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

Min-Seok Park¹ ∙ Jeahoon Cho¹ ∙ Soonyong Lee² ∙ Youngkun Kwon² ∙ Kyung-Young Jung¹,*

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.
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.

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 deembedding 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 ($\Gamma$) and the transmission coefficient ($T$) are related to the $S$-parameters,

$$\Gamma = X \pm \sqrt{X^2 - 1}$$
$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma}$$

where

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

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

$$\mu_r = \frac{1}{\frac{1}{\Lambda^2} + \Gamma} \left(1 \pm \frac{1}{\sqrt{\frac{1}{\Lambda^2} - \frac{1}{\lambda_0^2}}} \right)$$
$$\varepsilon_r = \nu_r \mu_r \left(\frac{1}{\lambda_0^2} + \frac{1}{\Lambda^2}\right)$$

where

$$\frac{1}{\lambda_0^2} = -\frac{1}{2\pi L} \ln \left(\frac{1}{\Gamma}\right)^2$$

where $\lambda_0$ indicates the free-space wavelength, $\lambda_c$ 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,
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 ($S_{ij}^{\text{cal}}$) are successfully curve-fitted to the measured $S$-parameters with the Gaussian weighting moving average filter ($S_{ij}^{\text{meas}}$). 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 methods.

---

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

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 $\delta$ 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 $|S_{ij}^{\text{cal}} - S_{ij}^{\text{meas}}| \leq \delta$.

### 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-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.

This work is supported by Samsung Electronics Co. Ltd.

REFERENCES

[1] L. F. Chen, C. K. Ong, C. P. Neo, V. V. Varadan, and V. K. Varadan, *Microwave Electronics: Measurement and Materials Characterization*. Chichester, UK: John Wiley & Sons, 2004.

[2] D. Li, C. E. Free, K. E. Pitt, and P. G. Barnwell, "A simple method for accurate loss tangent measurement of dielectrics using a microwave resonant cavity," *IEEE Microwave and Wireless Components Letters*, vol. 11, no. 3, pp. 118-120, 2001.

[3] C. N. Works, T. W. Dakin, and F. W. Boggs, "A resonant-cavity method for measuring dielectric properties at ultrahigh frequencies," *Electrical Engineering*, vol. 63, no. 12, pp. 1092-1098, 1944.

[4] Z. Li, A. Haigh, C. Soutis, A. Gibson, and R. Sloan, "A simulation-assisted non-destructive approach for permittivity measurement using an open-ended microwave waveguide," *Journal of Nondestructive Evaluation*, vol. 37, article no. 39, 2018. https://doi.org/10.1007/s10921-018-0493-1

[5] A. M. Nicolson and G. F. Ross, "Measurement of the intrinsic properties of materials by time-domain techniques," *IEEE Transactions on Instrumentation and Measurement*, vol. 19, no. 4, pp. 377-382, 1970.

[6] W. B. Weir, "Automatic measurement of complex dielectric constant and permeability at microwave frequencies," *Proceedings of the IEEE*, vol. 62, no. 1, pp. 33-36, 1974.

[7] D. K. Ghodgaonkar, V. V. Varadan, and V. K. Varadan, "A free-space method for measurement of dielectric constants and loss tangents at microwave frequencies," *IEEE Transactions on Instrumentation and Measurement*, vol. 38, no. 3, pp. 789-793, 1989.

[8] F. Costa, M. Borgese, M. Degiorgi, and A. Monorchio, "Electromagnetic characterisation of materials by using transmission/reflection (T/R) devices," *Electronics*, vol. 6, no. 4, article no. 95, 2017. https://doi.org/10.3390/electronics6040095

[9] M. W. Hyde and M. J. Havvilla, "Measurement of complex permittivity and permeability using two flanged rectangular waveguides," in *Proceedings of 2007 IEEE/MTT-S International Microwave Symposium*, Honolulu, HI, 2007, pp. 531-534.

[10] M. W. Hyde, M. J. Havvilla, and A. E. Bogle, "A novel and simple technique for measuring low-loss materials using the two flanged waveguides measurement geometry," *Measurement Science and Technology*, vol. 22, article no. 085704, 2011. https://doi.org/10.1088/0957-0233/22/8/085704

[11] D. M. Pozar, *Microwave Engineering*. Hoboken, NJ: John Wiley & Sons, 2012.

[12] A. V. Oppenheim, J. R. Buck, and R. W. Schafer, *Discrete-Time Signal Processing*, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 1999.

[13] M. Ayari, Y. El Touati, and S. Altowaijri, "Method of moments versus advanced transverse wave approach for EM validation of complex microwave and RF applications," *Journal of Electromagnetic Engineering and Science*, vol. 20, no. 1, pp. 31-38, 2020.

[14] D. Y. Lee, J. I. Lee, and D. W. Seo, "Dynamic RCS estimation according to drone movement using the MoM and far-field approximation," *Journal of Electromagnetic Engineering and Science*, vol. 21, no. 4, pp. 322-328, 2021.

[15] S. Chilukuri and S. Gundappagari, "A wide dual-band metamaterial-loaded antenna for wireless applications," *Journal of Electromagnetic Engineering and Science*, vol. 20, no. 1, pp. 23-30, 2020.

[16] J. Cho, M. S. Park, and K. Y. Jung, "Perfectly matched layer for accurate FDTD for anisotropic magnetized plasma," *Journal of Electromagnetic Engineering and Science*, vol. 20, no. 4, pp. 277-284, 2020.

[17] S. Y. Hyun, "Improved discrete-time boundary condition for the thin-wire FDTD analysis of lossy insulated cylindrical antennas located in lossy media," *Journal of Electromagnetic Engineering and Science*, vol. 21, no. 1, pp. 60-63, 2021.

[18] J. Cho, S. G. Ha, Y. B. Park, H. Kim, and K. Y. Jung, "On the numerical stability of finite-difference time-domain for wave propagation in dispersive media using quadratic complex rational function," *Electromagnetics*, vol. 34, no. 8, pp. 625-632, 2014.

[19] S. G. Ha, J. Cho, J. Lee, B. W. Min, J. Choi, and K. Y. Jung, "Numerical study of estimating the arrival time of UHF signals for partial discharge localization in a power transformer," *Journal of Electromagnetic Engineering and Science*, vol. 18, no. 2, pp. 94-100, 2018.

[20] K. Y. Jung and F. L. Teixeira, "Numerical study of photonic crystals with a split band edge: polarization dependence and sensitivity analysis," *Physical Review A*, vol. 78, no. 4, article no. 043826, 2008. https://doi.org/10.1103/PhysRevA.78.043826
Min-Seok Park
received his B.S. degree in Electrical Engineering from Myongi University, Yongin, Republic of Korea, in 2015 and his M.S. degree in Electrical Engineering from Hanyang University, Seoul, Republic of Korea, in 2017. From 2018 to 2020, he was a researcher at EM-Tech. He is currently pursuing his Ph.D. degree in Electronic Engineering. His current research interests include computational electromagnetics, wave propagation, and multi-physics.

Jeahoon Cho
received his B.S. degree in Communication Engineering from Daejeon University, Pocheon, Republic of Korea, in 2004 and his M.S. and Ph.D. degrees in Electronics and Computer Engineering from Hanyang University, Seoul, Republic of Korea, in 2006 and 2015, respectively. From 2015 to August 2016, he was a postdoctoral researcher at Hanyang University. Since September 2016, he has worked at Hanyang University, where he is currently a research professor. His current research interests include computational electromagnetics and EMP/EMI/EMC analysis.

Soonyong Lee
received his B.S. degree in Information and Communication Engineering from Seokyong University, Seoul, Republic of Korea, and his M.S. and Ph.D. degrees in Electronics and Computer Engineering from Hanyang University, Seoul, Republic of Korea, in 2008 and 2012, respectively. Since 2012, he has worked at Samsung Electronics Co. Ltd., where he is currently a staff engineer. His current research interests include computational electromagnetics and EMP/EMI/EMC analysis.

Youngkun Kwon
received his B.S. and M.S. degrees in Electrical Engineering from the Department of Electronics Information Engineering, Yeungnam University, Gyeongsan, Republic of Korea, in 1998 and 2000. Since 2000, he has worked at Samsung Electronics Co. Ltd., where he is currently a principal engineer. His current research interests include manufacturing technology, applied RF, and signal integrity.

Kyung-Young Jung
received his B.S. and M.S. degrees in Electrical Engineering from Hanyang University, Seoul, Republic of Korea, in 1996 and 1998, respectively. Later, in 2008, he received his Ph.D. degree in Electrical and Computer Engineering from Ohio State University, Columbus, OH, USA. From 2008 to 2009, he was a postdoctoral researcher at Ohio State University. From 2009 to 2010, he worked as an assistant professor in the Department of Electrical and Computer Engineering, Ajou University, Suwon, Republic of Korea. Since 2011, he has worked at Hanyang University, where he is now a professor in the Department of Electronic Engineering. His current research interests include computational electromagnetics, bioelectromagnetics, and nanoelectromagnetics. Dr. Jung received a Graduate Study Abroad Scholarship from the National Research Foundation of Korea, a Presidential Fellowship from Ohio State University, a HYU Distinguished Teaching Professor Award from Hanyang University, and an Outstanding Research Award from the Korean Institute of Electromagnetic Engineering and Science.