

A Tiny 2.4 GHz Monopole Water Antenna

Koyu Chinen, and Ichiko Kinjo

Abstract—We designed, fabricated, and evaluated a monopole water antenna (WA) filled with pure water. A 2.4 GHz patch antenna (PA) was used for measurement comparison, and the current density distribution and 3D field strength radiation distribution and reflection coefficient of the PA had a fundamental mode and a higher-order mode at 3.5 GHz, whose polarization was 90 degrees different. The 2.4 GHz monopole WA could receive only the fundamental mode of the PA. The 3.5 GHz WA could receive the higher-order mode of the PA by rotating the WA by 90 degrees. The transmission coefficient of the 2.4 GHz WA decreased with the square of the spacing, similar to the spatial propagation characteristics of electromagnetic waves. Almost the same results could be expected if planar or three-dimensional antennas were used instead of monopole electrodes.

Keywords—water antenna; polar molecule; S-parameter; monopole antenna; underwater wireless communication

I. INTRODUCTION

WATER antennas are characterized by their small size and flexible shape, which are achieved by taking advantage of the high permittivity of water. Therefore, water antennas have been widely studied for wireless communications in seawater and freshwater because of their excellent affinity with liquids. Many reports have been on monopole-type water antennas because of their simple structure [1-27] and evaluated the reflection coefficient S_{11} by changing the electrode structure and liquid structures (aqueous solution material and shape) [5, 11, 23]. Most of the proposed water antenna structures are open-end, which makes their size rather large [3, 9, 14, 17, 21, 26]. There are many reports on using frequencies below 1 GHz and a few hundred MHz in the case of seawater due to high attenuation rates [3, 8, 9, 11, 13, 15, 16, 23]. Many research reports have investigated the changes in frequency and reflectivity of dielectric resonance caused by immersing a planar antenna, such as a patch antenna, in a liquid [2, 4, 6, 10, 14, 18, 24]. There are few detailed reports on the evaluation of transmission characteristics in the GHz band using water antennas as transmitting and receiving antennas.

In this study, we designed and fabricated a small and portable water antenna that can be used to transmit and receive high-frequency signals in the 2.4 GHz band used in wireless LANs and investigated its transmission characteristics.

II. 2.4 GHz BAND MONOPOLE WATER ANTENNA AND TRANSMISSION MEASUREMENT SYSTEM

We evaluated the 2.4 GHz monopole water antenna's characteristics and signal transmission and reception by S-parameter measurements. The configuration of the S-parameter measurement system is shown in Figure 1.

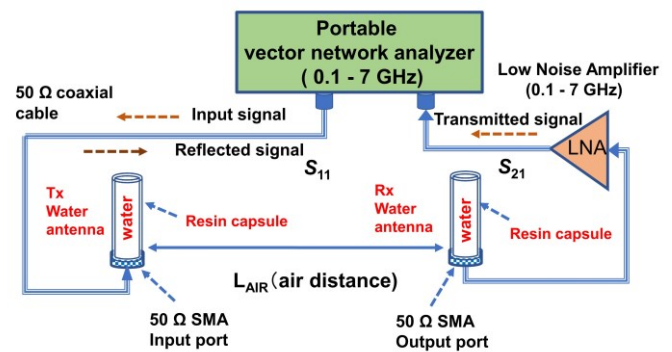


Fig. 1. Measurement system for transmission characteristics of water antennas

The reflection coefficient S_{11} and transmission coefficient S_{21} were calculated by measuring the reflection and transmission signals of RF signals in the 0.1 to 6 GHz band using a portable vector network analyzer (VNA) [27]. The high-frequency signal was fed from the output port of the VNA to a monopole water antenna (Tx-WA) for transmission using a 50 Ω coaxial cable. The output signal from the receiving monopole water antenna (Rx-WA) was connected to a low-noise amplifier with a bandwidth of 0.1 to 7 GHz and a gain of 20 dB, which was designed and fabricated using a coplanar line and a single-stage SiGe bipolar transistor. The output of the LNA was connected to the input port of the vector network analyzer. The measurement system was calibrated using SOLT (short, open, load, and through) terminals between the output connector of a 50 Ω coaxial cable connected to the output port of the VNA and the input port of the VNA. The measured S-parameters are expressed in complex or polar coordinates, but in this paper, they are evaluated in terms of their magnitude. cylindrical acrylonitrile butadiene styrene (ABS) resin capsule

Koyu Chinen is with GLEX, Yokohama, Japan (email: koyu.chinen@nifty.com).

Ichiko Kinjo is with Information and Communication System Engineering Dept., National Institute of Technology, Okinawa College, Nago, Japan (email: ichi@Okinawa-ct.ac.jp).



The 2.4 GHz band monopole water antenna consists of a with an inner diameter of 8 mm and an outer diameter of 10 mm, and a 50 Ω SMA (Sub Miniature Type A) electrode. The central signal pin of the SMA electrode was placed inside the capsule, and the capsule was filled with pure water purified by ion exchange resin and reverse osmosis membrane. The capsule length L_{WA} is 25 mm or 50 mm. A photograph of the external appearance is shown in Figure 2. The impedance matching between pure water and SMA electrodes in the 2-4 GHz frequency range was investigated by varying the length of the center signal pin of the SMA electrode and measuring the frequency of the minimum value of the reflection coefficient S_{11} . The measured and simulated electromagnetic field values are shown in Figure 3. The signal pin length of the impedance-matched SMA electrode at 2.4 GHz was 8 mm. The minimum value of S_{11} is relatively large, about -5 dB. When the size and shape of the ground were changed to enclose the lower part of the signal pin of the SMA electrode [20], S_{11} was reduced to less than -10 dB, but the transfer coefficient S_{21} also decreased. One possible cause of this is the effect of changes in the current density distribution of the signal pins. A flat SMA connector flange was therefore used for the ground.

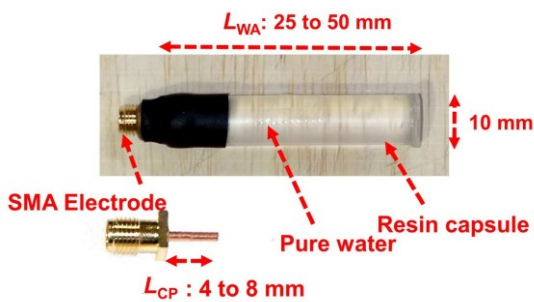


Fig. 2. Appearance of 2.4 GHz band monopole water antenna

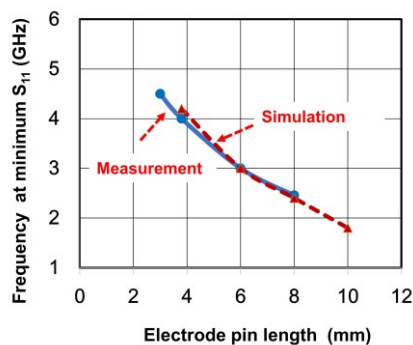


Fig. 3. Relationship between the electrode pin length of the monopole water antenna and the frequency at which the minimum value of S_{11} of the monopole water antenna is reached

III. DESIGN, FABRICATION, AND CHARACTERIZATION OF 2.4 GHz BAND PATCH ANTENNAS

To evaluate the transmission and reception characteristics of the 2.4 GHz band monopole water antenna, we designed and fabricated a 2.4 GHz band patch antenna as a reference antenna

for comparison. Patch antennas are suitable as reference antennas for evaluating the antenna characteristics of designed and fabricated monopole water antennas because they are directional, have a narrow bandwidth frequency response, and have stable characteristics. The 2.4 GHz band patch antenna was fabricated using a 36 μm double-sided copper-clad FR-4 (Flame Retardant Type 4) substrate with a thickness of 1.6 mm. We used an electromagnetic simulator AXIEM [28] to determine the antenna length L_{PAL} and width L_{PAW} , for which the reflection coefficient S_{11} at 2.4 GHz is a minimum. The feeder line was designed as a 50 Ω MSL (Micro Strip Line), and 50 Ω SMA was used for the connectors.

The current density distribution and electric field intensity radiation pattern (E_θ and E_ϕ) of the 2.4 GHz band patch antenna obtained by electromagnetic field simulation are shown in Figure 4. The current flows in the direction along L_{PAL} (X-axis direction), and the vertical (E_θ) and horizontal (E_ϕ) polarization components of the radiated electric field intensity of the electromagnetic wave generated by this current are shown. The results of the measured and simulated values of the reflection coefficient S_{11} obtained from the electromagnetic field simulation are shown in Figure 5. In the 0.1 to 6 GHz frequency range, in addition to the fundamental frequency of 2.4 GHz, higher-order mode frequencies appear at 3.5 GHz and 4.5 GHz.

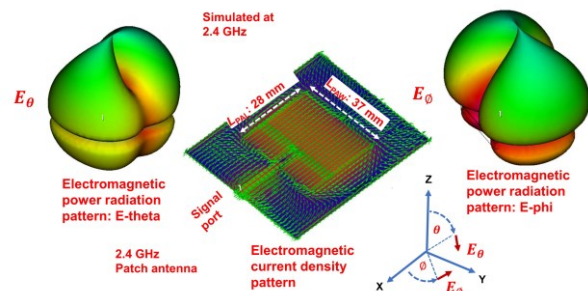


Fig. 4. Current density distribution and electric field intensity radiation pattern of 2.4 GHz patch antenna

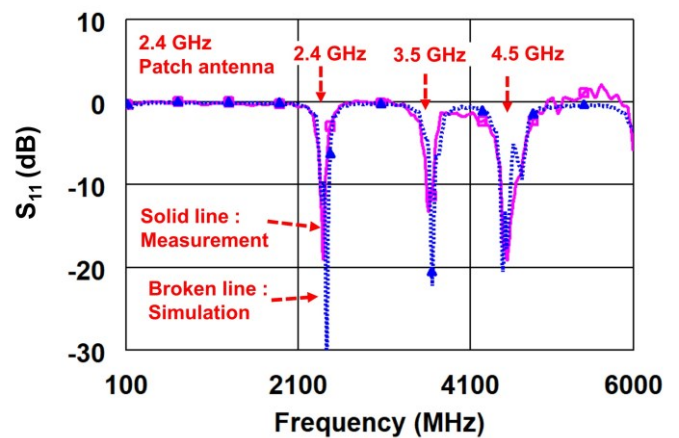


Fig. 5. Measured and simulated S_{11} values for the 2.4 GHz patch antenna

The current density distribution and electric field intensity radiation pattern at 3.5 GHz for the higher-order modes are shown in Figure 6. The current density distribution is bisected at the antenna width L_{PAW} , indicating resonance of the second higher-order mode (TE_{02}). The current shows a direction rotated by 90 degrees relative to the 2.4 GHz fundamental resonance mode TE_{10} , and the field strength radiation pattern (E_θ) generated by the current also shows a direction rotated by 90 degrees. The electric field strength radiation pattern (E_ϕ) divided into two parts by the resonance mode divided into two parts in the Y direction is shown.

The higher-order mode at 4.5 GHz represents a resonant frequency close to TE_{12} . Because the TE_{10} mode was added to TE_{02} mode, the electric field intensity radiation pattern showed the same direction as the fundamental resonance mode with E_θ rotated another 90 degrees, and the E_ϕ mode showed the same pattern as TE_{02} mode. In this paper, the 3.5 GHz frequency is treated as a representative example of higher-order mode transmission and reception. Therefore, higher-order mode transmission and reception at 4.5 GHz will not be discussed.

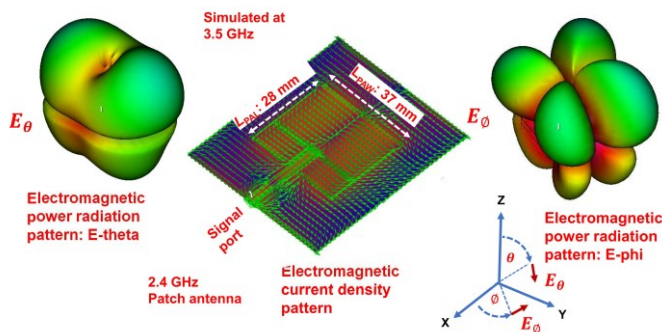


Fig. 6. Current density distribution and electric field intensity radiation pattern of the 2.4 GHz patch antenna at 3.5 GHz

IV. TRANSMISSION AND RECEPTION CHARACTERISTICS OF 2.4 GHz BAND MONOPOLE WATER ANTENNAS

We measured the S-parameter reflection coefficient S_{11} and transmission coefficient S_{21} by placing the 2.4 GHz patch antennas at the transmitting and receiving antenna positions of the transmission measurement system (Figure 1). The measurement result is shown in Figure 7. The transmitting coefficients S_{21} corresponding to the resonance frequencies of 2.4 GHz, 3.5 GHz, and 4.5 GHz, as shown in the measured value of the reflection coefficient S_{11} , were measured. Hence both fundamental mode and higher-order mode signals were transmitted and received. This result indicates that electromagnetic waves with different frequencies and electric field intensity patterns are transmitted and received when the transmitting and receiving antennas have the same structure and characteristics.

The reflection coefficient S_{11} and transmission coefficient S_{21} were measured using a 2.4 GHz patch antenna as the transmitting antenna and a 2.4 GHz monopole water antenna as the receiving antenna, as shown in Figure 8. The 2.4 GHz fundamental mode signal was received normally, but the higher-order mode signal could not be received. This is because the

receiving monopole water antenna has an 8 mm electrode pin length, which optimizes the impedance to 2.4 GHz and eliminates higher-order modes. When the lengths of the resin capsule L_{WA} were 25 mm and 50 mm, the transmitted signal S_{21} at 2.4 GHz was slightly larger but not significantly different when a monopole water antenna with an L_{WA} length of 50 mm was used as the receiving antenna.

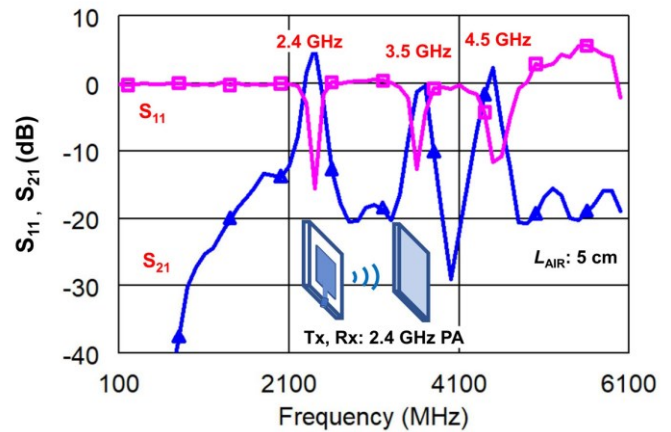


Fig. 7. Reflection coefficient S_{11} and transmission coefficient S_{21} measured with 2.4 GHz patch antennas

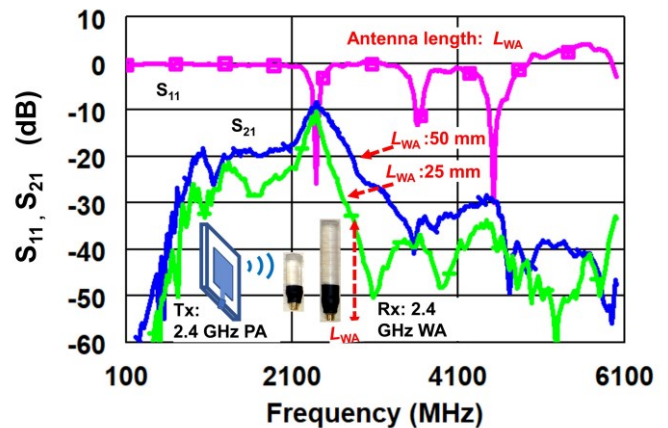


Fig. 8. Reflection coefficient S_{11} (PA) and transmission coefficient S_{21} measurement with 2.4 GHz band patch antenna (transmitter) and 2.4 GHz band monopole water antenna (receiver)

V. TRANSMISSION AND RECEPTION CHARACTERISTICS OF 2.4 GHz BAND MONOPOLE WATER ANTENNAS

The current density distribution and electric field intensity radiation pattern (E_θ and E_ϕ) of the 2.4 GHz band monopole water antenna in pure water obtained by electromagnetic field simulation are shown in Figure 9. The current density increases from the top (tip) of the signal pin toward the bottom, indicating the current density distribution of a typical monopole antenna. The electric field intensity radiation patterns (E_θ and E_ϕ) along this current direction (X-axis direction) are shown and have the same direction as the electric field intensity radiation pattern of the 2.4 GHz band patch antenna shown in Figure 4.

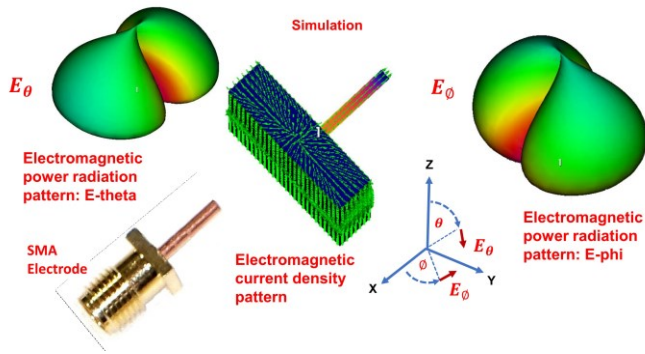


Fig. 9. Current density distribution and electric field intensity pattern of the 2.4 GHz band monopole water antenna

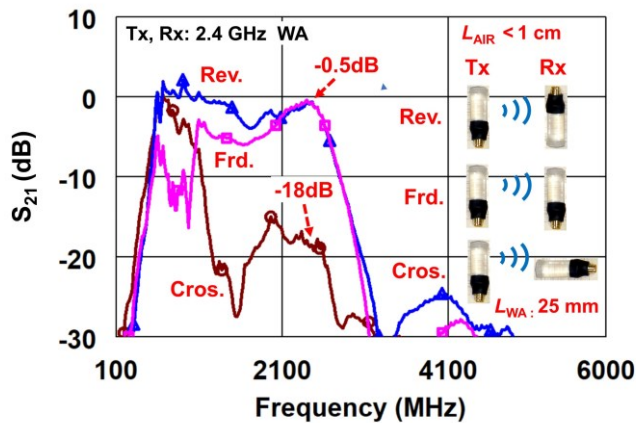


Fig. 10. Transmission coefficient S_{21} measurement for the 2.4 GHz band monopole water antennas with different antenna angles during the measurements

Figure 10 shows the results of the S_{21} transmission coefficient measurement using a 2.4 GHz monopole water antenna as the transmitting and receiving antennas. The direction of the receiving antenna was changed to forward (Forward), reverse (Reverse), and right-angle crossing (Cross) as the direction of the transmitting antenna. The measurement result of the S_{21} transmission coefficient at 2.4 GHz showed no significant difference between the forward and reverse counterparts but a decrease of about 17 dB for the right-angle crossing counterparts. This is because, as shown in Figure 9, the electric field intensity radiation pattern (E_{θ} and E_{ϕ}) of the monopole water antenna is determined by the current in the x-axis direction, and the electric field intensity radiation directions for transmission and reception are different when the antennas are placed at right-angles to each other.

The electric field intensity pattern in the air reflects that in pure water. The S_{21} value observed at frequencies below 1 GHz is due to omnidirectional signal transmission and reception using the cylindrical enclosure (ABS resin) of the water antenna as an antenna. It is considered to vary with the material and structure of the enclosure.

The 2.4 GHz patch antenna shows higher-order mode current density distribution and electric field intensity radiation pattern at 3.5 GHz (Figure 6). The signal pin length of the monopole

water antenna was shortened to about 4 mm so that signals in the higher-order mode at 3.5 GHz could be received by the monopole water antenna (Figure 3). As shown in Figure 6, the higher-order mode of the 2.4 GHz patch antenna exhibits an electric field intensity radiation pattern that is 90 degrees different from that of the fundamental mode. Therefore, the 3.5 GHz transmission coefficient S_{21} has a low value when received by a 3.5 GHz monopole water antenna placed opposite the 2.4 GHz patch antenna in the forward direction along the X axis. When the 3.5 GHz monopole water antenna was rotated 90 degrees relative to the 2.4 GHz patch antenna, the receiving sensitivity at 3.5 GHz was improved by about 9 dB (Figure 11). When a 3.5 GHz monopole antenna is placed opposite the 2.4 GHz patch antenna in the forward direction, the signal reception is possible over a wide frequency range from 1 to 5 GHz. However, the overall reception sensitivity is very low. Shortening the signal pin length of a monopole water antenna can extend the transmission and reception frequency range, but this is a trade-off for reducing receiver signal sensitivity.

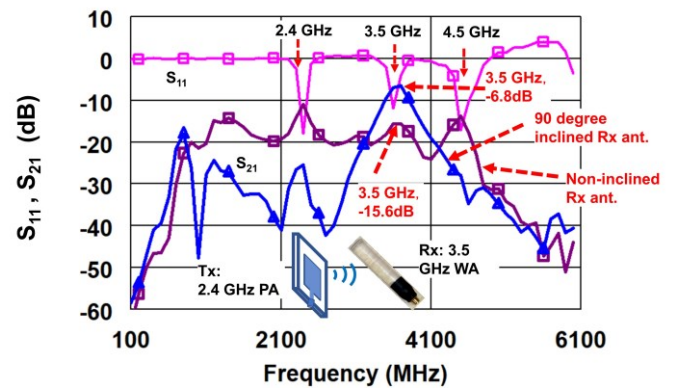


Fig. 11. Measured reflection coefficient S_{11} and transmission coefficient S_{21} with 2.4 GHz band patch antenna (transmitter) and 3.5 GHz band monopole antenna (receiver)

VI. S_{21} TRANSMISSION COEFFICIENT MEASUREMENTS FOR THE DISTANCE BETWEEN TRANSMITTING AND RECEIVING 2.4 GHz MONOPOLE WATER ANTENNAS

We measured the transmission coefficient S_{21} for a 2.4 GHz monopole water antenna ($L_{WA} = 50$ mm) with different distances L_{AIR} between transmitter and receiver. The measurement results are shown in Figure 12. The equation for the measured values of S_{21} is given in (1), and the constant K is given in (2). The value of S_{21} decreases with the square of the distance L_{AIR} , reflecting the spatial propagation attenuation characteristics of the electromagnetic wave. The S_{21} value is approximately 10 dB lower than the 2.4 GHz patch antenna. The reason for the lower transfer coefficient is the lower antenna gain due to the omnidirectional nature of the monopole water antenna compared to the highly directional patch antenna. Other possible factors are the low electric field intensity coupling between the electrode pin of the monopole water antenna and the pure water and the low-radiation efficiency of the electromagnetic power from the pure water to the air.

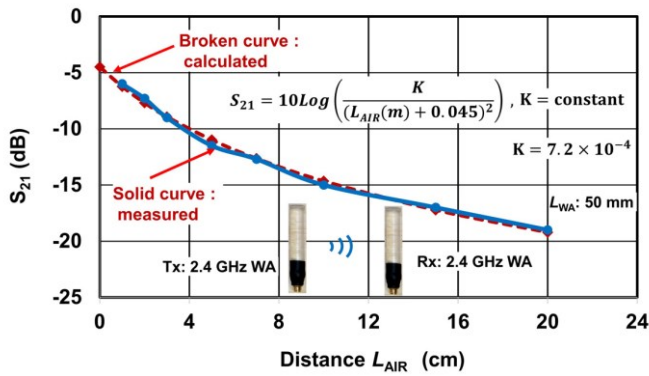


Fig. 12. Transmission coefficient measurement at different distances between the transmitter and receiver of the 2.4 GHz band monopole water antennas

$$S_{21} = 10 \log (K / \{L_{AIR}(m) + 0.045\}^2) \quad (1)$$

$$K = 7.2 \times 10^{-4} \quad (2)$$

VII. CONSIDERATION OF THE OPERATING MECHANISM OF MONOPOLE WATER ANTENNAS

We discuss the operating mechanism and antenna characteristics of monopole water antennas. As shown in Figure 13, the electrical signal is fed to the electrode pin through the external connector applies an electric field to the water molecules inside the capsule by generating an electric field between the ground on the bottom of the electrode pin and the electrode pin. The water molecule is a protonic polarized molecule with the highest polarization in liquids [29] and can be considered a dipolarized element [27]. When the electrical signal input to the electrode pin is a high-frequency signal, the applied electric field causes the dipole polarization element to move, rotate, and vibrate. The electromagnetic field generated by the movement, rotation, and vibration of the dipolarized elements is applied to the neighboring dipolarized elements, and high-frequency signals are propagated through the water molecules (H₂O) in the capsule. The electromagnetic field generated by this dipole polarizing element (polarized water molecules) is radiated outside the capsule and acts as an antenna.

In addition, depending on the intensity and frequency of the high-frequency signal inside the capsule and the state of the water molecules, the protons and electrons of the polarized molecules are released, drift, and vibrate to generate an electromagnetic field. The formation of hydrated ions such as NaCl and the polymerization of water molecules in the capsule causes collisions and scattering with polarized H₂O molecules, protons, and electrons. Hence it decreases antenna efficiency and increases noise figure. At lower frequencies, it is also affected by the complex permittivity of the capsule enclosure material.

The operating mechanism of the water antenna is expected to be the same even if the monopole antenna part is replaced by a planar or three-dimensional antenna (such as an F-shaped or a helical antenna).

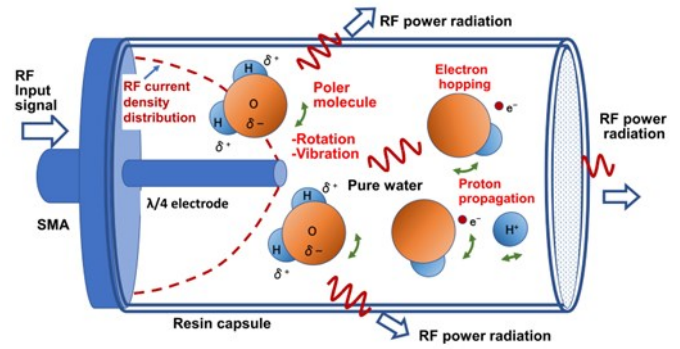


Fig. 13. A working mechanism of monopole water antenna

VIII. CONCLUSION

A 2.4 GHz band monopole water antenna with a monopole electrode and SMA connector, which has the basic structure of an antenna, was designed, fabricated, and mounted in a resin capsule filled with pure water. In the monopole water antenna design, the S-parameter's reflection coefficient S₁₁ and transmission coefficient S₂₁ were investigated using an electromagnetic field simulator AXIEM. The S-parameters were measured using a portable vector network analyzer, and an LNA with 20 dB gain in the 0.1-7 GHz band designed and fabricated with a single SiGe bipolar stage was used to amplify the received signal. A narrowband, directional 2.4 GHz patch antenna was designed and fabricated to compare measurements from a monopole water antenna. The measured and simulated frequency characteristics of the monopole electrode pin length (3-8 mm) and the reflection coefficient S₁₁ are almost in agreement, and an electrode pin length of 8 mm at 2.4 GHz and 4 mm at 3.5 GHz were obtained. The current density distribution, electric field intensity radiation pattern (E_θ, E_φ), and reflection coefficient S₁₁ of the 2.4 GHz patch antenna included a 2.4 GHz fundamental mode (TE₁₀) and a 3.5 GHz higher order mode (TE₀₂), whose polarization directions were 90 degrees different. Two types of monopole water antennas with the same polarization direction but different frequencies (2.4 GHz and 3.5 GHz) were compared. The 2.4 GHz monopole water antenna received only the fundamental mode signals from the patch antenna. By rotating the 3.5 GHz monopole antenna by 90 degrees, the patch antenna's 3.5 GHz higher-order mode signal was received. The S₂₁ values measured for different transmit-receive distances between the transmission and reception of the 2.4 GHz monopole water antenna decreased with the square of the antenna distance, similar to the spatial propagation characteristics of electromagnetic waves. The same results are expected to be obtained by replacing the monopole electrode with a planar or three-dimensional antenna [6, 8, 17, 21, 23]. This research method can be applied to seawater and freshwater wireless communication and biotechnology fields [4, 7, 10, 22].

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