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DESIGN OF DIPOLE ARRAY ANTENNA USING OPTICAL MODULATORS IN A BOREHOLE

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1. Introduction

Borehole radar is one of the Ground Penetrating Radar (GPR) techniques [1]-[3]. 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 [2]-[3], as directional borehole radar.

Generally, a borehole influences antenna characteristics inside a borehole [1]-[3]. In order to analyze the antenna theoretically, we need to calculate antenna characteristics in consideration of existence of a borehole. We have developed MoM, which utilizes Green's function considering multiple cylindrical boundaries around antennas in [2]-[3]. The MoM modified for the antenna in a borehole might be used to design the antennas. However, we have little knowledge whether the MoM can works to design the antennas in a borehole because of unexpected inhomogenity in subsurface, unlike antennas in air.

In this paper, we consider on designing the dipole antennas using optical modulators in a borehole by MoM. Especially, we will focus on two points to improve the antenna. One is improvement of impedance matching between a dipole antenna and an optical modulator in a borehole. The other is consideration on the antenna length, when the dipole antennas are arranged closely in a borehole. In both the two cases, we will confirm that the modified MoM works to model the dipole antennas in a borehole.

2. MoM Analysis of the dipole array antenna using optical modulator in a borehole

Fig. 1 shows the dipole array antenna using optical modulators for directional borehole radar [3]. 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. The array antenna is arranged in a borehole, whose diameter is usually less than 0.1 m. It should be noted that operating wavelength, which is usually more than 0.3 m in a borehole measurement, is much longer than the space available for the antennas.

We will review the MoM modified for the dipole array antenna using an optical modulator briefly in [2]-[3]. Boreholes are usually filled with fluid. The subsequent invasion of borehole fluid into the rock formation gives rise to an altered zone whose electromagnetic property varies radially away from the borehole. Fig. 2 shows the theoretical model for a dipole antenna in a borehole. The borehole filled with water or air may be approximated by infinitely long multiple dielectric cylinders. In the array type borehole radar, we can think of the several thin dipole antennas as being inside layers as shown in the Figure. We should notice that use of Green's function including the scattered field enables us to analyze the antennas in a borehole by MoM, even when scatters such as the cylindrical boundaries exists near the antenna [2]-[3]. Although evaluation of the Green's function including Sommerfeld integration is expensive, fast evaluation of the Green's function is possible like in [2]. In this paper, the model in Fig. 2 is adopted in all the calculation for dipole antennas in a borehole.

3. Designing the dipole array antenna using optical modulator and a field experiments

Fig. 3 shows a block diagram of the radar system developed for the directional borehole radar. The radar system is based on a network analyzer and step frequency radar. We can set seven dipole antennas in a borehole. Each of the antennas has one optical modulator. Using an RF switch, one of

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the several array signals can be selected to be electrically connected to the input port of the network analyzer. A compass is set near the receiver inside a sonde in order to determine the antenna location in a borehole. Fig. 4 shows experiments, which was conducted in a field experiment site in Shijonawate, Japan. A diameter of the dipole antenna using an optical modulator is 1 mm.

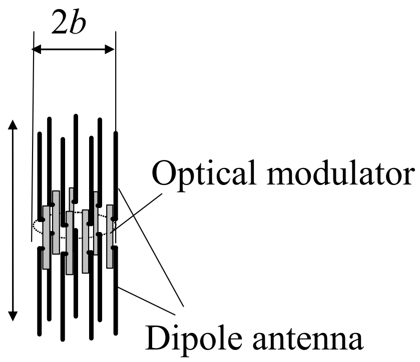


Fig. 1 dipole array antenna using optical modulators.

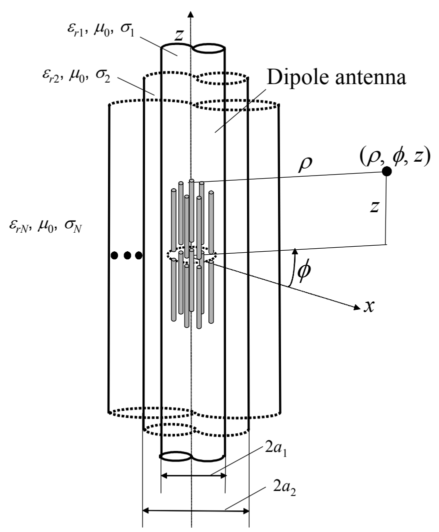


Fig. 2 MoM model of dipole antenna array.

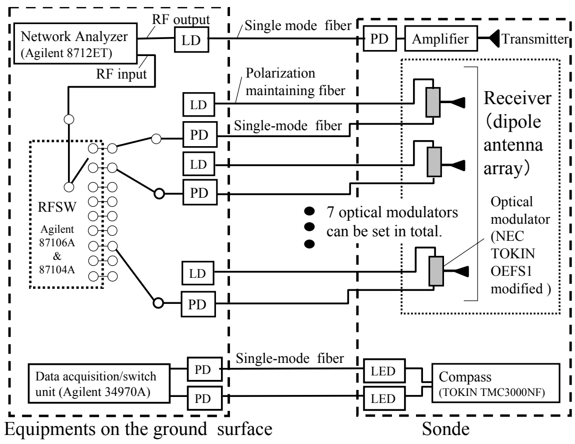


Fig. 3 Radar system block diagram.

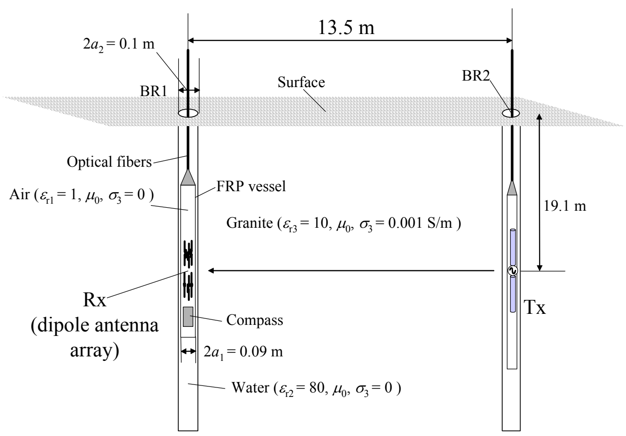


Fig. 4 Experiment to transmit a wave to the array antenna from outside the borehole in Shijonawate.

3.1 **Improvement of impedance matching**

Improvement of impedance matching between the antenna and the optical modulator leads to higher sensitivity of the dipole antenna. Tajima et al. showed that we can improve sensitivity of a dipole antenna with the optical modulators with loading inductance in air [4], since the optical modulator can be modeled as a capacitance in Fig. 5. Even when the dipole antenna with an optical modulator exists in a borehole, we might improve sensitivity of the antenna similarly, although the borehole influences antenna characteristics. In order to consider effect of the inductance loading, we set single dipole antenna with an optical modulator as a receiver in borehole BR1, and a wave was transmitted from another borehole BR2 as in Fig. 4. Fig. 6 shows amplitude of signals received by the inductance loaded dipole antenna using a optical modulator. The received signals in Fig, 6 are normalized by signals received by a dipole antenna with no inductance in the experimental data and MoM results. Therefore amplitude of signals received by the dipole antenna without inductance should be 0 dB at all the frequencies. Two types of coils, which are a solenoid coil and a toroidal coil, were used for inductance 1000 nH. We find that a few decibel is improved around 90 MHz in the experimental data. We should notice that similar phenomena to the experimental data can be seen around 100 MHz in MoM results. This implies that we may utilize the modified MoM to design a dipole antenna for improvement of sensitivity with the inductance, although the antenna impedance is influenced by the borehole.

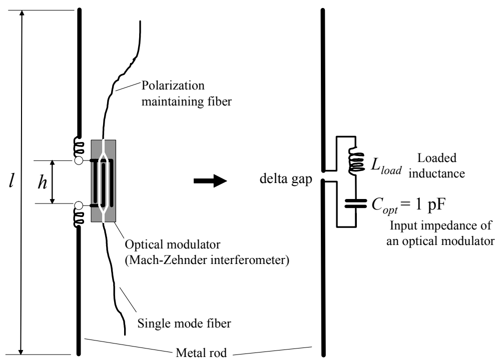


Fig. 5 Inductance loaded dipole antenna

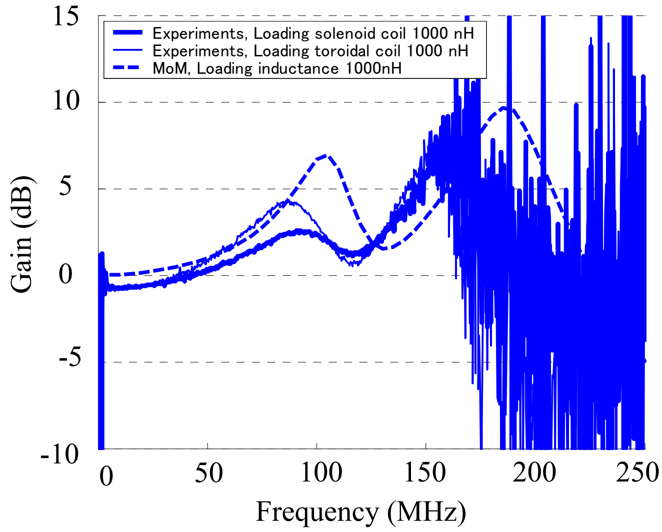


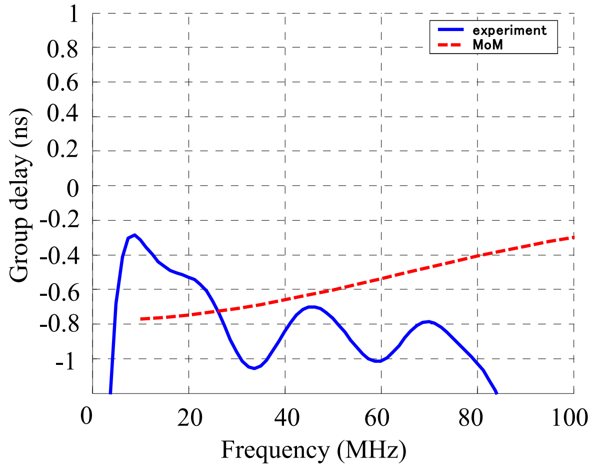
Fig. 6 Relative amplitude. Antenna length l = 1.8 m.

3.2 **Influence of the antenna length on estimation of delay**

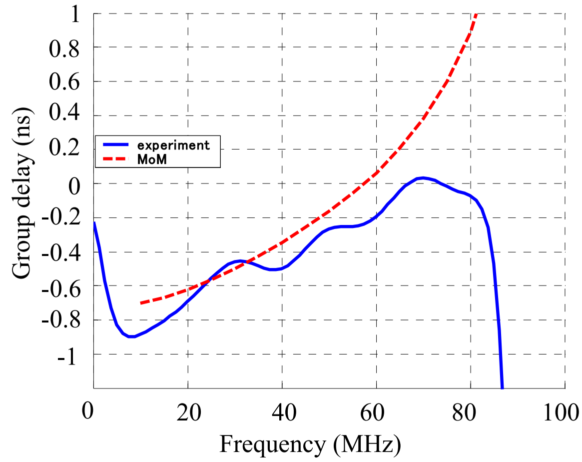
In the dipole array antenna, we estimate direction of arrival (DOA) with time delay among the antenna elements. We prefer much time delay for accurate estimation of DOA. In this section, we will consider relationship between antenna length and estimation of time delay. Fig. 7 shows group delay between two elements of the seven antenna elements arranged on a circular array in a borehole as in Fig. 1. Experiments were done as in Fig. 4. We used two type antennas, whose length l is 0.7 m in one and 1.5 m in the other. The Blackman-Tukey method was utilized to estimate the group delay and the coherence. In MoM, diameter $2b$ = 0.07 in Fig. 1 was used. In both the experimental data and MoM, we find that the shorter antenna has more group delay by about 0.5 ns around 50 MHz, which is the highest frequency of measured data having high coherence. We should notice that using the shorter antenna for the antenna elements enable us to estimate DOA more accurately in the case. Group delay between the antenna elements is zero around 70 MHz in the experimental results and 57 MHz in MoM results, when antenna length l is 1.5 m. In this case, we cannot estimate DOA with the dipole array antenna. It should be noted that the MoM shown in the section 2 describes the group delay occurring between the elements, and we may design to optimize the antenna length theoretically with the MoM, although the borehole affect the antenna characteristics. Note that there is difference between the experimental data and the MoM results because of low coherence of the experimental data above about 60 MHz. Low signal noise ratio may causes the low coherence.

4. Summary

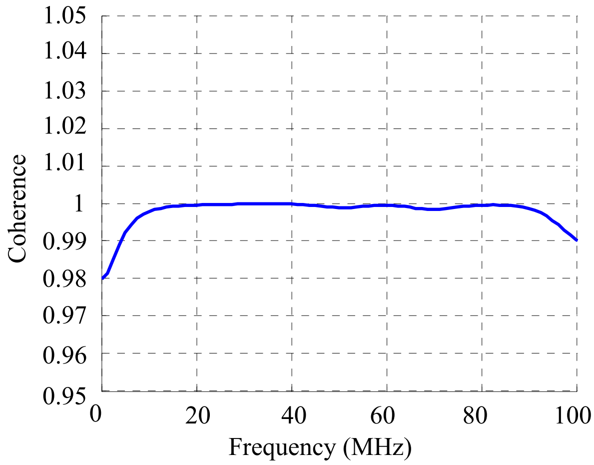
For the first step to optimize the dipole array antenna using optical modulator in a borehole, we investigated in two points. We investigated improvement of impedance matching between the antenna and the optical modulator in a borehole. Also, we confirmed that the antenna length of the dipole array causes group delay among antenna elements in a borehole, which is important for DOA estimation. What is important is that calculated values by the MoM, which is modified for antennas in a borehole, agreed to the experimental data, although there is unexpected inhomogenity in subsurface. This implies that we may optimize the antenna in a borehole by making use of the MoM. Future work should be optimizing the several parameters of the antenna in a borehole with the MoM, and verifying the optimize parameters in a field experiments.



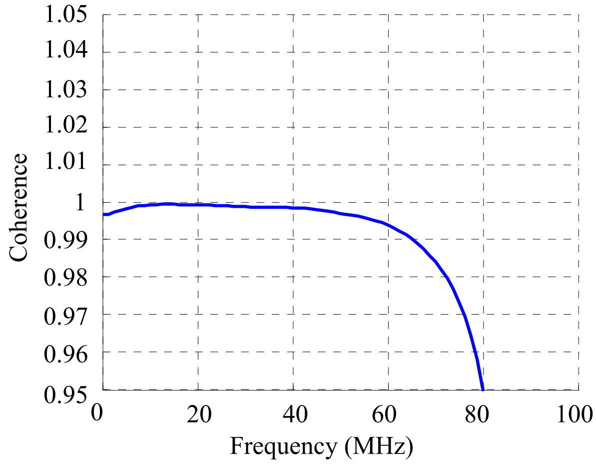
(a) group delay, l = 0.7 m



(b) group delay, l = 1.5 m



(c) coherence, l = 0.7 m



(d) coherence, l = 1.5 m

Fig. 7 Influence of antenna length on group delay and coherence measured between the antenna element which is near the transmitter and the element which is far from the transmitter.

Acknowledgements

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