

Free Space Method Material Characterization of 3D Printable Thermally Reconfigurable Dielectric

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Abstract—The characterization results of a temperature-controlled 3D printable composite dielectric material are presented in this paper. The material consists of vanadium dioxide nanoparticles suspended in a thermoplastic copolyester matrix. The dielectric constant, and loss tangent of the material were measured for both the metallic and insulator phases of the material. Experimental results indicate that the dielectric constant can be predictably augmented by greater than 15% between the distinct phases of the material.

Keywords—3D-printing, material characterization, vanadium dioxide, reconfigurable dielectric filament, phase change material.

I. INTRODUCTION

Recent developments in additive manufacturing (AM) capabilities have been an impetus for innovation in RF devices [1]. Specifically, a non-planar design paradigm has emerged, where there is demand for novel dielectric filaments that can be used to realize three-dimensional functional RF structures. Simultaneously, there is also a unique demand for reconfigurable electromagnetic devices operating in the millimeter wave (mm-wave) frequency regime [2]. Therefore, the confluence of AM fabrication, and reconfigurable dielectric filaments will enable new design topologies for traditional microwave devices. Whereby, spatial and cost efficiency are improved by fabricating microwave systems in three dimensions and utilizing multi-material printing systems.

Reconfigurable dielectric filaments are required to manufacture broadband and multiband microwave devices. To make use of the versatile designs enabled by AM, suitable materials must be developed that can be used to support demanding applications such as communications, remote sensing, and imaging. Increasingly, end use applications require rapid prototyping and adaptable product lines. Therefore, novel printable dielectric materials are vital to make full use of modern AM technologies to produce microwave devices at scale.

In this work we report the characterization results of a thermally reconfigurable dielectric filament, and the methodology used to extract temperature variant dielectric properties at W-band. The material under test (MUT) is a thermoplastic copolyester (TPC), doped with vanadium dioxide (VO₂) nanoparticles. Through the uniform suspension of VO₂ nanoparticles in a polymer matrix, a printable composite phase change material is realized. It is validated that the dielectric constant of the TPC-VO₂ material can be reversibly augmented by greater than 15% between its metal and insulator phases.

II. CHARACTERIZATION METHODOLOGY

To characterize the VO₂-TPC material across W-Band at temperatures above and below the metal-to-insulator phase transition point, a quasi-optical free space (QOFS) measurement setup is employed. A functional diagram of the

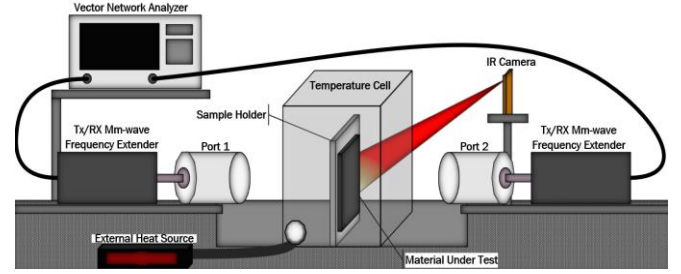


Figure 1. Functional diagram of free space measurement system.

QOFS system is provided in Fig. 1. With this method the sample is mounted between two gaussian optic lens antennas, wherein the transmittance and reflectance of the MUT is measured at normal incidence using a vector network analyzer. Subsequently, the dielectric properties of the sample are derived through the application of the following equations [3].

$$S_{11} = \frac{\Gamma(1 - T^2)}{1 - \Gamma^2 T^2} \quad (1)$$

$$S_{21} = \frac{T(1 - \Gamma^2)}{1 - \Gamma^2 T^2} \quad (2)$$

$$\Gamma_{TE} = \frac{\mu \cos(\theta) - (\mu\epsilon - \sin^2(\theta))^{\frac{1}{2}}}{\mu \cos(\theta) + (\mu\epsilon - \sin^2(\theta))^{\frac{1}{2}}} \quad (3)$$

$$\Gamma_{TM} = \frac{(\mu\epsilon - \sin^2(\theta))^{\frac{1}{2}} - \epsilon \cos(\theta)}{(\mu\epsilon - \sin^2(\theta))^{\frac{1}{2}} + \epsilon \cos(\theta)} \quad (4)$$

$$T = e^{-jk_0 t (\mu\epsilon - \sin^2(\theta))^{\frac{1}{2}}} \quad (5)$$

$$k_0 = \frac{2\pi}{\lambda_0} \quad (6)$$

Where,

S_{11} and S_{21} are calibrated scattering parameters

T is the transmission coefficient

Γ is the reflection coefficient

k_0 is the propagation constant of air

θ is the angle of incidence

t is the thickness of the MUT

ϵ is the permittivity in the material

μ is the permeability in the material

(TE denotes transverse electric)

(TM denotes transverse magnetic)

To extract the dielectric properties of the MUT, the transmission-epsilon-fast (TEF) algorithm is employed to solve Equation 1. TEF is an iterative technique used to calculate the complex permittivity, utilizing only the transmission coefficient [4]. It should be noted that for thin samples the accuracy of reflection measurements on free space systems is degraded, therefore the TEF algorithm is preferred in this context. It is assumed that the MUT is homogeneous, isotropic, and nonmagnetic. The minimum sample length and width are $\sim 76\text{mm}$, limited by the beam waist at the reference plane of the sample. Additionally, the minimum sample thickness is determined to be half the guided wavelength at the geometric mean of the upper and lower operating frequencies.

III. CHARACTERIZATION RESULTS

The dielectric parameters measured across W-Band of the MUT, and the TPC control sample are presented in Fig. 2.

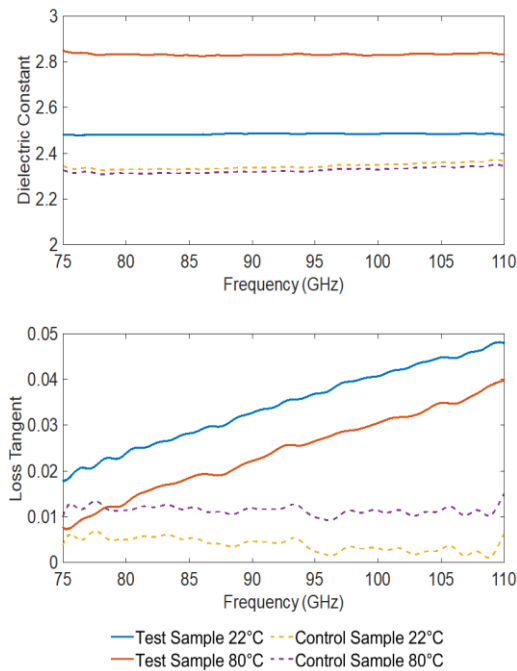


Figure 2. Dielectric parameters of the MUT and Control Sample at 22 & 80 degrees Celsius.

Notably, the dielectric constant of the MUT is relatively stable across the whole W-band. Additionally, the loss tangent of the MUT is lower at 80 degrees Celsius than it is at room temperature. Whereas the loss tangent of the control sample changes directly with temperature. It is observed that the loss tangent of the MUT exhibits a nonlinear relation with temperature attributed to the distinct phases of the VO_2 nanoparticles suspended in the filament.

It should be noted that 3D printed dielectric materials are not strictly homogeneous, and the degree of non-ideality is dependent on the infill volume of the specific AM fabrication system [5]. Therefore, it is important to quantify the density of 3D printed dielectric materials as the measured permittivity is directly dependent on the number of molecular interactions an incident electromagnetic wave experiences in the medium.

The described structural variance is visualized in Fig. 3, where the infill density deviates slightly between the MUT and the control sample. An optical coordinate measuring machine (CMM) was used to inspect the MUT and control sample after several thermal cycles.

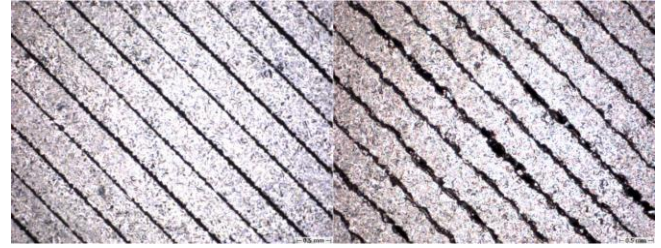


Figure 3. Structure of printed TPC control (left) and structure of printed TPC- VO_2 MUT (right)

Both samples were inspected after prolonged exposure to temperatures up to 100 degrees Celsius. Deviation in roughness was observed between the measured surfaces of the MUT, resulting as an artifact of the fused deposition modeling (FDM) fabrication process employed, however this had no significant effect as the dielectric properties derived from S21 and S12 measurements respectively were identical.

IV. CONCLUSION

This paper presented the dielectric characterization results of a 3D-printable reconfigurable TPC- VO_2 material at W-band. A brief description of the measurement methodology, and dielectric extraction technique is also included. The measurement results show strong potential for this material to be used for 3D printed reconfigurable electromagnetic devices operating in the mmWave frequency regime. Additionally, the TPC- VO_2 material is quite versatile as the loading of VO_2 nanoparticles encapsulated in the polymer substrate can be controlled during synthesis, and the print density in the fabrication process can be adapted to produce structures with the desired set of emergent reconfigurable dielectric properties.

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