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A Method for Determining the Dielectric Constant of Microwave PCB Substrates

Serhan Yamacli · Caner Ozdemir · Ali Akdagli

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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 designed on the PCB substrate with a user-predicted dielectric constant value is implemented for a given center frequency. The simulation results of the designed bandpass filter are obtained by the help of microwave design 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. The results obtained by using the presented method agree with the previous studies in the literature.

Keywords Dielectric constant · PCB substrate · Microstrip filter · FR4

1 Introduction

The recent development of microwave commercial applications such as mobile telephony, wireless paging and wireless LANs, direct manufacturers to seek for lower cost techniques to fabricate microwave circuits. An important input of the microwave circuit manufacturing

S. Yamacli
Department of Electronics and Computer Education, Faculty of Technical Education, Mersin University, 33480 Tarsus, Mersin, Turkey

C. Ozdemir · A. Akdagli (✉)
Department of Electrical and Electronics Engineering, Faculty of Engineering, Mersin University, 33343 Ciftlikkoy, Mersin, Turkey
e-mail: akdagli@mersin.edu.tr

is the printed circuit board (PCB) substrate material [1, 2]. There are three main substrate materials, namely Getek, Rogers RT/Duroid and Flame Resistant-4 (FR4) that are widely used as the microwave PCB substrate. Among these, Getek and RT/Duroid substrates better result in homogenous and isotropic electrical characteristics, whereas, FR4 provides the lowest cost [2–4].

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. The general expression for the permittivity of a dielectric material is given by

$$\varepsilon = \varepsilon' - j\varepsilon = \varepsilon'(1 - j\tan\delta) \tag{1}$$

in which the real part is the dielectric constant (relative permittivity) and the imaginary part is the term for the losses of the substrate. For the low cost substrate materials such as FR4, the loss factor, tanδ has a typical value that is valid in a broad range of frequencies [5]. However, the dielectric constant value of FR4 is usually given at low frequencies by the manufacturer [3]. Also, relative dielectric constant, ε', of FR4 changes with frequency above 1 GHz, and the dielectric value characterization of the FR4 material should be carried out by the design engineer [4]. In addition, the dielectric constant of microwave substrate is usually in a specific range of values due to manufacturing tolerances. Therefore, there is a need to obtain the accurate dielectric properties of PCB substrates at high frequencies to acquire the frequency response of the substrate material.

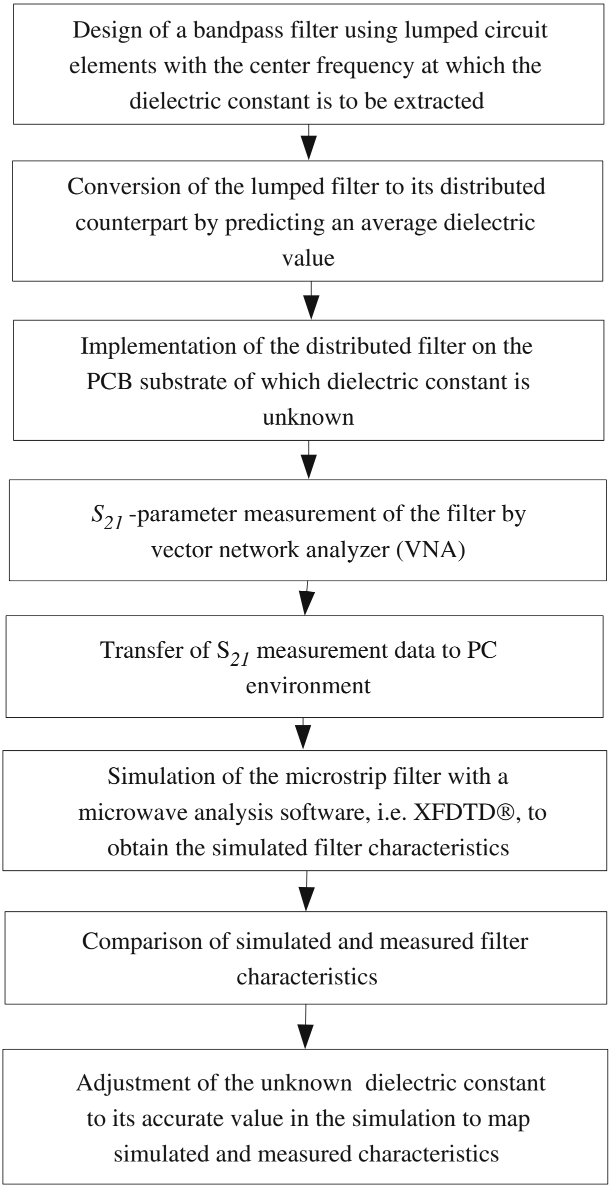
Several related methods, varying in accuracy and in computational effort, are available in the literature [6–14]. One of them is the transmission line method [6, 7] in which the scattering parameters of a single transmission line on the substrate are measured and the dielectric constant is then determined. Another one is the use of a cavity resonator formed by metallization of all faces of a substrate, and the microwave signal is fed via a small hole. Then, dielectric constant information can be extracted from the resonance frequency expression [7–9]. Alternatively, the dielectric constant of substrate can be calculated from the resonance frequency by using a ring resonator [10–13]. It 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 measurements 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 realization 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. The method proposed in this study can be utilized by any microwave designer practically without requiring complex mathematical computations.

2 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 is designed using lumped circuit elements. The center frequency of the bandpass filter is set as the frequency at which the dielectric constant value of the PCB substrate is to be extracted. The designed lumped filter is the LC-ladder type filter that is appropriate to be converted to stepped-impedance type filters [5]. These lumped elements

Fig. 1 The method to estimate the dielectric constant of a PCB substrate.



are then converted to their distributed counterparts, stepped-impedance filters, according to the well-known formulas given below

$$X = 2Z_0 \tan\left(\frac{\beta l}{2}\right) \quad (for\, inductor) \tag{2}$$

$$B = \frac{1}{Z_0} \sin(\beta l) \quad (for\, capacitor) \tag{3}$$

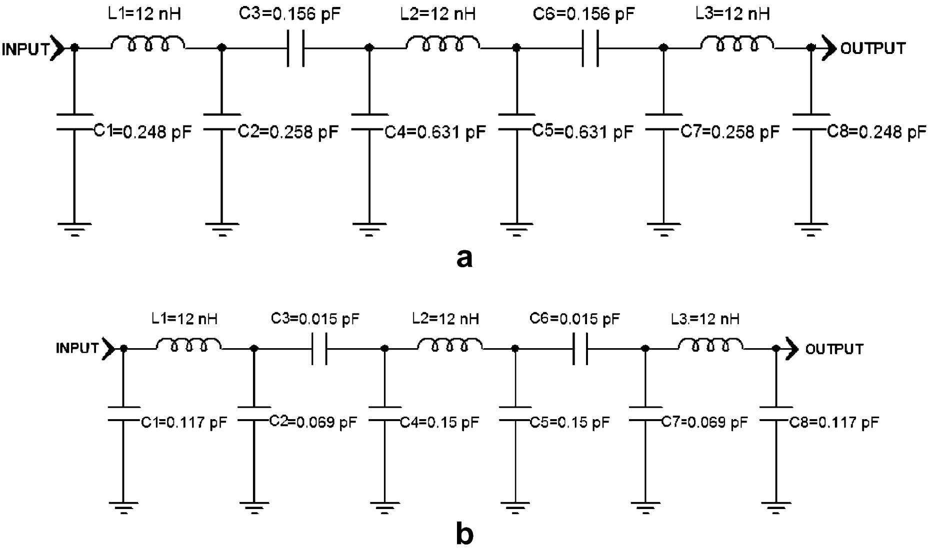


Fig. 2 The bandpass filters with (**a**) f_o=2.4 GHz and (**b**) f_o=5.1 GHz.

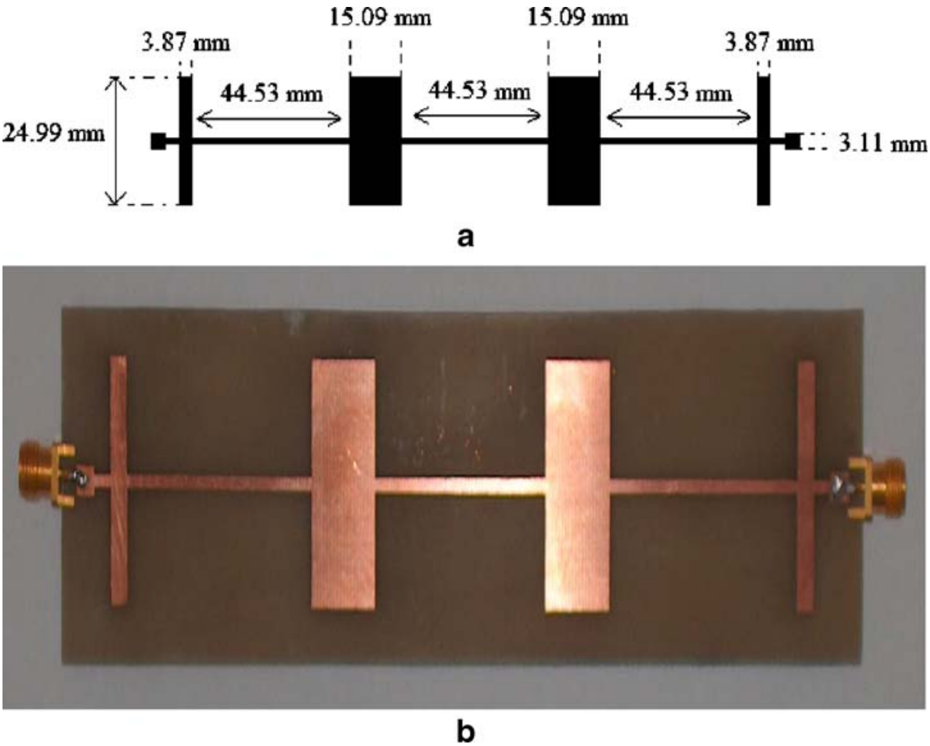


Fig. 3 (**a**) Microstrip layout and (**b**) filter 1 implemented on FR4 substrate.

where X is the impedance of the inductor element, B is the susceptance of the capacitor element, β is the wave number and, Z_0 and l are the characteristic impedance and length of the microstrip line, respectively. During the conversion of the lumped filter to microstrip filter, dielectric constant value of the PCB substrate is needed. But, at this stage, the exact value of the dielectric constant has not known yet. So, a user-predicted dielectric constant value is used for calculating microstrip line widths and lengths. The dielectric value of an FR4 material is between 3.5 and 4.9 [2–4] depending on the manufacturing process, production tolerances and the operating frequency, so predicted value can be selected as any numerical value between 3.5 and 4.9. In the next step, the frequency domain characteristics of the prototyped microstrip filter are measured by Agilent ENA5071B vector network analyzer (VNA), and the S-parameters of the measurement are acquired by a personal computer (PC) via VNA's GBIP port. Afterwards, simulation results of the designed bandpass filter are obtained with the help of microwave design software, XFDTD® [18] that uses finite difference time domain (FDTD) method in its inner structure to solve the electromagnetic equations without requiring additional external calculations by the designer. Both the simulation and experimental results for the frequency characteristics of the filter are carried over to the same plot. The simulation results of the designed filter and

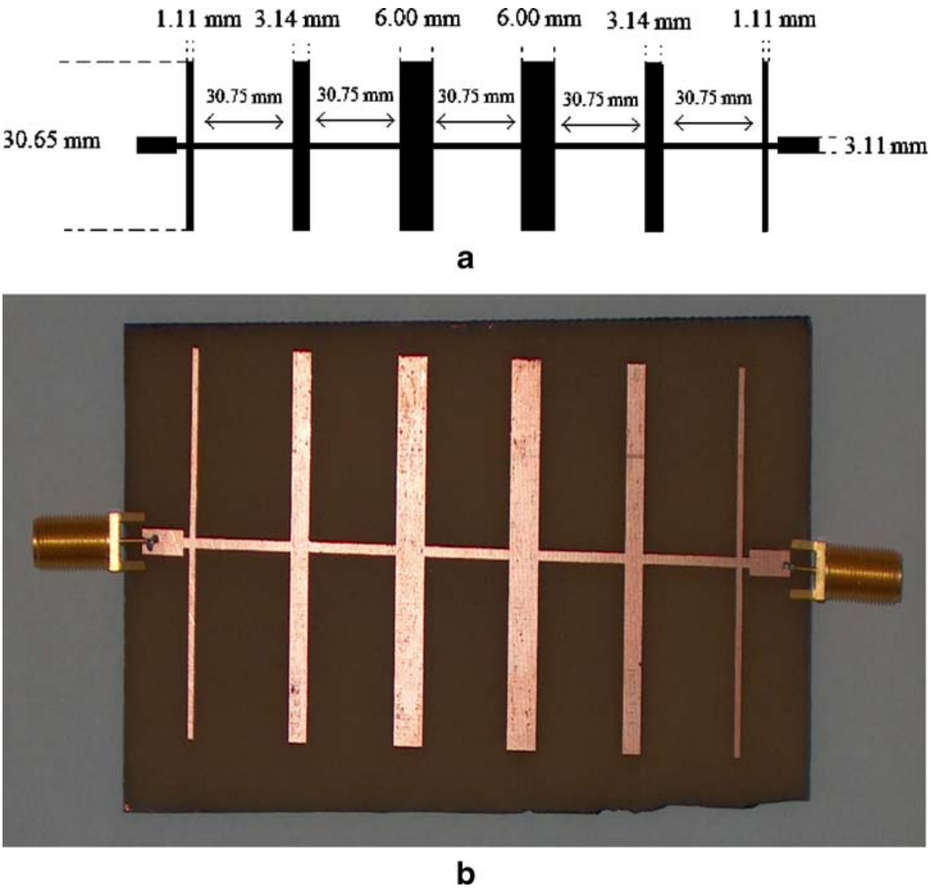
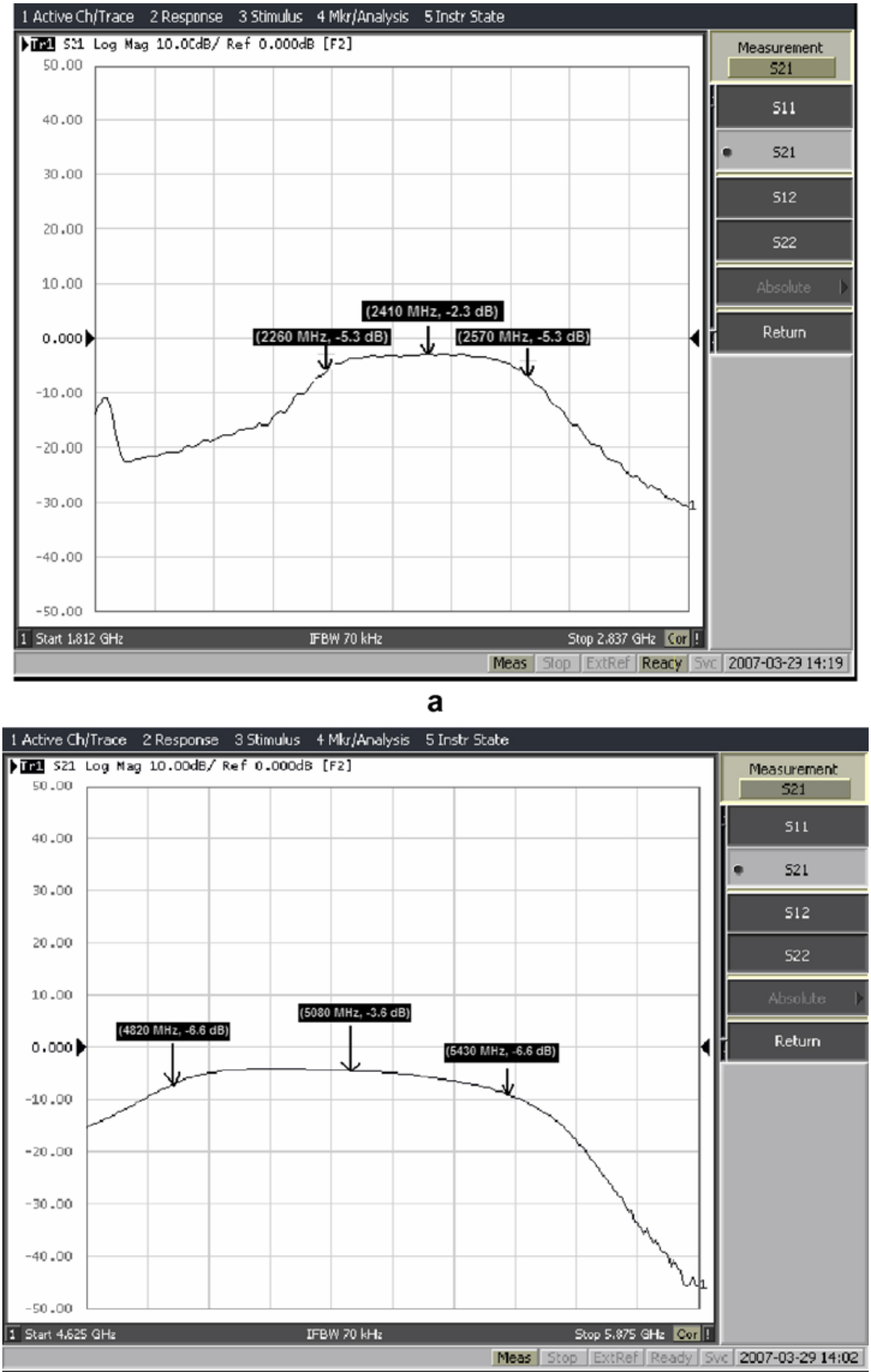


Fig. 4 (**a**) Microstrip layout and (**b**) filter 2 implemented of on FR4 substrate.


1 Active Ch/Trace 2 Response 3 Stimulus 4 Mkr/Analysis 5 Instr State
S21 Log Mag 10.00dB/ Ref 0.000dB [F2]
(2410 MHz, -2.3 dB)
(2260 MHz, -5.3 dB)
(2570 MHz, -5.3 dB)
Start 1.812 GHz
IFBW 70 kHz
Stop 2.837 GHz
2007-03-29 14:19
(5080 MHz, -3.6 dB)
(4820 MHz, -6.6 dB)
(5430 MHz, -6.6 dB)
Start 4.625 GHz
Stop 5.875 GHz
2007-03-29 14:02
Measurement
S21
S11
S12
S22
Return

a

b

Fig. 5 Measured S_{21} traces of the (**a**) filter 1 and (**b**) filter 2.

the experimental ones are mapped by varying the dielectric constant value in the simulation. The accurate value of dielectric constant is then selected by overlapping the simulation and the experimental results.

3 Numerical examples and results

To check the validity of the proposed method, the dielectric constant values of two different types of FR4 substrates operating in two different microwave frequencies are determined. The frequencies are, respectively, selected as 2.4 GHz and 5.1 GHz which fall into the

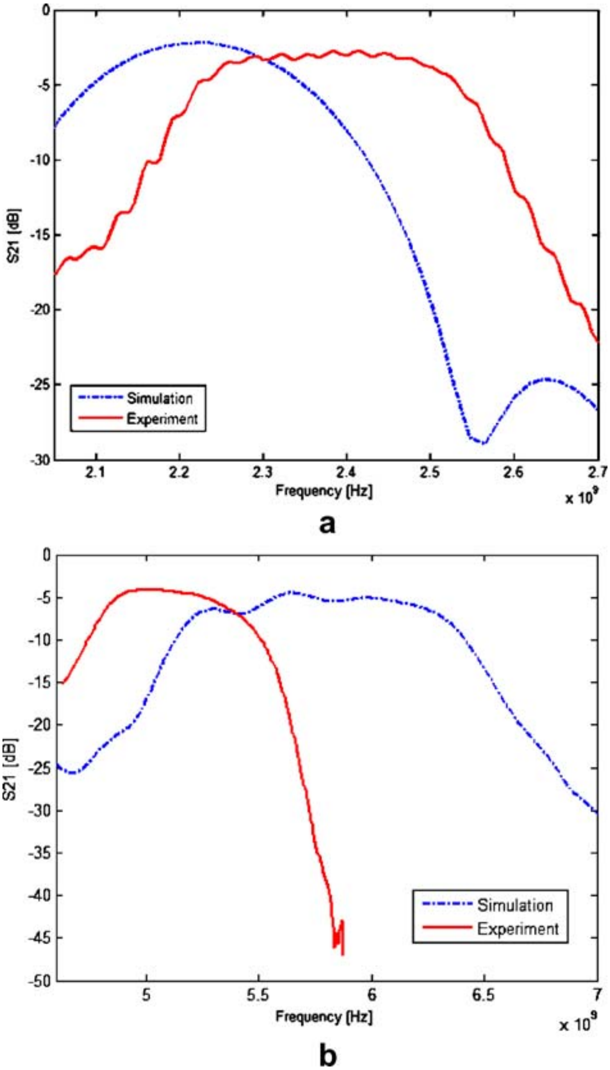


Fig. 6 The simulated and measured S_{21} traces for (**a**) filter 1 and (**b**) filter 2 before correcting the dielectric constant to its accurate value.

standard IEEE 802.11b/g and IEEE 802.11a wireless local area network (WLAN) applications [15–17]. 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).

Both bandpass filters 1 and 2 have the same input and output impedances of 50 Ω and are the third order of Butterworth characteristics. The filters, whose schematics are given by Fig. 2a and b, are implemented as the microstrip filters. Both of the FR4 substrate types used in this study has a 1.6 mm dielectric thickness, and 35 μm of copper cladding thickness. The value for dielectric constant for both FR4 types are taken as a predicted value of ε_r=4 while calculating the microstrip stub dimensions. Microstrip filter layouts are illustrated in Figs. 3a and 4a for filter 1 and filter 2, respectively.

The filter layouts given in Figs. 3a and 4a are implemented on FR4 materials and are shown in Figs. 3b and 4b, respectively. The ferric chloride (Fe_2Cl_3) etch bath is utilized to get sharp stub shapes [19]. Gold plated subminiature version-A (50 Ω - SMA) connectors

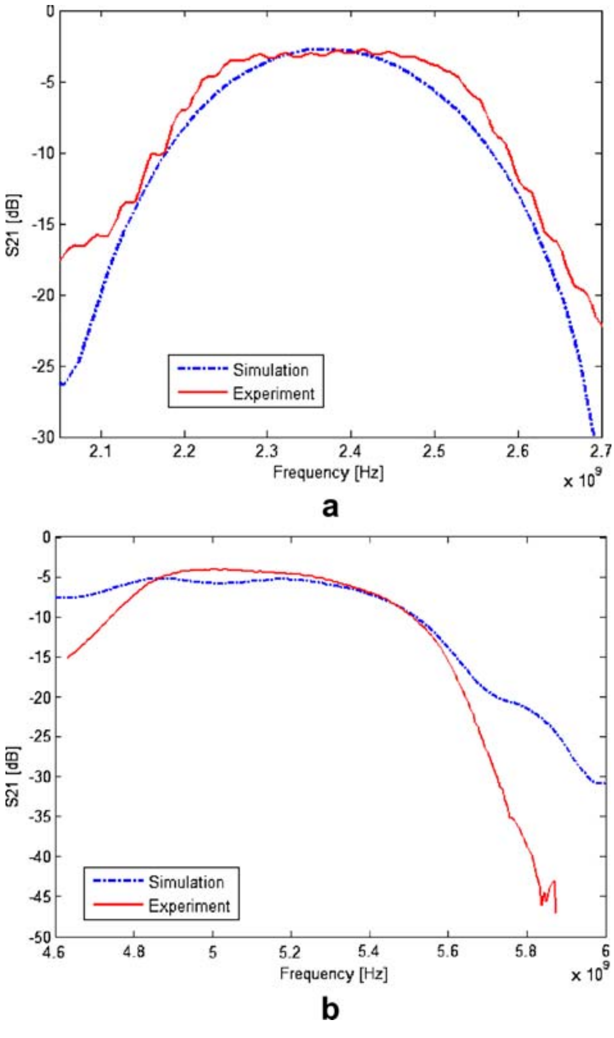


Fig. 7 The simulated and measured S_{21} traces for (**a**) filter 1 and (**b**) filter 2 after correcting the dielectric constant to its accurate value.

are used. The filters are tested inside boxes with aluminum coating to minimize the effects of electromagnetic interference (EMI).

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 equally spaced frequency points for each filter. Measured transmission coefficients namely S_{21} traces of filter 1 and filter 2 are given in Fig. 5a and b, respectively. Since the microstrip layouts of filters are generated by predicting the dielectric constant of the substrate, the measured and simulation results are not matched, as expected. This inconsistency can easily be seen from Fig. 6a and b.

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 Fig. 7a and b for filter 1 and filter 2, respectively. The tangent losses of FR4 PCB materials can be taken as $\tan\delta=0.015$ for a wide frequency range of 10 kHz to 12 GHz [3]. So, the tangent loss of PCB materials used in this work are entered as $\tan\delta=0.015$ in simulations. The simulated and measured cases overlap for $\varepsilon_r=4.5$ and $\varepsilon_r=3.6$ for filter 1 and filter 2, respectively. Thus, the dielectric constant of the first type of FR4 substrate is determined as 4.5 for IEEE 802.11b/g standard frequency (2.4 GHz) and the dielectric constant of the second type of FR4 substrate is found to be 3.6 for IEEE 802.11a standard frequency (5.1 GHz).

The dielectric constant values of FR4 PCB material at 2.4 GHz and 5.1 GHz found in this study can be compared to other numerical values in the references. In [3, 4, 7], the dielectric constant has a value in the range of 4.9 and 3.5 between the frequencies of 2 GHz to 6 GHz, respectively depending on the FR4 batch that is under test. Thus, dielectric constant values found in this study agree with the values given in these references. Also, in this work, the systematic errors of measurement are minimized by putting the filters into boxes with aluminum cladding to minimize EMI. In the simulation, an FDTD simulator, XFDTD® is employed to account for all the electromagnetic effects thus leading to accurate simulation.

4 Conclusions

In this paper, an effective 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. The dielectric constant values of FR4 materials are determined for 2.4 GHz and 5.1 GHz that fall into the frequencies of the standards IEEE 802.11b/g and IEEE 802.11a, respectively. 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.

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