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Complex permittivity determination based on a radio frequency device

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ABSTRACT

We describe the design, fabrication, and evaluation of a new on-wafer four port device for measurement the complex permittivity of materials over the continuous frequency range from 1.5 GHz to 2.75 GHz. The proposed device consists of two 3dB directional coupler connected through two U-shaped slot line sections with the same length. This method can afford high accurate measurement results by only two measurements of scattering parameters. One measurement is for the empty device and the other for the material under test loaded on U-shape slot-line of the device. Additionally, we compute the complex permittivity of the materials under test from the measured scattering parameters. Our measurements show excellent agreement with transmission methods.

1. Introduction

When microwave technology develop rapidly for a variety of applications in industry, medicine and electromagnetic compatibility (EMC) [1–3], complex permittivity measurement for dielectric materials plays more and more important role. Such as, in industrial processes, a very important physical parameter to be monitored is the moisture content of materials. Because water has a very high dielectric constant, it can immensely affect the permittivity of the moist material. Also, we must take into serious consideration the electromagnetic interference (EMI) in the design of circuits, components, packaging and so on [4]. So, it is important to measurement electromagnetic properties of materials used in the fields mentioned above [5,6]. In the domain of medicine, dielectric property of biological tissue is tested to distinguish different cells [7,8]. For these reasons, various microwave techniques [9–16] have been introduced to characterize the electromagnetic properties of materials.

Generally, these methods [13] can be categorized into two groups as resonant [14–16] and non-resonant [9–12]. A resonant method is that he change of the quality factor (Q) of a resonator loaded and unloaded the MUT is measured. Consequently, the complex permittivity of the MUT will be computed from measured change of the Q. This method has high accuracy, but suffers from complicated calibration, band-limited and destructed measurement for solids. It is usually used for low-loss materials.

While non-resonant methods are broadband, require less sample preparation and can be used for the characterization of low-to-high-loss materials. They mainly cover free-space (antennas) [10], transmission and reflection method [9,11–13]. A measurement using free-space method [9] includes two antennas with materials under test (MUT) placed in the middle of the antennas, and measuring send/ receive signals, then calculating the permittivity of MUT by measured information. The measurement accuracy of the antenna method is relatively low. Moreover, it has requirement for the thickness of the MUT. In transmission/reflection methods [9,11–13], complex S-parameters of a transmission line loaded the MUT are measured. Then, permittivity of the MUT will be reconstructed by a suitable algorithm (such as genetic algorithm) from the measured information. The transmission/reflection method has been widely utilized for measuring characterization of materials due to its relative simplicity, high frequency structure, and relative high accuracy. It is even used to measure the characterization of Low-K dielectric thin film [12].

However, this method requires de-embedding and calibration procedures. The sensitivity of the transmission method is also relatively limited by background signals that come from transmission lines. There have been many efforts and progress to improve measurement sensitivity and accuracy, such as, new calibration independent measurement methods [17], on-chip cancellation of

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Table 1
Comparison of a few methods.

method	Applications	advantages	disadvantages	uncertainties
Free-space [10,13]	Mainly used low-to-high loss block solids	Non-contact, ultra-wideband and nondestructive measurement	**Low accuracy, high demands for the shape, size and placement of the MUT**	**±(1–10)%for real permittivity and from ±5% to over 20% for dielectric losses**
Resonant [13,16]	Low-to-high loss materials	The highest possible accuracy of measurement of real permittivity, Non-contact measurement	Narrow band, destructive measurement for the solid	**Different uncertainties for different mode resonators, TM_{010} mode cavity with 0.5%–2%and 5×10^{-5} for real permittivity and dielectric loss tangent, respectively.**
Transmission [11–13]	High and medium loss materials, difficult to use for solid materials, especially those having large permittivity	Broadband, high accuracy, non-destructive simple structure, suitable for measurement of magnetic materials.	**Demands for the de-embedding and calibration procedure**	**Better than ±1% for real permittivity, typically ±0.01 for loss tangent measurements.**
Reflection [13]	High and medium loss liquids, powders and soft solids	Quick, easy and relatively cheap to use compared with other methods, broadband and well suited for non-destructive	Low accuracy, easy to meet multiplicity	**Measurement uncertainties increase with increasing frequency, typically ±3% for real permittivity.**

parasitic efforts [8,18–21], simplified measurement procedure with new structure. Some of them are born with narrow bandwidth or unable to integration with other circuits; others might meet multivalve and low sensitivity of measurement fixture for one port.

Table 1 shows the comparison of the above-mentioned methods. They are typically free-space, resonant, transmission and reflection methods. A lot of improve techniques exist that were not covered [14,15].

To overcome the limitations of the previous configurations, we propose and demonstrate a new high frequency structure that has four-port based on the transmission method [22,23]. The proposed method can improve dielectric property measurement accuracy by comparison two S-parameters measurements. One measurement is the empty device and the other for the device loaded the MUT. Besides, calibration and de-embedding for measured S-parameters are not necessary. The permittivity of the MUT can be calculated from amplitude variation of S-parameters, which are measured for the device unloaded and loaded the MUT. Multiple solutions of extracting complex permittivity from measured results can be avoided for the four port of the sensor. And the sensor has high sensitivity and accuracy for the requirement of amplitude-only of S-parameters over the whole ranges (1.5–2.75 GHz), which are not affected by any small shift from the calibration plane of materials. Therefore, the proposed sensor can be used for low-loss materials without any reference materials. Different technologies can be adopted (e.g. microstrip, coplanar waveguide (CPW), coaxial waveguide, etc.) for the realization of the fixture. In the paper, CPW and slot-line technologies have been chosen.

2. Circuit configuration of the sensor

Fig. 1 is a schematic of the proposed broadband planar radio frequency (RF) device. Two 3-dB directional coupler and two branches having the same length (one being loaded with MUT and the other being loaded with reference material) are used to compose the device. The input and coupling ports of the two directional couplers are composed by CPW, while the direction and isolation ports are composed by slot-line, which are connected through two U-shape slot-line sections respectively. The two U-shape slot-line sections are the two branches of the device. The MUT will be placed on test branch with a line length equal to$L$.

An incoming RF signal from port1 will mostly transmit through the above path (test branch) and arrive to the port 3 of the device. Meanwhile, part of the signal will pass through the bottom path (reference branch) to the port 2. Ideally, no signal propagates to the port 4. In the work, the permittivity of MUT can be calculated without any reference material by simply comparing the S-parameters of the device, which are measured with the test branch loaded and unloaded the MUT, respectively.

For a direction coupler, there exist two propagation modes, the odd- and even-mode corresponding to short-circuit [electrical wall (EW)] and open-circuit [magnetic wall (MW)] respectively [24]. The coupled region is characterized by two transmission lines with even and odd characteristic impedancesZ_{oo},Z_{oe}.Meanwhile, the coupling degree (C), the characteristic impedanceZ_{01} and the mode characteristic impedances must satisfy the following relations:

$$Z_{01} = \sqrt{Z_{oo}Z_{oe}} \quad (1)$$

$$Z_{oo} = Z_{01}\left(\frac{1-10^{C/20}}{1+10^{C/20}}\right)^{1/2}, Z_{oe} = Z_{01}\left(\frac{1+10^{C/20}}{1-10^{C/20}}\right)^{1/2} \quad (2)$$

A simplified analysis shows that S-parameters of the device are given by:

$$S_{11} = \frac{\Gamma_e}{2}\left(1-\frac{1-\Gamma_e^2}{\exp(2j\beta_{oe}L)-\Gamma_e^2}\right) + \frac{\Gamma_o}{2}\left(1-\frac{1-\Gamma_o^2}{\exp(2j\beta_{oo}L)-\Gamma_o^2}\right) \quad (3)$$

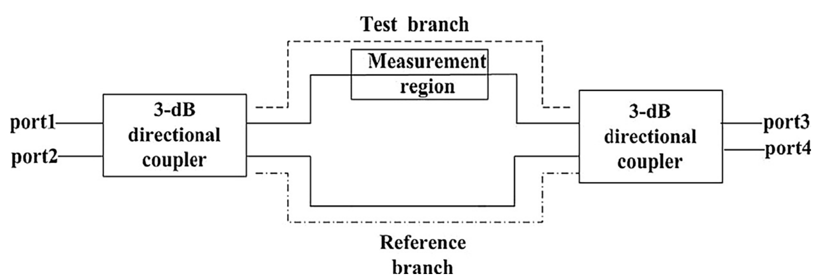

Fig. 1. Schematic of the proposed device.