A METHOD TO DETERMINE THE DIELECTRIC CONSTANT VALUE OF MICROWAVE PCB SUBSTRATES

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ABSTRACT

This paper presents a simple method for determining the dielectric constant of microwave PCB substrates. In the presented method, a bandpass microstrip filter on the PCB substrate with a user-predicted dielectric constant value is designed for a given center frequency, and it is implemented. The simulation results of the designed bandpass filter are obtained by the help of electromagnetic analysis software; XFDTD®. Experimental results regarding the filter frequency characteristic are accomplished by means of a vector network analyzer. The simulation results of the designed filter are modified to overlap with the experimental ones by varying the dielectric constant value. When the simulation and experimental results are overlapped, the value of dielectric constant is accurately selected. In order to illustrate the validity of proposed method, the dielectric constant values of flame resistant-4 (FR4) substrates are acquired at IEEE 802.11b/g and IEEE 802.11a wireless local area network (WLAN) application frequencies.

I. INTRODUCTION

Modern microwave and radio frequency (RF) engineering is an exciting and dynamic field due in large part to the symbiosis between recent advances in modern electronic device technology and the current explosion in demand for voice, data, and video communication capacity. Prior to this revolution in communications, microwave technology was the nearly exclusive domain of the defense industry; the recent and dramatic increase in demand for communication systems for such applications as wireless paging, mobile telephony, broadcast video, and computer networks is revolutionizing the industry. These systems are being employed across a broad range of environments including corporate offices, industrial and manufacturing facilities. The diversity of applications and operational environments has led to tremendous advances in cost-efficient manufacturing capabilities of microwave and RF products. This has lowered the implementation cost of a host of new and cost-effective wireless as well as wired RF and microwave services. Nevertheless, most of the microwave designers find the traditional approaches for the microwave circuits unsuitable for high volume and cost sensitive commercial applications, and manufacturers seek for lower cost techniques to fabricate microwave circuits. An important input of the microwave circuit manufacturing is the printed circuit board (PCB) substrate materials [2]. The substrate materials such as Getek, Rogers RT/Duroid and Flame Resistant-4 (FR4) are widely used as the microwave PCB substrate. Among these, Getek and RT/Duroid substrates better result in homogenous and isotropic electrical characteristics; however, FR4 provides the lowest cost [2, 3]. Since FR4 leads to unstable relative dielectric constant, ε_r when it operates above 1 GHz, the dielectric characterization of the FR4 material should be carried out by the design engineer [4].

The dielectric constant of microwave substrate is an important parameter to design the passive devices such as filters and antennas or microwave electronic packaging for microwave integrated circuit, however the dielectric information of substrate is usually given at low frequencies by the manufacturer [1, 2, 5]. In addition, due to manufacturing errors, the dielectric constant of microwave substrate is usually in a range. There is a need to obtain the accurate dielectric properties of substrate at high frequencies to acquire the frequency response of the substrate material.

Several methods [6-14] varying in accuracy and computational effort are available in the literature to determine the dielectric constant of microwave substrates. One of these is the transmission line method [6, 7] in which the scattering parameters of a single transmission line on the substrate are measured and the dielectric constant is then determined. Another method is to use a cavity resonator formed by metallization of all faces of a substrate, and the microwave signal is injected via a small hole. Then, dielectric constant information can be extracted from the resonance frequency expression [7-9]. Alternatively, by using a ring resonator, the dielectric constant of substrate can be calculated from the resonance frequency [10-13]. The dielectric constant can also be determined by measuring the capacitance with a parallel plate capacitor. To do so, a piece of PCB substrate without metallization is inserted into a waveguide, and the dielectric constant is calculated from scattering parameters using reflection of microwaves [14]. These methods with their relative merits and limitations can be used in microwave frequencies.

In this paper, a procedure based on the microstrip filter is presented to determine the dielectric constant of a microwave substrate. Two examples of (FR4) substrate are illustrated to confirm the validity of proposed method, for the frequencies of 2.4 GHz and 5.1 GHz, which are, respectively, the standard IEEE 802.11b/g and IEEE 802.11a wireless local area network (WLAN) applications [15-17]. The method proposed in this study can be utilized by any microwave designer practically without any background in sophisticated mathematical techniques.

II. DETERMINATION OF THE DIELECTRIC CONSTANT BY USING MICROSTRIP FILTERS

The block diagram that summarizes the proposed method is shown in Fig. 1. A bandpass microstrip filter constructed on the PCB substrate with a user-predicted dielectric constant value is designed to satisfy a given center frequency f_o, and it is implemented. The simulation results of the designed bandpass filter are obtained with the help of electromagnetic analysis software, namely XFDTD® which uses finite difference time domain (FDTD) method [18] in its inner structure to solve electromagnetic equations without requiring additional external calculations by the circuit designer. The frequency domain characteristics of the prototyped filter are measured by *Agilent ENA5071B vector network analyzer* (VNA), and the *S*-parameters of the measurement is acquired by a personal computer (PC). Both the simulation and experimental frequency characteristic results of the filter are transferred to the same diagram. The simulation results of designed filter and the experimental ones are mapped by varying the dielectric constant value. The accurate value of dielectric constant is then selected by overlapping the simulation and experimental results.

III. NUMERICAL EXAMPLES AND RESULTS

In order to check the validity of the proposed method, the dielectric constant values of FR4 substrate operating in two different microwave frequencies are determined. The frequencies are selected as 2.4 GHz and 5.1 GHz The schematic diagrams of designed bandpass filters are given in Fig. 2a for f_o=2.4 GHz (filter 1) and Fig. 2b for f_o=5.1 GHz (filter 2).

The bandpass filters 1 and 2 have input and output impedances of 50 Ω and both are the third order of Butterworth characteristics. The filters whose schematics are given by Figs. 2a and 2b are implemented as the microstrip filters. FR4 substrate used in this study has a 1.6 mm dielectric thickness, and 35 μm of copper cladding thickness; and these values are directly applied to XFDTD® software. The value for dielectric constant for FR4 is taken as a predicted value of ε_r=4. Microstrip filter layouts are illustrated in Figs. 3a and 3b for filter 1 and filter 2, respectively.

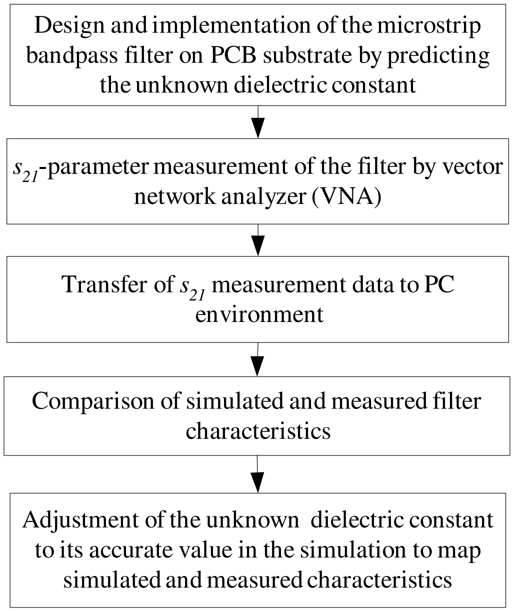
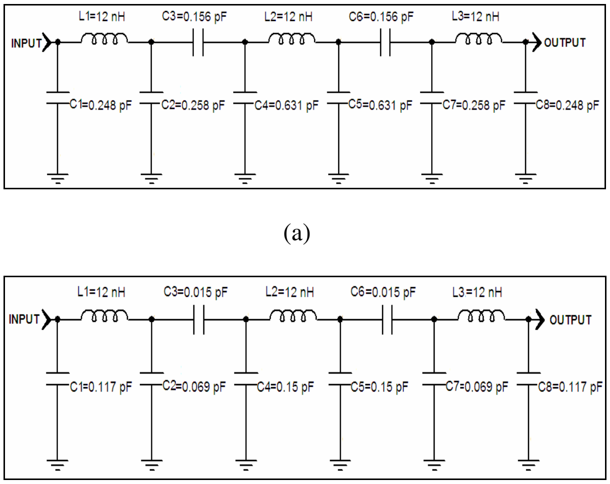


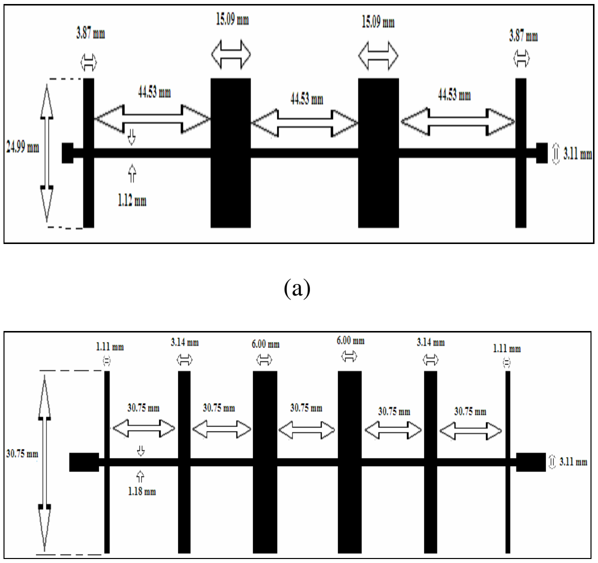
Figure 1. Algorithm to estimate the dielectric constant of a PCB substrate



(a)

(b)

Figure 2. The bandpass filters with f_o=2.4 GHz (a) and f_o=5.1 GHz (b)



(a)

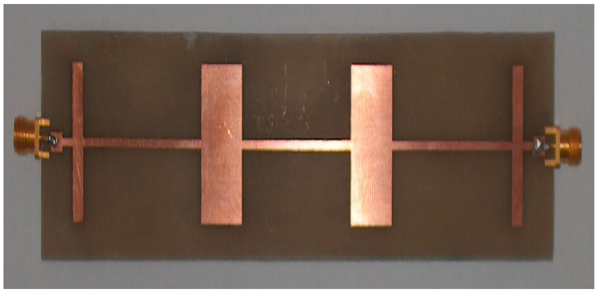
(b)

Figure 3. Microstrip layouts of filter 1 (a) and filter 2 (b)

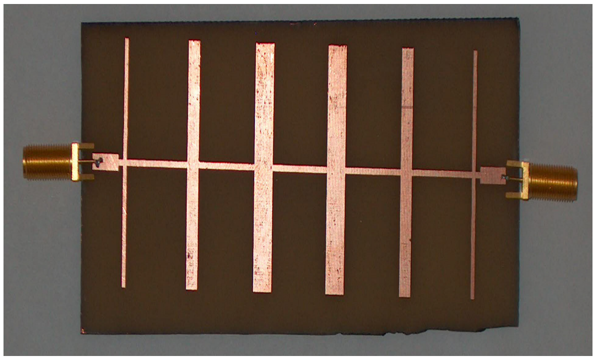
The filter layouts given in Figs. 3a and 3b are implemented on FR4 material and are shown in Figs. 4a and 4b, respectively. The ferric chloride ($FeCl_3$) etch bath is utilized to get sharp stub shapes [19]. Gold plated subminiature version A (50 Ω - SMA) connectors are used.

The measurement values obtained by using VNA are extracted in the range of 1.812 GHz and 2.637 for filter 1 and 4.625 GHz and 5.875 GHz for filter 2. The measurement is carried out on 201 points for each filter. Measured s_{21} traces of filter 1 and filter 2 are given in Fig. 5a and Fig. 5b, respectively.

Since the microstrip layouts of filters are generated by predicted the dielectric constant of the substrate as an average value, the measured and simulation results are not matched properly, as expected. This inconsistency can easily be seen from Figs. 6a and 6b.

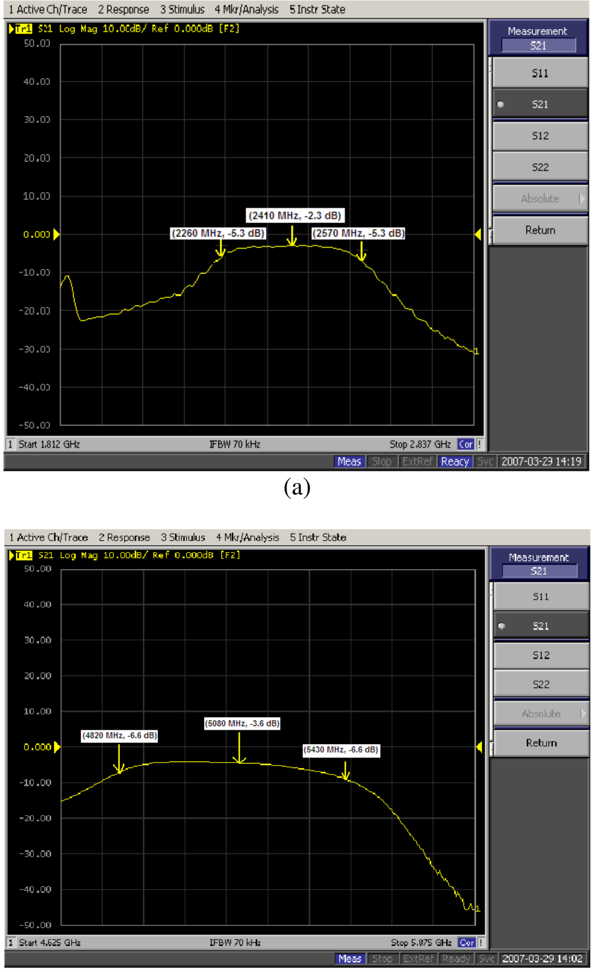


(a)



(b)

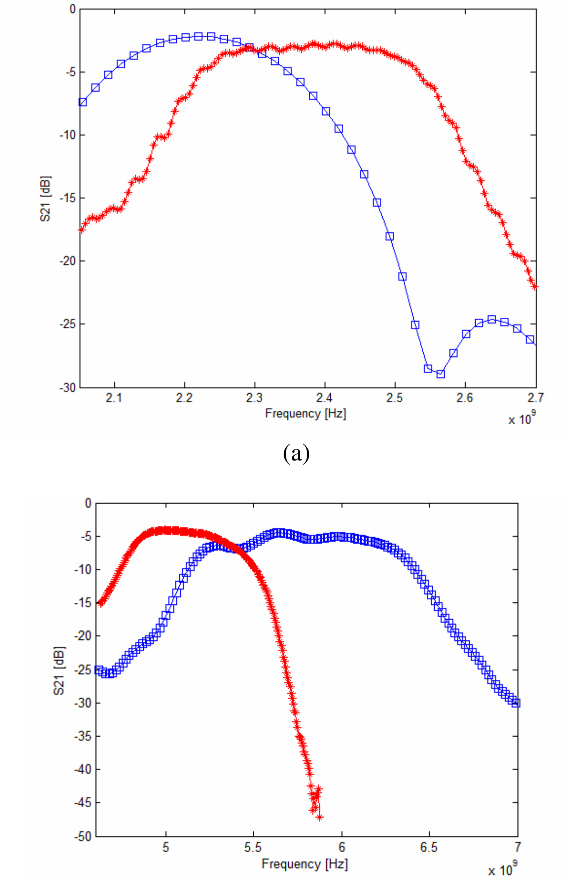
Figure 4. Filter 1 (a) and filter 2 (b) implemented on FR4



(a)

(b)

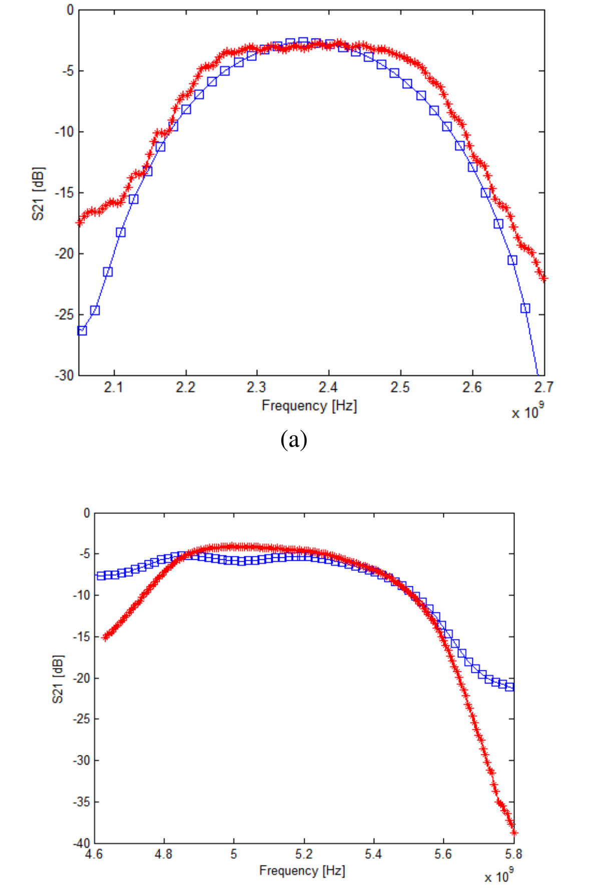
Figure 5. Measured S_{21} traces of the filters 1 (a) and 2 (b)



(b)

Figure 6. The simulated (●) and measured (■) s_{21} traces for the filter 1 (a) and filter 2 (b) before correcting the dielectric constant to its accurate value

The center frequencies of the prototyped filters are found to be 2.41 GHz for filter 1 and 5.08 GHz for filter 2 by measurements. In order to determine the dielectric constant, its value in the simulation process is adjusted to overlap the simulated and measured filter characteristics as given in Figs. 7a and 7b for filter 1 and filter 2, respectively. The simulated and measured cases overlap for $\varepsilon_r = 2.6$ and $\varepsilon_r = 5.5$ for filter 1 and filter 2, respectively. Thus, the dielectric constant of the substrate is determined as 2.6 for IEEE 802.11b/g standard frequency (2.4 GHz) and 5.5 for IEEE 802.11a standard frequency (5.1 GHz). It is worth noting that the consistent agreement between simulated and measured filter characteristics at transfer bands is obtained. However, the agreement at attenuation bands is not good as in the case of transfer bands because of the fact that the dielectric constant of the substrate at those frequencies changes firmly. It should be noted that the accuracy of the proposed method is also affected by the numerical noise of the microwave design software used.



(b)

Figure 7. The simulated (●) and measured (■) s_{21} traces for the filter 1 (a) and filter 2 (b) after correcting the dielectric constant to its accurate value

IV. CONCLUSIONS

In this paper, a practical and accurate method for the determination of the dielectric constant of PCB substrates is presented. The method utilizes the microstrip bandpass filters designed for a center frequency at which the dielectric constant value is to be found. As the applications, the dielectric constant values of FR4 materials are determined for 2.4 GHz and 5.1 GHz that are frequencies of the standards IEEE 802.11b/g and IEEE 802.11a, respectively. The advantage of this method is that any microwave designer can use it practically without any background in sophisticated mathematical techniques.

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