Analysis of Wave Reflection from Open-ended Coaxial Lines and Application to the Measurement of Soil Moisture and Salinity

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1. Introduction

Open-ended coaxial lines among others have been used to measure permittivity and soil moisture because of their simplicity [1]. The preciseness of the permittivity measurement, however, depends on the calibration of the dielectric probe. An exact analysis of the open-ended coaxial line is also required for development of a good dielectric probe.

In this paper, at first, the wave reflections from various types of open-ended coaxial lines contacted on the various materials have been analyzed exactly using the finite-difference time domain(FDTD) technique. Due to the coordinate transformation from three-dimensional rectangular structure to two-dimensional cylindrical structure [2], the characteristics of wave reflection was computed very efficiently. Then, an open-ended coaxial line was selected based on the numerical analysis, and calibrated precisely for permittivity measurement. Many samples of soil[3] and saline water[4] were used for calibration of the probe. It was found that the soil moisture and the salinity estimated by the dielectric probe agreed very well with the measurements.

2. FDTD Analysis

The FDTD technique has been widely used for the electromagnetic analysis of complex structures having inhomogeneous media, specially in a wide frequency band.

Figure 1 shows the geometry for the analysis of an open-ended coaxial line. Because of the symmetric structure, two-dimensional problem is formulated using coordinate transformation instead of three-dimensional formulation. A Gaussian-type pulse was excited at A-A' plane and the reflected wave was collected at B-B' plane (Fig. 1) after time-marching. Then, the characteristics of wave reflection (S11) at the frequency domain was obtained using the fast Fourier transform(FFT).

Figure 2 shows a typical computation result compared with a measurement. In this computation, a coaxial cable of a=0.815mm, b=3.175mm, dielectric filling with ε_r=2.03, contacted to air was used. The time step of Δt=0.441ps, the cell size of $\Delta r = \Delta z$=0.20375mm, and the second-order dispersive absorbing boundary condition(ABS) were used in the FDTD simulation. The S11 of the coaxial probe (UT 250-A-SP) measured using the HP8510C network analyzer agreed well with the simulation results in the region of 1< f <20GHz as shown in Fig. 2. Figure 2 also shows that the S11 depends on the frequency, in other words, the wave reflection characteristics depends on the size of the coaxial probe even though the ratio of inner and outer radius (a/b) is fixed. The FDTD method was partially proved by comparison of theoretical reflection coefficients and computation results of an infinite coaxial line with discontinuity of inner dielectric constant.

The wave reflection from a layered medium can be also easily analyzed by the FDTD method. Figure 3 shows an example of the multi-layer computation. As the dielectric constant of the medium decreases, the reflection decreases, and the S11 of the case b (two-layer with ε_{r1}=3,

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$\varepsilon_{r2}=10$) is quite similar with the S11 of case d (single layer with $\varepsilon_r=3$) as shown in Fig. 3.

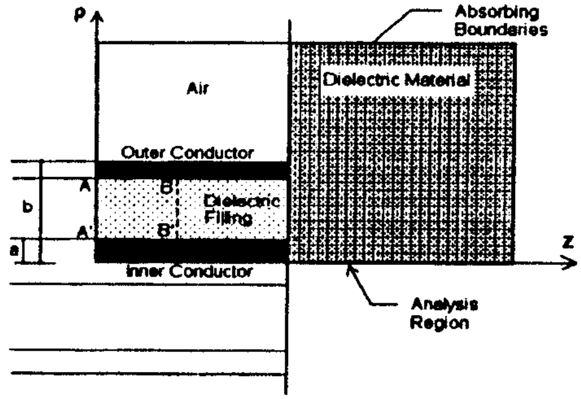


Figure 1. Geometry for the FDTD analysis

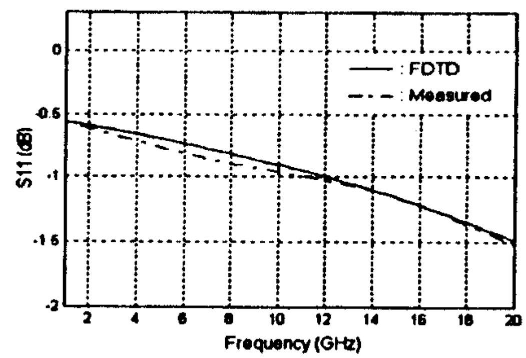


Figure 2. Computed S11 compared with measurements.

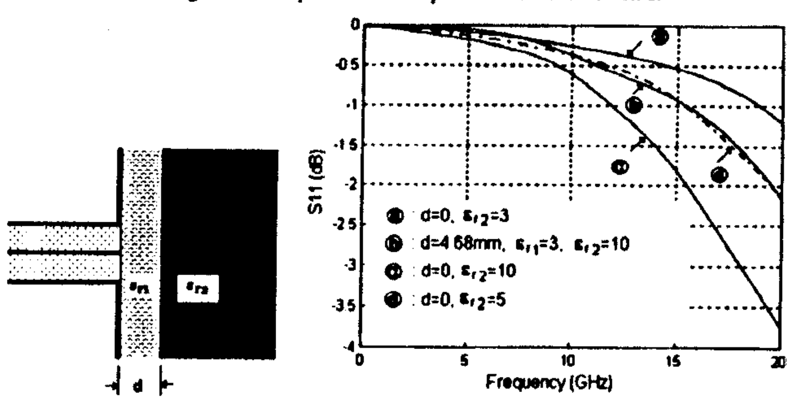


Figure 3. FDTD analysis for a layered medium.

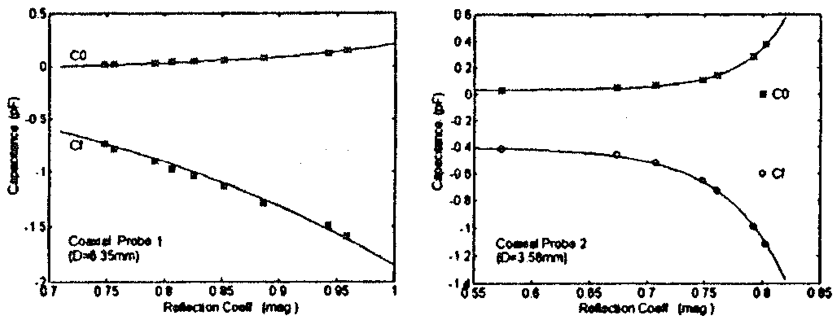
3. Soil Moisture Estimation

A capacitive equivalent circuit model was used for calibration of an open-ended coaxial line.

The circuit model consists of two parallel capacitors, *i.e.*, a capacitance of medium $C = \varepsilon_r C_0$ and a fringing capacitance C_f. Assuming the capacitance C is proportional to the dielectric constant, the values of C_0 and C_f should be found precisely, which are usually functions of the dielectric constant or the reflection coefficient.

Figures 4 show the values of C_0 and C_f obtained by calibration of two different dielectric probes, *i.e.*, relatively large probe (a) and small probe (b), using many samples of soil. The functions of C_0 and C_f for coaxial probe I (Fig. 4a) are given below, which are used for soil moisture detection.

$$C_0 = 0.01\exp\left[|\Gamma| + 0.485\right]^3 - 0.052, \qquad C_f = -0.01\exp\left[|\Gamma| + 2.1\right]^{1.5} + 0.49 \tag{1}$$



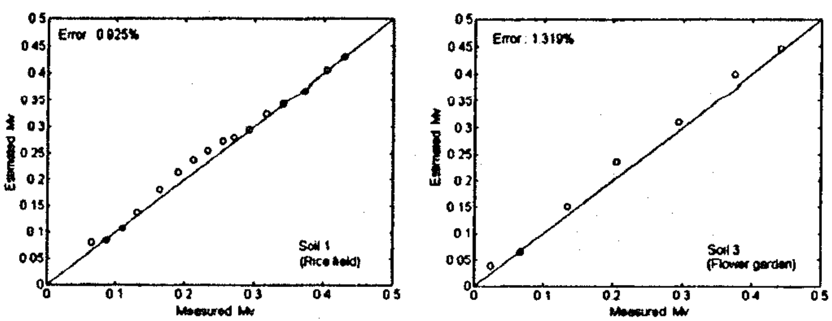
(a) (b)

Figure 4. Equivalent-circuit parameters for open-ended coaxial lines of (a) D=6.35mm and (b) D=3.58mm.

Using the relationship between the complex reflection coefficient and the capacitance, the relative permittivity can be obtained from the reflection coefficient measured by a vector network analyzer as follows.

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' = \frac{1-\Gamma}{jwZ_0C_0(1+\Gamma)} - \frac{C_f}{C_0} \tag{2}$$

Figures 5 show that the soil moisture estimated by using the calibration technique and an empirical model of the dielectric constant[3] agrees very well with the soil moisture measured by an oven-dry technique.

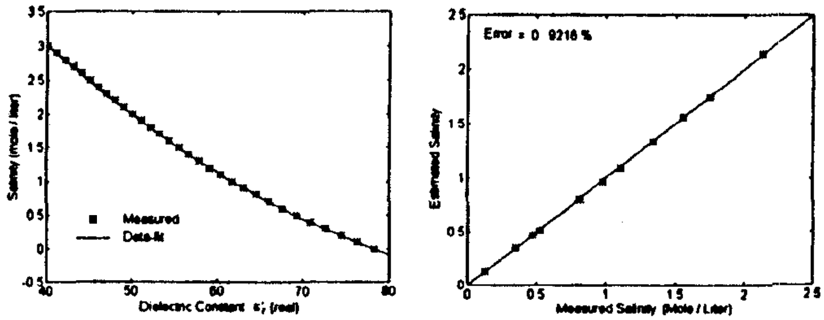


(a) (b)

Figure 5. Comparisons of the estimated and the measured moisture contents for (a) soil sample 1 (sand:silt:clay=21.8:68.6:9.6) and (b) soil sample 2 (sand:silt:clay=91.8:7.3:0.9).

4. Salinity Estimation

The relative permittivity of water or saline water can be obtained by the Debye equation which is function of Cole-Cole parameters[4]. Many samples of saline water were used for calibration of the dielectric probe, and the values of C_0 and C_f obtained by the calibration, which are function of the magnitude and phase of reflection. The relationship between salinity and the real part of the relative permittivity was obtained by experimental results as shown in Fig. 6(a). Then, the salinity could be retrieved by measuring reflection from the open-end of the dielectric probe. The salinity estimated by this calibration technique agrees very well with that measured by weighting as shown in Fig. 6(b).



(a) (b)

Figure 6. Salinity estimation; (a) relation with dielectric constant, (b) comparison with measurements.

5. Conclusions

A technique for retrieving relative permittivity, soil moisture, and salinity from measurement of microwave reflection at an open-ended coaxial line was presented in this paper. The characteristics of wave reflection at various types of the dielectric probes was analyzed exactly and efficiently using the FDTD method. The calibration of the dielectric probe was performed by many samples of soil and saline water. It was found that the soil moisture and salinity estimated with the calibration technique agreed very well with the measured ones.

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