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Dielectric Characterization of Materials at 5G mm-Wave Frequencies

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***Abstract*—The development of the next-generation 5G wireless networks depends critically on the engineering of optimized high-frequency devices, employing dielectric materials. This work presents a comprehensive broadband dielectric characterization of polymers, ceramics and glasses from 5 GHz until 115 GHz. Various measurement techniques including split-post, split cavity, open resonator and free-space transmission are utilized to obtain wideband spectra. The frequency-dependent permittivity and loss tangent are analyzed to identify suitable candidate materials exhibiting minimal dispersion and loss in the 5G millimeter-wave bands. The characterization reveals almost constant permittivity and a loss tangent that increases linearly with the frequency.**

***Index Terms*—characterization, ceramic, dielectric, glass, loss, material, measurements, substrate, 5G, 6G.**

I. INTRODUCTION

The implementation of 5G millimeter-wave (mm-wave) wireless networks has required the redesign of RF front-end components like antennas, filters, and amplifiers so they can operate at higher frequencies than previous generations [1]. These devices are usually fabricated using dielectric substrate materials and metal conductors, which need to be characterized at the new frequency bands is essential.

Materials with both low dielectric constants and low loss are desirable for 5G applications [2]. Lower dielectric constants enable faster signal propagation through the substrate, allowing for higher data rates and lower latency. Additionally, low loss tangents help compensate for the intrinsically higher attenuation present at mm-wave frequencies, ensuring acceptable propagation loss through devices [3], [4].

However, the dielectric properties of materials exhibit frequency dependence arising from intrinsic relaxation mechanisms. These atomic-scale processes cause resonance peaks and dispersion effects that span the electromagnetic spectrum. In solid materials, dipolar relaxation of molecular dipoles tends to occur in the MHz frequencies, while vibrational resonances of lattice ions are found in the THz region [5], [6]. The dielectric behavior in the GHz range relevant for 5G devices lies in an intermediate region that may be influenced by the tails of the dipolar and ionic relaxations, around MHz and THz frequencies, respectively. Therefore, accurate broadband characterization is crucial to fully capture the frequency variations of dielectric properties arising from these underlying physical processes. Measuring only the low-frequency response could provide an incomplete picture of a material's suitability for 5G applications. However, there are limited published studies characterizing the GHz dielectric properties of materials suited for 5G applications. While some work has measured insulating materials for printed circuit board (PCB) laminates [7], some materials until 35 GHz in [8], some representative materials from 20 to 110 GHz in [9], and the characterization of silicates until THz frequencies has been done by the authors [10], [11], comprehensive data on ceramics and polymers in the 5G mmWave range is lacking. Bridging this knowledge gap with broadband dielectric metrology is imperative to facilitate the development of 5G-enabled technologies.

In this paper, we provide the measurement results of many commercial glasses, fused silica, quartz, some ceramics and polymers.

II. MEASUREMENT TECHNIQUES

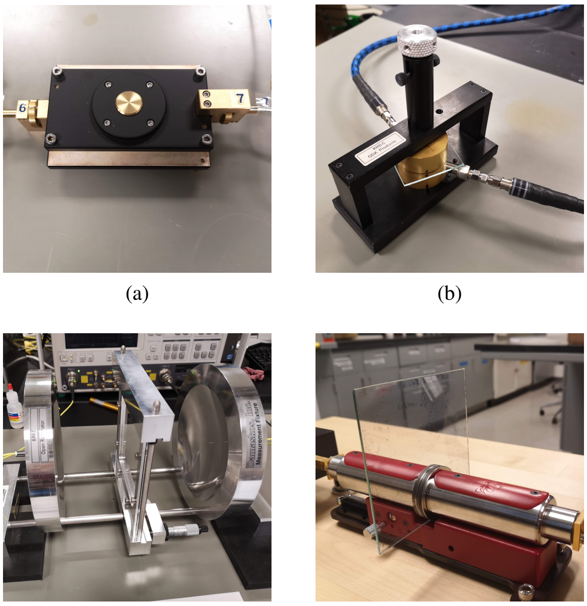
To obtain wideband dielectric characterization, a range of measurement techniques spanning different frequency bands must be employed. For dielectric characterization from 5 GHz to 115 GHz, the Materials Research Institute at Penn State University possesses the following measurement techniques, which are shown in Fig. 1:

- Split-post dielectric resonator (SPDR) from QWED, operating at 5.1 GHz.
- Split cavity or resonant mode dielectrometer (RMD-C, GDK Product Inc.), with a single frequency below 20 GHz.
- Fabry-Perot open resonator (from Damaskos, Inc.) can provide measurement results between 15-67 GHz.
- Material characterization kit (MCK, from SWISSto12) provides measurement results between 70-115 GHz.

The resonant techniques (split-post, split cavity, and open resonator) can obtain more accurate loss measurements than the free-space transmission techniques (MCK) [12]. However, each technique has its own loss threshold. For this reason, not all frequency points could be measured for all the materials. Further explanation about the measurement techniques can be found in [10].

III. RESULTS

A wideband frequency characterization of the dielectric properties of several glasses, fused silicas, crystalline materials (quartz, sapphire, alumina), ceramics and polymers is shown in Fig. 2 and Fig. 3. A flat response of the real part of the permittivity can be seen in Fig. 2. Polymers are the dielectrics with the lowest permittivity, which goes between 2 and 3.



(a) (b)

(c) (d)

Fig. 1. Characterization techniques employed. (a) Split-post dielectric resonator (b) Split cavity. (c) Open resonator. (d) MCK from SWISSto12.

The measured Rogers ceramics, RO3003 and RO4835, come after the polymers, with dielectric constants of 3 and 3.7, respectively. Fused silicas come next, with a permittivity of 3.8, followed by quartz. The commercial glasses measured range between 4.4 and 8, depending on the percentage of network modifiers. The materials with higher permittivity measured are sapphire and alumina, both crystalline aluminum oxides, but with different crystal structure. Sapphire has a hexagonal crystal structure, while alumina has a cubic one, which leads to different properties.

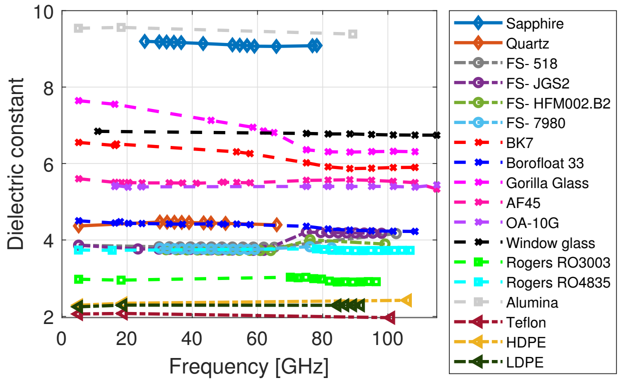


Fig. 2. Dielectric constant of different materials as a function of frequency. FS stands for fused silica.

The loss tangent is plotted in Fig. 3. The tendency is an increment of one order of magnitude over 100 GHz. Crystalline materials exhibit the lowest loss, due to their ordered internal structure. They reach the minimum loss threshold of the measurement techniques available at lower frequencies. The lowest loss measurable by the MCK is 10^{-3}, therefore it is not possible to measure the crystalline materials at the highest part of the spectrum. Fused silicas are the materials with lower loss after crystalline materials, followed by polymers. Glasses are the materials with the highest loss.

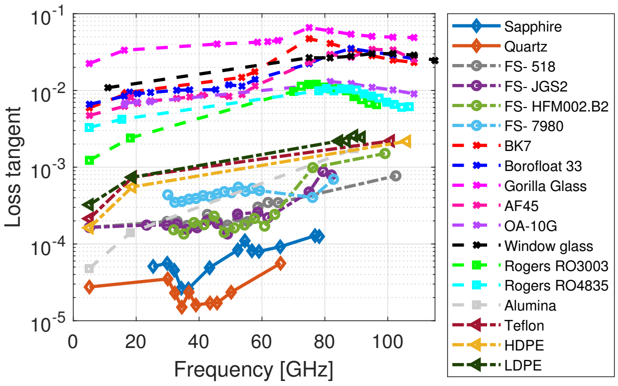


Fig. 3. Frequency evolution of the loss tangent of different materials.

IV. CONCLUSION

In conclusion, this work has demonstrated broadband dielectric characterization of various materials classes over a wide frequency range from 5 GHz to 115 GHz relevant to 5G applications. The results revealed that of the materials characterized, crystalline substrates provided the lowest loss on the order of 10^{-4}, followed by fused silicas and certain polymers with loss below 10^{-3}. Ceramic materials displayed loss tangents generally less than 10^{-2}, while glasses exhibited the highest losses but still below 10^{-1} at 100 GHz. Meanwhile, the dielectric constant was observed to be relatively constant over the full frequency span for most materials. These insights highlight the need for broadband metrology and confirm crystals, fused silicas, and select polymers as promising candidate substrate materials for 5G antennas, packaging, and other wireless components due to their stable and low-loss dielectric properties.

ACKNOWLEDGMENT

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