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New Measurement Technique for Complex Permittivity in Millimeter-Wave Band Using Simple Rectangular Waveguide Adapters

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Abstract

This research presents a novel methodology for measuring the complex permittivity of a material under test (MUT) in a millimeter-wave (mmWave) band by using two rectangular waveguide adapters. Contrary to the conventional Nicolson-Ross-Weir (NRW) method, the proposed complex permittivity measurement method does not require a material fabrication process for exact MUT insertion into a waveguide. In our complex permittivity measurement, simple commercial waveguide adapters are employed instead of large flange structures. The proposed complex permittivity measurement of a non-destructive MUT is achieved by combining the NRW method, the Gaussian weighting moving average filtering technique, a full-wave electromagnetic analysis, and an optimization technique. Furthermore, the proposed methodology is validated by fabricating a Teflon-based MUT and by measuring the complex permittivity of the MUT in the Ka band (26.5–40 GHz). The results indicate that the proposed methodology exhibits good agreement with the data sheet.

Key Words: Complex Permittivity, Dielectric Constant Measurement, Waveguide Adapter.

I. Introduction

With the rapid increase in the operating frequency of RF devices, research on the application of dielectrics in RF technology has been actively conducted. In particular, the extraction of complex permittivity in a millimeter-wave (mmWave) band is necessary for the development of new 5G communication devices. There are several ways to extract the complex permittivity of dielectrics, including resonant methods, open-ended methods, free-space methods, and transmission/reflection methods [1]. Among these, resonant methods use the Q-factor of a resonator to extract complex permittivity [2, 3]. However, although these methods are the most accurate, their bandwidth is very limited.

For resonant methods, it is necessary to manufacture many resonators at different interested frequencies, leading to considerable manufacturing costs and time consumption. Meanwhile, open-ended methods [4] use a waveguide or a coaxial cable to extract the complex permittivity based on the reflection coefficient S_{11}. Such methods can extract the complex permittivity of non-destructive materials that have electrically large thicknesses. However, to extract the complex permittivity of an electrically thin material, an additional metal plate needs to be attached precisely to the material under test (MUT). Moreover, while measurement errors are susceptible to the contact conditions of the open-ended device, the MUT, and the metal plate, they are significantly increased in the case of a mmWave band.

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Free-space and transmission/reflection methods extract the complex permittivity of the MUT using a two-port network. Generally, S_{11} and S_{21} are measured, following which the complex permittivity is extracted using the Nicolson-Ross-Weir (NRW) technique [5, 6]. Free-space methods measure *S*-parameters by placing the MUT between two antennas [7]. Notably, free-space measurement is possible without additionally processing the MUT in a wide bandwidth. However, its accuracy is relatively low due to multiple reflections/diffractions, besides the requirement for expensive measurement equipment. Another method that uses a two-port network is the transmission/reflection method [5, 6, 8], which extract the complex permittivity by inserting the MUT inside a waveguide or a coaxial cable. Although these methods can extract the complex permittivity in a wide frequency range, they require highly refined processing of the MUT, since it must be inserted precisely into the waveguide or the coaxial cable. Moreover, although a time-gating technique may be used in the case of a non-destructive MUT, this methodology would require very large flanges [9, 10].

This study proposes a novel measurement technique for determining the complex permittivity of a non-destructive MUT in a mmWave band. In the proposed measurement method, two commercial rectangular waveguide adapters are used, without any additional large flanges. The complex permittivity of the non-destructive MUT is extracted using a combination of the NRW method, the Gaussian weighting moving average filtering technique, a full-wave electromagnetic analysis, and an optimization technique.

The remainder of this manuscript is organized as follows. First, the NRW method is reviewed, following which our new measurement method for complex permittivity using two simple rectangular waveguide adapters is presented. Next, the complex permittivity measurement results of Rogers RO3003 in the Ka band (26.5–40 GHz) are provided to validate the proposed measurement technique.

II. Methodology

Fig. 1 depicts the conventional transmission/reflection method using two ports for the complex permittivity measurement of the MUT. As shown in Fig. 1, the measurement structure is divided into three subsections. Sections I and III represent an empty waveguide at the input and output ports, respectively, while Section II represents the region where the MUT is present.

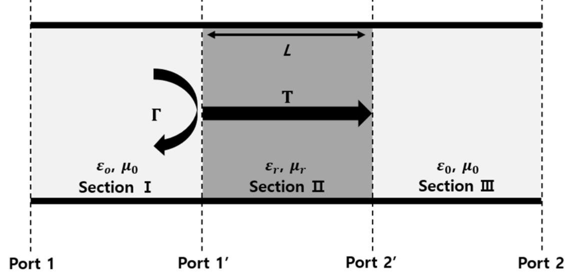

Fig. 1. Transmission/reflection method.

When measuring the *S*-parameters for the structure in Fig. 1 using a vector network, the reference planes of the measured *S*-parameters are Port 1 (in Section I) and Port 2 (in Section III). However, to extract the complex permittivity of the MUT, *S*-parameters that consider only Section II are required. This de-embedding process can be achieved by thru-reflect-line (TRL) calibration [11], leading to shifts in the S-parameter reference planes to Port 1' and Port 2'. In the following measurements, all *S*-parameters calibrated by the TRL technique are considered.

The NRW method can easily calculate the complex electromagnetic properties of the MUT [5, 6]. First, the partial reflection coefficient (Γ) and the transmission coefficient (T) are related to the *S*-parameters,

$$\Gamma = X \pm \sqrt{X^2 - 1} \tag{1}$$

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \tag{2}$$

where

$$X = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}}.$$

Then, the complex permittivity and permeability are calculated using the following equations:

$$\mu_r = \frac{1}{\Lambda}\frac{1+\Gamma}{1-\Gamma}\frac{1}{\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}} \tag{3}$$

$$\varepsilon_r = \frac{\lambda_0^2}{\mu_r}\left(\frac{1}{\lambda_c^2} + \frac{1}{\Lambda^2}\right) \tag{4}$$

where

$$\frac{1}{\Lambda^2} = -\left[\frac{1}{2\pi L}\ln\left(\frac{1}{T}\right)\right]^2$$

where λ_0 indicates the free-space wavelength, λ_c refers to the cutoff wavelength, and *L* is the MUT length.

The above-mentioned NRW method is highly suitable for cases in which the material is inserted precisely into a waveguide. However, it is difficult to fabricate the material so that it fits precisely inside the waveguide, especially in a mmWave band. The complex permittivity measurement of a non-destructive material using rectangular waveguides would be possible by including two additional large flanges [9, 10].

Fig. 2 depicts a schematic diagram of the two proposed simple waveguide adapters for the complex permittivity measurement of a non-destructive MUT. Considering that the MUT is not inserted into the waveguide in the measurement configuration,

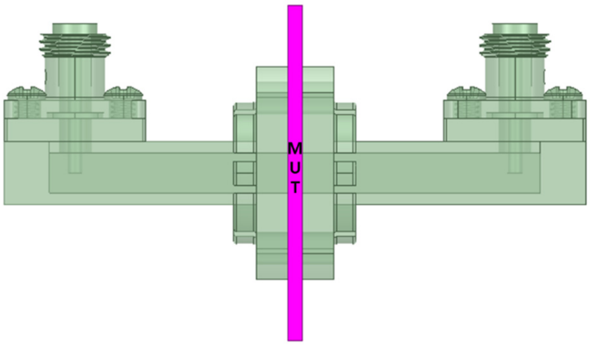

Fig. 2. Schematic diagram of the two proposed simple waveguide adapters for complex permittivity measurement.

two main issues should be addressed. First, since electromagnetic scattering occurs in opened waveguide regions, unwanted ripples may exist in the S-parameters. To tackle this issue, we apply the Gaussian weighting moving average filter [12] to measure the S-parameters in this study. As an explanatory example, the measured S-parameters of Rogers RO3003 in the Ka band are considered to illustrate the effects of the Gaussian weighting moving average filtering technique. Fig. 3 demonstrates the magnitude and phase of S_{11}, depending on whether the Gaussian weighting moving average filtering technique is applied or otherwise. The black line indicates the original S_{11} result, while the red line shows the S_{11} result on the application of the Gaussian weighting moving average filter. In the case of the original unfiltered S_{11} result, noticeable ripples are observed in both the magnitude and phase because scattered electromagnetic fields deteriorate the result. On the other hand, these unwanted ripples are remarkably removed from the result when the Gaussian weighting moving average filter is employed. Similarly, the Gaussian weighting moving average filtering technique eliminates unpleasant ripple effects in the S_{21} result as well, as shown in Fig. 4.

Second, the conventional NRW technique does not work properly in our measurement configuration, because the complex permittivity of the MUT in this method is determined by the closed waveguide condition. To address this issue, the combination of a full-wave electromagnetic analysis and an optimization technique is employed. Specifically, the full-wave electromagnetic analysis is iteratively performed by optimizing the complex permittivity such that the calculated S-parameters (S_{ij}^{cal}) are successfully curve-fitted to the measured S-parameters with the Gaussian weighting moving average filter (S_{ij}^{meas}). In this study, the method of moment (MoM) [13, 14] with a parallel-plate Green's function is employed to calculate the S-parameters [10]. It should be noted that MoM is highly suitable for the optimization-based approach because it is significantly faster than other

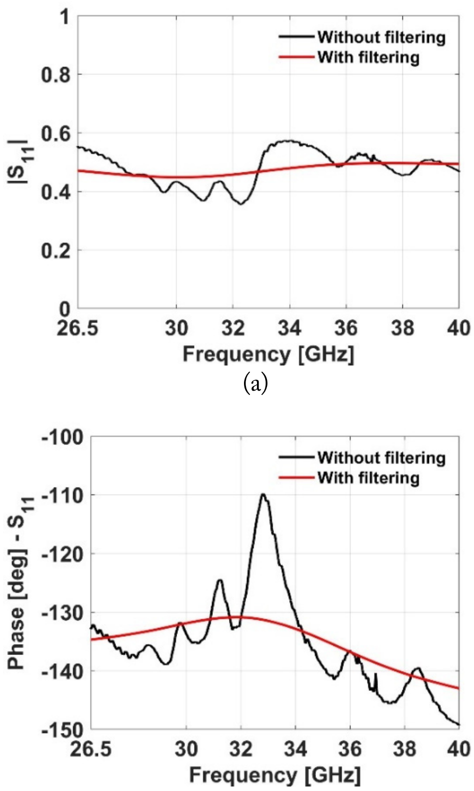

Fig. 3. S_{11} results with and without the application of the Gaussian weighting moving average filtering technique: (a) magnitude and (b) phase.

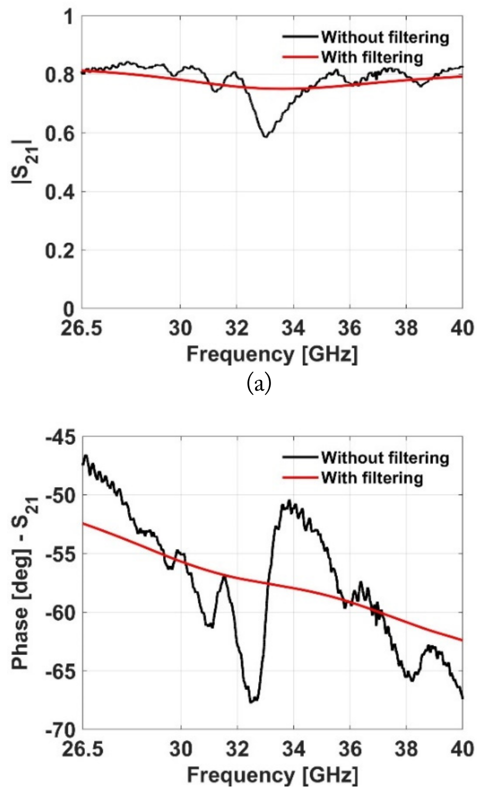

Fig. 4. S_{21} results with and without the application of the Gaussian weighting moving average filtering technique: (a) magnitude and (b) phase.

full-wave electromagnetic analysis methods, such as the finite element method [15] or the finite-difference time-domain method [16–20]. The complex permittivity extracted by the NRW method is used as an initial value for the MoM solver in the optimization process. Furthermore, both the S_{11} and S_{21} parameters are considered in the optimization, with the step tolerance δ set as 10^{-6}. The procedure of the complex permittivity measurement method used in this study is as follows:

- Measure the S-parameters.
- Apply the TRL calibration.
- Use the Gaussian weighting moving average filter for the TRL-calibrated S-parameters.
- Extract the complex permittivity using the conventional NRW method for the S-parameters obtained from 3.
- Use the complex permittivity extracted in 4 as the initial value of the MoM solver for optimization.
- Calculate the S-parameters using the MoM solver.
- Repeat the MoM calculation to optimize the complex permittivity for $|S_{ij}^{cal} - S_{ij}^{meas}| \leq \delta$.

III. Measurement Results

This section presents the measurement results to validate the proposed method for measuring the complex permittivity of a non-destructive MUT in a mmWave band. Fig. 5 shows the measurement setup, which is composed of a vector network analyzer (Anritsu MS4647B), two commercial Ka-band waveguide adapters (Fairview Microwave UG-599), and a non-destructive MUT. In this study, the complex permittivity of Rogers RO3003 ($\varepsilon_r' = 3$, $\varepsilon''_r = 0.001$, 0.77 mm) in the frequency range of 26.5–40 GHz is measured by the conventional NRW method using the original measured S-parameters, the NRW method using the Gaussian filtered S-parameters, and our proposed method.

Fig. 6 presents the complex permittivity for the three above-

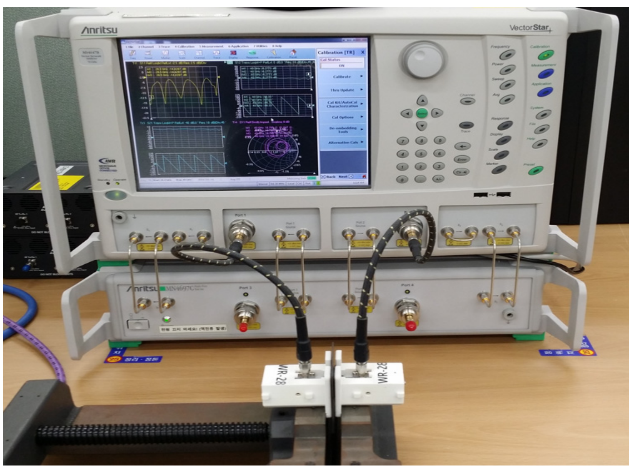

Fig. 5. Measurement setup.

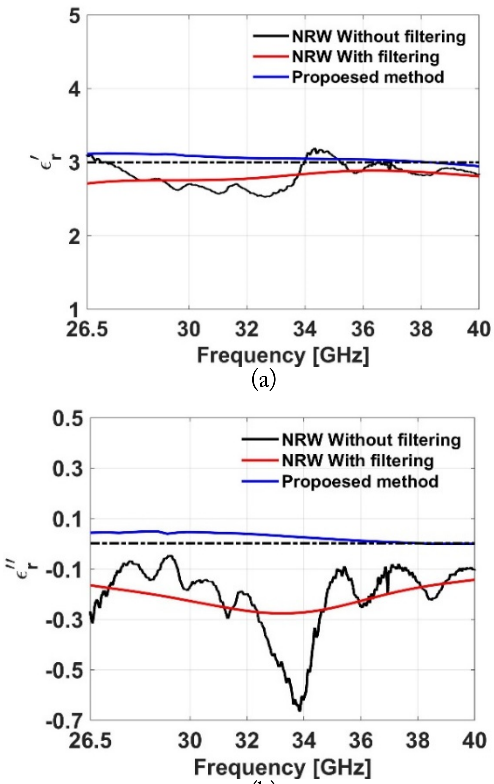

Fig. 6. Complex permittivity results: (a) real part and (b) imaginary part.

mentioned cases. The extracted complex permittivity results using the conventional NRW method are observed to be very inaccurate due to the effect of electromagnetic scattering, and they change severely compared to the frequency. When the NRW method is applied to the measured S-parameters using the Gaussian weighting moving average filtering technique, the accuracy of the complex permittivity results shows an improvement compared to the original NRW method. However, the presence of an active material is indicated by this approach (negative values in the imaginary part of the complex permittivity). In contrast to the above two methods, the measurement results of our proposed method agree well with the reference results for both the real and imaginary parts of the MUT's complex permittivity in the frequency range of interest. Notably, its root-mean-square relative error (RMSRE) is 2.56%.

IV. Conclusion

This research proposes a novel technique for measuring the complex permittivity of a MUT. The proposed measurement technique utilizes two simple commercial waveguide adapters, without a requirement for any additional large flanges, to determine the complex permittivity of a non-destructive MUT. First, the Gaussian weighting moving average filtering technique is employed to alleviate the effects of electromagnetic scattering from the open structure. Next, the complex permittivity extracted by the conventional NRW method using the filtered *S*-parameters is used as the initial value for the MoM calculation. Finally, the complex permittivity is determined by curve fitting the calculated *S*-parameters with their filtered measurement counterparts. The experimental results validate our proposed non-destructive measurement method for complex permittivity in a mmWave band.

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