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Experimental and Simulated Investigation of S-parameters and Power Loss Characteristics of PTFE/Glass Composites at X-band Frequency

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ABSTRACT

Polytetrafluoroethylene (PTFE)-based substrates are in high demand for high-frequency (microwave) applications because of their low relative permittivity, enabling efficient signal transfer. In this work, PTFE composites have been prepared with different content (5 wt.% - 25 wt.%) of soda lime silica glass (SLSG) for substrate application. The composites were characterized by their complex permittivity and S-parameters through the rectangular waveguide (RWG) measurement method over x-band frequency (8.2 GHz – 12.4 GHz). The RWG set-up was connected to a vector network analyser for the characterization. Power loss of the composites due to material absorption was calculated using the measured S-parameters. As the content of the SLSG increased from 5 - 25 wt.%, complex permittivity ε^* rose from 2.18-j0.0035 to 2.56-j0.0047 in the frequency range considered. In addition, $|S_{11}|$ reduced from 0.623 and 0.700 to 0.418 and 0.441, whereas $|S_{21}|$ varied from 0.780 and 0.713 to 0.906 and 0.895 for 5 wt.% and 25 wt.% SLSG contents at 8.2 GHz and 12.4 GHz, respectively. The calculated power loss increased from 2.94 dB to 3.29 dB and 4.01 dB to 4.88 dB for the same filler contents and frequency. Furthermore, the S-parameters were simulated using the finite element method (FEM) via COMSOL software and compared with the measured values. The comparison revealed a mean relative error of < 0.1, denoting the accuracy of the RWG method. Also, the electric field distribution across the waveguide length was visualized. Thus, the optimal performance of the composite was found at 5 wt.% SLSG filler content for microwave substrate application.

Keywords:
Rectangular Waveguide, RWG, S-parameters, x-band, PTFE

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1. Introduction

The congestion of the lower frequencies (0.3-1 GHz) in the electronics and communication sectors due to the exponential development of smart and data-consuming mobile phones and antennas necessitates the opening up of higher frequencies to sustain the current drive to meet the requirements of immediate and future technological challenges [1]. In response to this challenge, substrate materials with low complex permittivity, high mechanical strength and excellent thermal properties are being developed [2–5]. Polymer dielectric materials are mostly preferred for microwave substrate application due to their desired electrical and mechanical properties [3, 6, 7]. However, polytetrafluoroethylene stands out among the polymers because of its excellent properties such as lowest and steady complex permittivity (~2.02-j0.0021) over a large spectrum of high frequencies, chemical inertness, and high operating temperature (~260°C) [8–10]. However, it has a high coefficient of thermal expansion and very low thermal conductivity, thus limiting its ability to function as a stand-alone dielectric material for microwave substrate application [11-12]. Thus, a suitable modifying filler needs to reinforce the PTFE for optimal performance.

Numerous research works on PTFE-based composites with excellent dielectric, mechanical, thermal and moisture absorption properties have been reported [11–18]. These works of literature developed composites with excellent dielectric, mechanical, thermal and moisture absorption properties for high-frequency applications. However, none of the consulted works analysed the S-parameters (S11 and S21) and power loss due to materials absorption of the composites developed for the microwave substrate application. The S11 and S21 are line parameters that describe the nature of reflection and transmission of electromagnetic waves in a high-frequency network, in addition to defining the microwave signal reflection and absorption loss behaviour of a material [19]. The incorporation of the analysis of the S11 and S21 and power trend loss among other properties provides a holistic assessment of the suitability of the composites for substrate application at microwave frequencies.

Thus, this work studied and analysed the S-parameters and power loss due to material absorption of the PTFE/Glass composites at the x-band for substrate application. Soda lime silica glass (SLSG) was chosen as the reinforcing glass filler due to its suitable dielectric properties and excellent tensile strength. Although, few works were reported on the dielectric properties of PTFE/soda lime silica glass composite, however, none studies the effects of filler content on the S-parameters and power loss due to material absorption on the composites [20, 21]. In addition, a finite element method (FEM) implemented in COMSOL software was used to simulate the S-parameters and compare them with the ones obtained from measurement. Furthermore, the mean relative error between measurement and simulation was calculated to ascertain the accuracy of the RWG measurement method.

2. Methodology

2.1 Materials

PTFE purchased from Fujian Sannong New Materials Co., Ltd, China and soda lime silicate glass (SLSG) waste were used as the preparatory materials to fabricate the PTFE/SLSG composites. The SLSG powder was prepared via milling and, then mixed with PTFE using a high-speed shear mixer for 10 min, before being pressed hydraulically for 5 min at 10 MPa. Weight percentages of the SLSG filler in the composites were 5 wt.%, 10 wt.%, 15 wt.%, 20 wt.% and 25 wt.%, respectively.

2.2 Scattering Parameters

The S11 and S21 of the composites were measured in the 8.2-12.4 GHz microwave frequency (X-band) using a rectangular waveguide (RWG) measurement technique. The RWG setting was connected to a vector network analyser for the measurement. Also, the mean complex permittivity given in Eq. 1 was characterised over the same frequency.

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

where, ε' and ε'' are the relative permittivity and loss factor, respectively.

2.3 Finite Element Method (FEM) Simulation of Reflection and Transmission Coefficients

In this study, the finite element method (FEM) implemented in COMSOL Multiphysics® version 3.5 (COMSOL, Inc., Burlington, MA, USA) was also used to calculate the magnitude of S_{11} and S_{21} based on the RWG model geometry shown in Figure 1. Generally, the S_{11} and S_{21} are determined in FEM simulation using four essential steps [22]: (a) discretizing the region of solution into a finite number of elements, (b) deriving the governing equation for a given region, (c) assembling all the elements in a given region, and (d) solving the systems of equations derived. Furthermore, the simulation process was implemented using the steps defined in Figure 2 with the mean complex permittivity values, shown in Table 1, obtained from RWG measurement as inputs. The simulated and measured results were, then compared for validation, and electric field distribution across the waveguide regions was, also visualized.

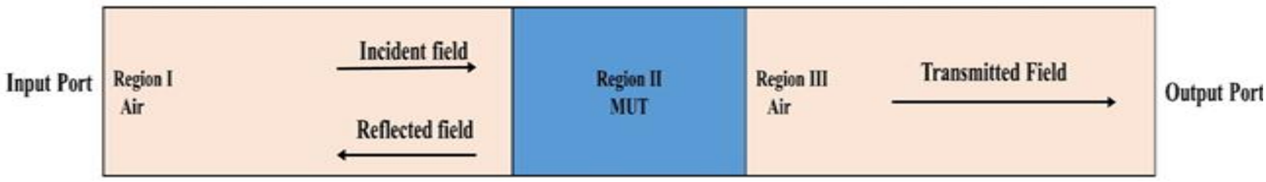

Fig. 1. RWG model geometry

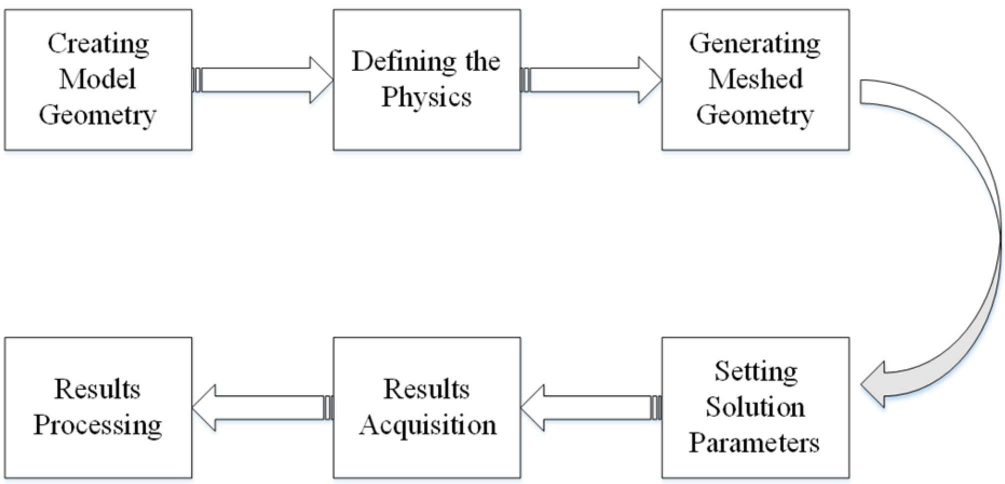

Fig. 2. FEM simulation process

Table 1
Mean complex permittivity of the composites at X-band frequency

SLSG (wt.%)	$\varepsilon^* = \varepsilon' - j\varepsilon''$
5	2.18-j0.0035
10	2.28-j0.0038
15	2.40-j0.0041
20	2.47-j0.0043
25	2.56-j0.0047

2.4 Material Absorption

The intrinsic capacity to attenuate electromagnetic energy by materials can be determined by calculating the power loss due to absorption using the $|S_{11}|$ and $|S_{21}|$. Typically, the energy absorbed is dissipated as heat via phase cancelling, causing dimensional instability of the material. Hence, the determination of the absorption capability of composite materials is paramount, especially for microwave substrate applications, where little or no power loss is desired. Thus, from a waveguide measurement perspective, the power loss due to ohmic loss and measurement error for an empty waveguide can be calculated via Eq. (2) using the measured $|S_{11}|$ and $|S_{21}|$.

$$P_{loss}(air) = 1 - |S_{11}|^2{}_{air} - |S_{21}|^2{}_{air} \tag{2}$$

while the material power loss for a sample in the same waveguide can be expressed as Eq. 3:

$$P_{loss}(sample) = 1 - |S_{11}|^2{}_{sample} - |S_{21}|^2{}_{sample} \tag{3}$$

Hence, the power loss due to absorption can be obtained from the difference in the power losses of the loaded and empty waveguide using the following Eq. 4 [23].

$$Power\ loss\ (dB) = 10log_{10}P_{loss}(sample) - 10log_{10}P_{loss}(air) \tag{4}$$

3. Results
3.1 S-parameters

The reflection and transmission coefficients were investigated for filler content and frequency, while the result is presented in Figures 3 and 4. It can be seen in Figure 3 that the $|S_{11}|$ increased with filler loading and reduced with frequency. At 8.2 GHz, the |S11| varied from 0.623, 0.647, 0.671, 0.684, and 0.700 to 0.418, 0.427, 0.436, 0.439, 0.441 at 12.4 GHz for 5 wt.%, 10 wt.%, 15 wt.%, 20 wt.%, and 25 wt.% SLSG contents, respectively. Figure 4 shows the variation of $|S_{11}|$ with SLSG filler content for the composites at specified frequencies. A similar trend was reported by Ahmad et al. [24], where the $|S_{11}|$ was found to increase with more filler content. This notable change arises from impedance mismatch between the input and RWG impedances, as described by the following Eq. (5) and Eq. (6).

$$S_{11} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{5}$$

$$Z_{in} = Z_0\sqrt{\frac{1}{\varepsilon_r}}\tanh\left(j\omega l\frac{\sqrt{\varepsilon_r}}{c}\right) \quad (6)$$

where Z_{in} and Z_0 are the input and RWG impedances, respectively, l is the sample thickness with ω being the angular frequency. It is clear from Eq. 7, for non-magnetic materials, that input impedance is proportional to the frequency of operation. Thus, as the frequency increases, Z_in gets more prominent, reducing the impedance mismatch, which further decreases the $|S_{11}|$.

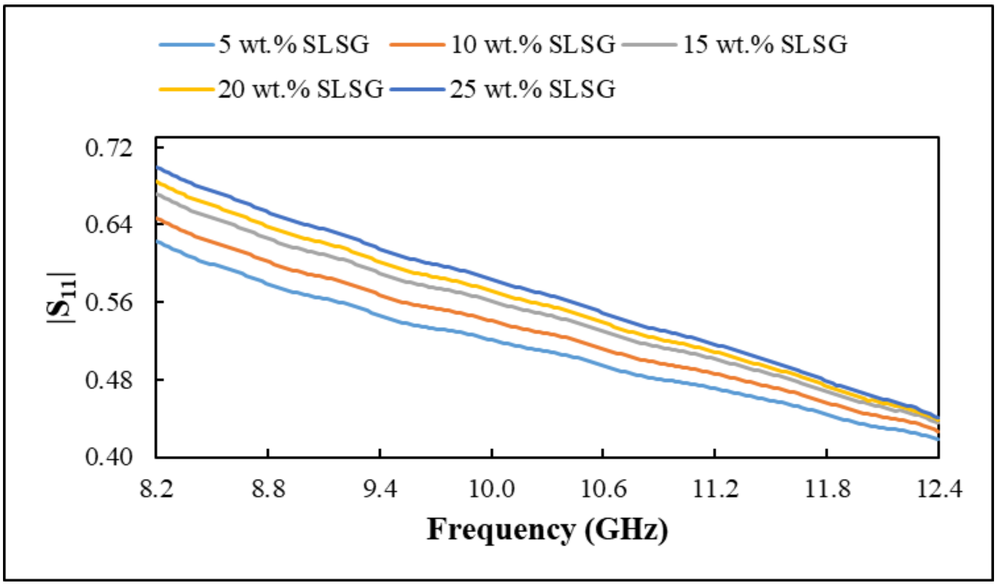

Fig. 3. Variation of $|S_{11}|$ with SLSG filler content and frequency

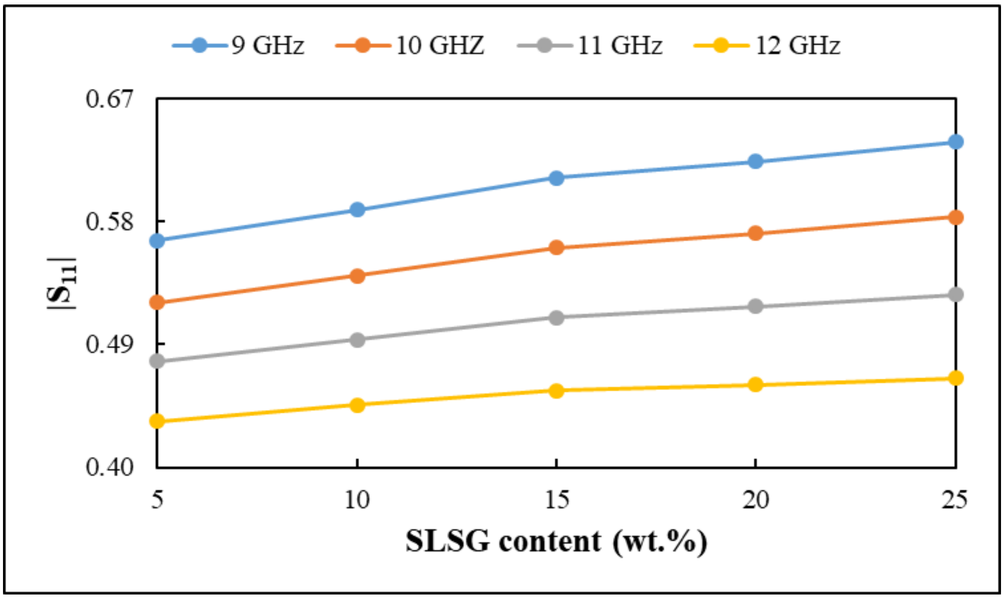

Fig. 4. Variation of $|S_{11}|$ with SLSG filler content and frequency

The $|S_{21}|$ depicted in Figure 5 also decreases with more filler content due to higher impedance mismatch, while it increases with frequency because at higher frequencies $Z_{in} \sim Z_0$, improving the signal transmission for the PTFE/rBRS composites. Thus, at 8.2 GHz $|S_{21}|$ appreciated from 0.780, 0.761, 0.739, 0.727, and 0.713 to 0.906, 0.902, 0.898, 0.896, and 0.895 at 12.4 GHz for 5 wt.%, 10 wt.%, 15 wt.%, 20 wt.%, and 25 wt.% SLSG filler content, respectively. A similar result was reported

[25]. Figure 6 shows the variation of $|S_{21}|$ with SLSG filler content for the composites at specified frequencies.

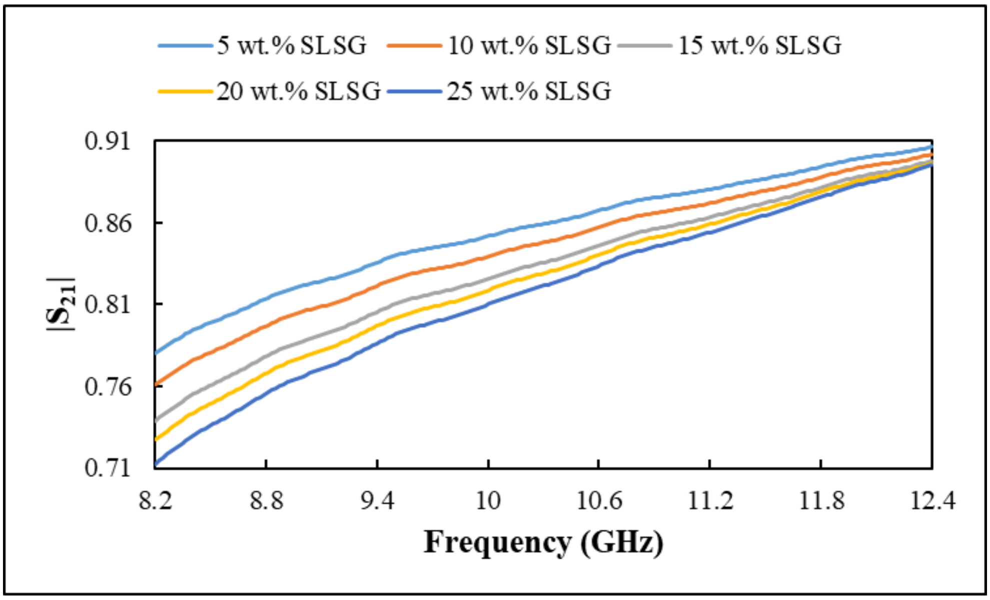

Fig. 5. Variation of $|S_{21}|$ with SLSG filler content and frequency

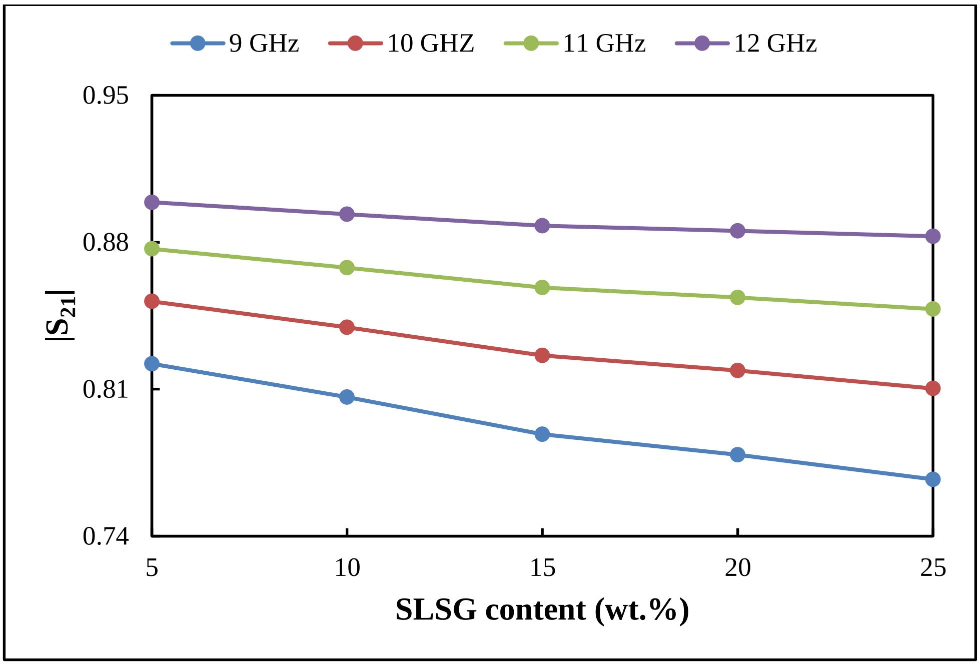

Fig. 6. Variation of $|S_{21}|$ with SLSG filler content at certain frequency

3.2 Comparison of Measured and Simulated $|S_{11}|$ and $|S_{21}|$

The comparison between the measured and simulated values of $|S_{11}|$ and $|S_{21}|$ is illustrated in Figures 7 and 8. The $|S_{11}|$ decreased with SLSG filler content and increased with frequency. Whereas, the $|S_{21}|$ increased with frequency and decreased with SLSG filler content, as indicated by both the measured and simulated data. Although the experimental and computational values of $|S_{11}|$ and $|S_{21}|$ exhibited a similar curve, there is a noticeable difference between them. This difference may be attributed to the ideal nature assumed in the simulation environment, where no stray radiation or reflection exists between the sample holder and the waveguide adapters [19]. The mean relative error given in Table 2 was calculated using Eq. 7 and Eq. 8 and indicated a good agreement between measurement and simulation as both $|S_{11}|$ and $|S_{21}|$ achieved mean relative errors of < 0.1.

$$Mean\ relative\ error\ |S_{11}| = \frac{1}{201}\sum_{i=1}^{201}\left(\frac{|S_{11}(measured)-S_{11}(simulated)|}{S_{11}(measured)}\right) \tag{7}$$

$$Mean\ relative\ error\ |S_{21}| = \frac{1}{201}\sum_{i=1}^{201}\left(\frac{|S_{21}(measured)-S_{21}(simulated)|}{S_{21}(measured)}\right) \tag{8}$$

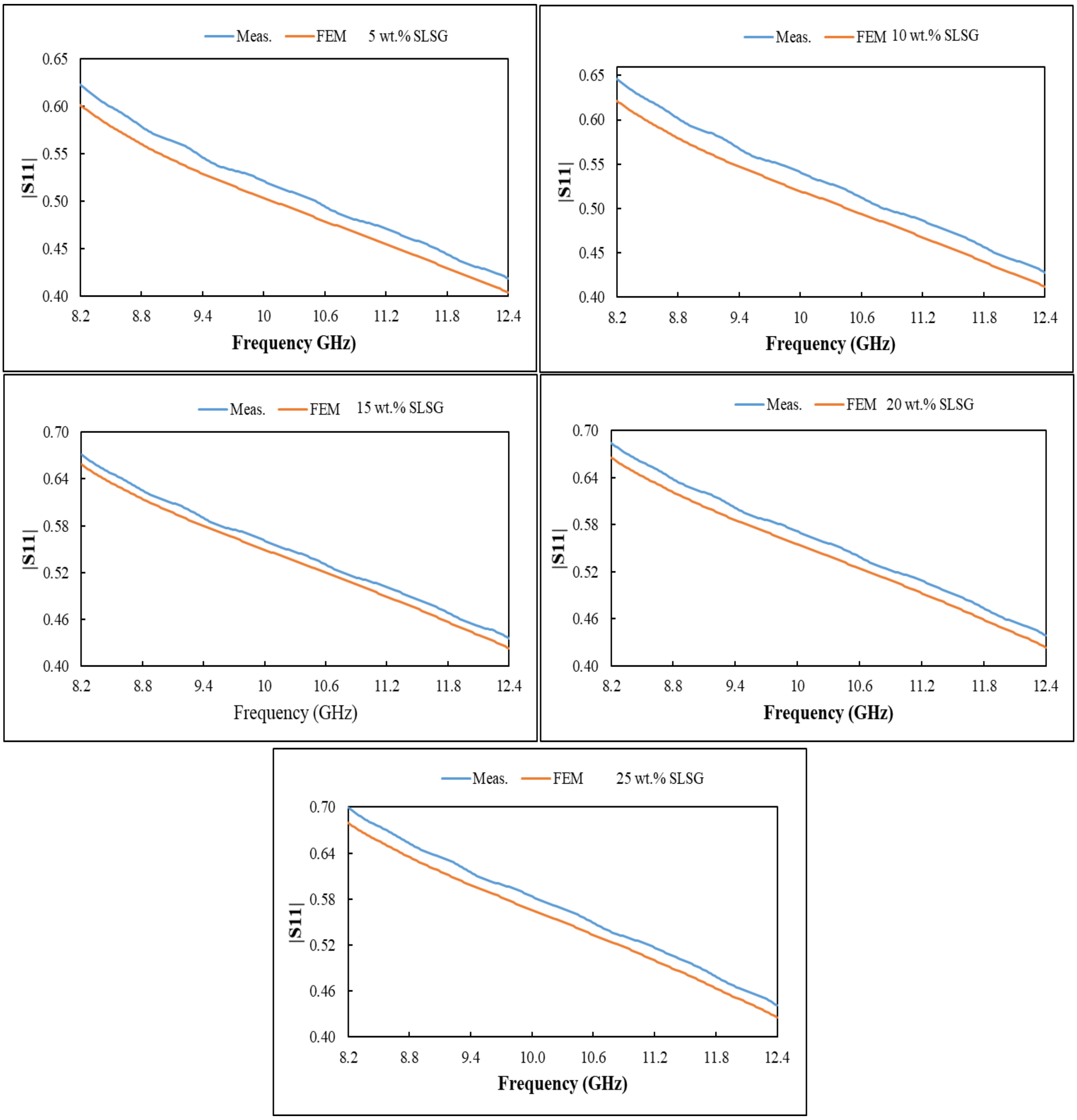

Fig. 7. Comparison of measured and simulated $|S_{11}|$ with SLSG filler content

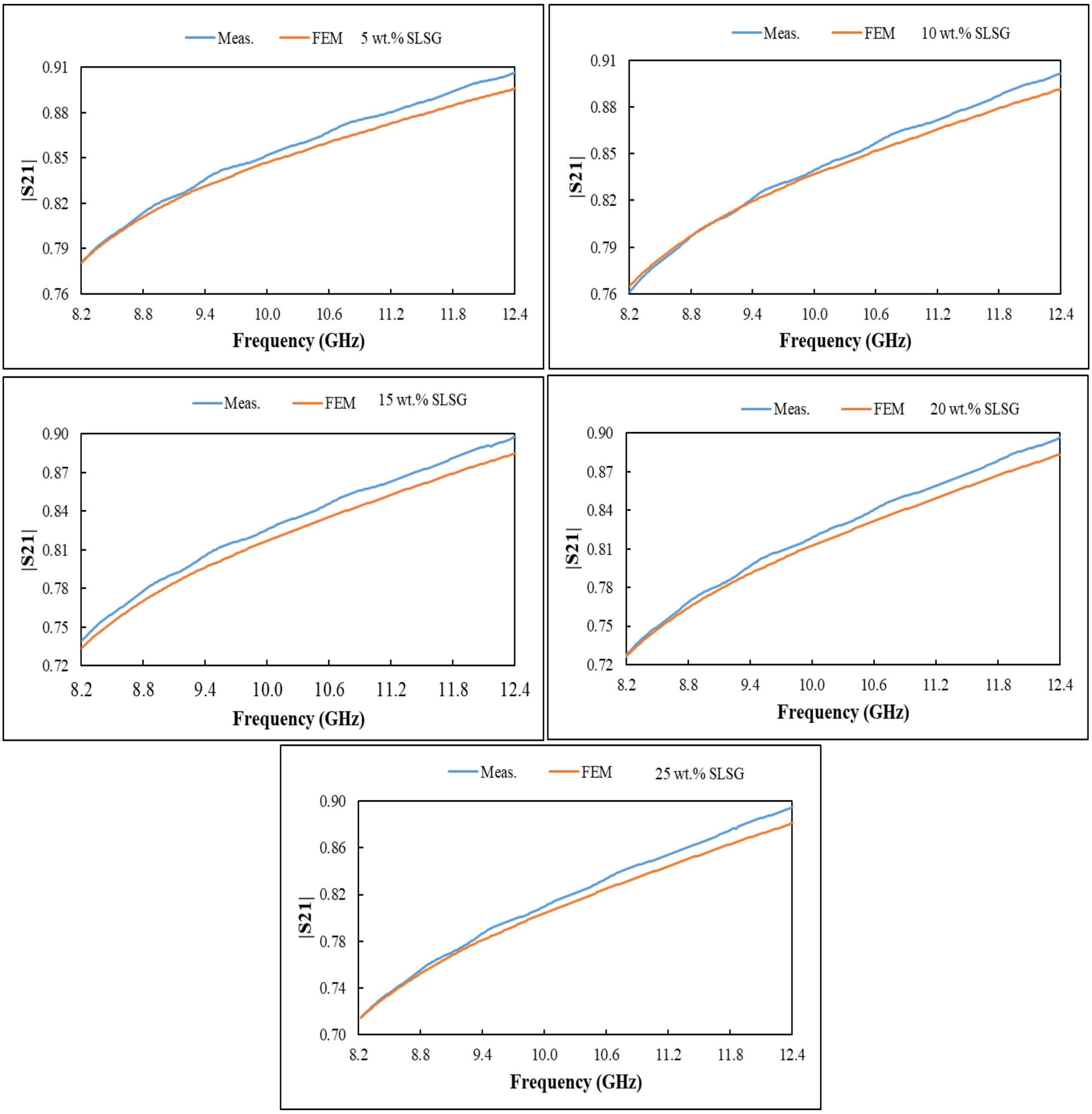

Fig. 8. Comparison of measured and simulated |S_{21}| with SLSG filler content

Table 2
Mean relative error for measured and simulated |S_{11}| and |S_{21}|

SLSG (wt.%)	Relative Error	
	|S_{11}|	|S_{21}|
5	0.033	0.007
10	0.037	0.005
15	0.021	0.012
20	0.028	0.009
25	0.030	0.009

3.3 Visualisation Electric Field Distribution

The electric field distribution across the length of a rectangular waveguide (RWG) is shown in Figure 9. It can be noticed that the RWG length of 40 cm was divided into three regions: I, II, and III. Regions I and III are air media, while region II contains the dielectric sample. In addition, the length of the regions was 20 cm, 0.6 cm, and 19.4 cm, respectively. Furthermore, input and output ports were located in regions I and III. As the electromagnetic waves propagate along the z-axis of the RWG, it is seen to diminish in intensity as it passes from Region I through the dielectric sample (Region II) to Region III of the RWG. The reduction in intensity is due to absorption by the dielectric sample.

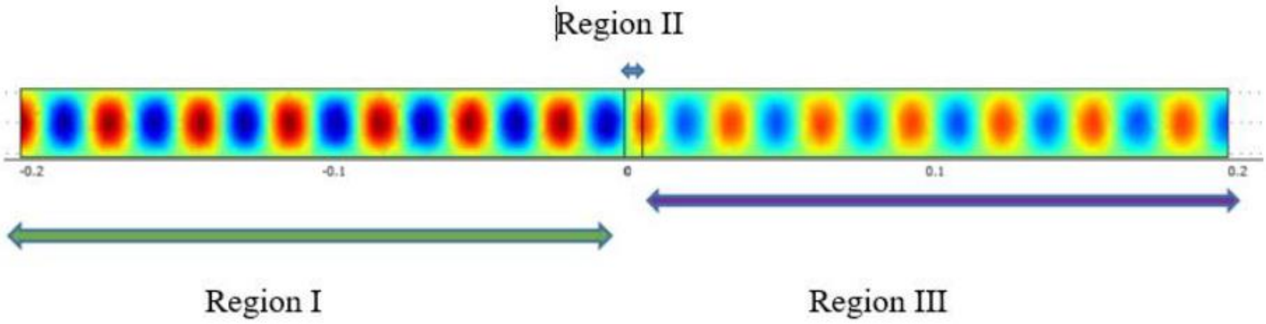

Fig. 9. Visualisation of electromagnetic field distribution across a rectangular waveguide

3.4 Power Loss

Figure 10 shows the variation of power loss due to absorption for the PTFE/SLSG composites. The power loss increased in conjunction with SLSG filler content and frequency. Khamis et al. reported a similar finding [23]. In addition, the PTFE/SLSG composites showed a respective increase of 2.94 dB to 3.29 dB for 5 wt.% SLSG content and 4.01 dB to 4.88 dB for 25% SLSG volume fraction at X-band. All composites exhibit a similar trend. The increased power loss with SLSG filler loading is attributed to the higher magnitude of dielectric loss. The loss is responsible for material absorption; therefore, increasing the SLSG content resulted in higher values of the dielectric loss, resulting in decreased signal transmission because of more absorption. A similar trend was observed in [26]. Furthermore, the power loss values at specified frequencies are given in Table 3.

Table 3
Power loss (dB) at specified frequencies

SLSG (wt.%)	Frequency (GHz)			
	9	10	11	12
5	3.22	3.48	3.56	3.87
10	3.28	3.58	3.70	4.04
15	3.27	3.62	3.82	4.18
20	3.28	3.67	3.89	4.39
25	3.41	3.85	4.10	4.54

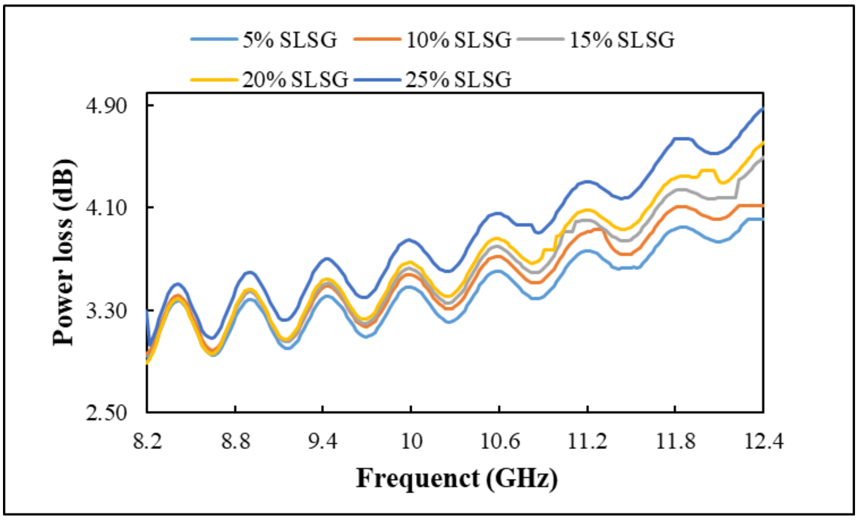

Fig. 10. Variation of power with SLSG filler content and frequency

4. Conclusions

The S-parameters of the PTFE/SLSG composites were studied and analysed. The S_{11} showed an increasing nature with SLSG filler content and decreases with frequency. However, the S_{21} displayed an increasing trend with frequency and decreased with SLSG filler content. In addition, the comparative studies of the measured and simulated values of S_{11} and S_{21} exhibited a similar trend with a mean error of <0.1, indicating the accuracy of the measurement method. Also, the electric field distribution in the RWG was visualised, showing a diminishing pattern in the field after passing through the dielectric sample. Furthermore, the power loss due to material absorption increased with both frequency and SLSG filler content. However, the composites recorded low power loss, thereby making them suitable for microwave substrate application.

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