observing the transmission coefficient $S21$, and digital counter with frequency resolution 10^{-7} for the measurement of the frequencies f_n. Due to the small coupling, reflection coefficients $S11$ and $S22$ approach unity and strong interference between the incident and the reflection waves causes deterioration of some resonance curves. Therefore, one suitable approach to overcome this constrain is to use attenuators (6–10 dB) connected to the input and output of the test fixture. The influence of the signal level instability over the measurement is reduced using a reference signal (ratio A/R is measured with averaging). In addition to that, 5–10 readings are used to get mean values of the experimental data.

Manuscript received July 3, 2002; revised October 3, 2002. The review of this letter was arranged by Associate Editor Dr. Shigeo Kawasaki.

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Digital Object Identifier 10.1109/LMWC.2003.814599

The determination of the attenuation coefficient is based on the expression $\alpha_{\text{tot}} = \pi/Q_0\lambda_g$ [2], where Q_0 is the unloaded quality factor. Thus, the application of the ring resonator method requires additional measurements of the resonance linewidth Δf_n (at -3 dB) and transmission coefficient $S21_n$ at each resonance. Using measured data one can determine the attenuation coefficient from the expression

$$\alpha_{\text{tot}} = 8.685\,89.\frac{n}{D}.\frac{\Delta f_n}{f_n}.\left(1 - 10^{\frac{-S21_n}{20}}\right),\ \left[\frac{\text{dB}}{\text{unit length}}\right]. \tag{2}$$

The accuracy of (2) depends mainly on the measurement error of resonance linewidth Δf_n. Therefore, the network analyzer has to be calibrated with a frequency span of several times Δf_n.

Determination of the substrate permittivity ε_r may be done through the expressions for effective permittivity $\varepsilon_{eff}(\varepsilon_r, W/h, t/h, f)$, derived by Kirschning and Jansen [4] on the basis of a large quantity of theoretical and experimental results. According to [6], their formulae are the best approximation for determination of the frequency dependence of microstrip effective permittivity with an accuracy of 0.6%. Below the set of expressions in [4], together with the formulae for determination of the static value of the effective permittivity $\varepsilon_{\text{eff}}(f = 0)$ in [6], are used. The calculation procedure is arranged as Fortran code **MICROF**, where microstrip line parameters: substrate thickness h, strip width W and conductor thickness t have to be substituted. Then, the value for substrate permittivity in the expressions for the effective permittivity is varied at every measured frequency f_n, until the calculated and measured values of the effective permittivity coincide (e.g. up to 3 or 4 digits after the decimal point). The current value of permittivity corresponding to this requirement is the search value of the substrate permittivity. The described procedure could be performed with modern transmission line calculators as TRL 8.0 included into the circuits design tool Serenade developed by Ansoft Corporation [5]. The comparison of the results obtained with a calculator [5] and with expressions summarized in [6] show very good correlation. The differences are less than 1% and can be explained with the use of slightly different expressions for the determination of the static permittivity $\varepsilon_{eff}(f = 0)$.

III. Experimental Results

The described procedure for determination of microstrip line parameters was applied in the investigation of a microstrip line realized on different substrate materials. All measurements are done for ring resonators with a mean diameter $D = 40.04$ mm, coupled to the exciting microstrip lines with a gap of 0.2 mm. For substrate permittivity $\varepsilon_r = 3 - 4$ the number of the observed resonances n varies between 2 and 11 in the frequency range 3–17 GHz. As far as the measurements are performed for known substrates, the identification of number n is not a problem. When the preliminary information for the substrate permittivity is not enough, one can recommend n to be determined from the standing wave pattern, proven with a small electric dipole antenna scanning near to the ring circumference. During the experimental measurements the influence of a metal/absorbing plate, placed at a height ten times the substrate thickness above the ring resonator, was checked. No visible shifting of the resonance frequencies and deterioration of the resonance curves shape was observed, so a conclusion for the absence of radiation loss was made.

TABLE I
COMPARISON OF MEASURED AND CALCULATED DATA FOR 50 Ω MICROSTRIP LINE ON RO3003 SUBSTRATE WITH THICKNESS 0.26 MM

n	2	3	4	5	6	7	8	9	10	11
f_n, MHz	3081	4620	6160	7700	9237	10768	12309	13837	15350	16883
Δf_n, MHz	27.41	33.73	41.52	50.67	60.30	66.41	70.54	77.88	86.17	93.39
$S21_n$, dB	48.5	44.7	41.5	39.7	36.7	39.4	38.2	39.0	35.0	31.7
ε_{eff}	2.3943	2.3961	2.3961	2.3964	2.3977	2.4014	2.4006	2.4042	2.4117	2.4124
ε_{eq}	3.022	3.021	3.018	3.014	3.012	3.011	3.006	3.007	3.012	3.007
α_{tot}, dB/cm	0.0385	0.0473	0.0580	0.0707	0.0838	0.0926	0.0983	0.1084	0.1154	0.1285
α_{tot}, Tr. line	0.0367	0.0482	0.0588	0.0695	0.0799	0.0898	0.0995	0.1089	0.1234	0.1320
α_{tot}, Ref. [6]	0.0423	0.0546	0.0653	0.0749	0.0837	0.0920	0.0999	0.1074	0.1146	0.1215
α_{tot}, Ref. [5]	0.0480	0.0618	0.0738	0.0845	0.0944	0.1036	0.1123	0.1206	0.1285	0.1363

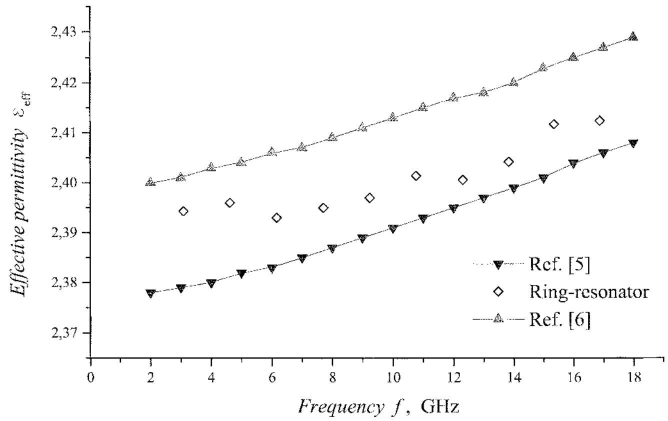

Fig. 1. Comparison of the measured and calculated data for the effective permittivity of microstrip line with dimensions $W = 0.5909$ mm and $t = 17.5$ μm on RO3003 substrate with thickness 0.26 mm.

At first, the ring-resonator method was used for characterization of microstrip line on isotropic material—RO3003 laminate substrate with thickness of 0.26 mm. The results of measurements and calculations for microstrip line of width $W = 0.5909$ mm and conductor thickness $t = 17.5$ μm ($\approx$50 Ω) are presented in Table I. The measured data are summarized in the first four rows while the latter relates to microstrip line parameters calculated from expressions (1), (2), and [5], [6].

The experimental results for the effective permittivity (1) presented in Table I show weak frequency dependence. In Fig. 1 the measured data for the effective permittivity are compared with the values calculated by the expression in [6] and with TRL 8.0 [5]. As it can be seen, except lower frequencies where the relative error of the ring-resonator method is somewhat higher, the measured data correlate better with those obtained by the calculator TRL 8.0. This fact should be considered as an argument to use the calculator TRL 8.0 for determination of the microstrip line effective permittivity with a good accuracy (error less 1 percent). Therefore, later on the evaluation of substrate equivalent permittivity is done by design tool TRL 8.0. The sixth row of Table I contains these permittivity values recalculated through measured data for effective permittivity. Its mean value $\varepsilon_{\text{eq}} = 3.013\ (+0.01/-0.007)$ is very close to the reference value $\varepsilon_{\text{r}} = 3.0 \pm 0.04$ announced by the manufacturer [7]. Thus, the proposed procedure can be used for precise determination of the substrate permittivity in the case of isotropic materials.

The data for attenuation coefficient α_{tot} determined from expression (2) are shown in the seventh row of Table I. The validation of the data for the attenuation coefficient obtained by the ring-resonator method is done in two different ways—one experimental and the other theoretical. The experimental verification is made by a conventional measurement of a straight microstrip line. The Insertion Loss of three microstrip lines of length $l = 177$, 99, and 60 mm were measured with the Vector Network Analyzer Hp 8510C. Afterwards the measured data are used for determination of the attenuation coefficients of the pure microstrip lines with length $\Delta l = 117$, 78 and 39 mm. Their average values are plotted in next row of Table I for comparison. As one can see, the values of the attenuation coefficients measured by the ring-resonator method and straight microstrip line are very close to each other—the difference varies from 1.9 to 5.7%.

The theoretical estimation of the attenuation coefficient $\alpha_{tot} = \alpha_d + \alpha_c$ uses the expressions for dielectric and conductor losses summarized in [6], as well as corresponding results obtained with the design instrument TRL 8.0. The calculations are done for the microstrip line with the same dimensions as the above mentioned and RO3003 substrate parameters from the manufacturer [7]: permittivity $\varepsilon_{\rm r} = 3.0$, dielectric loss factor—$\tan\delta_\varepsilon = 0.0013$, Cooper surface resistance $R_s = 1.82\,\mu\Omega$.cm and conductor roughness $\Delta = 1.9\,\mu$m. The results from calculations are presented in Table I also (last 2 rows). The comparison shows that the values of the attenuation coefficients measured through the ring-resonator method are closer to data calculated from [6]—the differences vary from 12–15% at lower frequencies to 1–2% at higher frequencies (except the last one). The average value of the difference in the range 3–17 GHz is 5.88% and one can consider the expressions in [6] as a realistic basis for a theoretical estimation of the attenuation coefficient of a microstrip line (the corresponding difference for the results obtained with the calculator TRL 8.0 is 16.95%).

The procedure described above is applied for investigation of microstrip line on RO3203 substrate with thickness $h = 0.26$ mm also. This material is ceramic filled PTFE reinforced with woven glass. Hence, one can expect some increasing of both the effective and equivalent permittivity to a certain extent. The equivalent values for permittivity ε_{eq} are greater than the reference value $\varepsilon_{\rm r} = 3.02 \pm 0.04$ announced in [7]. Depending on the microstrip line width W, the equivalent permittivity varies from $\varepsilon_{\rm eq} = 3.123\ (+0.009/-0.018)$ for narrower strip ($W = 0.313$ mm), through the value $\varepsilon_{\rm eq} = 3.116\ (+0.009/-0.002)$, for middle sized strip ($W = 0.595$ mm), to $\varepsilon_{\rm eq} = 3.094\ (+0.013/-0.004)$ for wider strip ($W = 1.019$ mm). Thus, the increment of the strip width W causes a slight fall of the equivalent permittivity which tends to the reference value ε_r, measured through the method of the "wide enough linear resonator" [8], where the electric field is predominantly normal to the substrate plane. The reference value $\varepsilon_{\rm r}$ is related to the permittivity $\varepsilon_\perp$ associated with perpendicular orientation of the applied electric field. The permittivity in the plane of the substrate $\varepsilon_{||}$ measured with a cylindrical resonator operated on $\rm TE_{011}$ mode is $\varepsilon_{||} = 3.23 \pm 0.04$. On the basis of these results one can conclude that RO3203 substrate material has anisotropy in the order of 7 percent. Therefore, the use of equivalent permittivity $\varepsilon_{\rm eq}$ introduced first in [9] will simplify the design of microstrip circuits on anisotropic substrates undoubtedly, as this parameter depends weakly on the frequency and strip width.

The measured attenuation coefficients for microstrip lines on RO3203 substrate have a similar frequency behavior and dependence of strip width W as those for RO3003 in Table I. For the case of a 50 Ωmicrostrip line ($W = 0.595$ mm) on RO3203 substrate, the values for the attenuation coefficient are somewhat higher, because the dielectric loss factor $\tan\delta_\varepsilon$ of substrate material RO3203 is slightly greater (0.0016 against value 0.0013 for RO3003).

IV. Conclusions

In addition to the traditional application of the ring-resonator method—measurement of the effective permittivity—determination of the total attenuation coefficient of the microstrip line and equivalent permittivity of the substrate material are proposed. The measured values for the attenuation coefficient are in good agreement with data obtained through Insertion Losses of straight microstrip lines and theoretical prediction in [6]. The equivalent permittivity is found to be a useful parameter for the characterization of a microstrip line on anisotropic substrates. In comparison with the traditional method of the linear stripline resonator [8], the proposed procedure for determination of the equivalent permittivity gives more realistic data for a microstrip line application and number of other cases when the electric field is not predominantly normal to the substrate plane. The described method is simple in realization and accurate enough for the estimation of both—microstrip line parameters and substrate permittivity.

Acknowledgment

The authors wish to thank SkyGate Bulgaria for the technical assistance during manufacturing of the test fixtures and used measurements facilities.

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