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30 October 2026

Ad-hoc Double-Extended-Bitten Ridge Waveguide for Broadband Dielectric Characterization of Lossy Dispersive Solid and Semi-solid Materials

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***Abstract*—Dielectric characterization of materials is an essential component of a wide range of applications, from antenna design to biomedical modeling. However, it might be susceptible to sample manufacturing and procedural errors that affect the reproducibility, reliability, and accuracy. To mitigate these issues, this paper proposes and examines an ad-hoc double-extended-bitten ridge waveguide (DEB-RW) aimed for broadband dielectric characterization of lossy dispersive materials, and compares it with a baseline double-ridge waveguide (D-RW). The DEB-RW reduces field instabilities in the high-sensitivity region due to sample misalignment and air gaps, enhancing both the accuracy and repeatability of dielectric property retrieval, retaining the advantages of the D-RW in terms of operational frequency band, $1-4$ GHz. Finally, a gap waveguide implementation is proposed to simplify the measurement system while maintaining performance.**

***Index Terms*—Dielectric characterization, double-ridged waveguide, gap waveguide, microwave propagation.**

I. Introduction

Dielectric properties (DPs) govern electromagnetic (EM) energy storage and dissipation mechanisms, which involve EM waves propagating through materials and dictate device performance, scattering response, and sensing capabilities, among others, across a wide range of engineering and scientific applications, from the design of electronic components and antennas to the development of realistic emulators of biological tissues [1]–[3]. Determining the DPs is a challenging task. It has been widely studied over the years and continues to be studied nowadays due to the evolving application requirements.

Traditional and well-established methods—such as the open-ended coaxial probe, waveguide, and resonant cavity techniques—present complementary advantages and limitations depending on the material state, frequency range, and measurement constraints [4]–[6]. Specifically, in this work, we consider the partially filled waveguide approach. It provides broadband and reduces the sample size requirements of the material under test (MUT), making it especially suitable for characterizing solid and semi-solid materials with small dimensions. However, it can lead to high field instability within the measurement region where the EM field is most sensitive.

Building on the characterization method introduced in [7], and taking as a baseline the double-ridge waveguide (D-RW) [8], this paper focuses on the development of a more robust measurement system based on a double-extended-bitten ridge waveguide (DEB-RW) for the dielectric characterization of solid and semi-solid materials.

The proposed DEB-RW setup reduces field instabilities in the high-sensitivity region, where the sample is placed, enhancing both the accuracy and repeatability of the dielectric property measurements, particularly for dispersive and lossy materials. Finally, the same waveguide is implemented using gap waveguide technology [9], [10], in which the lateral metallic walls are replaced by an electromagnetic band-gap (EBG) structure. This approach is particularly attractive because its inherent contactless nature enables a robust measurement system with a movable lid, which simplifies the placement of the sample, without compromising measurement accuracy.

II. Waveguide Configurations

In this section, two different double-ridge waveguide configurations, D-RW and DEB-RW, are analyzed to investigate the sensitivity of the retrieved DPs caused by submillimeter gaps between the MUT sample and the top ridge, which represents the most critical and common error in practice, due to the strong electric field concentration in that region.

This sensitivity is evaluated in terms of the scattering parameters and the EM field distribution. Since the focus of this work is on the characterization of solid, lossy materials, the analysis considers a representative case of a polyurethane rubber and graphite powder composite. Such solid mixtures are commonly employed in applications such as antenna matching medium [11] and tissue-mimicking phantoms due to their mechanical stability and tunable dielectric response [12]. In particular, a sample composed of 50% polyurethane rubber and 50% graphite powder is selected, as it exhibits high permittivity and conductivity, making it a challenging and meaningful case for broadband dielectric characterization. The material is modeled using a second-order Debye model [13] as follows:

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{\varepsilon_{s1} - \varepsilon_\infty}{1 + j\omega\tau_1} + \frac{\varepsilon_{s2} - \varepsilon_\infty}{1 + j\omega\tau_2}, \tag{1}$$

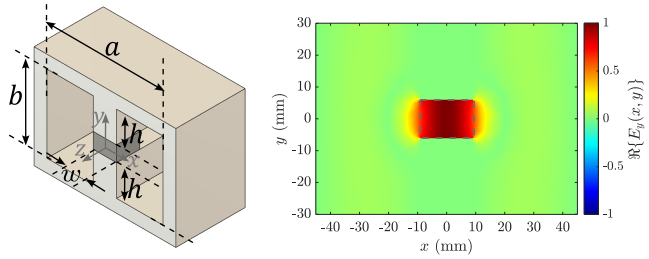
where $\varepsilon(\omega)$ is the complex relative permittivity as a function of the angular frequency ω, ε_∞ is the permittivity at infinite frequency, ε_{s1} and ε_{s2} are the static permittivities associated with the two relaxation processes, and τ_1 and τ_2 are the corresponding relaxation times. The model parameters are set as reported in Table I.

TABLE I
SECOND-ORDER DEBYE MODEL PARAMETERS FOR THE POLYURETHANE–GRAPHITE SAMPLE.

Parameter	ε_∞	ε_{s1}	ε_{s2}	τ_1 (ps)	τ_2 (ns)
Value	5.27	60.85	600	26.86	5

A. Double-Ridge Waveguide

The D-RW, illustrated in Fig. 1(a), combines a compact cross-section with a wide operational bandwidth, making it well-suited for the broadband characterization of lossy and dispersive material samples as shown in [7]. It highly concentrates the EM field at the H-junction, the sample holder, as illustrated in Fig. 1(b), presenting the dichotomy of having a good sensitivity to the MUT itself, but also to even minor imperfections in sample positioning, which can substantially alter the measured scattering parameters and, consequently, the retrieved DPs.



(a) (b)

Fig. 1. (a) D-RW, the black block corresponds to the sample to be measured. (b) Real part of the E-field at the cross section $z = 0$, at 2.5 GHz, the dashed outline shows the position of the sample. The dimensions in mm are: $a = 90, b = 60, w = 18, h = 23$.

To illustrate this effect, Fig. 2 shows the scattering parameters of the D-RW loaded with a small sample of dimensions $12 \times 18 \times 18\,\mathrm{mm}^3$. To assess the sensitivity of the measurement system to undesired imperfections—such as air gaps caused by irregular sample shapes—a parametric analysis is performed to evaluate the effect of gaps ranging from 0 to 1 mm, dubbed δ, between the sample and the top ridge, representing plausible human and instrumentation errors during sample placement. The results show that even for gaps as small as 0.25 mm, the scattering parameters exhibit differences as large as 1.5 dB in reflection and 19 dB in transmission with respect to the reference case, i.e., $\delta = 0$ mm, such differences are even more pronounced as δ grows.

B. Double-extended-bitten Ridge Waveguide

To overcome the high sensitivity of conventional D-RW, an optimized design of this waveguide is proposed, hereafter referred to as the DEB-RW. The structure, illustrated in Fig. 3(a), introduces two lateral extensions and a central recess (the "bitten" region) on the ridges, designed to redistribute the EM field and reduce its sensitivity to mechanical imperfections at the sample interface. As shown in Fig. 3(b), this geometry achieves a more uniform electric field distribution in the sample region, significantly mitigating the strong field localization observed in the D-RW.

The DEB-RW is evaluated under the same test conditions used for the D-RW, analyzing the variation of the scattering

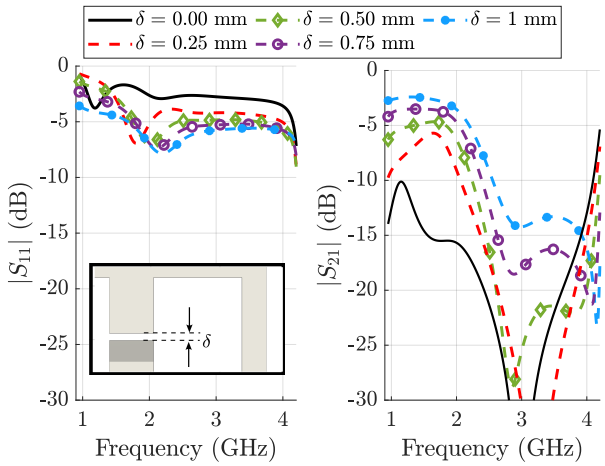
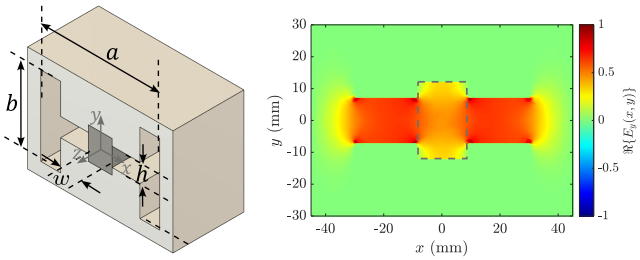


Fig. 2. Scattering parameters of the D-RW loaded with a small sample for different gap sizes δ.

parameters as a function of the air gap between the sample and the top ridge loaded with a small sample of dimensions $24 \times 18 \times 18\,\mathrm{mm}^3$, which is only 12 mm taller than that used in the D-RW. The results, shown in Fig. 4, confirm that the modified design exhibits significantly lower sensitivity to gap variations. For instance, a 0.25 mm gap induces only marginal changes in both reflection and transmission coefficients, highlighting the improved robustness and stability of the proposed structure for broadband dielectric characterization of lossy and dispersive materials.



(a) (b)

Fig. 3. (a) DEB-RW, the black block corresponds to the sample to be measured. (b) Real part of the E-field at the cross section $z = 0$, at 2.5 GHz, the dashed outline shows the position of the sample. The dimensions in mm are: $a = 90, b = 60, w = 18, h = 14$.

C. Retrieved Dielectric Properties

The DPs of the sample are retrieved by applying the broadband characterization methodology presented in [7]. The S-parameters obtained from the EM full-wave simulations of the D-RW and DEB-RW structures, for different values of the top air gap, represent possible measurement data and are used as input for the optimization-based retrieval algorithm. This procedure minimizes the discrepancy between the input measured S-parameters and the modeled ones in the ideal scenario (with the dielectric sample perfectly matching its expected dimensions) by iteratively adjusting the Debye parameters of the modeled dielectric sample until convergence is achieved.

The frequency-dependent relative permittivity ε_r and conductivity σ extracted from the optimization are reported

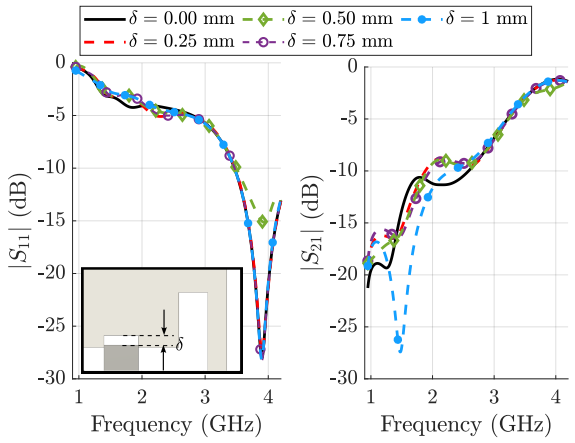


Fig. 4. Scattering parameters of the DEB-RW loaded with a small sample for different gap sizes δ.

in Fig. 5. For the reference configuration ($\delta = 0$ mm), both waveguides provide dielectric values in close agreement with the nominal values, confirming the reliability of the retrieval approach. However, when air gaps are introduced, the D-RW configuration exhibits a significant deviation in both permittivity and conductivity, with errors exceeding 60% for $\delta = 0.5$ mm. Conversely, the DEB-RW shows much lower sensitivity to gap variations, maintaining deviations below 13% across the entire frequency band.

The relative error in the retrieved DPs is summarized in Fig. 6, where the DEB-RW clearly demonstrates superior robustness and stability compared to the standard D-RW. These results confirm that the modified waveguide design effectively mitigates the influence of air-gap uncertainties, enabling more accurate and repeatable dielectric characterization of lossy and dispersive materials.

III. Simplified Measurement System Based on Gap Waveguides

A measurement system, based on the previously discussed DEB-RW configuration, can be implemented using gap waveguide technology [9]. A gap waveguide offers several advantages—most notably, the ability to safely employ a movable top lid, thereby simplifying the overall measurement procedure by facilitating the placement of the sample. This feature arises from the use of an EBG structure, which effectively shields the waveguide from unwanted leakage. The schematic of the proposed waveguide is shown in Fig. 7, where the lateral pins are designed such that the stopband they generate aligns with the desired operational bandwidth of the waveguide.

IV. Conclusion and Future Works

This work presented a novel double-extended-bitten ridge waveguide for the broadband dielectric characterization of lossy and dispersive solid materials. Numerical results demonstrated that the DEB-RW significantly mitigates field instabilities in the high-sensitivity region, enabling more accurate retrieval of permittivity and conductivity compared to a D-RW. The analysis of air-gap effects further confirmed that the proposed design maintains low sensitivity to small misalignment, whereas the standard waveguide exhibits substantial deviations.

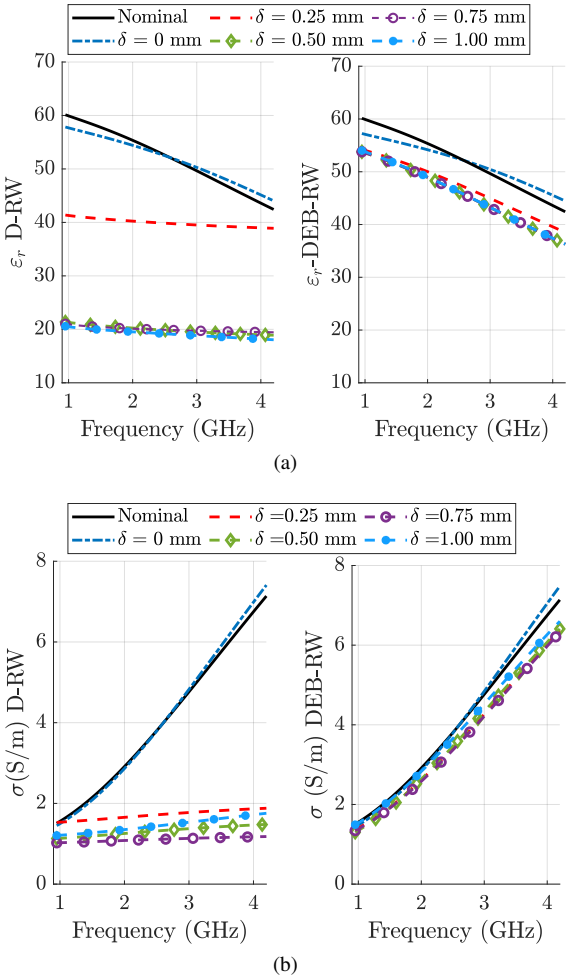


Fig. 5. DPs retrieved from the D-RW and DEB-RW. The first row shows the relative permittivity, and the second row shows the conductivity.

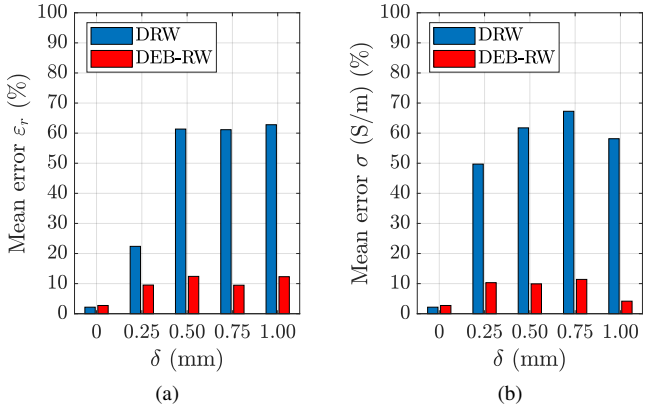


Fig. 6. Comparison of the relative error in the DPs retrieved from the D-RW and DEB-RW configurations: (a) relative permittivity, (b) conductivity.

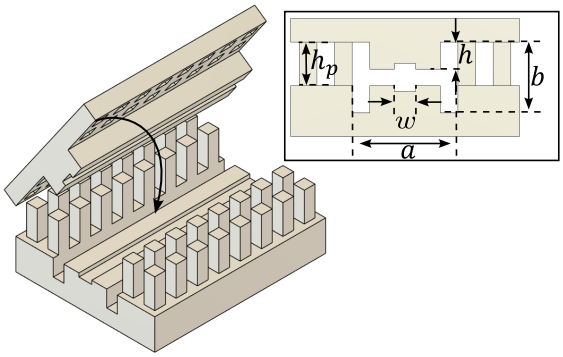


Fig. 7. Schematic of the gap waveguide implementation of the proposed DEB-RW. The dimensions in mm are: $a = 90$, $b = 60$, $w = 18$, $h = 14$, and $h_p = 46$.

Future work will focus on the fabrication and experimental validation of the DEB-RW with the optimized dimensions presented here, aiming to verify its improved measurement accuracy and repeatability. Additionally, the integration of the DEB-RW into a gap-waveguide-based measurement system will be explored to simplify sample handling and study the possibility of extending the operational bandwidth for a wide range of solid and even semi-solid lossy materials.

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