Estimating the dielectric constant of water in the decimeter-wave (UHF) range

Objects of the experiment

- To compare the wavelength λ of the UHF transmitter in air and in water
- To estimate the dielectric constant ε of water in the decimeter-wave (UHF) range

Principles

Dielectric materials attenuate the electric field between the plates of a capacitor, increasing the capacitance. The factor by which the capacitance increases is called the dielectric constant ε.

Electromagnetic waves can also propagate in dielectric materials. However, their phase velocity

$$c = \lambda \cdot \nu \qquad \text{(I)}$$

λ: wavelength, ν: frequency

is less than in vacuum (ε = 1), and is a function of the dielectric constant. We can say

$$c(\varepsilon) = \frac{c_0}{\sqrt{\varepsilon}} \qquad \text{(II)}$$

c_0: speed of light in a vacuum

As water molecules have a permanent dipole moment, the dielectric constant ε of water is high. In contrast, we can assume the dielectric constant of air as 1 as a sufficiently close approximation. As the frequency ν remains constant in each case, the wavelength of electromagnetic waves in water is shortened considerably as compared to propagation in air. The “contraction factor” can be deduced from (1) and (II), and we can say that:

$$\frac{\lambda_1}{\lambda_0} = \frac{1}{\sqrt{\varepsilon}} \qquad \text{(III)}$$

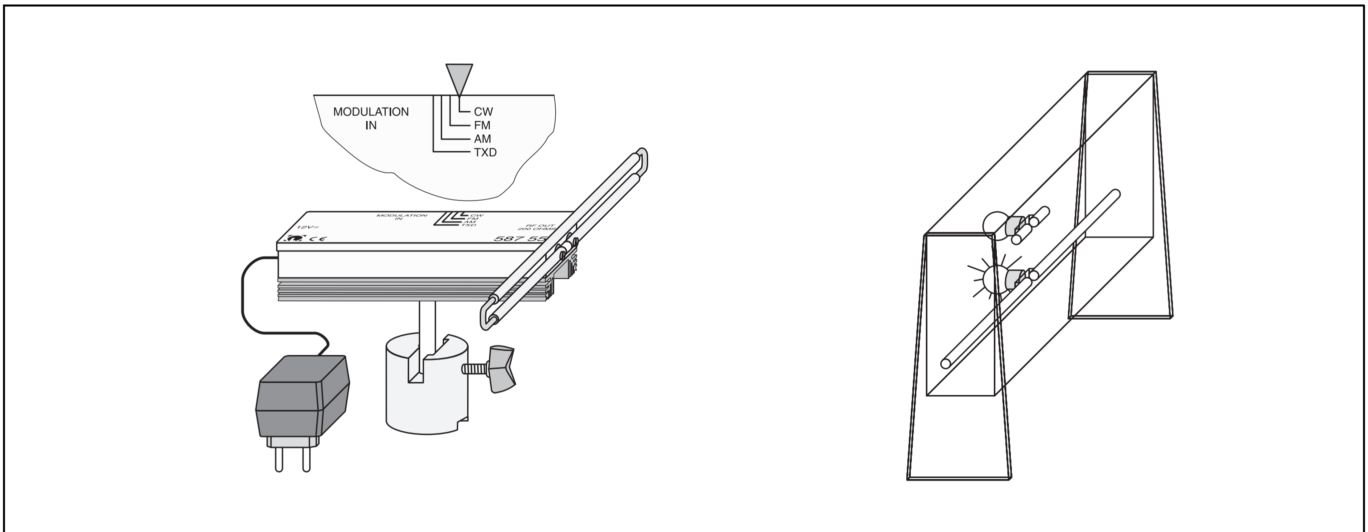
λ_1: wavelength in water, λ_0: wavelength in air

This experiment demonstrates this contraction phenomenon using decimeter waves (UHF, ν = 433.92 MHz) with the aid of two dipole antennas of different lengths. Here, the absorption of the decimeter waves by the two dipoles is observed in air and in water. Each of the two dipoles is provided with an incandescent lamp at its middle extending above the surrounding water, which lights up when resonant absorption of the decimeter waves at the appropriate wavelength occurs. The condition for resonant absorption is:

$$s = \frac{\lambda}{2} \qquad \text{(IV)}$$

The lengths *s* of the two dipoles have been matched to the experiment such that resonant absorption of the electromagnetic waves will occur in one of the two, depending on the respective propagation medium. This allows us to estimate the wavelength λ of the decimeter waves both in the air and in water.

Fig. 1: Experiment setup for estimating the dielectric constant of water in the decimeter-wave range



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Apparatus

1 UHF transmitter 587 55
1 Plug-in unit 230 V AC/12 V AC 562 791
1 Set of dipoles in water tank 587 54
1 Saddle base 300 11

Additionally required:

1.2 l distilled or demineralized water

Setup and carrying out the experiment

Set up the experiment as shown in Fig. 1.

Note: This experiment can only produce satisfactory results when distilled or demineralized water is used.

– Clamp the UHF transmitter securely in the saddle base and connect the loop dipole to the antenna output of the UHF transmitter as shown in Fig. 1.
– Select operating mode CW.
– Set up the water tank approx. 30 cm away from the transmitter and align the loop dipole parallel to the λ/2 dipoles in the water tank.
– Connect the plug-in supply unit of the UHF transmitter.
– Slowly fill the water tank with distilled or demineralized water and observe when the lamp of the long λ/2 dipole goes out and the short λ/2 dipole comes on.

Safety notes

Experiment setups using the UHF transmitter may not always conform to the limit values of class A (group 2 of the standard EN 55011). The device can interfere with other equipment in the experiment room of the educational facility. Also, radio interference can occur up to a distance of several hundred meters. It is the responsibility of the user to take all precautions to ensure that equipment installed outside of the experiment room can continue to function properly.

- See the information contained in the Instruction Sheet of your UHF transmitter.
- Do not operate the transmitter longer than is required to conduct the experiment; when the experiment is concluded, shut down the device immediately by switching off the plug-in supply unit.

Measuring example

The lamp of the long λ/2 dipole lights up in the empty tank. s_0 = 31.5 cm.

The lamp of the short λ/2 dipole lights up when the tank is filled with water. s_1 = 6 cm.

Evaluation and results

Comparing the wavelengths λ_0 in air and λ_1 in water:

From equation (III) we obtain λ_0 = 63 cm, λ_1 = 12 cm

Decimeter waves thus have a much shorter wavelength in water than in the air.

Estimating the dielectric constant ε in the decimeter-wave range

To estimate the dielectric constant ε in accordance with (III) we need to calculate the wavelengths more exactly, as a 1.8 cm long segment of each dipole (lamp with fitting) is in the air even when the tank is filled with water.

A 4.2 cm section of the short dipole is immersed and a 1.8 cm section is in the air; the long dipole has a length of 31.5 cm. We thus calculate

$$1.8\text{ cm} + 4{,}2\text{ cm} \cdot \sqrt{\varepsilon} = 31.5\text{ cm}$$

and obtain a value for the dielectric constant in the decimeter wave range of

$\varepsilon = 50$.

Literature value: ε = 81 (static dielectric constant)

In the decimeter wavelength range, the dielectric constant of water is significantly greater than 1.

We can calculate the wavelength of the decimeter waves more precisely as

$$\lambda_1 = \frac{63\text{ cm}}{\sqrt{50}} = 8.9\text{ cm}$$

Additional information

It is important to understand that the estimation of wavelengths from the lengths of the dipoles is only approximate. The resonance condition at λ/2 applies for the elementary (Hertzian) dipole with the diameter D = 0. For diameters D > 0, however, a contraction factor becomes apparent for the overall length, and the bandwidth is increased due to a flatter resonance curve of the antenna. In addition, the resonance condition is affected by the built-in light bulb.

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