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FRPM Pipeline Remote Sensing by Microwave Using Radio-over-Pipewall (RoP) and Radio-over-Fiber (RoF) Techniques

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Abstract

We propose a new remote diagnostic technique using microwave time-domain response and Radio-over-fiber (RoF) technology to efficiently diagnose underground Fiberglass-Reinforced Plastic Mortar (FRPM) pipelines in a non-destructive and non-excavation scheme.

We focused on the "Radio-over-Pipewall (RoP)" characteristics, in which microwaves propagate along the FRPM pipe wall and converge inside the cylindrical dielectric wall (FRPM) as guided modes, when the FRPM is buried underground to compose three layers of soil/FRPM/air. We demonstrate that this characteristic can be used to identify defects and foreign objects on or in the walls of the pipeline. In this study, we attempted to use a RoF link with a DFB laser, silica optical fiber, and photodiode to develop more advanced RoP-based diagnostic technique. Experimental results demonstrated that remote measurement is possible with the measurement equipment required for diagnosis installed at a distance (~km) from the pipe to be inspected, such as on the ground.

1 Introduction

Fiberglass-reinforced plastic mortar (FRPM) has many excellent characteristics such as mechanical robustness, corrosion resistance, water tightness, and workability compared to concrete or cast iron pipes. For this reason, FRPM is widely used in underground pipelines for various applications, including agricultural water pipes [1]. However, in rare cases, foreign objects such as boulders might be left at the bottom of the pipes accidentally. Especially in agricultural water pipelines that use high-pressure water, stress concentrates in the area where a foreign object is in contact with the pipe wall, causing failure [2]. Therefore, there is a need for a technology to efficiently diagnose underground FRPM pipelines non-destructively and without excavation in order to remove these foreign materials.

Therefore, we focused on the interesting characteristics that FRPM is a relatively low-loss dielectric material (dielectric constant ε_r~10, dielectric loss tanδ~0.01) for the microwave (1-10 GHz) frequency range. When the FRPM pipe is surrounded by soil (ε_r~4) and air (ε_r~1) inside, a cylindrical dielectric waveguide is formed and microwave energy is confined to the FRPM pipe wall and its vicinity during propagation [3]-[5]. This unique property is named as 'Radio-over-Pipewall (RoP)'. We have demonstrated that this RoP property allows us to identify defect and foreign object in the FRPM pipe by using their microwave reflection and scattering [6],[7].

In our previous diagnostic methods ([6],[7]), it was necessary to move the measurement equipment or return to the ground each time the inspection location was changed. In order to construct a more efficient and advanced inspection method, we considered that a RoF link using a DFB laser, silica optical fiber, and photodiode is effective. By converting microwave signals into optical signals and using silica optical fibers, remote measurement and diagnosis from the ground can be performed.

In this report, we outline our proposed remote inspection and diagnostic method for FRPM pipelines and describe the diagnostic method using the microwave time-domain response.

2 Nondestructive diagnostic method for FRPM pipelines

A schematic diagram of our proposed diagnostic method for FRPM pipelines is shown in Figure 1. A dipole antenna can be used as the transmitting antenna and an optical electric field (EO) sensor as the receiving antenna to diagnose the FRPM pipeline. A RoF link consisting of a DFB laser and photodiode connected by optical fiber is used between a vector network analyzer (VNA) and a transmitting antenna, to convert microwave signals to optical signals, and to transmit them by optical fiber. This allows measurement equipment such as VNAs to be installed at ground or other locations (~km) away from the pipe to be inspected. The receiving antenna is also connected by optical fiber. This enables complete remote measurement and diagnosis from the ground.

A standard FRPM pipeline is constructing a fixed length FRPM pipe connected successively as shown in Figure 1, and a gap of several millimeters exists at the connection. The transmitting antenna and receiving antenna are to be installed in this gap. A microwave waveguide mode with a frequency of 1 to 9 GHz is excited from the transmitting antenna to propagate microwaves along the FRPM pipe wall. When a foreign object or defect are present on the pipe wall or near its surface, microwave propagation is disturbed, causing reflection and scattering. This causes a decrease in the signal strength of the microwaves arriving at the end face opposite to the transmitting antenna side, compared to a sound pipe without foreign object or defect. Therefore, the presence of a foreign object or defect on the pipe wall or its surface can be detected. It is also possible to identify the position of a defect and foreign object by measuring the time-domain response of reflected and scattered waves.

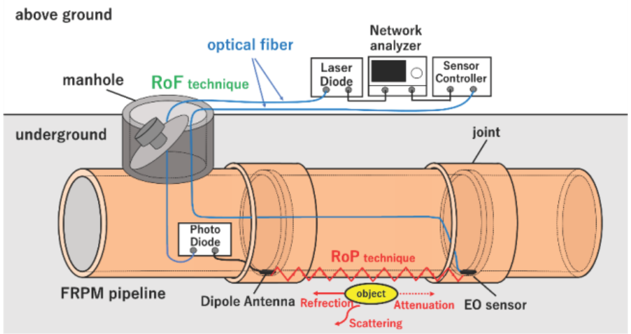


Figure 1. Schematic diagram of nondestructive diagnostic method for FRPM pipelines.

3 Basic experiment using RoP and RoF

To demonstrate that the RoP signal in the FRPM pipeline can be measured using a RoF link, the experiment shown in Figure 2 was conducted. In Figure 2, the signal from the VNA was relayed and transmitted by the RoF link. This signal was input to the dipole antenna, which is the transmitting antenna (Tx) to the FRPM pipe wall. Then, a microwave waveguide mode was excited from the dipole antenna and measured by the EO sensor as the receiving antenna. A FRPM pipe with a length of 1000 mm, an inner diameter 250 mm, and a thickness of 18 mm was used for this experiment. The transmitting antenna (Tx) was placed on the end face of the FRPM pipe, and the receiving sensor was placed on the surface of the pipe wall at a distance of 200 mm from the transmitting antenna (Tx). The experimental results are shown in Figure 3.

From Figure 3, it can be seen that the delay time of the signal is equally shifted by increasing the distance between the transmitting antenna (Tx) and the receiving sensor. From this result, the group velocity was determined to be v=1.56×10^8 m/s, which is consistent with the measured velocity value in the other experiments [4]-[7]. Therefore, it was found that the RoP signal in the FRPM pipeline can be measured even when using the RoF link.

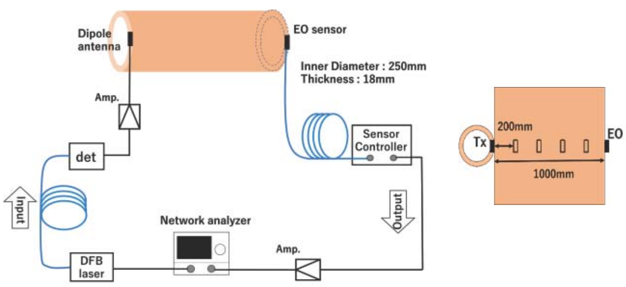


Figure 2. Basic experiment set-up using RoP and RoF.

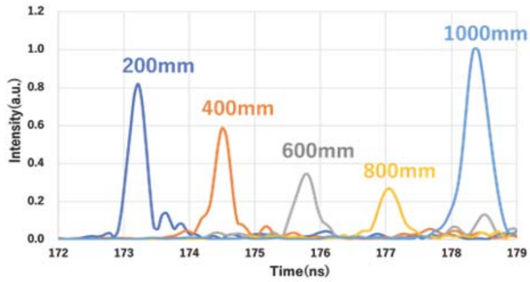


Figure 3. Measured RoP signal in time domain using a RoF link.

4 Foreign object detection experiment using RoP and RoF

In the previous study [7], we found and reported that when a dipole antenna (Tx) and an EO sensor are arranged as shown in Figure 4, microwave signals corresponding to the five paths from (A) to (E) are observed in time domain response: (A) shortest path, (B) clockwise / (C) counterclockwise path reached after one rotation, and (D) clockwise / (E) counterclockwise path reached after two rotations.

Then we conducted a new experiment that a copper foil (circumferential direction: 75 mm, axial direction: 150 mm) was placed on the pipe wall as a foreign object to block only each path from (A) to (E).

The experimental results are shown in Figure 5. From Figure 5, (A) the shortest path component / (B), (C) the component with one rotation / (D), (E) the component with two rotations could be confirmed even with the RoF link in a sound pipe. Figure 5(a) shows that only component (A) is attenuated due to the presence of the foreign object on the path of (A). Figure 5(b) shows that only the (B) and (C) components are attenuated due to the presence of the foreign object on the (B) and (C) paths, respectively. When the foreign objects were present on both paths (B), (C), the signal intensity became about half that of the case when only one of the paths had the foreign object. Figure 5(c) similarly shows that only the (D), (E) components are attenuated due to the presence of foreign object on the respective paths of (D) and (E).

These experimental results indicate that when a foreign object is present on the path, only the component of the corresponding path is attenuated due to reflection and scattering of the microwaves. Therefore, it was found that it is possible to determine whether a foreign object exists or not on the path.

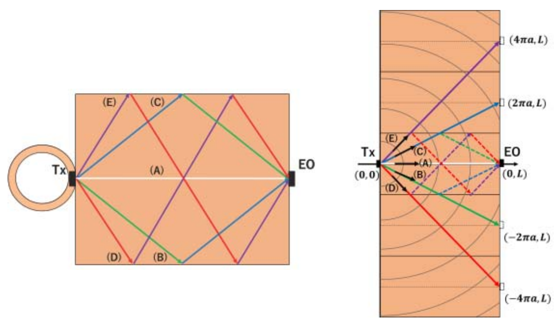


Figure 4. Microwave Propagation Model.

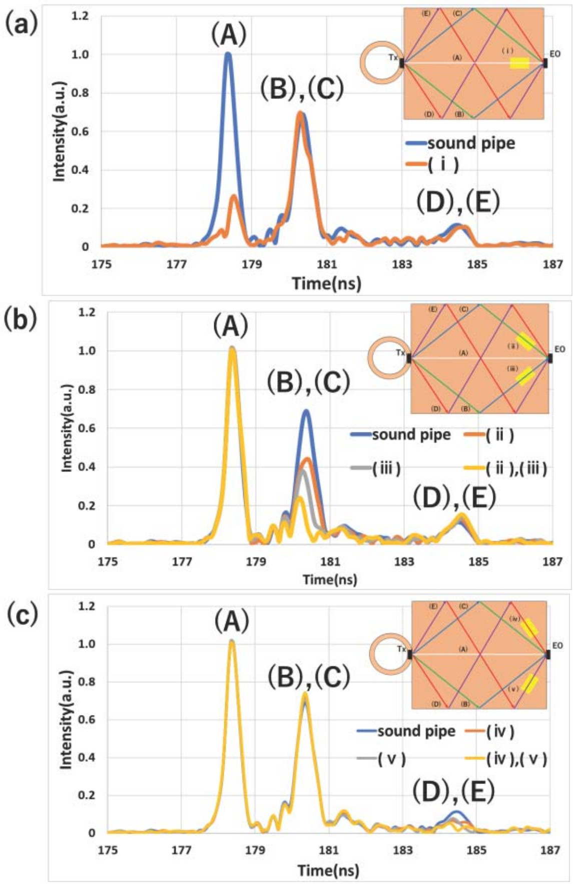


Figure 5. Time domain response of microwave signals. (a) Foreign object installed on path in (A). (b) Foreign objects placed on path (B), (C). (c) Foreign objects placed on paths (D), (E).

5 Imaging experiment for detecting foreign object using reflected waves

From Section 4, it was confirmed that microwaves are reflected and scattered at the position of a foreign object and defect. Using this interesting a characteristic, the experiment shown in Figure 6 was conducted to identify the position of a foreign object or defect. In the experimental system shown in Figure 6, the receiving antenna is placed on the same end face as the transmitting antenna (Tx). The transmitting antenna is fixed, and the position of the receiving antenna is moved along the circumferential direction of the FRPM pipe to repeat the measurement to acquire imaging data using reflected waves. The position of a foreign object or defect is identified by comparing the difference between a sound pipe and a pipe with a foreign object or defect. The *x*-axis and *y*-axis were set for the position of the foreign object and defect, as shown in the development diagram in Figure 6. Figure 7 shows the experimental results.

Figure 7(a) shows that clear two signals appear around 0 ns and 13 ns in the sound pipe case. The 0 ns signal is considered as the component that reaches the EO sensor directly from the transmitting antenna through the air. The 13 ns signal is the component that propagates from the transmitting antenna along the FRPM pipe wall and then is reflected at the opposite end face of the pipe, and then propagates again backward along the wall as the guided mode and reaches the EO sensor. No other signals were observed between these two signals.

Figure 7(b) shows the experimental results when a copper foil (150 mm-long along the *x* axis, 75 mm-long along the *y* axis) was placed as a foreign object at *x*=500mm and *y*=420mm. As in the same with the sound pipe, two signals were observed at times around 0 ns and 13 ns. However, it can be seen that the signal intensity around 13 ns is reduced due to the effect of foreign object. In addition, signals around 6 ns and 8 ns can also be identified. This signal around 6 ns is considered to be a reflection component due to the front edge of the copper foil, and the signal around 8ns is considered to be a reflection component due to the rear edge of the copper foil. The delay times of these signals are almost coincided with the results calculated using the group velocity obtained in Section 4. Therefore, it was found that the position of foreign object is identified along *x*-axis. In addition, the signals around 6 ns and 8 ns are with arc-like patterns in Figure 7(b) and (c), where their center position is around *y*=420mm. Therefore, it is considered that the foreign object is present around *y*=420mm. These results indicate that it is possible to determine the position where a foreign object exists using the RoP and RoF techniques.

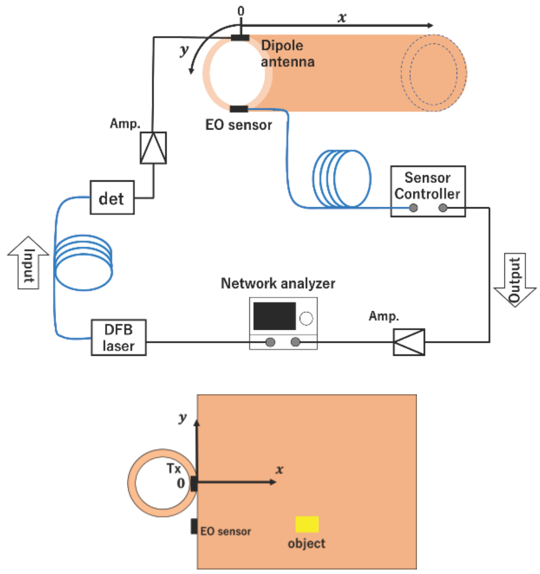
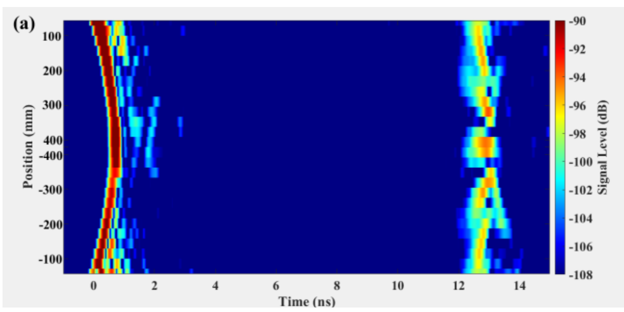


Figure 6. imaging experiment for detecting foreign object.



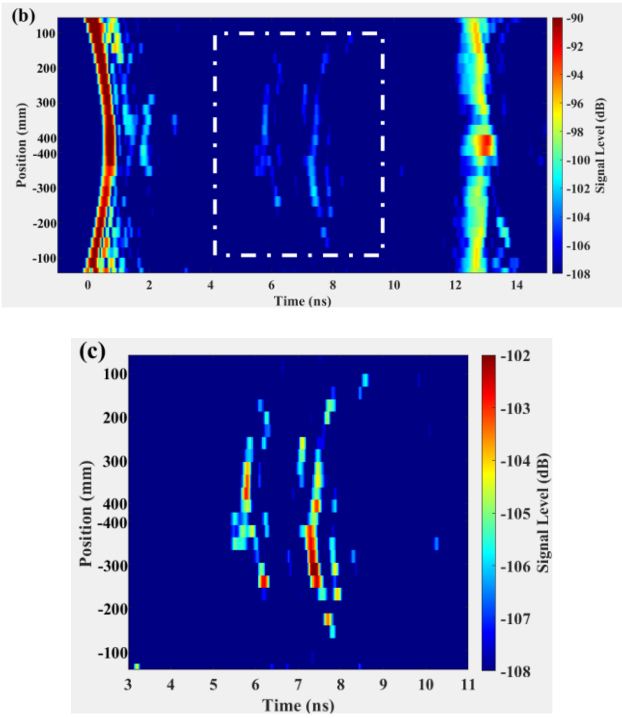


Figure 7. Imaging map of FRPM pipe using microwave time domain response. (a) Sound pipe. (b) Copper foil (x=500mm, y=420mm). (c) Magnified view of the measurement results in (b).

6 Conclusion

The new microwave remote sensing technique for FRPM pipelines using RoP and RoF was reported. It was found that the RoF link, which converts microwave signals into optical signals and transmits them via optical fiber, is rather useful for the remote sensing of FRPM pipelines, and that remote pipeline sensing is applicable with control and electronic measurement equipment at a remote location such as on the ground. We have also succeeded in detecting foreign objects using the proposed system. In the future, we are going to try evaluation experiments in actual underground pipelines.

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