Waveguide Dielectric Permittivity Measurement Technique Based on Resonant FSS Filters

Filippo Costa, *Student Member, IEEE*, Claudio Amabile, Agostino Monorchio, *Senior Member, IEEE* and Enrico Prati

***Abstract*— A method to determine the dielectric permittivity of materials is presented. Such method exploits the use of a low cost frequency selective structure (FSS), transversally placed in a waveguide in the proximity of the sample. The additional dielectric placed close to the FSS, leads to a shift of band-pass and band-stop resonance frequencies. The relationship between the frequency shift and the permittivity of the dielectric under test allows the determination of the unknown permittivity. Such procedure is particularly suitable for measuring the dielectric permittivity of thin slabs.**

***Index Terms*—Frequency Selective Surfaces (FSS), Waveguide Filter, Resonant Dielectric Measurement Technique.**

I. Introduction

The measurement of dielectric permittivity of materials is a key task in microwave engineering for the wide number of applications. A broad variety of measurement techniques has been proposed in the past [1]-[8]. Generally, the choice of a method depends on the kind of material and characterization. The transmission/reflection methods are commonly employed for a wideband characterization of unknown materials [2]-[5]. Such techniques require the measurement of transmission and reflection coefficients for a section of waveguide or coaxial line filled with a sample of the material under test. Waveguide measurements are preferred to other transmission-line devices because of the easy preparation of the sample. The procedure is easy to apply as it does not require an ad-hoc setup. The bulky sample thickness and the problems related to air gap between the wall of the waveguide and the sample (which excites higher-order modes) represent the major critical points. Conversely, resonant methods are more reliable when the characteristic of the unknown material has to be provided in a narrow frequency band with high accuracy [6], [7]. The closed resonator based methods have the highest accuracy, even in the case of materials with low loss. However, sample preparation can be a difficult task in cavity perturbation techniques as the sample requires a regular geometry. There, the sample permittivity is evaluated from the shift of the resonant frequency. All the resonant methods are limited either to specific frequency range, or to some kinds of materials, or to some specific applications.

The method proposed in this paper is a hybrid technique. It employs a waveguide – which is a common transmission/reflection device – in conjunction with a resonant device (the planar frequency selective surface), inserted in the waveguide. When the dielectric sample is accommodated close to the FSS, the resonant frequencies of the transfer function of the resulting cascaded structure (FSS and sample) are shifted as a function of the thickness and the dielectric permittivity of the sample [9]. The advantage of the proposed technique is the cheapness of the printed FSSs and its simplicity, being based on the only amplitude measurement without the need of phase measurements. The technique allows to measure with high precision the dielectric permittivity without employing any ad-hoc device: the accuracy is given by the high value of the quality factor of the resonance. The procedure is particularly suitable for the characterization of thin dielectric slabs, difficult to characterize with standard transmission/reflection techniques.

II. FSS Design

The method is based on typical resonant peaks of transmission or reflection profile of the FSS. In order to estimate both the real and the imaginary parts of the dielectric permittivity, the reference filter is designed to be pass-band in correspondence of the upper frequency limit of the employed waveguide. The FSS is designed on a low loss supporting dielectric substrate both to obtain a mechanical robust setup and to preserve deep resonant peaks at the same time. The filter is designed through an efficient Periodic MoM (PMoM) solver. The MoM analysis within the waveguide is performed by simulating the free-space periodic counterpart as a consequence of the fact that the fundamental mode of a rectangular waveguide can be interpreted as a pair of plane waves bouncing at an oblique incidence between the waveguide lateral walls [10], [11].

III. Measurement Methodology

The aim of the technique is the determination of the unknown permittivity of a dielectric with arbitrary thickness added to the free side of the printed FSS. The procedure can be summarized in the following steps:

- the transmission/reflection response of the unloaded filter is initially measured identifying the resonant peak;
- the additional dielectric is placed close to the FSS measuring the new response and hence the frequency shift of the resonant peak;

Manuscript received October 13th 2010, revised on December 7th, 2010.

F. Costa and A. Monorchio are with Department of Information Engineering, University of Pisa, Via G. Caruso, 56122 - Pisa, Italy. E-mail: filippo.costa@iet.unipi.it, a.monorchio@ieee.org

C. Amabile and E. Prati are with “Laborarorio Nazionale MDM”, INFM-CNR, Via C.Olivetti 2, 20040, Agrate Brianza, Italy. E-mail: claudio.amabile@mdm.infm.it, enrico.prati@mdm.infm.it

- the frequency shift is associated to the unknown permittivity through a Shift-Permittivity Map which is pre-defined through an iterative MoM simulation.

The frequency shift versus permittivity map, which is determined for a specific FSS, allows a straightforward determination of the unknown permittivity from the measured frequency shift. A similar behavior is observed also for different FSS elements since the shift of the resonance is due to the characteristics of the dielectrics and it is weakly dependent on the shape of the printed pattern [12]. The mentioned map, for a specific example here considered, is reported in Fig. 1.

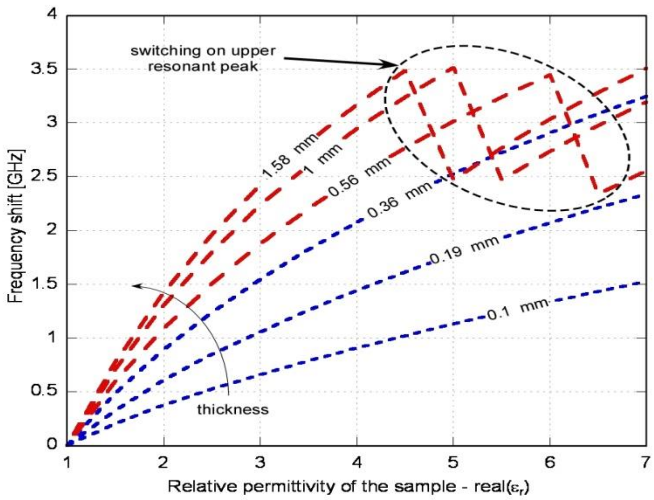

Fig. 1 – Shift-Permittivity Map: unknown dielectric permittivity as a function of the frequency shift of the resonant peak.

The presence of an additional dielectric substrate close to the FSS determines the shift of the resonance frequency towards lower values depending on the slab thickness. A helpful way to understand the behavior of a frequency selective surface is its analogy with lumped circuit. Under the hypothesis of single resonant shape, the frequency response of a capacitive FSS can be represented by a simple LC circuit. If the FSS is loaded with thick dielectrics, the capacitance value approaches to $\varepsilon_r C_0$ (where C_0 is the freestanding capacitance value) with a consequent reduction of the resonance frequency by a factor $\sqrt{\varepsilon_r}$. If the dielectric thickness is lower than half FSS periodicity, its effect can be described by an effective permittivity dependant on dielectrics thickness [13]. A simple relation which describes the behavior of the effective permittivity as a function of the dielectric thickness is available in [12]. As it is evident from Fig. 1, when the thickness of the unknown dielectric is thin compared to the cell periodicity, the shift of the resonance frequency as a function of the sample permittivity is small and the determination of the unknown parameter is unambiguous even for high values of ε_r. For this reason the method is particularly suitable for a precise estimate of the dielectric permittivity of thin slabs. On the contrary, a thickness larger than 1/10 of the cell periodicity determines a considerable shift of the resonance frequency with respect to the thin dielectric case. If the considered resonant peak shifts below the cut-off frequency of the waveguide, a second resonant peak appears

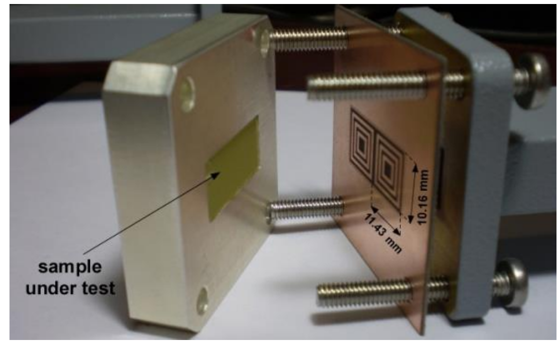

Fig. 2 – A picture of the experimental setup used to test the method for computing the dielectric permittivity here presented.

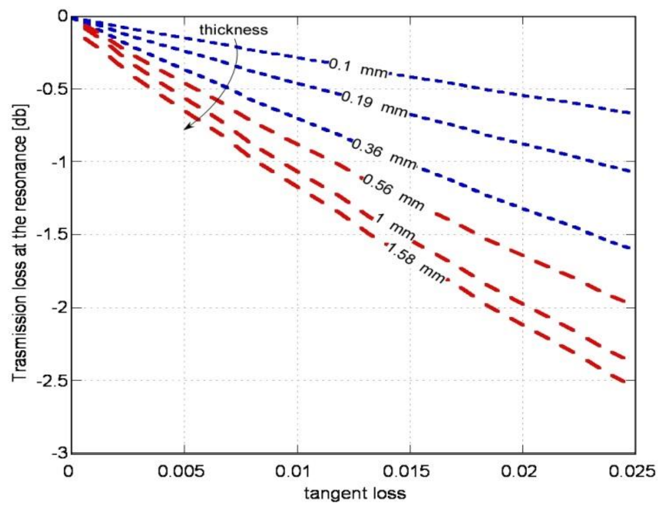

Fig. 3 – Transmission loss at the resonance as a function of the tangent loss of a material with a dielectric permittivity of 4.

in the upper frequency range of the waveguide. The change from the first to the second resonant peak determines an abrupt transition in the map. In this situation, the procedure generates an ambiguity in the determination of the permittivity. Another possible source of inaccuracy is the air gap between the FSS and the unknown sample. In order to avoid the mentioned inaccuracies, the unknown sample should be put in contact against the FSS (for instance, pressed with some glue).

Once determined the real part of the dielectric permittivity, the tangent loss of the material is evaluated by considering the amount of losses in correspondence of the pass-band peak due to the presence of the additional dielectric. Let us consider the transmission peak in Fig. 5 at 13 GHz. When the additional dielectric is positioned close to the FSS, the transmission peak shift towards lower frequencies and it is attenuated proportionally to the loss of the additional dielectric. In Fig**. 4** the transmission loss within the transmitting band of the structure when an additional dielectric slab with a permittivity equal to 4 is placed in the measuring setup is reported.

IV. Experimental validation

The procedure has been tested in a WR90 waveguide operating in the frequency range 8.2 GHz ÷ 12.8 GHz. The size of the unit cell is fixed by the short side of the waveguide (10.16 mm). The selective structure is composed by two unit cells and it is printed on a 0.64 mm Taconic TLX9 slab. A picture of the manufactured FSS is shown in Fig. 2. The electric continuity of the waveguide through the dielectric slab is ensured by a high number of vias which connects the two metalized sides of the slab around contour of the waveguide.

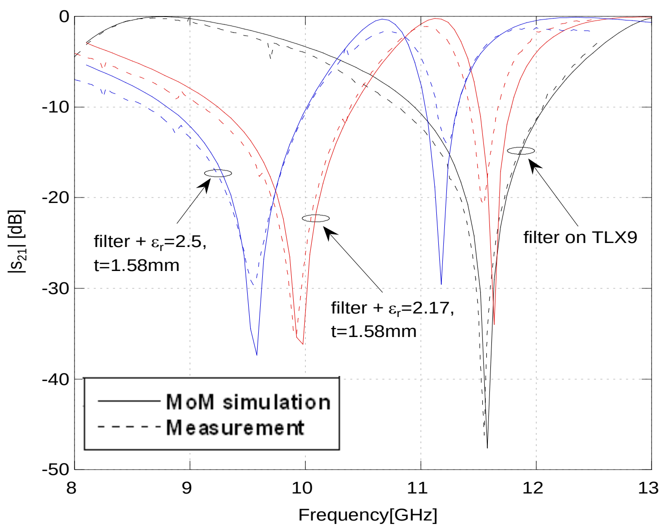

Fig. 4 – Frequency shift of the FSS transmission coefficient in presence of different additional dielectrics with the same thickness.

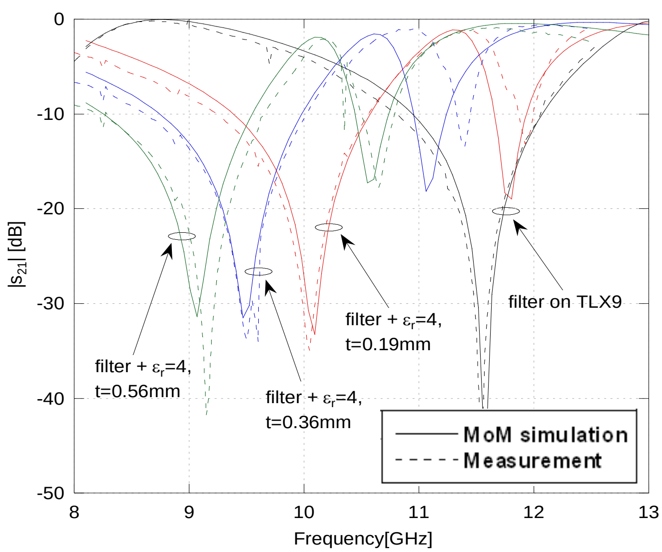

Fig. 5 - Frequency shift of the transmission coefficient of the FSS filter in presence of Fr4 with various thickness.

In Fig. 4 the measured transmission coefficient of the manufactured FSS filter is reported both in the absence and in the presence of two known, 1.58 mm thick, additional dielectrics. In Fig. 5 the transmission coefficient of the unloaded FSS is compared to the ones measured when three FR4 samples with different thickness are positioned close to the FSS. As it is evident, the increasing of the thickness determines a shift of the resonant peaks. The procedure is weakly influenced by small errors in the determination of the sample thickness. The permittivity of the measured FR4 slabs has been estimated to be 4. The comparison between the measured and the simulated data shows a good agreement in both cases. This allows us to employ the maps to derive the permittivity of the materials. A summary of the experimental results is shown in Table 1.

Table 1 – Summary of the nominal and estimated properties of the analyzed samples.

	Meas. ε_r'	Nom. ε_r'	Meas. tanδ	Nom. tanδ
TLY-5A	2.18	2.17	0.012	0.0009
TLX9	2.51	2.5	0.02	0.0019
FR4	4	3.8-4.7	0.025	~0.02

V. Conclusion

A resonant technique to measure the dielectric permittivity which employs a conventional transmission/reflection non resonant device is presented. The procedure combines the simplicity and the low cost setup typical of a transmission/reflection measurement with the precision of resonant techniques. The measurement procedure, which employs an FSS structure within a waveguide, has been described and verified through experimental measurements.

Acknowledgments

The authors wish to thank Ing. Luigi Avagliano for his valuable contribution in performing measurements.

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