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Characterization of Dielectric Properties of Non-Magnetic Materials Using Superstrate-Loaded Antennas

Saininad Naik[1], Maria Pour[1, *], and Curtis Hill[2]

Abstract—A free-space and non-invasive measurement technique to characterize the dielectric properties of a non-magnetic NASA-developed composite material is presented. To estimate the dielectric properties of the composite material, the material under test is placed as a superstrate over a pre-characterized benchmark antenna. The reflection coefficients and gain of the superstrate-loaded antenna are then utilized to estimate the relative permittivity and loss tangent of the composite under test, respectively. Using numerical analyses and measurements of the benchmark antenna loaded with the superstrate, the aforementioned properties are estimated to be 6 and ~ 0.12, respectively. To validate the accuracy of the method, a square microstrip patch antenna is also designed on a grounded NASA-developed composite material at the ISM band.

1. INTRODUCTION

This paper presents an inexpensive and unambiguous method to estimate the dielectric properties of a non-magnetic material developed by NASA, which is a composite material of PVDF-TrFE (Poly(vinylidene fluoride-co-trifluoroethylene) polymer, loaded with lead zirconate (PZT) piezoelectric material. It consists of $< 1\%$ Carbon nanotubes, 10–40% PZT, 5–15% PVDF-TrFE, and 70–90% organic solvent and surfactant. The knowledge of dielectric properties assists engineers in implementation of materials in space applications, microwave absorbers, and satellite communications [1]. Numerous measurement techniques have been developed to determine the material properties [2] at fixed frequency [3] and wide-band frequency ranges for dispersive materials [4]. The Nicolson-Ross method [4] has been widely used as the standard method to measure and retrieve permittivity and permeability of isotropic materials. The method was later modified by Wier [5] to determine the permittivity and permeability of rock, soil, and other non-standard materials. Several methods have also been established using horn antennas [6, 7], resonators [8–10] and patch antennas [11]. The methods presented in [8] and [9] require high Q factor for accurate measurement, thus do not show enough accuracy for lossy materials such as FR-4. In fact, 8% inaccuracy in permittivity was reported [10]. As for [11], the patch antenna needed to be completely immersed in the liquid, however, the effect of dispersion was not fully accounted for. Hence, it is worth exploring a non-invasive method to estimate the dielectric properties of unknown materials regardless of their Q-factors and potential dispersion impact of the surrounding medium.

In this paper, a free-space and non-invasive method to characterize dielectric properties of non-magnetic materials is introduced by employing a pre-characterized microstrip patch antenna as a benchmark antenna. The benchmark antenna is then loaded with the material under test as a superstrate. As such, its resonant frequency will shift down and its peak gain will drop. The amount of the frequency shift and the gain drop are then used to estimate the permittivity and loss tangent of

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* Corresponding author: Maria Pour (maria.pour@uah.edu).
[1] Department of Electrical and Computer Engineering, The University of Alabama in Huntsville, Huntsville, AL 35899, USA.
[2] ESSCA/Quantitech NASA MSFC, Huntsville, AL 35808, USA.

the composite material, respectively. This is done by fitting the measured results with the quantized simulated data obtained by the finite-element based full-wave EM solver [12]. The main advantages of the presented superstrate-loaded microstrip patch antenna technique are that it is low profile, inexpensive as opposed to commercial dielectric probe kits, easy and simple to use, and non-invasive. To confirm the estimated properties and to examine the validity of the method, a square microstrip patch antenna is fabricated directly on the grounded composite material and fully characterized in practice.

2. THE BENCHMARK ANTENNA

To use the composite material developed by NASA for antenna and other microwave applications, first the material needs to be characterized. To this end, a microstrip patch antenna is chosen as a benchmark antenna owing to its broadside radiation pattern, planar structure, and easy installation for the measurement of dielectric properties of the NASA-developed material. The benchmark antenna is designed on a 1.57 mm-thick Rogers 5880 [13] dielectric substrate with $\varepsilon_r = 2.2$ and loss tangent = 0.0009 at the frequency of 2.9 GHz and its impedance and radiation properties are fully investigated through both full-wave analysis and measurements. The benchmark antenna is a rectangular microstrip patch of length l and width w, designed based on [14–17], mounted on the grounded Rogers 5880 dielectric slab and fed by an SMA probe, as depicted in Figure 1.

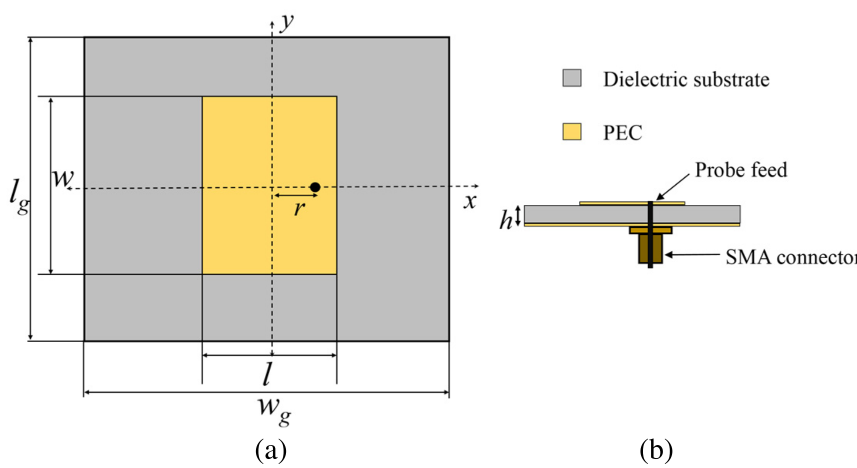

Figure 1. (a) Top- and (b) cross-sectional views of the benchmark microstrip patch antenna operating at 2.9 GHz, with $l_g = 15.1$ cm, $w_g = 11.5$ cm, $l = 3.29$ cm, $w = 4.95$ cm, and $r = 7.56$ mm; the substrate is RT Duroid 5880 with $h = 1.57$ mm, $\varepsilon_r = 2.2$, and loss tangent = 0.0009.

The benchmark antenna was full-wave analyzed and tested using the vector network analyzer for scattering parameters and the spherical near-field anechoic chamber of the University of Alabama in Huntsville (UAH) for its peak gain. The simulated and measured reflection coefficients are plotted in Figure 2, which are closely aligned with each other, confirming the resonant frequency of 2.9 GHz. The antenna peak gain was also measured in the anechoic chamber, and the corresponding results are summarized in Table 1, which are in good agreement.

Table 1. Simulated and measured results of the benchmark antenna shown in Figure 1.

Benchmark Antenna	f (GHz)	Gain (dBi)
Simulated	~ 2.9	9.19
Measured	~ 2.9	8.84

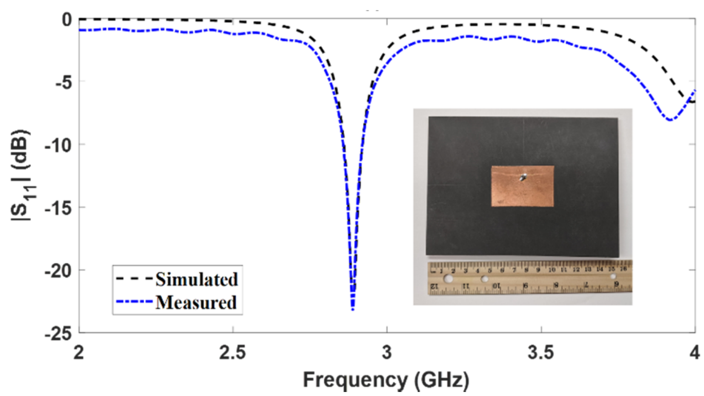

Figure 2. Measured and simulated reflection coefficients of the benchmark antenna shown in Figure 1 with the photograph of the fabricated benchmark antenna on the inset of the plot.

3. THE SUPERSTRATE METHOD

In antenna engineering, superstrate materials have been used for enhancing various antenna properties [18–25]. Herein, we utilize the frequency shift and gain drop occurring in the benchmark antenna after loading it with the unknown composite material as a superstrate to determine its dielectric permittivity and loss tangent. The antenna loaded with the unknown material as a superstrate is investigated through full-wave analysis and measurement. The dimensions of the sample provided by NASA were $42\,\text{mm} \times 42\,\text{mm} \times 1.8\,\text{mm}$. Geometry of the superstrate-loaded antenna is shown in Figure 3, where the superstrate is placed about 0.5 mm above the benchmark antenna using a styrofoam. This small air-gap is considered due to the solder joint of the SMA probe on the patch and the non-uniformity of the sample as it had some air bubbles, surface roughness, and a non-uniform thickness.

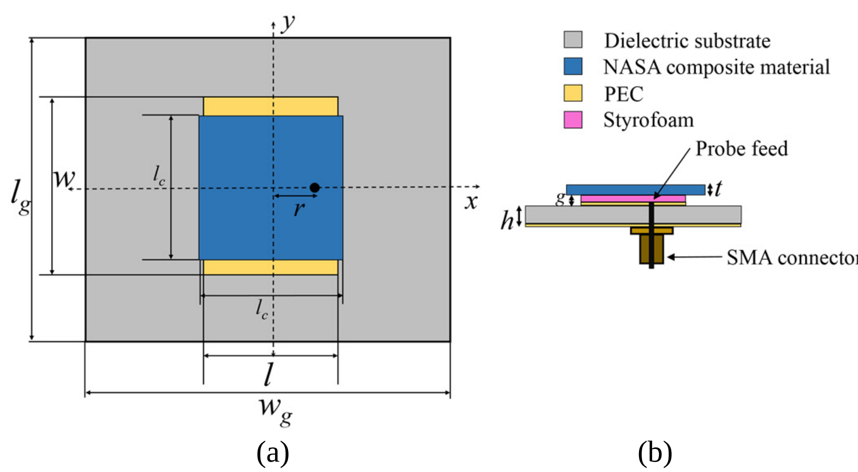

Figure 3. (a) Top- and (b) cross-sectional views of the benchmark antenna loaded by the composite material as a superstrate with $l_g = 15.1\,\text{cm}$, $w_g = 11.5\,\text{cm}$, $l = 3.29\,\text{cm}$, $w = 4.95\,\text{cm}$, $r = 7.56\,\text{mm}$, $t = 1.8\,\text{mm}$, $g = 0.5\,\text{mm}$, $h = 1.57\,\text{mm}$ and $l_c = 4.2\,\text{cm}$.

The measurement results of the fabricated antenna are summarized in Table 2. The composite superstrate reduces the resonant frequency by 0.08 GHz as the effective dielectric constant of the antenna increases due to the presence of the high-contrast composite superstrate. Moreover, the measured peak gain drops by about 0.8 dB due to the expected lossy nature of the composite superstrate.

Table 2. Measured results of the composite superstrate antenna shown in Figure 3.

Antenna with composite superstrate	f (GHz)	Gain (dBi)	$\lvert S_{11}\rvert$ (dB)
Measured results	2.82	8.05	−22.4

To estimate the dielectric properties of the unknown material, the benchmark antenna loaded with the NASA composite material as the superstrate layer on top is simulated by the full-wave solver and parametric studies on dielectric constant and loss tangent of the composite are conducted. That is, the dielectric permittivity and loss tangent of the composite material are linearly changed in the simulation to obtain the similar frequency shift and gain drop in the fabricated and measured model in the lab. To this end, first the antenna shown in Figure 3 is investigated for different values of ε_r by comparing the resonance frequency of the measured antenna in the lab and that of the simulated antenna. Based on the parametric studies performed on ε_r, the resonant frequency reaches to the measured 2.82 GHz, when ε_r is close to 6. Some representative scattering parameters of the antenna are plotted in Figure 4, further illustrating the trend in the frequency reduction with such a high-contrast superstrate.

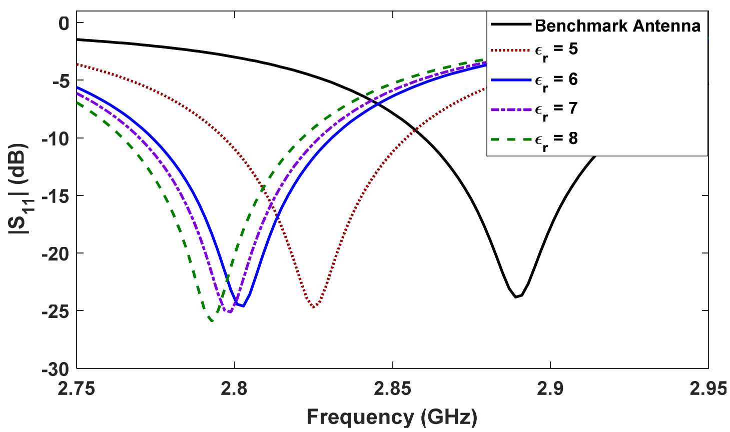

Figure 4. Reflection coefficients of the superstrate antenna shown in Figure 3 for different ε_r.

In general, the frequency of operation of the antenna is inversely proportional to the square root of dielectric constant. Interestingly enough, when ε_r changes from 5 to 8, there is almost a linear relationship between the resonant frequency of the antenna and the relative permittivity (ε_r) of the composite material whose relationship is expressed by Eq. (1). This equation will help estimate the relative permittivity of the composite materials of identical dimensions based on the resonant frequency of the antenna.

$$\varepsilon_r = 207.15 - 71.29f \tag{1}$$

where f is the frequency in GHz. The relative permittivity using the measured data in Figure 4 against frequency is plotted in Figure 5 and also compared with a fitted curve obtained by the least square method based on Eq. (1).

To estimate the loss tangent of the composite, another parametric study is carried out with respect to different values for the loss tangent, while keeping the dielectric constant unchanged at 6. Different values of $\tan\delta$ are investigated, which are listed in Table 3. As expected, the loss tangent of the superstrate mainly affects the peak gain of the antenna, whereas its resonant frequency is slightly impacted by it. As listed in Tables 1 and 2, a gain drop of 0.8 dB occurs in the measured results of the antenna when the benchmark antenna is loaded with the superstrate. The same gain drop of ~ 0.8 dB is obtained as per Table 3, when $\tan\delta$ is close to 0.12.

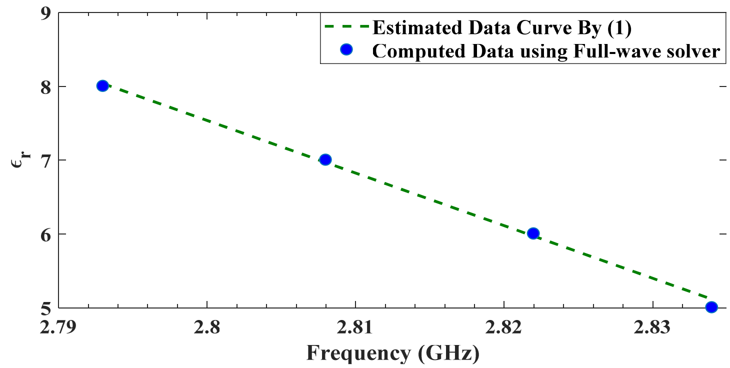

Figure 5. Measured and estimated data of dielectric constant by (1) versus frequency for the NASA-developed composite material.

Table 3. Simulated results of the antenna in Figure 3 for different loss tangent values of the superstrate for $\varepsilon_r = 6$.

Loss Tangent ($\tan\delta$)	f (GHz)	Gain (dBi)	$\lvert S_{11}\rvert$ (dB)
0.08	2.80	8.75	−27.56
0.1	2.81	8.60	−30.42
0.12	2.81	8.40	−31.23
0.14	2.81	8.32	−26.31

The proposed technique has resulted in estimated values of $\varepsilon_r = 6$ and loss tangent = 0.12 for the composite material under test. Sensitivity analysis has also been conducted to demonstrate the effect of position of the superstrate on the antenna frequency. Table 4 summarizes the analysis conducted with a 2 mm displacement along the resonant length of the radiating patch in positive and negative directions along the x-axis for the antenna shown in Figure 3. The error in frequency shift is less than 0.5% and that in ε_r is less than 10%.

Table 4. Sensitivity analyses on dielectric constant based on position of superstrate for superstrate loaded antennas.

	Frequency (GHz)	% error in frequency	ε_r	% error in ε_r
Nominal position	2.81	-	6	-
2 mm displacement on $+x$ axis	2.82	0.35%	5.5	8.33%
2 mm displacement on $-x$ axis	2.818	0.28%	5.6	6.66%

To conduct sensitivity analysis on the loss tangent, the superstrate loaded on the surface of the patch is tilted by $\theta = 1^\circ$ as this is the maximum tilt possible by the superstrate along the resonant length of the radiating patch in the positive and negative directions along the x-axis, as shown in Figure 6. The variation in loss tangent is less than 10% when the superstrate is tilted compared to the ideal case. The analysis conducted on the angular tilt of the superstrate is summarized in Table 5 and compared to the ideal scenario with no tilt. Figure 7 plots the peak gain in the E-plane, i.e., $\phi = 0^\circ$, for different case studies, resulting in less than 10% error. Subsequently, the loss tangent determined with this method has a better accuracy for materials with such high loss tangent than other methods reported in [6–8].

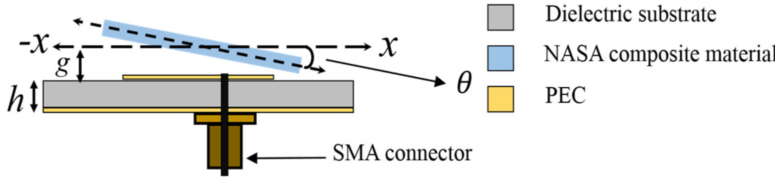

Figure 6. Cross-sectional view of the benchmark antenna loaded by the tilted composite material as a superstrate to perform sensitivity analysis on loss tangent with $g = 0.5$ mm and $h = 1.57$ mm.

Table 5. Sensitivity analyses on loss tangent based on tilt angle of the superstrate as shown in Figure 6.

	Gain (dBi)	Approx. Loss tangent	% error in $\tan\delta$
Nominal position ($\theta = 0°$)	8.50	0.11	-
$\theta = 1°$ tilt towards $+x$ axis	8.54	0.106	3.6%
$\theta = 1°$ tilt towards $-x$ axis	8.39	0.12	9.09%

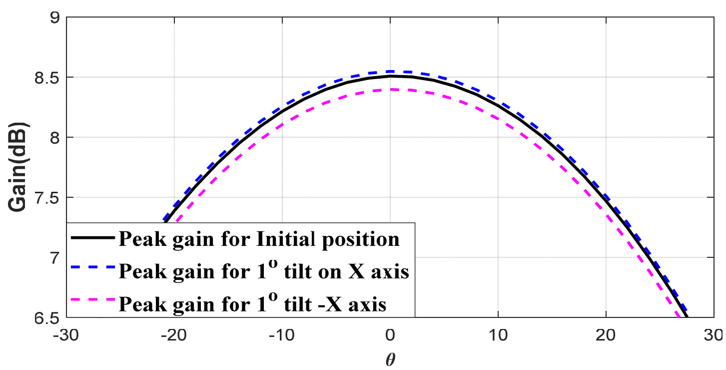

Figure 7. Variations of the antenna peak gain with different orientations of the superstrate material under test, as illustrated in Figure 6.

4. VALIDATION OF PROPOSED METHOD

To validate the estimated properties and examine the accuracy of the proposed method, a square microstrip patch antenna is designed wherein the composite material is used as the substrate with the same dimensions of 42 mm × 42 mm × 1.8 mm. The newly designed antenna is illustrated in Figure 8, where the frequency of operation is 2.55 GHz with the established $\varepsilon_r = 6$ and loss tangent = 0.12. The fabricated antenna was first simulated using the full-wave solver [12] and then tested in the anechoic chamber. The fabricated antenna when measured resonated at 2.55 GHz with the peak gain of −1.86 dBi. The simulated and measured reflections coefficients are shown in Figure 9, exhibiting good agreement between them. This confirms the dielectric constant of the composite material as 6.

The measured and simulated radiation patterns of the antenna at the resonant frequency of 2.55 GHz are plotted in Figure 10, which are well matched in the principal planes. The measured peak gain of the antenna is −1.85 dBi at 2.55 GHz and the simulated peak gain is −1.80 dBi, which are quite close to each other. Therefore, this confirms the estimated loss tangent of ~ 0.12 for the composite

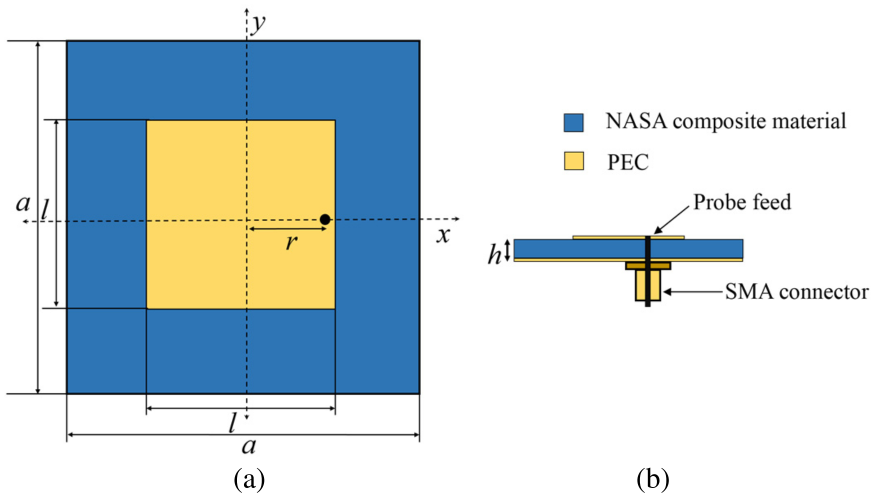

Figure 8. (a) Top- and (b) cross-sectional views of the square microstrip patch antenna printed on the composite material operating at 2.55 GHz, with $a = 42$ mm, $l = 23.2$ mm, $r = 10.5$ mm, and $h = 1.8$ mm.

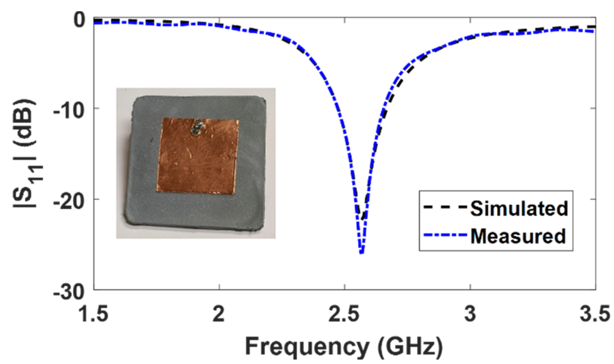

Figure 9. Measured and simulated reflection coefficients of the microstrip patch antenna printed on the composite substrate in Figure 8 with a photo of the fabricated antenna on the inset of the plot.

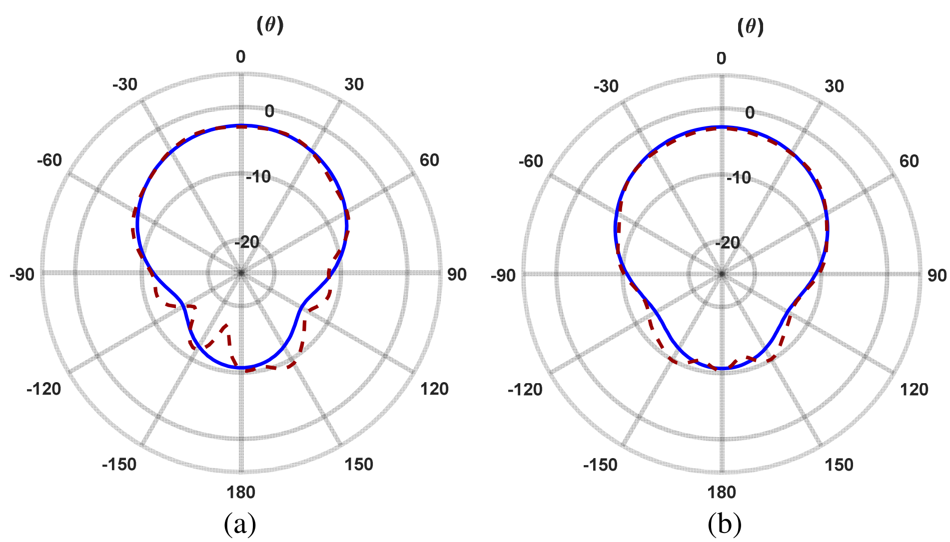

Figure 10. Simulated and measured radiation patterns of the fabricated antenna in Figure 9 in the (a) E-plane and (b) H-plane at 2.55 GHz; —— Simulated – – – – Measured.

material. The dissimilarity in the backlobe region between the measurement and simulation results is attributed to the reflections from the connecting coaxial cable in the test chamber.

5. CONCLUSION

An affordable, unambiguous, and non-invasive approach was proposed to estimate the dielectric properties of non-magnetic materials without any tedious or expensive installation of measurement apparatus. The NASA-developed composite material was put under test to determine its dielectric constant and loss tangent by employing the composite material as a superstrate on a pre-characterized benchmark antenna. The dielectric constant was estimated close to 6, which was determined by the shift in the resonant frequency as the equivalent dielectric constant of the antenna increases. The loss tangent was estimated close to ~ 0.12, based on the peak gain drop with the presence of the lossy superstrate. The results were further verified by developing a square patch antenna using the composite material as the substrate. The experiment confirmed the accuracy of the proposed method to estimate the dielectric properties of the composite material.

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