MoM MODELING OF DIPOLE ANTENNA ARRAY WITH OPTICAL MODULATORS IN A BOREHOLE, AND VERIFICATION IN FILED EXPERIMENTS

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1. **Introduction**

Borehole radar is one of the Ground Penetrating Radar (GPR) techniques [1]. In the borehole radar, radar operates in a borehole, and they can detect some targets such as fractures and geological layers. Most conventional borehole radar system uses dipole antennas, which are omnidirectional. Recently, 3-D estimation of target positions becomes important. For the measurement, we proposed dipole antenna array with an optical modulator, which is called an optical electric field sensor [2], [3], as directional borehole radar. Using the modulator, we can transfer received electrical signals of an antenna to optical signals in small space and with no battery. If we use the antennas in a borehole, we could measure the fields with no electrical disturbance, since there is no conducting part. Also it may be easy to increase number of elements. In order to process the array signals to estimate directions of arrival waves, we need to calculate a steering vector (mode vector) of the array theoretically. The optical modulator as well as the dipole antennas should be modeled properly. Also, since cylindrical structures around the antennas, which are caused by existence of a borehole, can seriously influence the electromagnetic fields, such structure must be considered in processing the borehole radar signals.

In this paper, we try modeling the dipole antennas in a borehole by MoM. In section 2, after explanation on the optical modulator, we will model it with a capacitance. Also, we will consider on a fast evaluation method of Green's function including scattered fields caused by existence of a borehole. In section 3, we compare experimental results with numerical results by MoM.

2. **Modeling dipole antenna array with optical modulators in a borehole**

In the dipole antennas with optical modulators, voltage signals of the dipole antennas are transmitted to photo diodes with optical fibers [2], [3]. The light intensity of output signal of the optical modulator corresponds to the electric field induced by voltage of the feeding point. We can measure the received signal of the antenna at a location, which is far from the receiving antenna. In the system, there are no conductor except the antenna element and the small modulator. A commercial electric field sensor such as OEFS1 system, TOKIN Corporation, Japan has been already available.

We specially modified an optical modulator of the OEFS1 so that the modulator could be set in a borehole. Using the modulator, we arranged several dipole antennas on an acrylic pipe as shown in Fig.1. There is no conductor around the antenna, except for the antenna element by itself. Bandwidth of the optical modulator is 0.3MHz-1GHz.

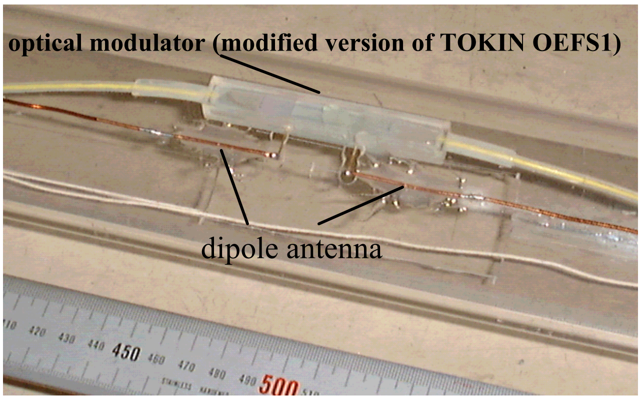


Figure 1 Dipole antenna with a optical modulator

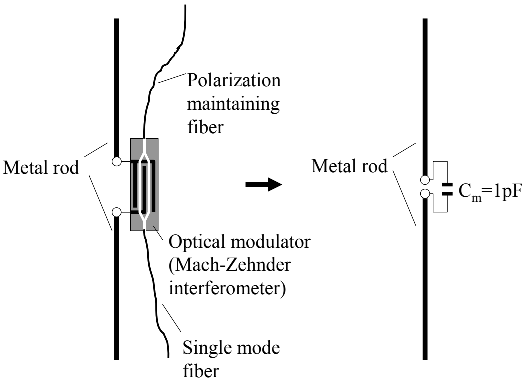
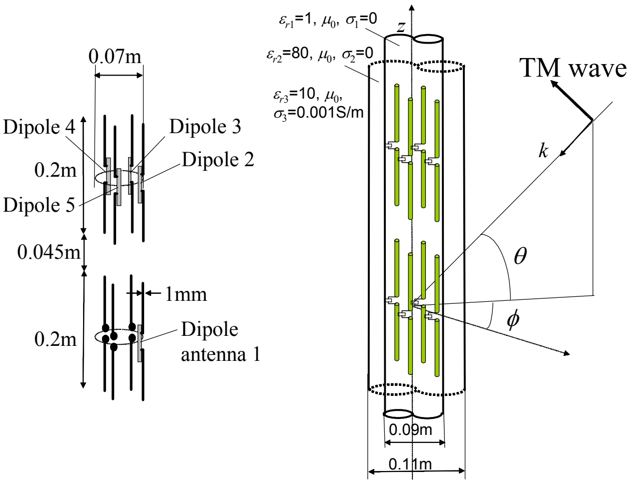


Figure 2 Modeling the optical modulator

Several studies have been made on estimation of equivalent circuit of the optical modulator, when the optical modulator is used for the E-field sensor. For example, Kuwabara et al. suggested that an input impedance of the optical modulator can be represented by linear connection of an inductance and a capacitance [2]. Since length of electrode of the optical modulator is much shorter than operating wavelength in our measurement, the inductance can be ignored. Therefore, in this paper, input impedance of the optical modulator is modeled by only a capacitance as shown in figure 2.



(a) Arrangement of dipole antennas (b) Theoretical model of the antennas

Figure 3 Dipole antenna array with optical modulators

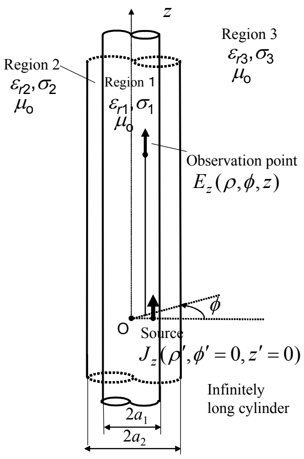


Figure 4 Source in cylindrical medium

3. MoM analysis of dipole antenna array with optical modulators in a borehole

In our radar system, an array of the dipole antennas with optical modulators is set in a borehole. Diameter of a borehole is around 0.1m, and there is fluid such as fresh water, inside a borehole. Generally, the antennas are put in a cylindrical vessel. This condition implies that there are multiple cylindrical layers around the antennas. This structure around the antenna always exits during the borehole radar measurement, and the cylindrical structure can seriously influence the electromagnetic fields [1]. If dipole antennas are in homogeneous medium, we can calculate current on a dipole antenna by MoM. In our case, as we stated, cylindrical inhomogeneity exists around the antennas. Even if such a case, use of Green's functions including influence of the inhomogeneity allows us to calculate for the borehole radar case.

3.1 Fast evaluation of Sommerfeld integrals

In this paper, $\exp(-i\omega t)$ is assumed and suppressed. Consider a vertical point current dipole $\mathbf{J} = \hat{z}Il$ at (ρ', ϕ', z') in an inner layer of cylindrical three layers as shown in figure 4. Referring to [4], the E_{1z} and H_{1z} components of scattered fields at (ρ, ϕ, z) are represented by

$$\begin{bmatrix} E_{1z} \\ H_{1z} \end{bmatrix} = \frac{iIl}{4\pi\omega\varepsilon_1} \sum_{n=-\infty}^{\infty} e^{in\phi} \int_{-\infty}^{\infty} dk_z e^{ik_z z} J_n(k_{1\rho}\rho') J_n(k_{1\rho}\rho) \tilde{\mathbf{R}}_{1,2} \cdot \tilde{\mathbf{D}}'_1 . \qquad (1)$$

Where k_z is z-component of wave number in all the mediums, $\tilde{\mathbf{D}}'_1$ is 2-D vector representing a source, $k_{i\rho} = \sqrt{k_i^2 - k_z^2}$ (i = 1, 2, 3), and k_i (i = 1, 2, 3) are wave numbers of a plane wave in each medium. $\tilde{\mathbf{R}}_{1,2}$ is 2×2 reflection matrix representing all reflection from cylindrical boundaries. This matrix includes influence of multiple reflections in middle layers.

Medium in innermost layer is usually air in borehole radar. In this case, a guided mode does not exist, but leaky modes. Consider relative permittivity: ε_{r1}=1, ε_{r2}=80, ε_{r3}=10, $\sigma_1 = \sigma_2 = 0$, $\sigma_3 = 10^{-3}$ S/m, frequency: 300MHz, $\rho = \rho'$=0.035m, and a_1=0.045m, a_2=0.055m. Contour plot of the integrand of (1) is shown in Figure 5 for z = 0 and n = 1 case. Chew showed that only branch points exits at $k_z = \pm k_N$, where k_N is a wave number of a plane wave in an outermost layer [5]. However, since the equation (1) does not include direct fields from the current source, $\pm k_1$ is also branch points in the equation (1) case. Therefore, there are branch points at k_1=6.29 as well as k_3 = 19.88 + 0.060 in figure 5. Also, we can see that one surface wave pole is around $k_z = 12.5 + 12i$. The term $\exp(ik_z z)$ rapidly oscillates along the path 1 referred as Sommerfeld Integration Path (SIP), when z is large. However, integration along a path 2, which is deformed form SIP without crossing the singular points, is easy, since the term $\exp(ik_z z)$ exponentially decays, if $0 < \mathrm{Im}\,k_z$ [6]. Since possible locations of the surface wave poles are $0 \le \mathrm{Re}\,k_z \le k_{\max}$, where k_{max} is a maximum value of Re k_i (i = 1, 2, 3), it is possible to calculate the integral without tracking the pole location with the integration path 2. Computation time via path 1 with a computer having 1.7GHz Pentium 4 CPU was 307s, while 22s via the path 2. Fast evaluation of the integration can be done with the path 2.

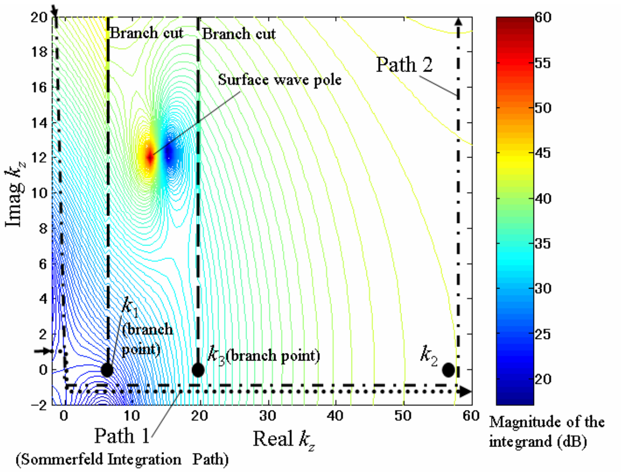


Figure 5 Contour plot of the integrand and integration paths

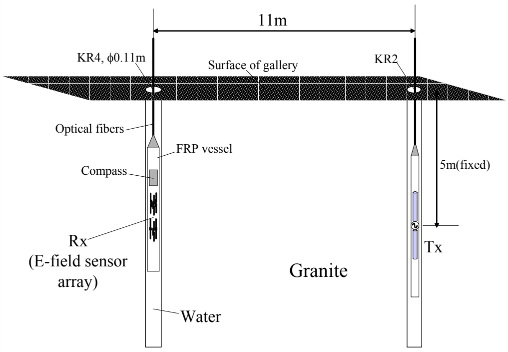


Figure 6 Cross-hole measurement in Kamaishi mine.

3.2 MoM

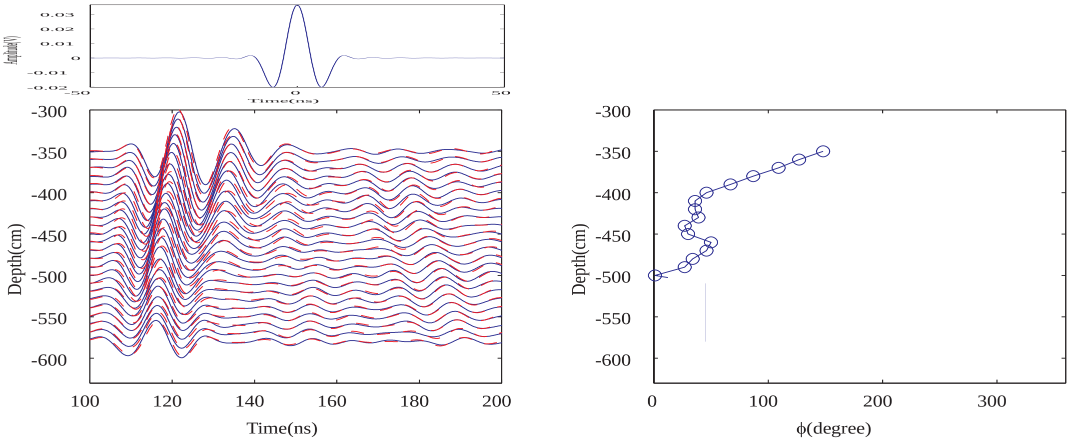
The thin dipole antennas in air can be theoretically modeled by Method of Moment (MoM) using free-space Green's function G_0. If dielectric material exists, we should use Green's function for a space including the dielectric body. When the exact dyadic Green's function G_d is obtained, self and mutual impedance can be evaluated by substituting the free space dyadic Green's function G_0 with the G_d in MoM. In this paper, we utilize Richmond's MoM, which use Galerkin's method and piece-wise sinusoidal functions [7], with the Green's function driven from the equation (1).

4. Field experiments and comparison between experimental and numerical results

Field experiments were carried out in granite in Kamaishi mine, Japan. The dipole antenna array with the optical modulators was packed in a FRP vessel. Also, a compass was set in the vessel to measure positions of the antennas. The dipole antenna array was inserted in a borehole, KR4 shown in figure 6. Since the boreholes are filled with fresh water, the dipole antenna array with the optical modulators can be modeled as shown in figure 3(b). Another dipole antenna as a transmitter was set in a borehole, KR2, which is 11m apart from KR4. Figure 7 shows signals received at the dipole 2 and dipole 4, when the transmitter was fixed at 5m depth in KR2, while the receiving array is scanned in KR4. In the figure, around 120ns, a direct wave from the transmitter arrives. We can see difference of arrival times of the direct wave between the dipole 2 and dipole 4. Difference of amplitude and phase between the two dipoles can be estimated from the measured signals with cross-spectrum analysis [8]. Since the difference corresponds to azimuth directions ϕ of arrival waves, it is important information. The estimated results are shown in figure 8. Also, MoM analysis results, which were numerically calculated as we stated in the previous section, were added in the figures. MoM gives fairly good agreement with the experiments results in lower frequencies than 150MHz. We can find that the MoM results and the radar system are accurate enough for estimation of directions of arrival waves. Disagreement between MoM and experimental results above 150MHz happened because of low coherency, which is caused by low signal-noise ratio.

5. Conclusions

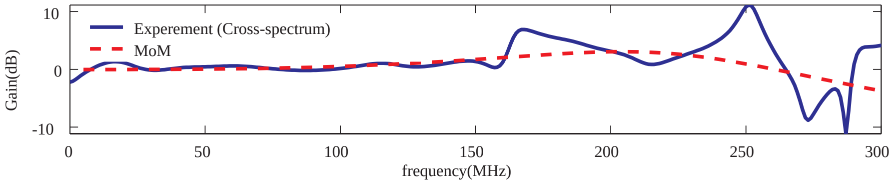
Dipole antenna array with optical modulators for directional borehole radar was modeled with MoM. An optical modulator was modeled by a capacitor, and inhomogeneity caused by a borehole was modeled by multiple dielectric cylindrical layers. To compute Green's functions including scattered fields from a borehole, fast valuation method the Green's functions was considered. For verification of the theoretical model, we did experiments using the dipole antennas with the optical modulators in granite, Kamaishi mine. The MoM results gave agreement with the experimental results enough for direction finding in a borehole.



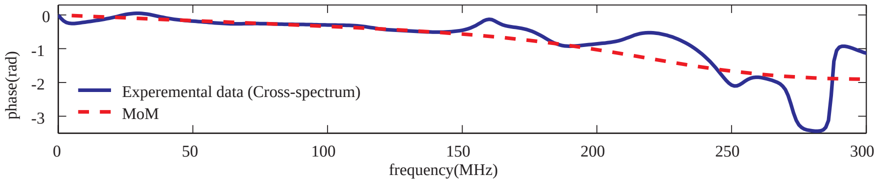
(a) Time domain signals. Solid line:antenna 2, Broken line:antenna 4. The top signal corresponds to a excited pulse at the transmitter.

(b) Azimuth angle ϕ of the antenna 2, which was measured by a compass

Figure 7 Crosshole measurements results. Transmitter fixed at -5m in KR2, and receiver scanned in KR4.



(a) Relative amplitude



(b) Relative phase

Figure 8 Cross spectrum analysis (Blackman-Tukey method).

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References

[1] S.Ebihara, M.Sato, and H.Niitsuma, "Super-resolution of Coherent Targets by a Directional Borehole Radar," IEEE Transactions on Geoscience and Remote Sensing, Vol.38, No.4, Part 1, July, 2000.

[2] N.Kuwabara, K.Tajima, R.Kobayashi, F.Amemiya, "Development and analysis of electrical field using LiNbO3 optical modulator," IEEE Trans. Electromagn. Compat., Vol.34, No.4, pp.391-396, November, 1992.

[3] K. Tajima, R. Kobayashi, N. Kuwabara and M. Tokuda, " Improving design method for sensitivity and frequency response of E-field sensor using a Mach-Zehnder interferometer," IEICE Trans. Electron., vol. E83-C, No.3, pp.347-354, March 2000.

[4] W. C. Chew, Waves and Field in Inhomogeneous Media, IEEE Press, 1995.

[5] W. C. Chew, The singularities of a Fourier-type integral in a multicylindrical layer problem, IEEE Trans. Antenna Propagat., vol. AP-31, pp. 653-655, July 1983.

[6] S. Ebihara and W. C. Chew, "Fast Evaluation of Sommerfeld Integrals for Modeling Dipole Antenna Array in a Borehole," *Proceedings of the 2002 IEICE general conference*, C-1-3, pp.3, Tokyo, Japan, March 27-30, 2002.

[7] J.H.Richmond, and N.H.Gery, "Mutual impedance of Nonplanar-skew sinusoidal dipoles," IEEE Transactions on Antennas and Propagation, vol.AP-23, no.3, pp.412-414, May 1975.

[8] S.M. Kay, Modern spectral estimation, Prentice Hall. 1988.