3D-Printed Waveguide Structure for Filtering and Sensing Applications

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***Abstract*— The proposed report presents the design and study of an innovative waveguide filter with ridge resonators and its implementation for sensing the dielectric permittivity of a dielectric slab. The dielectric slab being tested is placed under the ridge resonators, where the electric field shows its maximum intensity due to the component's geometry. The sensor operates at approximately 10 GHz and the variation of the frequency response can be used to determine the electrical characteristics of the material under test by evaluating the shift of transmission zeros. The setup demonstrates to be more robust to positioning errors of the sample compared to other traditional methods. The manufacturing process is based on 3D printing with plastic material and the subsequent metallization. Commercial dielectric laminates were utilized to verify the sensor's performance.**

***Keywords*—Additive manufacturing, dielectric permittivity, sensor, waveguide.**

I. Introduction

Dielectric materials are crucial in the field of microwave engineering and have a broad range of applications, such as acting as substrates for planar components and circuits, and loading resonant cavities to produce compact filters and multiplexers. The dielectric permittivity ε_r is a fundamental parameter of these materials and any difference between the nominal and actual values results in a change in the device performance. The ability to characterize this parameter accurately and quickly is crucial, and various sensors based on measuring the frequency shift of a resonator when loaded with the material under test have been proposed [1],[2]. On the other hand, multiple resonators can be coupled together to obtain filters with transmission zeroes, and the presence of a dielectric material near the resonators can affect their frequency response.

This work presents a sensor that utilizes slanted ridge iris resonators integrated into a rectangular waveguide. The use of this topology allows for the presence of transmission zeroes in a compact layout. Additionally, the resonant mode of slanted irises results in an electric field that is highly concentrated in a small gap, making the device highly sensitive to even small amounts of material with low dielectric permittivity. The component is fabricated using additive manufacturing, which offers benefits such as flexibility in design, cost reduction, and improved integration [3].

II. Sensor Design

The presented sensor is based on the bandpass filter design described in [4]. The device's topology can be perturbed asymmetrically by placing a dielectric slab under one of the slanted irises, as shown in Fig. 1*a*. Consequently, its resonance frequency is lowered, and the position of the transmission zeroes is affected. Thus, the sensor can retrieve the value of ε_r by measuring the shift in the frequency of the transmission zeroes when the component is loaded with a sample of known thickness. Furthermore, the small gap under the iris behaves in a capacitive manner even when unloaded, with the electrical field being vertical and concentrated under the iris (Fig. 1*b*). The frequency shift of the transmission zero compared to the unloaded case can be interpolated by the equation:

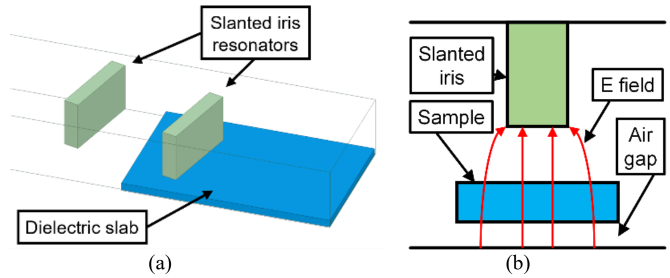

Fig. 1. (*a*) Topology of the 3D printed slanted iris resonators dielectric sensor; (*b*) Detail of the electric field distribution below the slanted iris.

$$\Delta f_z = a \cdot {\varepsilon_r}^b + c \qquad (1)$$

where the value of coefficients *a*, *b*, *c* can be extracted from the results of electromagnetic simulations and depend on both the size of the slab and the transmission zero which is being considered. In the measurement phase, the frequency shift is determined, and the dielectric permittivity of the slab is retrieved by inverting the previous equation.

The prototype fabrication and the detailed description of the measurement results have been documented in a paper presented at the 2023 International Microwave Symposium (2023 IMS) conference [5].

In the second step of this research activity, a novel geometry of compact resonators has been investigated with the aim to minimize the sensitivity to fabrication inaccuracies (Fig. 2). The upgraded sensor is shown in Fig. 2*b*. This structure comprises two elongated ridges that extend along the longitudinal direction of the waveguide. The shape of these irises is distinctive as it exhibits a notch along the lower portion of both components. This cut was implemented to prevent additional higher order modes from entering within the desired bandwidth. In order to demonstrate the improved accuracy, this device has been compared with a single slanted iris resonator sensor, shown in Fig. 2*a*. The air gap sensitivity, which is critical for the single ridge version, is improved by increasing the shape of the ridge resonator: fringing fields are reduced and

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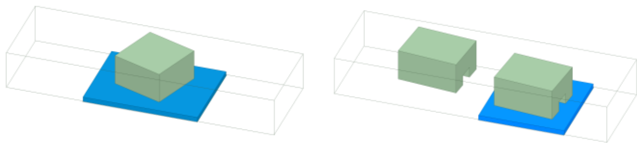


(*a*) (*b*)

Fig. 2. (*a*) Typical sensor structure with a single slanted iris resonator configuration; (*b*) Final version of the 3D printed slanted iris resonator dielectric sensor.

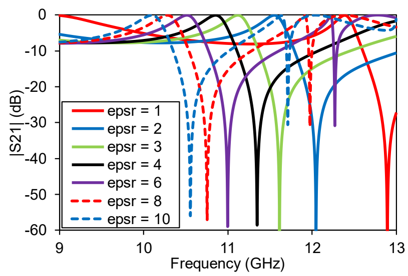


Fig. 3. Transmission parameters of the single slanted iris resonator sensor (Fig. 2*a*) when varying the dielectric permittivity of the slab. Results obtained with slab thickness of 50 mils.

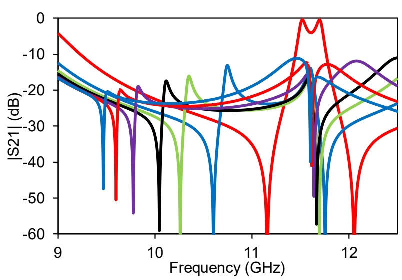
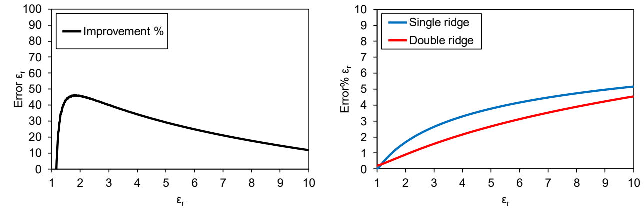


Fig. 4. Transmission parameters of the upgraded sensor (Fig. 2*b*) when varying the dielectric permittivity of the slab. Results obtained with slab thickness of 50 mils.

the electrical field is mostly concentrated under the ridge. As a result, the sensor became more resilient to sample positioning errors related to air gaps between the dielectric slab and the waveguide's bottom. Once the slanted iris is duplicated, instead of quantifying the shift in the frequency of one transmission zero, the upgraded sensor can retrieve the ε_r value of the slab under test through a differential measurement, utilizing the separation between the two transmission zeros. This approach significantly reduces the sensitivity to manufacturing inaccuracy. To further improve the precision of the measurement, a shallow groove has been placed on the lower side of the structure to reduce the horizontal positioning error of the sample. The sensor performance is illustrated in the simulation of Fig. 3 and 4, where the dielectric permittivity of a slab with 50-mils thickness is swept between 1 and 10. The frequency responses refer to the first higher mode, compared to the fundamental one, as it is less sensitive to errors due to the manufacturing process. Fig. 5 shows the performance of the two structures in terms of measurement uncertainty when each component is loaded with different values of ε_r.



(a) (b)

Fig. 5. (a) Percentual improvement in the retrieval of the dielectric permittivity using the two-ridge configuration; (b) performance comparison between the two sensor structures when varying the dielectric permittivity of the slab.

III. Conclusion

This work presented a dielectric sensor that employs a waveguide filter based on slanted iris resonators, which exhibits a passband and two transmission zeros. The sensing mechanism is based on the frequency shift of the transmission zeros. The configuration of the two slanted irises has been modified to improve the sensor's precision by reducing errors introduced during the additive manufacturing process. Prototype fabrication by additive manufacturing and measurements of this device have been illustrated and discussed.

IV. Acknowledgment

The MTT-S Undergraduate/Pre-graduate Scholarship Award has been a great accomplishment and a source of motivation as it is the first major achievement of my academic career. I will be traveling to attend the IMS2023 conference in San Diego and I am delighted to be present and actively participate in the event as a student volunteer. This is a great opportunity to get in touch with the interesting world of microwaves. My next plan after graduating is pursuing a PhD in the microelectronics field, as I aim to perpetuate my passion for innovation and contribute to the progress of technology. I would like to thank Professor Maurizio Bozzi for supporting me to apply for the MTT-S scholarship awards.

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