Terahertz Shielding Enabled by the Micro-Porous Structure of Melamine Resin Sponge

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***Abstract*—Melamine resin sponges have a porous cell structure on the micrometer scale, comparable to the terahertz wavelength. Hydrating the sponge with water introduces a micro-scale rough surface which greatly attenuates the terahertz reflection. When combined with the high absorption of water, the hydrated sponge shows a perfect shielding characteristic by reflecting less than 1% of the light intensity in 0.75-3.5 THz.**

I. INTRODUCTION

THE development of terahertz (THz) technology has promoted growing amounts of applications in communications, radar, security and bio-sensing. Among them, THz shielding materials play important roles in many cases, such as absorbers in anechoic chambers, stealth in military and health consideration by screening intense radiations. A good shielding material should reflect and transmit minimum amount of THz light by absorbing most of the radiation. Metamaterials have been widely applied to achieve tunable absorption in one/multiple narrow bands[1], which is not applicable for broadband systems. Conductive porous structures offer a broader bandwidth by introducing Ohmic loss and multiple scattering[2], [3]. Here, we utilize the micro-cell structure of hydrated melamine resin sponge to efficiently absorb the THz light. Water is a naturally "black" material in the THz range. However, the large index mismatch in the air-water interface gives rise to a large reflection that makes it "shiny". The micro-porous structure of the sponge produces a rough water surface formed by its surface tension, which can effectively reduce the reflectance by over 10 times compared to pure water.

II. RESULTS

The melamine resin sponge has a high porosity of 99%, resulting in a refractive index of 1.0064 in 0.2-3.5 THz, as shown in Fig. 1. It performs as a highly transparent window to THz light with a nearly zero reflection according to Fresnel's formulas. This can be expected from the effective medium theory by considering the 99% of air fractions. The porous cells of the sponge have an average distance of 200 μm, corresponding to the wavelength of 1.5 THz. However, it should be noticed that the skeleton width of the sponge is only few micrometers, combining with its low dielectric permittivity they will scatter negligible THz light up to 3.5 THz. Hydrating the sponge with water generates hemisphere-like water bubbles on the surface due to the surface tension of water, as shown in the microscope image in Fig. 2a. The water bubbles vary in height due to the random cell structure. The height variation and the distance between the adjacent water bubbles are both wavelength-comparable, given the approximate 200 μm cell dimension. The distribution results in a rough water surface.

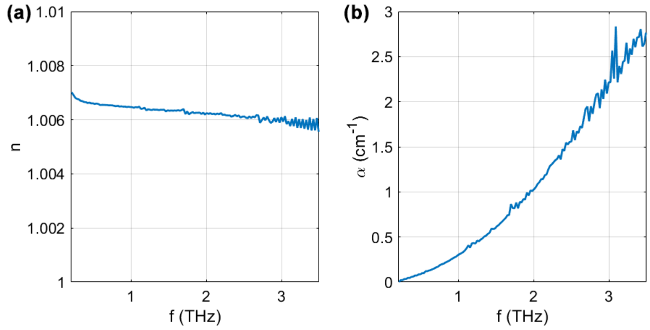

Fig. 1. (a) Refractive index n and (b) absorption coefficient α of the melamine sponge.

Such a surface profile is expected to provide a combination of antireflection and scattering effects at the THz band. At low frequencies (e.g. <0.3 THz) where the wavelength is larger than the roughness, different heights of the water surface can be effectively equivalent to composites of air and water, with the water fraction increases from 0% to 100% from the top to the inside of the surface. This generates a gradual complex refractive index variation from air to water, performing as an antireflection interface similar to the Moth-eye structure[4]. At high frequencies where the rough features (i.e. water-bubble distances) are below the diffraction limit, the surface cannot be regarded as a homogeneous composite of air and water. The wavelength-comparable roughness gives rise to Mie scattering to reflect the incident light to a broad angular range. In this case, scattering plays a major role in reducing the specular reflection.

We simulated the reflectance from a random rough water surface. The incident angle was set at 7° incident with equal s- and p- components, same as the experiment configuration. We mimic the observed structure by distributing random spherical bubbles with an average distance of 200 μm, while the height

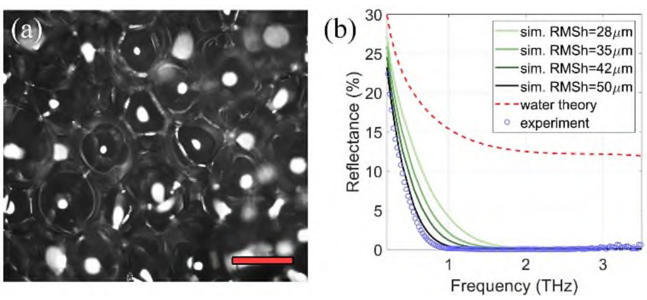

Fig. 2. (a) Microscope image of the surface of the hydrated melamine resin sponge. The scale bar is 200 μm. (b) Simulations (green to black) of the specular reflectance from a random rough water surface with different RMSh, compared to the theoretical reflectance of water (dashed red) and experimental reflectance of the hydrated sponge (open circles).

variation was assigned with different values since it cannot be directly estimated from the microscope image. The simulation results with RMSh (root-mean-square height) of 28, 35, 42 and 50 μm are shown in the solid curves from green to black in Fig. 2b. A monotonically decreased reflectance can be found in the with the increased height variation. This is in consistent with our analysis that a larger roughness enhances both the antireflection and scattering effects. The theoretical reflectance of water and the experimental reflectance of the hydrated sponge are shown in the dashed red curve and blue open circles, respectively. The experimental result shows a very weak reflectance, which matches well with the simulation result of RMSh = 50 μm. The reflectance is less than 1% in 0.75-3.5 THz, over 10 times smaller than that by pure water. In addition to surpassing the high absorption of water, zero transmission can be achieved with a small sample thickness (e.g. transmittance<1% when d>500 μm), making it ideal for shielding electromagnetic radiations in the THz regime.

III. CONCLUSIONS

IV. WE HAVE EXPERIMENTALLY VERIFIED THAT USING A WAVELENGTH-COMPARABLE POROUS STRUCTURE CAN CREATE AQUEOUS SURFACES WITH A DRAMATIC REDUCTION OF THE SPECULAR REFLECTION. THE SIMPLE COMPOSITE EFFICIENTLY DARKENED WATER AT THZ WAVELENGTHS, ESPECIALLY AT HIGHER FREQUENCIES. ALTHOUGH HYDRATED SPONGES MAY FIND INCONVENIENCE IN PRACTICAL APPLICATIONS, MORE ROBUST ABSORPTIVE MATERIALS CAN BE FURTHER EXPLORED TO REPLACE WATER TO EXTEND THE ADAPTABILITY. FOR EXAMPLE, EPOXY RESIN, SILICONE OR PARAFFIN WAX MIXING WITH CONDUCTIVE INCLUSIONS CAN GENERATE ABSORPTIVE LIQUIDS TO BE EMBEDDED INTO THE SPONGE. RIGID SAMPLES CAN THEN BE ACHIEVED BY CURING/SOLIDIFYING THE COMPOSITE.ACKNOWLEDGEMENT

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