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Determination of complex permittivity and permeability of lanthanum iron garnet filled PVDF-polymer composite using rectangular waveguide and Nicholson–Ross–Weir (NRW) method at X-band frequencies

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ABSTRACT

In our previous work, the lanthanum iron garnet-filled PVDF-polymer nanocomposite has been prepared. The reflection and transmission coefficients (*S*-Parameters) of PVDF-13% LIG were measured using rectangular waveguide in conjunction with a microwave vector network analyzer (VNA) at X-band frequencies (8–12 GHz). In order to determine simultaneously the real and imaginary parts of complex permittivity and permeability of nanocomposite sample the Nicholson–Ross–Weir (NRW) method was applied based on the measurement of the *S*-Parameters of the materials. The general observations of the results indicate that the decreasing in real and imaginary part of complex permeability and real part of complex permittivity resulted in increasing the frequency; meanwhile imaginary part of permittivity tends to become constant when frequency increased.

1. Introduction

The application of nanocomposites in microwave and electronic devices requires the exact knowledge of all parameters a single wave carrier signal. Determination of reflection and transmission coefficients (*S*-Parameters), complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) and complex permeability ($\mu = \mu' - j\mu''$) of garnet ferrites loaded polymer nanocomposites have attracted the interest of many researchers and scientists due to their applications in microwave and electronic devices such as isolators, filters and circulators [1–3].

As a soft ferrite material, lanthanum iron garnet ($La_3Fe_5O_{12}$) has been used in various applications in electronic devices. This is because of its efficient absorption of electromagnetic waves, low saturation flux density, low losses at high frequencies, high resistivity and easy to magnetize and demagnetize. As a result, polymer-based composites filled with ferrite particles, such as cobalt-ferrite [4], NiZn-ferrite [5], and MnZn-ferrite [6,7] have attracted considerable attention over the years.

The parameters of a single wave carrier signal such as frequency, phase, amplitude and DC component were determined by a general method based on four different samples [8]. The relative error of the estimated parameters was decreasing linearly as the signal-to-noise ratio (SNR) increases. For portable DSP, a simple and precise instantaneous frequency estimation method of single sinusoid signals were conducted based on instrumentation to obtain an analytical formula [9,10]. A quantized multiple sinusoids signal estimation algorithm was presented. The accuracy of the initial values of iterations has a large influence on the speed of convergence. An iterative process was performed in order to reduce the cost function [11,12].

Many methods have been used for measuring reflection and transmission coefficients as electromagnetic properties of the materials [13]. In previous our work, the transmission reflection rectangular waveguide technique (T/R)

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was conducted in order to obtain the reflection and transmission coefficients of the materials [14].

In this paper the Nicholson–Ross–Weir (NRW) method was applied to calculate simultaneously the complex permittivity and permeability of the lanthanum iron garnet-filled PVDF-polymer as nanocomposite sample. The calculations are based on measured reflection and transmission coefficients (S_{11} and S_{21}) of mentioned sample which positioned in rectangular waveguide at X-band frequencies. In addition, The NRW method was introduced in order to calculate the reflection and transmission coefficients of the mentioned sample by applying obtained complex permittivity and permeability as well as [14,15]. The comparisons of the results of measured and NRW method for S_{11} and S_{21} were presented to show the validation of obtained complex permittivity and permeability of mentioned nanocomposite sample.

2. Material and methods

LIG was prepared according to the previous our work [16]. Amorphous LIG was synthesized by sol–gel method. The pure phase crystalline cubic LIG was obtained by the heat-treatment of the as-prepared amorphous material at 700 °C for 2 h in air atmosphere. PVDF-13% LIG as a nanocomposite sample was prepared by solvent method with 13% filler and 87% of PVDF in the form of a rectangular sheet with 1–3 mm thicknesses. PVDF-13% LIG's as nonocomposite samples were snugly fitted into a WR-90 waveguide then reflection and transmission coefficients (S_{11} and S_{21}) were measured in the frequency range of 8–12 GHz by using an Agilent N5230A PNA-L network analyzer (Fig. 1). In this technique the fundamental transverse electromagnetic (TEM) mode is the only mode that propagates in rectangular waveguide. Network analyzer was calibrated by implementing a standard full two-port calibration technique (SOLT) for 201 frequency points. The complex permittivity and permeability of PVDF-13% LIG was calculated by NRW method which based on measured S_{11} and S_{21} using T/R rectangular waveguide method [17,18]. As combined transmission–reflection method, the both complex permittivity and permeability of the sample could be obtained by matching the measured S_{11} and S_{21} and the calculated values [19,20].

Here, as can be shown in Fig. 2 the standard procedure of calculating the reflection and transmission coefficients of a sample which placed between two planar boundaries of unbounded was reviewed [21]. The details could be found in most electromagnetic textbooks. The complex

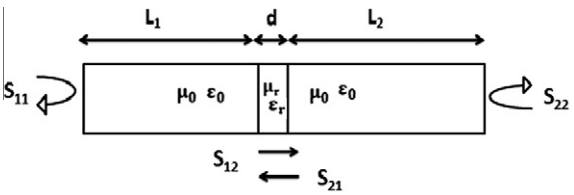

Fig. 1. Measurement of the S-Parameters (S_{11} and S_{21}) using rectangular waveguide.

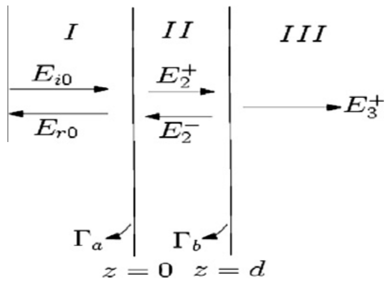

Fig. 2. Reflection and transmission for a sample placed between unbounded medium.

impedance of each medium is related to its complex permittivity:

$$Z_{I,S,III} = \frac{Z_0}{\sqrt{\varepsilon^*_{I,S,III}}} \quad (1)$$

where Z_I, Z_S and Z_{III} are the complex impedances in media *I*, *II* and *III* respectively which $Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$ is the free space impedance. The reflection and transmission coefficients (S_{11} and S_{21}) can be calculated by applying boundary conditions at $z = 0$ and $z = d$ to give:

$$S_{11} = \frac{E_{r0}}{E_{i0}} = \frac{(Z_{III}+Z_S)(Z_S-Z_I)\exp(-\gamma_S d) + (Z_{III}-Z_S)(Z_S+Z_I)\exp(\gamma_S d)}{(Z_{III}+Z_S)(Z_S+Z_I)\exp(-\gamma_S d) + (Z_{III}-Z_S)(Z_S-Z_I)\exp(-\gamma_S d)} \quad (2)$$

$$S_{21} = \frac{E_3^+}{E_{i0}} = \frac{4(Z_S)Z_{III}}{(Z_{III}+Z_S)(Z_S+Z_I)\exp(-\gamma_S d) + (Z_{III}-Z_S)(Z_S-Z_I)\exp(-\gamma_S d)} \quad (3)$$

In above equations γ_I, γ_S and γ_{III} are the propagation constant in media *I*, *II* and *III* respectively. General forms of the above equations can be written as follows [22]:

$$S_{11} = \frac{\Gamma_a + \Gamma_b P^2_{theory}}{1 + \Gamma_a \Gamma_b P^2_{theory}} \quad (4)$$

$$S_{12} = \frac{(1 + \Gamma_a \Gamma_b) P_{theory}}{1 + \Gamma_a \Gamma_b P^2_{theory}} \quad (5)$$

where

$$\begin{cases} \Gamma_a = \frac{(Z_S - Z_I)}{(Z_S + Z_I)} = \frac{(\sqrt{\varepsilon^*_I} - \sqrt{\varepsilon^*_S})}{(\sqrt{\varepsilon^*_I} + \sqrt{\varepsilon^*_S})} \\ \Gamma_b = \frac{(Z_{III} - Z_S)}{(Z_{III} + Z_S)} = \frac{(\sqrt{\varepsilon^*_S} - \sqrt{\varepsilon^*_{III}})}{(\sqrt{\varepsilon^*_S} + \sqrt{\varepsilon^*_{III}}))} \\ P_{theory} = \exp(-\gamma_S d) \end{cases}$$

In above equations Γ_a and Γ_b are the reflection coefficients at interfaces $Z = 0$ and $Z = d$ respectively and P_{thoery} is the propagation factor due sample. It can be assumed that $Z_I = Z_{III}$ or $\Gamma_{theory} = \Gamma_a = \Gamma_b$ as the media *I* and *III* are identical. Therefore, Eqs. (4) and (5) are further simplified to: