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Spectral and technological studies of polyurethane films for flexible sub-THz antennas

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Abstract. Efficient antenna solutions are demanded by variety of applications nowadays. As a part of subterahertz (sub-THz) electronics, they are of use in modern wireless modules and systems, providing opportunities for an ultra-high speed data transfer, remote sensing, energy harvesting, etc. The appearance of robust flexible antennas and metasurfaces can substantially widen the scope of potential application of sub-THz wireless technologies, bringing them to practical use cases. This study focuses on the properties of polyurethane and hydrogel polyurethane films in the context of their spectral characteristics and technological robustness. The thicknesses of the films are 0.18±0.01 mm and 0.15±0.01 mm. Calibrated quartz handle-wafers are used to mount them into the optical path of the employed sub-THz reflectometer. At 130–160 GHz, we measure complex permittivities of 2.95 (1 + 0.01*i*) and 3.15 (1 + 0.01*i*), making both films well-suited for designs of planar antennas on quartz. Hydrogel polyurethane film, however, does not demonstrate selectivity to acetone-assisted lithographic processes, leaving polyurethane film as the only candidate for cleanroom fabrication.

Keywords: subterahertz, reflection spectrum, dielectric film, polyurethane, hydrogel polyurethane, complex permittivity, flexible antenna, cleanroom fabrication

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Спектральные и технологические исследования полиуретановых пленок для гибких суб-ТГц антенн

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Аннотация. В этом исследовании основное внимание уделяется свойствам полиуретановых и гидрогелевых полиуретановых пленок в контексте их спектральных характеристик и технологичности. В диапазоне частот 130–160 ГГц измерены комплексные диэлектрические проницаемости пленок 2.95 (1 + 0.01*i*) и 3.15 (1 + 0.01*i*), что делает обе пленки хорошо подходящими для проектирования планарных антенн на кварце. Однако гидрогелевая полиуретановая пленка не демонстрирует селективности к литографическим процессам с использованием ацетона, что делает полиуретановую пленку единственно возможным выбором для производства с использованием процессов чистой зоны.

Ключевые слова: субтерагерцовый диапазон, спектр отражения, диэлектрическая пленка, полиуретан, гидрогель полиуретана, комплексная диэлектрическая проницаемость, гибкая антенна, производство в чистой зоне

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Introduction

Mastering the subterahertz (sub-THz) range makes it possible to expand the boundaries of the application of modern wireless modules and systems for an ultra-high speed data transfer, remote sensing, energy harvesting etc. [1]. On that ground, the development of the robust antenna designs is the key issue. In the process of development of new antenna solutions, it becomes clear that the inflexibility of systems due to form factor and weight is a crucial aspect. In terms of designing and manufacturing a flexible antenna, the attention is focused on conductive and isolating materials exhibiting superior properties with the possibility to significantly reduce fabrication cost and/or enhance (or not to compromise at least) the overall radiophysical properties of the design. The isolating substrate acts as a mechanical holder and is assessed on the basis of its dielectric and elastic properties. Together with the resistivity of conductive elements, it contributes to the antenna performance, ageing in deformation cycles. This research is focused on the properties of polyurethane and hydrogel polyurethane films in the context of their spectral characteristics and technological robustness as a platform for flexible planar antennas and antenna arrays operating above 100 GHz. Polyurethane is suitable for antenna applications due to its high mechanical strength and wear resistance, wide temperature range stability, good dielectric properties, chemical resistance to oils, solvents and moisture, is lightweight, and exhibits excellent adhesion to a variety of materials, making it a durable and versatile choice for flexible sub-THz antennas.

Materials and methods

To distinguish the relative permittivity of the chosen quartz substrates, the quartz material under the test (MUT) is represented by a two-inch diameter wafer. The thickness of the MUT is 500 μm. In order to evaluate the permittivity of the MUT, we assess the reflective properties of the material. The optical paths between 130–160 GHz transmitter (Tx) and receiver (Rx) with respect to MUT are identical and equal to Fraunhofer distance (FD).

Once the dielectric properties of quartz substrates are assessed, we apply polyurethane films on their surfaces. One side of the film has adhesive layer adhering to the quartz substrate and was smoothed out during application. After that the film was cut to size and shape of the substrate. The thicknesses of the polyurethane and hydrogel polyurethane films under study measured by micrometer are 0.18±0.01 mm and 0.15±0.01 mm. Thus, two quartz handle-wafers are used to mount them one by one into the optical path of the employed sub-THz reflectometer during measurements [2]. The measurements are conducted in two polarizations in the far-field.

Results and discussion

For frequency range of 130–160 GHz and angles of incidence within 30–60 deg, we fit measured spectra of the quartz wafers by reflectances derived from their frequency-dependent characteristic matrices (CMs) [3] and are compared with the predictions of Fresnel equations (FEs). For the two wafers, we acquire complex permittivities of 4.159 (1 + 0.01*i*) and 4.532 (1 + 0.015*i*), consistently measured for both transverse electric (TE) and transverse magnetic (TM) modes. The quartz substrates are enumerated to ensure correct interpretation of the obtained reflection spectra of structures. The measured spectra R_{TE} and R_{TM} with fit-functions CM and FE are provided in Fig. 1.

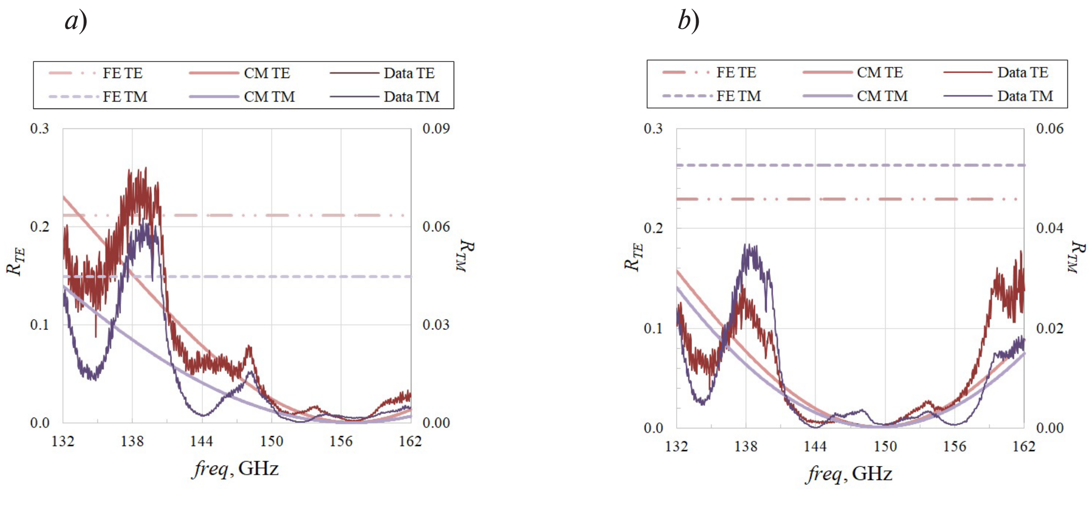

Fig. 1. Reflection spectra of first quartz substrate (*a*) and second quartz substrate (*b*) at the angle of incidence of 45 deg

Once the quartz handle-wafers are evaluated, we proceed with the second iteration: the measurements of the reflectance spectra of two bilayer structures quartz/polyurethane and quartz/hydrogel polyurethane. Examples of the measured spectra are provided in Fig. 2.

The spectral measurements are conducted in the same configurations as when measuring the reflectance spectra of quartz, and the CM method is used as a permittivity extraction tool again. Thus, the CM fit-functions depicted in Fig. 1 achieve an average accuracy of 10–20% of the values of the real and imaginary parts of the dielectric permittivity. The extracted complex permittivities of polyurethane film and hydrogel polyurethane film are 2.95 (1 + 0.01*i*) and 3.15 (1 + 0.01*i*), respectively. This potentially makes both films well-suited for designs of planar antennas and antenna arrays on quartz, as such values improve phase-amplitude characteristics.

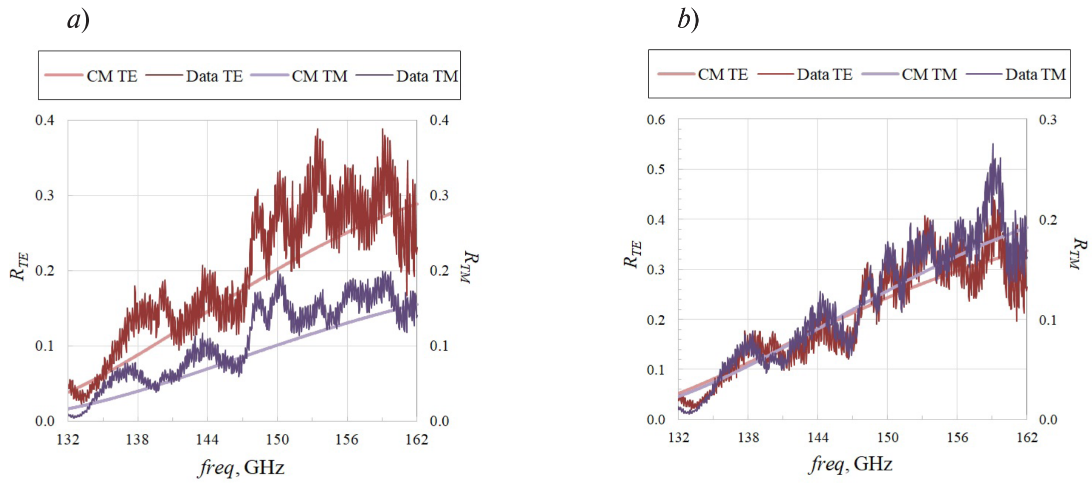

Fig. 2. Reflection spectra of quartz/hydrogel polyurethane (*a*) and quartz/polyurethane (*b*) sandwiches measured at the angle of incidence of 30 deg

We further assess technological robustness of the films under study and find out that hydrogel polyurethane does not demonstrate selectivity to acetone-assisted lithographic processes, whereas the polyurethane does. Thus, polyurethane film seems to be the only candidate for cleanroom fabrication. Nevertheless, it has poor adhesive properties of the surface that leads to the increase in complexity of fabrication process. The issue can be solved by structuring surface's roughness with mechanical treatment or by integration of additional adhesive polymer layers such as polymethyl methacrylate (PMMA).

We plan to use the film to implement an antenna array with 1.5k–2.5k elements similar to that reported by us in [4] in the future.

Conclusion

In this paper, we report on the reflective and technological properties of bilayer structures quartz/polyurethane and quartz/hydrogel polyurethane. Reflectometer-based measurement setup is used for the sub-THz spectral studies of the samples. At 130–160 GHz, the experimental values of complex permittivities of polyurethane film and hydrogel polyurethane film are 2.95 $(1 + 0.01i)$ and 3.15 $(1 + 0.01i)$, respectively. We also conclude that the polyurethane film is suitable for the fabrication of flexible reflectarrays in lift-off cleanroom processes. This should be interesting to developers of low-cost flexible sub-THz antennas.

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