DEVELOPMENT OF A BOREHOLE RADAR SYSTEM USING AN OPTICAL ELECTRIC FIELD SENSOR

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1.Introduction

Borehole radar is an effective tool to explore deep subsurface structure, and can be used for detection and localization of water pipes, subsurface fractures, and as expected, it also can be applied to the long term monitoring of underground nuclear waste and LNG storage.

Generally, a borehole radar system uses an omni-directional dipole antenna for transmission and reception, which gives us information on the radial distance of a target from a borehole but not the azimuth location of the target. In order to overcome this disadvantage, we have developed an array type receiver using such a passive sensor, as optical electric field sensor. There are many advantages in using the passive sensor. For instance, the optical electric field sensor, which contains small metallic parts and does not need metallic coaxial cable, can minimize the effect of phase distortion of the measured electric field caused by such metallic parts of antenna. This is a quite important feature because accurate phase extraction is necessary for detection of the azimuth of a target. Moreover, the optical electric field sensor, which does not need battery at the receiving point, fits well for the future application of long term subsurface monitoring. The optical electric field sensor has a large potential for many applications which could not be implemented before.

2.Optical electric field sensor

Fig.1 shows a developed optical electric field sensor (NEC TOKIN). Fig.2 shows its inner structure. An optical waveguide, which branches off at each end, is placed on elctro-optic crystals $LiNbO_3$ wafer. Electrodes are attached to one waveguide and the voltage between the electrodes, which is induced by the outer electric field, changes refraction coefficient of the $LiNbO_3$ around the waveguide and causes phase change of wave propagating through the waveguide. As a result, the incident optical wave is modulated due to the interferometric effect and outputs light intensity corresponding to the measured electric field strength.

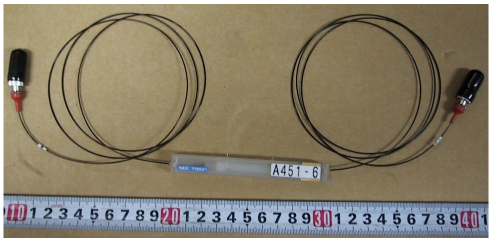

Fig.1 Optical electric field sensor

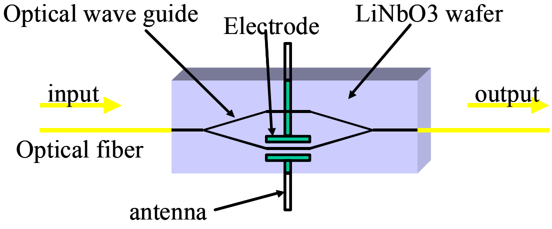

Fig.2 Structure of an optical electric field sensor

The optical electric field sensor has advantages of less distortion in measuring the electric field since it does not need a metallic coaxial cable and it consists of nonmetallic parts except the electrodes and the antenna element. It has wide bandwidth, large dynamic range, and most of all, its small size (1cm x 1cm x 10cm) and there is no need for electric power supply at the receiving point that enables us to install several sensors into limited space of a borehole radar sonde and construct an antenna array. Although the optical electric field sensor itself does not have directivity, by extracting phase differences acquired at the several sensors at the same time, it is possible to find out in which direction a target is located.

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3.Directional borehole radar system

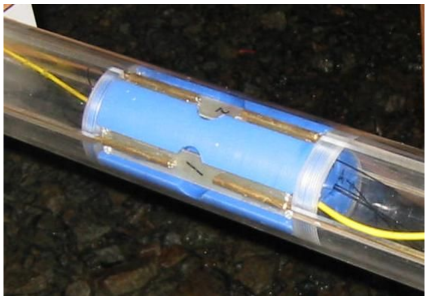
Fig.3 Receiving antenna array of the directional borehole radar

Fig.3 shows configuration of the new borehole radar. The measurement is carried out by a vector network analyzer in the stepped frequency mode. A transmitting antenna is a dipole antenna with the length of 150cm. In order to avoid disturbance of the measured electric field, transmission between the antenna and the vector network analyzer is implemented via an optical link, the E/O converter, a 50m optical fiber and the O/E converter. 4 optical electric field sensors are used as receiving antennas. An optical power supply sends the incident optical signal, divided into 4 at the brunch unit, to each optical electric field sensor through 150m optical fibers. The optical wave modulated by each optical electric field sensor is sent to the optical detector through 150m optical fibers and converted into the electric signal. The signal from each optical electric field sensor is selected by the switch and sent to the analyzer.

Fig.4 shows the receiving antenna we have developed, in which 4 optical electric field sensors are evenly arranged in circumferential direction constituting the antenna array. In order to increase the gain of the optical electric field sensor, a 120cm dipole antenna element is attached to each optical electric field sensor. The receiving antenna array and the transmitting antenna are installed into a waterproof downhole sonde of 90mm in diameter and 4m in total length.

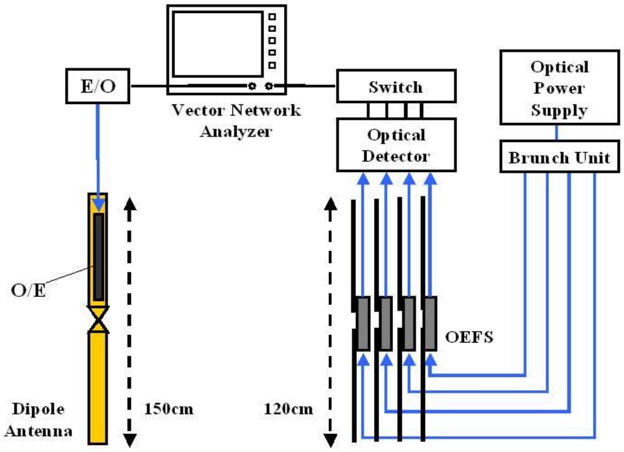

Fig.4 System configuration of the optical electric field sensor borehole radar

4.Single-hole reflection measurement

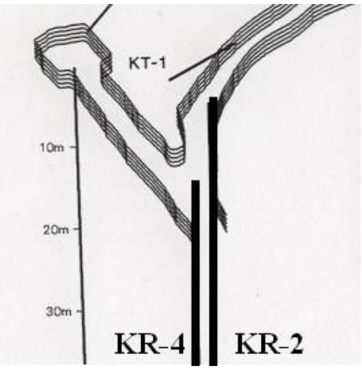

Fig.5 Borehole location in Kamaishi test site

We carried out a single-hole reflection measurement with the new borehole radar system in Kamaishi mine, Japan, to check its performance. Fig.5 shows borehole location in the test site. Before we conducted the single-hole measurement, we acquired a calibration data in the air for compensation of the system time delay. Fig.6 shows its power spectrum when the transmitting antenna and the receiving array antenna are 1m apart each other. It has a resonant frequency at 100MHz. Fig.7 shows a power spectrum received by No.2 optical electric field sensor when the transmitter is put into a borehole KR-2 at 5m depth and receiver is in KR-4 at the same depth. The two boreholes are 11m apart each other. Compared to the power spectrum in the air, the high frequencies are attenuated due to the dispersive medium. As a result, the low frequencies became dominant and the resonant frequency shifted to 60MHz. In the single-hole measurement, we put the borehole radar into the borehole KR-4 at the depth from 2m to 12m while measuring reflection with 20cm interval. Since the optical fiber of No.1 optical electric field sensor did not work in this measurement, we obtained radar images by No.2, No.3 and No.4. Fig.8 shows a power spectrum received by No.2 optical electric field sensor at the depth of 7.8m. Fig.9 shows a radar profile acquired by No.2 optical electric field sensor, which was processed by a 1-140MHz bandpass filter and each trace was normalized by its power to make the image clear.

As it was expected there exists many fractures around the borehole, our new borehole radar system successfully imaged such subsurface structure. We obtained similar results for No.3 in Fig.10 and No.4 in Fig.11.

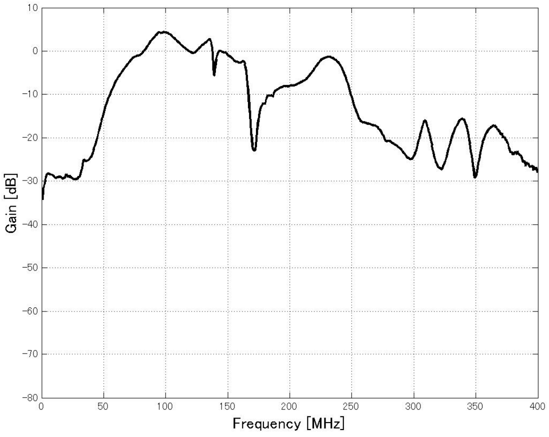

Fig.6 Power spectrum received by No.2 optical electric filed sensor in the air, Antenna separation is 1m

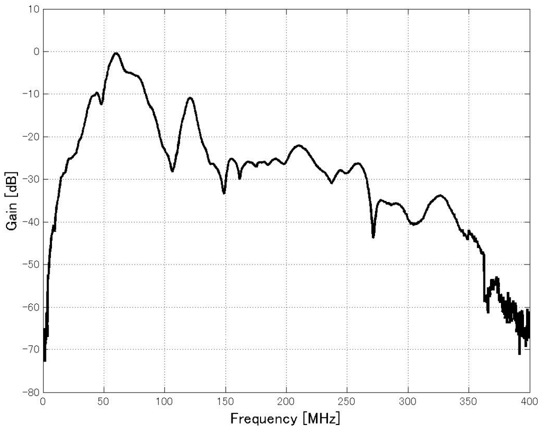

Fig.7 Power spectrum received by No.2 optical electric field sensor, Tx in KR-2 and Rx in KR-4, distance between KR-2 and KR4 is 11m

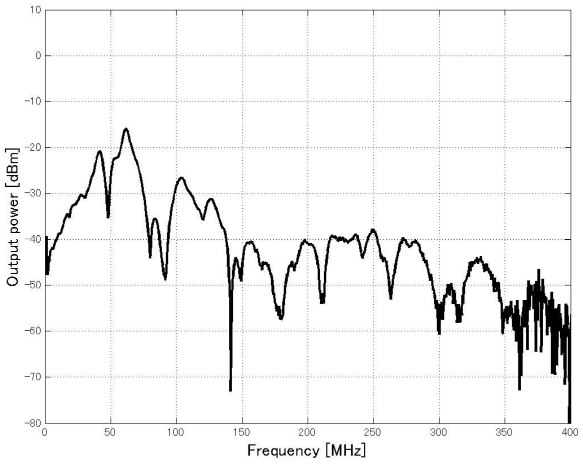

Fig.8 Power spectrum received by No.2 optical electric filed sensor in a single-hole measurement in KR-4, at the depth 7.8m

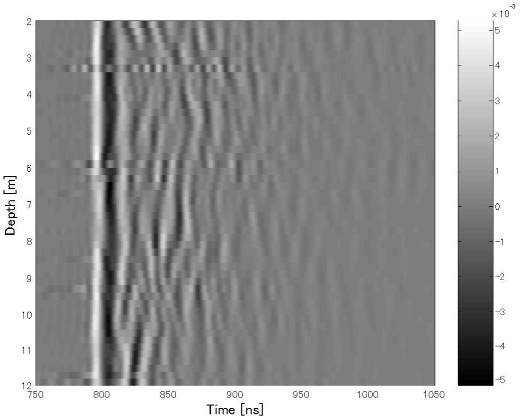

Fig.9 Borehole radar profile by No.2
optical electric filed sensor (KR-4)

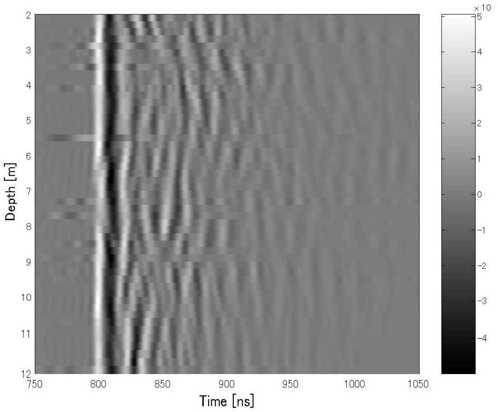

Fig.10 Borehole radar profile by No.3
optical electric field sensor (KR-4)

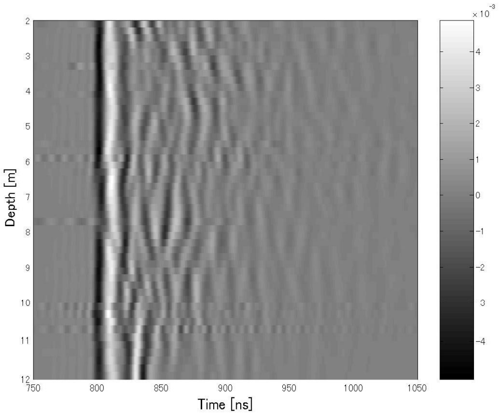

Fig.11 Borehole radar profile by No.4
optical electric field sensor (KR-4)

5.Conclusion

We developed borehole radar system with a receiver based on passive, optical electric field sensor, and verified that it can be used for borehole measurement. Moreover, the biggest advantage of the optical electric field sensor, namely its compact size, allowed construction of a borehole receiving array. In future work, we will discuss extraction of the phase difference between the optical electric field sensors for the detection of the target azimuth.

Acknowledgements

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