Water-Based Microwave Antennas.

Jacobsen, Rasmus Elkjær; Vandborg, Mads H. ; Laurynenka, Andrei; Arslanagic, Samel

Published in:
Proceedings of 2020 14th European Conference on Antennas and Propagation

Publication date:
2021

Document Version
Peer reviewed version

Water-Based Microwave Antennas

Rasmus E. Jacobsen[1], Mads H. Vandborg[2], Andrei V. Lavrinenko[1], Samel Arslanagić[2]
[1]Department of Photonics Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark, rajac@fotonik.dtu.dk
[2]Department of Electrical Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

***Abstract*— The interesting properties of water makes it an attractive material platform for many microwave applications including artificial material design, sensing, heating systems and dielectric resonator antennas. Presently, electrically small versions of the latter are considered. We present the numerical and experimental results for an antenna consisting of a short monopole fed against a large conducting ground plane and encapsulated by a water-filled cylindrical cavity. The resonant antenna is designed for 300 MHz operation and is successfully matched to a 50 Ohm transmission line and the surrounding air. The total efficiency is 33.4 % and the reflection coefficient is –28 dB. The reduced efficiency is due to water losses and the small antenna size. A prototype of the antenna was fabricated, and the measurements and numerical predictions exhibit good agreement. Additionally, frequency-tuning by extraction of water is investigated.**

***Index Terms*—dielectric resonator antenna, water-based, Mie resonance.**

I. Introduction

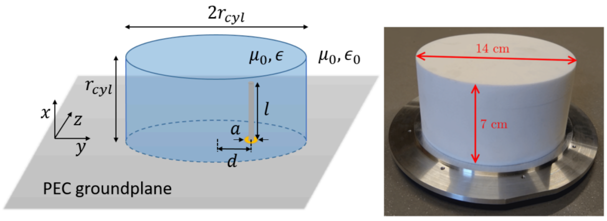
Development of electrically small antennas is important to satisfy the desire for smaller and compact technology designs as miniature versions of today's conventional antennas are inefficient radiators with their highly reactive input impedances [1]. Matching of such a load to a realistic source using a matching network results in poor bandwidth, high fabrication requirements and modest efficiencies. A different approach is to shape the radiator and/or add elements such that the antenna utilizes its occupying volume more efficiently while being matched to its feed-line and resonant. Several solutions have been proposed such as folded spherical helix antennas [2], metamaterial-based [3] and -inspired antennas [4] and dielectric resonator antennas (DRAs) [5]–[7]. The latter usually consists of a dielectric structure placed on a ground conducting plane and with a metallic radiator for excitation like e.g. a monopole or patch antenna positioned inside or close to it. Using high-permittivity dielectrics, the antenna size can be a small fraction of the operating free-space wavelength λ_0. However, the high permittivity and compact size also decreases the bandwidth of the antenna. Therefore, the relative permittivity is normally in the range from 8 to 100. Typically, low-loss ceramics are used, but it has also been shown that simple and natural water can function as an alternative material [6]–[7]. Beside DRAs, several applications of water have been demonstrated such as in metamaterial and metasurface designs as well as in sensing and heating systems [8]–[11]. It has been shown that water adds flexibility as well as several tuning capabilities to such systems.

In this work, we present numerical and experimental results for water-based DRAs. The investigated DRA consists of a short monopole antenna fed against a large ground conducting plane and encapsulated by an electrically small cylindrical water-filled cavity. The antenna is designed for 300 MHz operation and has been matched to a 50 Ohm transmission line, as well as the surrounding air medium, providing a total efficiency of 33.4 % and a reflection coefficient of –28 dB. In addition, the frequency-tuning by extraction of water from the cylindrical cavity is investigated. The presentation at the conference will also include results for some other water-based DRAs as well as their tuning abilities induced by temperature variations.

The paper is organized as follows. Section II introduces the water-based DRA. Section III presents the numerical and experimental results. Section IV includes a summary and conclusions of this work. Throughout the work, the time-factor $\exp(j\omega t)$, where ω is the angular frequency, and t is the time, is assumed and suppressed.

II. Configuration

The DRA consists of a short monopole fed over a large conducting ground plane and encapsulated by a water cylinder. A sketch of the antenna is shown in Fig. 1(a) with a Cartesian coordinate system introduced. The cylinder has equal radius and height r_{cyl}, and the monopole has the wire diameter of 1.6 mm and the length l; it is displaced a distance d from the cylinder center. The monopole is connected to a coaxial transmission line with inner (outer) diameter of 1.28 mm (4.1 mm). A model of the antenna is built in COMSOL Multiphysics 5.3 [12], which is used for the numerical calculations. The model consists of the antenna placed in a PML-supported hemisphere of free space and with a Perfect Electric Conductor (PEC) plane as the ground. On the bottom of the transmission line, a matched port is placed.



(a) **(b)**

Fig. 1. (a) Sketch of the antenna, and (b) photograph of the antenna prototype.

The permittivity of water is described by the Debye model [13]. The antenna parameters used in the paper are calculated as defined in [1].

III. Results and Discussion

First, the resonant size of the cylinder was determined through a scattering analysis of the cylinder without the monopole. At 300 MHz, the required radius and height of the water cylinder exhibiting a magnetic dipole resonance were found to be $r_{\mathrm{cyl}} = 49.4$ mm. Second, l and d providing the largest total efficiency were determined with the result shown in Fig. 2(a). The optimal values are $l = 37.05$ mm and $d = 9.88$ mm, and the spectral response of the optimized antenna is shown in Fig. 2(b) with a water temperature of 24 °C. At 302 MHz, the reflection coefficient and the total efficiency are minimal (–28 dB) and maximal (33.4 %), respectively, indicating good matching of the antenna to the transmission line as well as to the ambient air. Removing the water dramatically increase the reflected power such that nearly no power is radiated (<<1%) due the highly capacitive input impedance of the monopole. With the water, the input impedance of the antenna is $42.2 - j1.7$ Ohm.

The electrical size of the antenna is $r_{\max} = \lambda_0/14$, and is thus electrically small [1]–[4]. The small size and the losses in the water consequently reduce the total efficiency with the non-radiated power being dissipated as heat in the water. On the other hand, the losses have a positive effect on the bandwidth, and the 3–dB fractional impedance bandwidth is 5.5 %.

A prototype of the antenna was fabricated at the local workshop. The water cylinder was realized by milling a cylindrical cavity in a Rohacell 51 HF block with relative permittivity 1.057 [14]. The block was glued on to a circular aluminum plate in which holes for insertion of monopole antenna and destilled water had been drilled. A photograph of the prototype antenna is shown in Fig. 1(b). The ground plane was extended to 1 m during measurements, and a half-wavelength dipole was made for transmission measurements. An Anritsu MS2024A VNA was used to measure the S-parameters, and the measured reflection coefficient (S_{11}) is included in Fig. 2(b) showing good agreement with the numerical result. There is a small difference in resonance freqeuncy, which can be explained by small differences in water temperature, water volume and/or truncation of the ground plane.

The antenna was mounted on a tripod with a rotating joint such that the transmission from different angles could be measured. The measured transmission coefficient (S_{21}) is shown in Fig. 3(a) in the xy–plane together with numerical results showing good agreement. There are deviations at angles close to the ground plane, where the measured transmission coefficient start to decrease, which is expected with the truncated ground plane size.

Subsequently, water was extracted from the cavity to investigate the tunability of the antenna. The position of the antenna was fixed such that the water kept the cylindrical form. The resonance frequency is shown in Fig. 3(b) as a function of the reduction in the cylinder height of the water. From 0 mm to 10 mm, the monopole antenna is completely covered by water, where linear frequency blue-shift, as well as low reflection coefficient (not shown here), is achieved. Above 10 mm, the reflection coefficient greatly increases, and the tendency of the frequency shift changes.

Other types of water-based DRAs have been investigated with some based on the electric resonance and others based on both magnetic and electric resonances. We will show some of the representative results for these designs at the conference. We will also discuss the tunability by temperature as well as the effect from increasing water losseses at higher freqeuncies.

IV. Summary and Conclusions

In summary, an electrically small water-based cylindrical DRA designed for 300 MHz operation was investigated. We presented both numerical and experimental results exhibiting good agreement. The total efficiency and reflection coefficient of the DRA are 33.4 % and –28 dB, respectively. Additionally, we investigated the frequency-tuning of the proposed DRA by extraction of water.

Acknowledgment

The authors would like to thank the workshop at the Electromagnetic Systems group of the Technical University of Denmark for fabrication of the antennas.

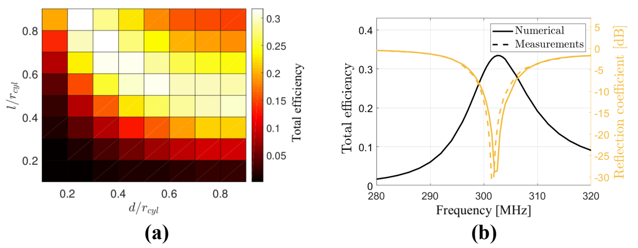


Fig. 2. (a) Total efficiency (colors) as a function of length and position of the monopole antenna used to find the optimum monopole design (water temperature: 20 °C). (b) Results for the optimized antenna with the spectrum of the total efficiency and reflection coefficient (water temperature: 24 °C). Measured reflection coefficient is included.

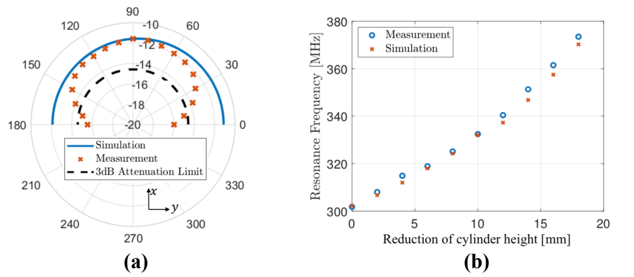


Fig. 3. (a) Simulated and measured radiation pattern (S_{21} in logarithmic scale) in the xy-plane. (b) Resonance freqeuncy as a function of reduction of the cylinder height due to extraction of water.

References

[1] C.A. Balanis, Antenna Theory, 3rd ed. New York, US: Wiley, 2005, pp. 64–69, 637–641.

[2] S.R. Best, “The radiation properties of electrically small folded spherical helix antennas,” IEEE Trans. Antennas Propag., vol. 52, no. 4, pp. 953–960, April 2004.

[3] R.W. Ziolkowski, and A. Erentok, “Metamaterial-based efficient electrically small antennas,” IEEE Trans. Antennas Propag., vol. 54, no. 7, pp. 2113–2130, July 2006.

[4] A. Erentok, and R.W. Ziolkowski, “Metamaterial-inspired efficient electrically small antennas,” IEEE Trans. Antennas Propag., vol. 56, no 3, pp. 691–707, March 2008.

[5] A. Petosa and A. Ittipiboon, "Dielectric Resonator Antennas: A Historical Review and the Current State of the Art," IEEE Antenn. Propag. M., vol. 52, no. 5, pp. 91-116, October 2010.

[6] S.P. Kingsley, and S.G. O'Keefe, “Beam steering and monopulse processing of probe-fed dielectric resonator antennas,” in Proc. IEE Radar, Sonar and Navigation, vol. 146, no. 3, 1999, pp. 121–125.

[7] R. Zhou, H. Zhang, and H. Xin, “Liquid-based dielectric resonator antenna and its application for measuring liquid real permittivities,” IET Microw., Antennas Propag., vol. 8, no. 4, pp. 255-262, March 2014.

[8] A. Andryieuski, S.M. Kuznetsova, S.V. Zhukovsky, Y.S. Kivshar, and A.V. Lavrinenko, “Water: promising opportunities for tunable all- dielectric electromagnetic metamaterials,” Sci. Rep., vol. 5, no. 13535, August 2015.

[9] M.A. Gorlach, M. Song, A.P. Slobozhanyuk, A.A. Bogdanov, and P. Belov, “Topological transition in coated wire medium,” Phys. Status Solidi RRL, vol. 10, no. 12, pp. 900–904, October 2016.

[10] X. Yang, D. Zhang, S. Wu, L. Li, K. Cao, and K. Huang, “Reconfigurable all-dielectric metasurface based on tunable chemical systems in aqueous solution,” Sci. Rep., vol. 7, no. 3190, June 2017.

[11] R.E. Jacobsen, A. V. Lavrinenko and S. Arslanagić, “Water-Based Metasurfaces for Effective Switching of Microwaves,” IEEE Antennas Wirel. Propag. Lett., vol. 17, no. 4, pp 571-574, April 2018.

[12] COMSOL Multiphysics 5.3. [Online]. Available: https://www.comsol.com/.

[13] W. Ellison, “Permittivity of pure water, at standard atmospheric pressure, over the frequency range 0–25 thz and the temperature range 0–100 c.,” J. Phys. Chem. Ref. Data, vol. 36, pp. 1–18, 2007.

[14] ROHACELL, Rohacell 51 HF. [Online]. Available: https://www.rohacell.com/.