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Theoretical Analysis of Slightly Exposed Sheath Dipole Antenna for Seawater Use

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Abstract In this report, the structure of slightly exposed sheath dipole antenna is studied by theoretical analysis. The transmission line theory is used to discuss the input impedance behavior of the full-sheath and exposed sheath dipole antennas with different conductivity sheaths. The equations of the input impedance in the case of the slightly exposed sheath dipole antenna is obtained. In addition, the modification of the theoretical analysis is performed and a parasitic part is added. The effective approximate equation of the slightly exposed sheath dipole antenna to obtain the input impedance is presented.

Keywords theoretical analysis, sheathed dipole antenna, input impedance

1. Introduction

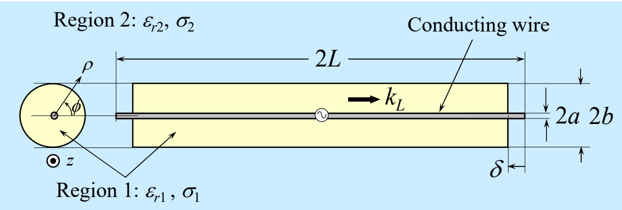
Recently, high quality of seawater wireless communications is required. The acoustic waves and the optical waves have been widely used in the seawater communications because of their low propagation loss characteristics. However, the main problem is that these two kinds of waves can be easily affected by the surrounding environment, such as obstacles under the seawater, resulting in the unstable communication. The electromagnetic waves can be expected for the accurate location estimation of under-seawater divers in the muddy seawater, which make it possible to achieve the reliable communication in the seawater.

The use of electromagnetic waves for the communication in the seawater has been studied. However, the EM waves are attenuated exponentially in the seawater due to the high conductivity, and the attenuation constant is -10.9 dB/m at 100 kHz. In order to protect the RF-circuits and the antenna conductor, a sheath is added to the antenna conductor in the seawater. In the previous study [1, 2], the sheathed dipole antenna was proposed and the transmission factor between transmitting and receiving antennas was evaluated by the full wave numerical analysis. In the case of exposed sheath dipole antenna, the transmission factor is nearly 40 dB higher than the case of full-sheath dipole antenna. When the length of the sheath equals to the half of the length of the antenna, the transmission factor is the largest when the length of the sheath changes. However, the calculation time increases greatly when the distance between the two antennas increases by using numerical full wave analysis. The theoretical method to analyze the full-sheath dipole antennas have been performed [3-8]. The approximated theoretical expression for the input admittance of an insulated antenna immersed in a highly conducting medium have been presented, and the experimental results agree well with the theoretical results. However, in the cases of the exposed sheath dipole antennas, the theoretical equations of the input impedance haven't been derived. The numerical results of the input impedance predicted by the theory haven't been presented.

In this report, the structure of slightly exposed sheath dipole antenna is studied by the theoretical analysis. The input impedance behavior in the cases of full-sheath and exposed sheath dipole antenna is discussed. The results of an approximated expression of the input impedance in the case of a slightly exposed sheath dipole antenna is derived and several numerical results are presented.

2. Structure of exposed sheath dipole in seawater

Figure 1 shows the structure of the slightly exposed sheath dipole antenna in the seawater. a and b represent the radius of the conducting wire and the sheath, respectively. L is the half length of the dipole antenna. δ is the length of the exposed region of the antenna. Region 1 is the sheath of the antenna with the relative permittivity and the conductivity of ε_{r1} and σ_1, respectively. Region 2 is seawater with the relative permittivity and the conductivity of ε_{r2} and σ_2, respectively. k_L is the wave number along the z direction. k_1 and k_2 are the wave numbers of the region 1 and region 2, respectively.



a=2 mm, b=50 mm, L=1 m, ε_{r1}=80, σ_2=4 S/m, ε_{r2}=80, σ_2=0.01 S/m

Figure 1 Structure of exposed sheath dipole antenna in the seawater

3. Theoretical analysis of the sheathed antenna

In this structure, both the relative permittivity inside and outside the sheath are 80 (ε_{r2}=ε_{r2}=80). When the conductivity σ_1 is sufficiently smaller than the conductivity σ_2, the relation $|k_1|<<|k_2|$ can be satisfied. When the outside medium is highly conducting at the operating frequency, the insulated antenna is essentially a coaxial line with a very extensive imperfect outer conductor in which the electromagnetic field is that associated with the volume density of free-charge current through the constitutive relation $J=\sigma E$ [5]. Conventional transmission-line theory is applicable.

As For the TM01 mode electromagnetic components as shown in Figure 2, the equations of electromagnetic field in cylindrical coordinate system is given by [9]

$$H_{\phi 1}=\frac{j\omega\varepsilon_1}{k_{r1}}[A\frac{H_1^{(2)}(k_{r1}r)}{H_1^{(2)}(k_{r1}a)}+B\frac{H_0^{(1)}(k_{r1}r)}{H_0^{(1)}(k_{r1}a)}]e^{j(\omega t-k_L z)} \quad (1)$$

$$E_{z1}=[A\frac{H_0^{(2)}(k_{r1}r)}{H_0^{(2)}(k_{r1}a)}+B\frac{H_0^{(1)}(k_{r1}r)}{H_0^{(1)}(k_{r1}a)}]e^{j(\omega t-k_L z)} \quad (2)$$

$$E_{r1}=\frac{jk}{k_{r1}}[A\frac{H_1^{(2)}(k_{r1}r)}{H_0^{(2)}(k_{r1}a)}+B\frac{H_1^{(1)}(k_{r1}r)}{H_0^{(1)}(k_{r1}a)}]e^{j(\omega t-k_L z)} \quad (3)$$

$$H_{\phi 2}=\frac{j\omega\varepsilon_2}{k_{r2}}C\frac{H_1^{(2)}(k_{r2}r)}{H_0^{(2)}(k_{r2}a)}e^{j(\omega t-k_L z)} \quad (4)$$

$$E_{z2}=C\frac{H_0^{(2)}(k_{r2}r)}{H_0^{(2)}(k_{r2}a)}e^{j(\omega t-k_L z)} \quad (5)$$

$$E_{r2}=\frac{jk}{k_{r2}}C\frac{H_1^{(2)}(k_{r2}r)}{H_0^{(2)}(k_{r2}a)}e^{j(\omega t-k_L z)} \quad (6)$$

$$k_{r1}^2=k_1^2-k_L^2 \quad (7)$$

$$k_{r2}^2=k_2^2-k_L^2 \quad (8)$$

where, $H_0^{(1)}$ and $H_1^{(1)}$ are the 0th- and1st-order of the first kind Hankel functions, respectively. $H_0^{(2)}$ and $H_1^{(2)}$ are the 0th- and1st-order of the second kind Hankel functions. k_{r1}, k_{r2} are wave numbers in radial direction in the region 1 and 2. The wave number along z direction, k_L can be represented by k_{r1} and k_1 or k_{r2} and k_2.

In order to calculate k_L, the boundary condition should be applied. On the surface of the antenna, the electric field in the z direction is 0. On the surface of the sheath, the

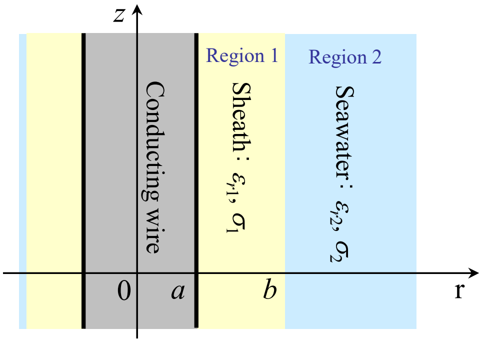


Figure 2 Section of sheathed dipole antenna

electric field in the z direction is continuous, and the magnetic field in the ϕ direction is continuous. The equations of boundary condition are

$$E_{z1}(r=a)=0 \quad (9)$$

$$E_{z1}(r=b)=E_{z2}(r=b) \quad (10)$$

$$H_{\phi 1}(r=b)=H_{\phi 2}(r=b) \quad (11)$$

Substitute the electromagnetic field equations into the boundary conditions, the equation which is contained k_{r1}, k_{r2} can be obtained as follow:

$$k_{r1}\varepsilon_2\frac{H_0^{(2)}(k_{r1}b)H_0^{(1)}(k_{r1}a)-H_0^{(1)}(k_{r1}b)H_0^{(2)}(k_{r1}a)}{H_1^{(2)}(k_{r1}b)H_0^{(1)}(k_{r1}a)-H_1^{(1)}(k_{r1}b)H_0^{(2)}(k_{r1}a)}=$$

$$-k_{r2}\varepsilon_1\frac{H_0^{(2)}(k_{r2}b)}{H_1^{(2)}(k_{r2}b)} \quad (12)$$

By applying the thin wire approximation and $|k_1|<<|k_2|$ to equation above, the wave number k_L along the infinite length sheath is given by

$$k_L=k_1\sqrt{1+\frac{H_0^{(2)}(k_2b)}{k_2bH_1^{(2)}(k_{r2}b)\ln(b/a)}} \quad (13)$$

Since the sheath region of the dipole antenna can be regarded as a transmission line, the model can be considered as a limited loaded transmission line.

When the conducting wire is totally inside the sheath ($\delta<0$), the model can be regarded as Figure 3.

It can be considered that the model consists of two transmission lines of length L, which ends is open. The function of input impedance is given by

$$Z_{in}^{O}=-j2Z_{ca}cotk_L L \quad (14)$$

The associated characteristic impedance of the transmission-line Z_{ca} is given by

$$Z_{ca}=\frac{\zeta_2 k_L}{2\pi k_2}ln\frac{b}{a} \quad (15)$$

where,

$$\zeta_2=\frac{\omega\mu_0}{k_2} \quad (16)$$

The Figure 4 shows the results of the input impedance by theoretical analysis and the FDTD analysis in the case of the full-sheath antenna when the conductivity of the

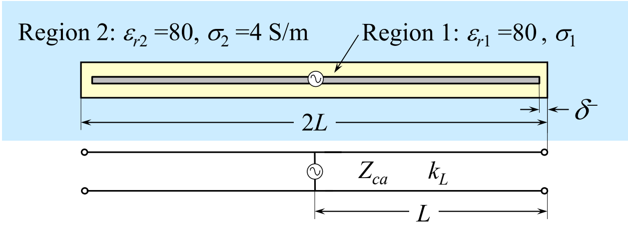
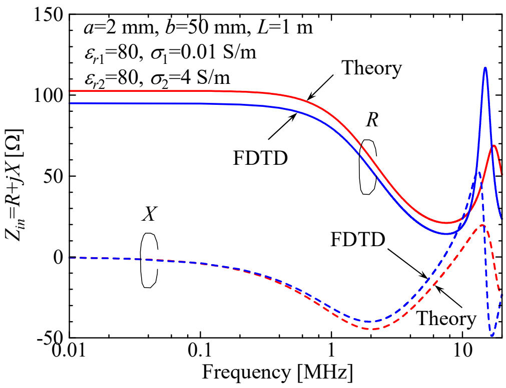
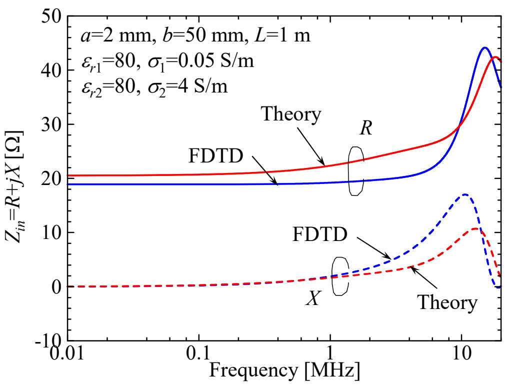


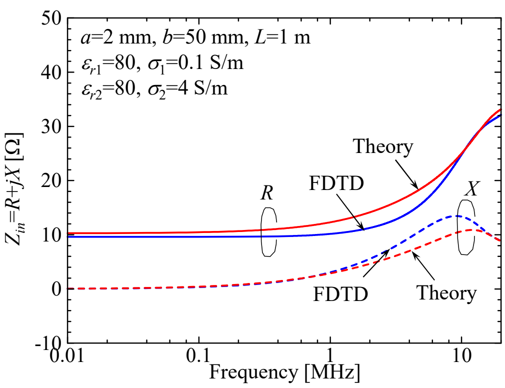
Figure 3 Equivalent model of the full-sheath antenna



(a) σ_1=0.01 S/m



(b) σ_1=0.05 S/m



(c) σ_1=0. 1 S/m

Figure 4 Input impedance (full-sheath)

region 1 changes from 0.01 S/m to 0.1 S/m. These cases are all satisfied with the restriction of $|k_1|<<|k_2|$ and thin wire

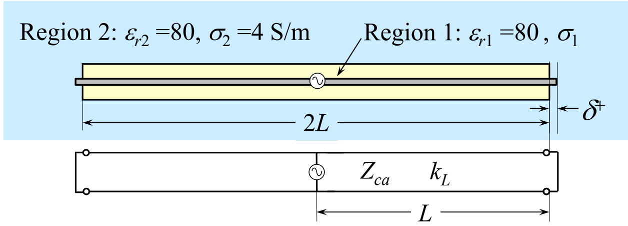
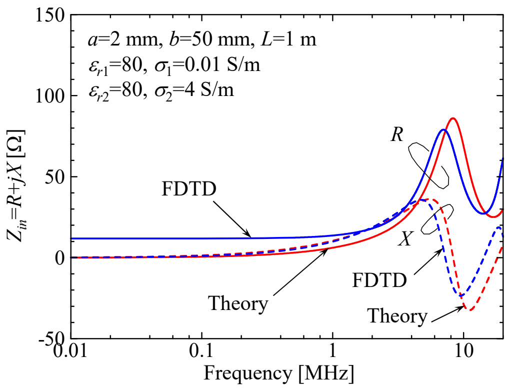
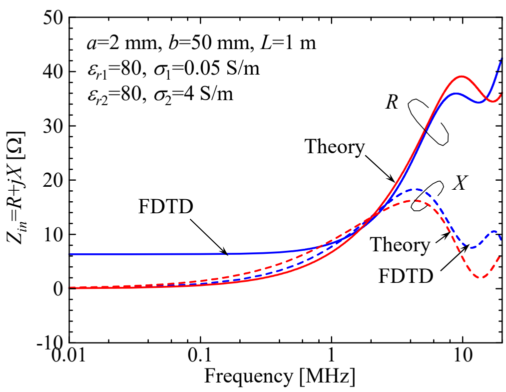


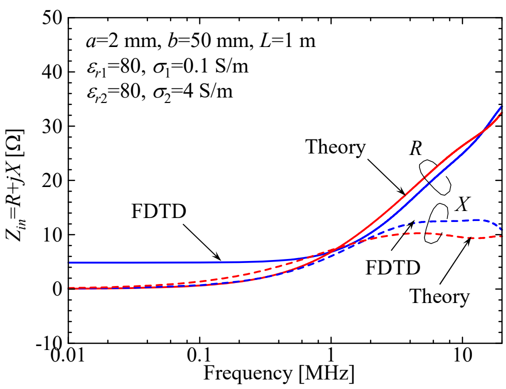
Figure 5 Equivalent model of the slightly exposed sheath antenna



(a) σ_1=0.01 S/m



(b) σ_1=0.05 S/m



(c) σ_1=0. 1 S/m

Figure 6 Input impedance (exposed)

theory. The theoretical results are represented by red line, and FDTD results are represented by blue line. The solid lines represent resistance, while the dashed lines represent reactance. The results of the theory almost agree with the results of the FDTD analysis in all frequency band.

When the conducting wire is slightly exposed to the outside of the sheath ($\delta > 0$), the model can be regarded as Figure 5.

It can be considered that the model consists of two transmission lines of length L, which the ends is shorted by seawater because of its high conductivity. The function of input impedance is given by

$$Z_{in}^{S} = -j2Z_{ca}\tan k_L L \qquad (17)$$

The Figure 6 shows the results of the input impedance by theoretical analysis and the FDTD analysis in the cases of slightly exposed sheath antenna when the conductivity of the region 1 is changed from 0.01 S/m to 0.1 S/m. Although in the low frequency band, the results of theory have some differences with FDTD results, the results of the theory almost agree with the results of the FDTD analysis in high frequency band. In addition, it is shown that the input impedance will change greatly depending on the presence or absence of the slightly exposed structure.

4. Modification of theoretical analysis

In the case of slightly exposed, the disagreement of the theoretical analysis and the FDTD analysis can be seen in the low frequency band. This is because the exposed regions are connected by the seawater, and the conductivity of the seawater is 4 S/m. The conductivity of the seawater is not as large as a conducting wire. Therefore, the end of the transmission-line cannot be considered as merely a shorted circuit. The parasitic part, Z_t, should be added to the end of the transmission-line as shown in Figure 7. In this case, the input impedance of the antenna is given by

$$Z_{in} = 2Z_{ca}\frac{Z_t + jZ_{ca}\tan k_L L}{Z_{ca} + jZ_t \tan k_L L} \qquad (18)$$

If Z_t is considered as infinity, which meaning the end of the transmission-line is open, the equation (14) can be obtained. If Z_t is considered as zero, which meaning the end of the transmission-line is shorted by wire, the equation (17) can be obtained. However, in the case of the exposed sheath antenna, if Z_t is considered as zero, the disagreement of the theoretical analysis and the FDTD analysis will appear in the low frequency band. Therefore, it's necessary to obtain the value of Z_t.

Z_t is produced by the conductive current in seawater between two ends of the exposed antenna. It is difficult to define it in the equations through theoretical analysis.

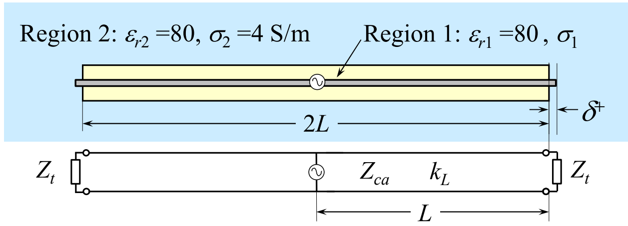


Figure 7 Equivalent model of the slightly exposed sheath antenna with considering Z_t

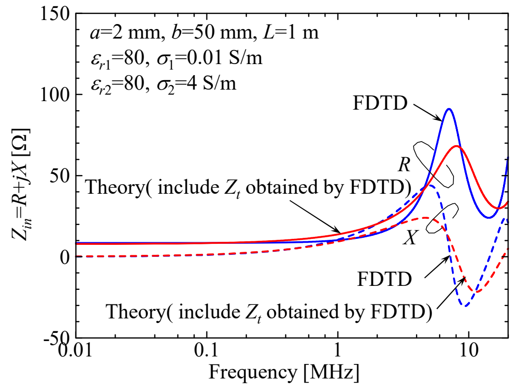


Figure 8 Input impedance (exposed) with considering Z_t

Therefore, the full-wave analysis has been applied to obtain Z_t.

In FDTD analysis, the input impedance seen by the feeding point can be obtain. At the end of the transmission line, the load impedance is Z_t with the characteristic impedance Z_{ca}. Z_t can be obtained as the load impedance of a transmission line by using the equation (18). The value of Z_t obtained by FDTD analysis can be applied to theoretical analysis. The results of theoretical analysis and FDTD analysis are obtained as shown in Figure 8.

As shown in Figure 8, the results of the modified theoretical analysis are in agreement with the results of FDTD analysis in all frequency bands. Although the full wave analysis has been used, it is only used to obtain the parasitic part, Z_t, of the exposed sheath antenna. In addition, it will save time to calculate a model with only one antenna compared to calculating a transmission model with two antennas by using full wave analysis. Furthermore, if the correct value of input impedance is obtained, the received power and transmission characteristics can be obtained through theoretical analysis.

5. Conclusion

In this report, theoretical analysis of the input impedance of the full-sheath and exposed sheath dipole antenna has been performed respectively.

In the case of full-sheath dipole antenna in seawater, the function of input impedance has been derived theoretically. The results show that the theoretical analysis has good agreement with full wave analysis under the effect of different conductivity of the sheath.

In the case of exposed sheath dipole antenna in seawater, firstly the function of input impedance has been derived by using theoretical analysis. However, in the low frequency band, the disagreement between the theoretical analysis and full wave analysis has occurred. Then, the modified theoretical analysis has been performed and a parasitic part, Z_t, has been added. The effective approximate equation has been obtained.

This theoretical method can make the calculation of the input impedance for sheath dipole antenna in seawater in short time easily. Although in the case of exposed sheath antenna in seawater, FDTD analysis is used in the improvement of the theoretical analysis, it takes less time to calculate an antenna than the transmission model. In this way, the value of input impedance of the sheath antenna in seawater can be obtained, which will make it easier to calculate the received power and transmission factors in transmission model by theoretical analysis.

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