Water metamaterial for ultra-broadband and wide-angle absorption

JIANWEN XIE,1 WEIREN ZHU,1* IVAN D. RUKHLENKO,2 FAJUN XIAO,3 CHONG HE,1 JUNPING GENG,1 XIANLING LIANG,1 RONGHONG JIN,1 AND MALIN PREMARATNE4

1Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
2Modeling and Design of Nanostructures Laboratory, ITMO University, Saint Petersburg 197101, Russia
3Key Laboratory of Space Applied Physics and Chemistry, Ministry of Education, Shaanxi Key Laboratory of Optical Information Technology, School of Science, Northwestern Polytechnical University, Xi’an 710129, China
4Advanced Computing and Simulation Laboratory (AχL), Department of Electrical and Computer Systems Engineering, Monash University, Clayton, Victoria 3800, Australia

*weiren.zhu@sjtu.edu.cn

Abstract: A subwavelength water metamaterial is proposed and analyzed for ultra-broadband perfect absorption at microwave frequencies. We experimentally demonstrate that this metamaterial shows over 90% absorption within almost the entire frequency band of 12–29.6 GHz. It is also shown that the proposed metamaterial exhibits a good thermal stability with its absorption performance almost unchanged for the temperature range from 0 to 100°C. The study of the angular tolerance of the metamaterial absorber shows its ability of working at wide angles of incidence. Given that the proposed water metamaterial absorber is low-cost and easy for manufacture, we envision it may find numerous applications in electromagnetics such as broadband scattering reduction and electromagnetic energy harvesting.

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References and links
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1. Introduction

Metamaterials, a kind of artificially structured materials, have attracted extensive attention in the last decade, owing to their exotic properties that are not readily available in nature [1, 2]. With the development of metamaterials, a series of intriguing applications have been emerged, such as artificial optical chirality [3, 4], wavefront modification [5, 6], and cloak of invisibility [7]. It is known that one of the main obstacles towards their engineering applications is the inevitable intrinsic loss in metamaterials. In fact, a great amount of effort has been devoted to achieving low-loss devices through optimizing structural geometries [8, 9] or using gain elements for loss compensation [10, 11]. However, by utilizing the full usefulness of loss, perfect absorption is possible through properly engineering the electric and magnetic resonances in metamaterials [12, 13]. In particular, perfect absorption with broad working frequency band is highly desired in various applications, including scattering reduction [14] and energy harvesting [15]. In order to expand the bandwidth of a metamaterial absorber, several absorption bands with different resonant units are combined through an in-plane arrangement [16]. Broadband absorption can also be achieved via layer-by-layer stacking of the resonant units [17] or using vertically standing nanowires [18]. It is also demonstrated that THz metamaterial absorbers made of highly doped silicon could have broadband absorption by utilizing the optical property of highly doped silicon [19]. However, these strategies are either at the cost of design complexity or significantly increase the overall thickness of the structure.

On the other hand, water is one of the most abundant resources in the world and take up the shape of the container due to fluidity. Water has relatively high permittivity, which is well suited for supporting multiple scattering resonances [20, 21]. It also shows reasonably high dielectric losses [20] and thus a promising candidate for perfect absorption. In particular, Yoo et al. [22] reported a broadband metamaterial absorber using periodically arranged water droplets and investigated the impact of droplet’s geometry on the absorption performance. Zhu et al. [23] studied the coherent interaction between two symmetrically incident waves in a water fishnet structure and achieved multiband coherent perfect absorption in such a water metasurface. The dielectric response of water is highly dependent on the temperature, so that water can also be used as a substrate for designing thermally tunable metamaterial absorbers [24, 25].
In this paper, we present the design of a subwavelength water metamaterial absorber capable of ultra-broadband perfect absorption at microwave frequencies. It is demonstrated experimentally that such a metamaterial can almost completely absorb the normally incident waves within the frequency band from 12 to 29.6 GHz. The impact of temperature on the absorption performance is further studied, which shows that our water metamaterial absorber has very weak dependence in the liquid phase temperature range. Similarly, the angular tolerance of the metamaterial absorber shows the possibility of working at wide angles of incidence. Owing to these desirable properties, we envision the proposed water metamaterial absorber may find many applications in areas such as broadband scattering reduction and electromagnetic energy harvesting.

2. Ultra-broadband metamaterial absorber

Figure 1 shows the water metamaterial absorber under consideration. Such a metamaterial is made of a structured water layer (with periodical holes) backed with a metal plate, where the water is placed in a resin container to maintain its shape. The thicknesses of the top resin layer, the water layer, and the bottom resin layer are \(d_1\), \(d_2\) and \(d_3\), respectively. The inner and outer radii of the resin hole are \(r\) and \(R\), respectively. The whole structure is periodically extended in the \(x\) and \(y\) directions with a lattice period of \(L\). It is worth noting that such a metamaterial absorber is much more convenient to be manufactured and maintained as compared with the water droplets based metamaterial absorber [22]. In such a structure, the electromagnetic absorptivity can be directly calculated from the reflection coefficient, \(A = 1 - |r|^2\), since the transmission is totally blocked by the thick metal plate.

\[
\epsilon(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 - j\omega\tau},
\]  

(1)

Fig. 1. (a) Schematic diagram of the water metamaterial absorber, (b) layer by layer view of the unit cell, and (c) cut plane view of the water layer.

The electromagnetic performance of the proposed water metamaterial is numerically investigated using the commercial software CST Microwave Studio. In our simulation, unit cell boundaries are applied in the \(x\) and \(y\) directions and open boundaries are added to the \(z\) direction. It is assumed that the incident electromagnetic wave is \(x\)-polarized and propagates from the +\(z\) direction normally upon the metamaterial. The metal plate is made of copper with a thickness of 15 \(\mu m\). The electric conductivity of copper is \(5.8 \times 10^7\) S/m and the permittivity of resin is 3.2(1 – \(j0.1\)). The permittivity of water at radio frequencies is described by the Debye formula [20]
where \( \varepsilon_\infty = 3.1 \), \( \varepsilon_s = 78.4 \), and \( \tau = 8.27 \times 10^{-12} \) s are the room-temperature high-frequency permittivity, static permittivity, and rotational relaxation time, respectively.

We start by considering the realization of a broadband absorption in the proposed water metamaterial absorber at room temperature. The geometrical parameters of such a are numerically studied via parametric sweep, for the purpose of achieving the bandwidth of high absorption (over 90% absorptivity) to be as wide as possible. After parametric sweep, the optimized geometrical parameters are obtained: \( d_1 = 2 \text{ mm} \), \( d_2 = 3 \text{ mm} \), \( d_3 = 0.8 \text{ mm} \), \( L = 18 \text{ mm} \), \( R = 5.2 \text{ mm} \), and \( r = 4.2 \text{ mm} \).

In Fig. 2, it is shown that the optimized water metamaterial absorber can achieve a broadband absorption. Within the entire frequency range from 12.0 to 29.6 GHz, the metamaterial shows over 90% absorptivity. Particularly, the absorptivities at 13.0, 19.6, and 27.3 GHz are 97.4%, 98.3%, and 97.8%, respectively. It is known that water itself has high absorption at microwave frequencies. Therefore, it is necessary to find out whether such a broadband absorption is predominantly due to the intrinsic high loss of water. For a fair comparison, we also consider the case of a full water layer without holes, which has the same thickness as that in the water metamaterial. We find that the absorptivities of a full water layer are only around 35% to 40% at the frequency band of interest, shown as the black curve in Fig 2. Secondly, we consider the case of the metamaterial absorber where water is unfilled, whose absorptivities are shown to be only around 20% to 40% at the frequency band of interest. Finally, we further consider the impact of the metal layer in our metamaterial absorber. Unlike metallic resonator based metamaterial absorbers [26], where the absorption performances almost completely disappeared without the metal ground layer, the water metamaterial still show high absorptivities above 77% at the whole frequency band. However, the bandwidth of over 90% absorptivity is significantly narrower than that with a metal layer, where the transmitted electromagnetic waves are totally blocked. These, beyond doubt, confirms that the broadband high absorption is achieved mainly due to the localized resonance in the metamaterial with structured water resonators.

![Fig. 2. Absorptivity spectra of the water metamaterial absorber, the full water layer backed by a metal plate, the metamaterial without water, and the metamaterial without metal back layer. The dotted horizontal line denotes the absorptivity of 90%.

In Fig. 2, we see that the absorption spectra of metamaterial absorber shows three peaks at around 13.0, 19.6, and 27.3 GHz, which indicates three resonances at these frequencies. To understand the physical mechanism behind the wideband absorption, the electric and magnetic field distributions are numerically investigated at these resonance frequencies, as shown in Fig 3. We see that for the first peak at around 13.0 GHz, the electric field mainly concentrates in the resin shell above the resin cavity and the magnetic field mainly concentrates at the place where the water contacts with the resin shell and the cavity. This indicates that there are both strong electrical and magnetic resonances at this frequency. For the second peak at 19.6 GHz, the
magnetic field is mainly concentrated on the two sides of the upper resin shell and the electric field is significantly weaker, indicating that the main role is a strong magnetic resonance and the electric resonance is much weaker at 19.6 GHz. Finally, for the third peak at 27.3 GHz, the electric field mainly concentrates above the resin cavity and the magnetic field mainly concentrates within the upper resin layer, indicating that both strong electric and magnetic resonances are contributed to this resonance. These behaviours show that there are different resonant modes for the three absorption peaks. These resonances in the metamaterial are close to each other in frequency, which are merged together to form a broadband absorption.

For a better illustration of the absorption inside the water metamaterial absorber, the power loss densities at the three resonance frequencies are further shown in Fig. 4. It shows that, in all cases, the power loss densities mainly concentrate in the water layer, which is simply due to the high dielectric loss of water over the frequency range of interest. For each case, it is also seen that reasonable level of power loss is found at the upper resin layer, whilst the power loss densities are extremely weak when reaching the lower resin layer. However, the absorption schemes are significantly different at these resonance frequencies, as clearly seen in Figs. 4(a2)-4(c2). At
13.0 GHz, the power loss densities reside around the hollow cylinder; at 19.6 GHz, the power loss densities concentrate at the two ends of the unit cell along the electric field polarization; while at 27.3 GHz, the majority of the power loss moves to the four corners of the unit cell (i.e., the center of four unit cells). The combination of these absorption modes leads to an ultrawide band of high absorption in the water metamaterial absorber.

![Absorptivity vs Frequency](image)

**Fig. 5.** The comparison of the simulated and measured absorptivity spectra of the water metamaterial absorber. The insert (a) shows the as-prepared metamaterial absorber consisting of 6 × 6 substructures (i.e., 12 × 12 unit cells) and (b) is a substructure made of 2 × 2 array of unit cells.

The experimental realization of such a metamaterial absorber could be achieved via the fabrication of a hollow resin container using 3D printing technology and filling it with water. Due to the limitations of the 3D printer we used, it was only possible to fabricate a structure of limited size. In our experiment, the metamaterial absorber is divided into 6 × 6 substructures and each substructure is a 2 × 2 array of the unit cells. The full 12 × 12 array of the resin cells are further adhered to a copper plate. As shown in Fig 5(b), a hole (diameter of 3 mm) is opened on the outer layer of each resin substructure for purpose of filling water.

The absorption performances of water metamaterial absorber are experimentally investigated through measuring the reflection using a vector network analyzer (Agilent 8720ET) with broadband horn antennas. The absorptivity can then be determined by $A = 1 - R$. It is worth noting that, in our measurement, the metamaterial’s reflectivity is normalized to that of a metal plate (same size as the metamaterial). In Fig. 5, we show the comparison between the measured and the simulated results. The experimental absorption curve show a broadband absorption characteristics, in good agreement with the simulated one. The slight difference is mainly due to the imperfections in the fabrication process.

3. **Thermal stability of absorption**

It is known that the permittivity of water is highly dependent on temperature. This is very important for a water metamaterial absorber since the electromagnetic energy of the incident waves is almost completely converted into heat inside the absorber, which may increase the temperature of water to some extent. Therefore, it is necessary to study the temperature dependence of the absorption performance in our water metamaterial absorber. In general, the change of temperature in the range from 0 to 100°C has negligible effect on the permittivity of resin or
the conductivity of copper. Therefore, we only consider the change of permittivity in water in our simulation and the rest parts of the model are remained the same. The high-frequency permittivity, static permittivity, and rotational relaxation time in the Debye formula of water are all directly dependent on temperature, \[ \varepsilon_0(T) = a_1 - b_1T + c_1T^{-2} - d_1T^3, \]  \[ \varepsilon_{\infty}(T) = \varepsilon_0(T) - a_2e^{-b_2T}, \]  \[ \tau(T) = c_2e^{rac{d_2}{T_0}}, \]

where \( a_1 = 87.9, b_1 = 0.404 \, ^\circ\text{C}^{-1}, c_1 = 9.59 \times 10^{-4} \, ^\circ\text{C}^{-2}, d_1 = 1.33 \times 10^{-6} \, ^\circ\text{C}^{-3}, a_2 = 80.7, b_2 = 4.42 \times 10^{-3} \, ^\circ\text{C}^{-1}, c_2 = 1.37 \times 10^{-13} \, \text{s}, d_2 = 651^\circ\text{C}, T_0 = 133^\circ\text{C} \) and \( T \) is the water temperature in \(^\circ\text{C}\). The temperature dependent permittivity of water can then be determined using the Debye formula.

Figure 6 shows the absorptivity spectra of the water metamaterial absorber from 0 to 100\(^\circ\text{C}\). It is seen that the absorptivity has a relatively small changes in the entire liquid phase temperature range. The maximum change is found around 16.5 GHz, where the sensitivity (defined as \( \Delta A/\Delta T \)) is below 0.001 per \(^\circ\text{C}\). This clearly confirms that the performance of our metamaterial absorber is very weakly dependent on the working temperature.

4. Angular tolerance

Fig. 7. Absorptivity spectra of the water metamaterial absorber for oblique incidence waves with incident angle from 0 to 75\(^\circ\). (a) TM mode and (b) TE mode.
The absorption performance of the water metamaterial absorber under oblique incidence are further analyzed. In Fig 7, we show the simulated permittivities for different angles of incidence. It is seen that, for the case of TM incidence, the absorptivity curves show very weak fluctuations and remain higher than 90% within almost the entire frequency band of interest for incidence angles below 60°. When incidence exceeding 60°, the absorptivities start decreasing. However, the absorptivities are still higher than 67.3% for an incident angle as high as 75°. For TE incidence, the absorptivities show more significant decrease with the increase of the incidence angle. Still, the metamaterial shows acceptable wideband high absorption for incidence angles below 45°. Both the TE and TM results show that the proposed water metamaterial absorber has good absorption performance for wide angle of incidence.

Similar to those metallic resonators based metamaterial absorbers [26], the absorption spectrum of the water based metamaterial absorber remains quite well as the increase of the incidence angle for the TM mode. This is because of the fact that metamaterial absorber’s performance is less sensitive to the intensity of the electric field which decreases with the increase of incident angle for TM case. While for the TE mode, the magnetic field decreases significantly with the increase of the incident angle. As a result, the absorption performance decreases remarkably. It is also seen that the resonance at around 19.6 GHz is not affected significantly with the increase of the incident angle. This is because that this resonance is mainly contributed to a strong magnetic resonance. Although this magnetic resonance weakens significantly as the decrease of the incident magnetic field, it is still strong enough to couple with the weak electric resonance for achieving impedance matching when the incident angle is below 60°.

5. Conclusion
We have presented the design and measurement of a subwavelength water metamaterial absorber which exhibits ultra-broadband perfect absorption at radio frequencies. Our experiment showed that the metamaterial absorber shows over 90% absorptivity for an ultrabroad frequency band from 12 to 29.6 GHz. Resonance induced field distributions were discussed at different frequencies for investigating the mechanism of the broadband absorption, which also confirms that the incident wave energies are mainly consumed in the structured water layer. Although the dielectric response of water is strongly temperature dependent, we show that the our metamaterial has very good thermal stability of absorption. This is crucially important for the use in complex or high power environments. The angular tolerance of the metamaterial absorber was further studied, which demonstrated that high efficient absorption can be well remained for incident angle below 45° (60°) for the TE (TM) oblique incidence. The proposed water metamaterial absorber is low-cost, which may prove useful in broadband scattering reduction and electromagnetic energy harvesting.

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