OAM Multiplexing of 5 GHz Band Microwave Signal Propagating Along PVC Pipe Walls for a Buried Pipe Inspection Robot

Akihiko Hirata
Faculty of Engineering, Chiba Institute of Technology, Japan
hirata.akihiko@p.chibakoudai.jp

***Abstract*— This study investigated the orbital angular momentum (OAM) multiplexing of a 5 GHz band microwave signal propagating along PVC pipe walls for a buried pipe inspection robot. The OAM modes that propagate along the PVC pipe wall were observed by electromagnetic simulation. The results showed that the OAM multiplexing system with the microwave signal propagating along the pipe was 2.5 times the system capacity compared to the system with the microwave signal propagating inside the pipe.**

***Keywords*— OAM, microwave, wireless.**

I. Introduction

Owing to the significant problem of aging of buried water and gas pipes, robotic inspection of buried pipes has attracted considerable attention as an efficient method of inspecting narrow buried pipes. However, one of the challenges of robotic buried pipe inspection is communication through the pipes. Using wired communication for signal transmission restricts the robot's movement. Therefore, wireless communication has been considered for buried pipes [1]. However, it is difficult to communicate with a robot moving in a thin pipe using microwave wireless LAN as microwaves propagating through narrow pipes suffer high loss [2-3].

Yoshida *et al.* demonstrated that a relatively low loss transmission of microwave signal can be achieved by using microwave guided-modes, which can propagate along fiberglass reinforced plastic mortar (FRPM) pipe walls [4]. Noma *et al.* demonstrated data transmission using microwave guided-modes propagating along polyvinyl chloride (PVC) pipe wall [5]. However, when a 2.4 GHz or 5 GHz wireless LAN is used for communication, the available bandwidth is approximately tens of MHz; therefore, the transmission speed is limited to approximately tens of hundreds of Mbps. To enhance the communication capacity using microwave guided-modes propagating along pipe wall, the multi-input multi-output (MIMO) technology has been investigated [3]. However, when the length of the pipe for transmission is increased, the spatial correlation between antennas increases, which decreases the capacity of the MIMO system.

Another way to enhance the capacity of communication using microwave guided-modes propagating along pipe wall is orbital angular momentum (OAM) multiplexing [6-7]. OAM is associated with the twisting of the wavefront of a propagating electromagnetic (EM) wave. The wavefront phase of an OAM beam can change from 0 to $2\pi l$ azimuthally, where l is the OAM number [6]. The OAM modes with different OAM numbers are spatially orthogonal, thereby enabling different OAM modes to be multiplexed [7]. Studies [6] and [7] have demonstrated a 32 Gbit/s, 60 GHz wireless transmission and 200 Gbit/s, 28 GHz wireless transmission using OAM multiplexing, respectively.

This study demonstrates the possibility of channel capacity enhancement of communication using 5 GHz band microwave guided-modes propagating along the pipe wall through OAM multiplexing. First, the propagation characteristics of OAM modes along the pipe wall are investigated using a three-dimensional electromagnetic simulator. Then, the capacity of communication along the pipe wall that multiplexes five different OAM modes ($l = -2, -1, 0, +1, +2$) is investigated. The enhancement of system capacity using microwave guided-modes propagating along the pipe wall is achieved by using OAM multiplexing.

II. Propagation of OAM Modes Along Pipe Wall

The propagation characteristics of the OAM modes along the pipe wall were investigated by using the three-dimensional electromagnetic simulator based on the finite element method (Ansys HFSS). Figure 1 shows the simulation model. The inner and outer diameters of the PVC pipe were 125 and 140 mm, respectively. The length of the PVC pipes were 1 m, 2 m, 4 m, and 8 m. The relative permittivity and loss tangent of PVC were 2.7 and 0.007, respectively. For the simulation of OAM mode propagation (Model A), eight transmitter antennas (Tx_1-Tx_8) were installed on one end of the pipe wall at 45° intervals, and eight receiver antennas (Rx_1-Rx_8) were installed on the other end of the pipe. The antennas used were dipole antennas for the 5 GHz band. The length, width, and thickness of the dipole antennas were 26.2 mm, 3.0 mm, and 0.2 mm, respectively.

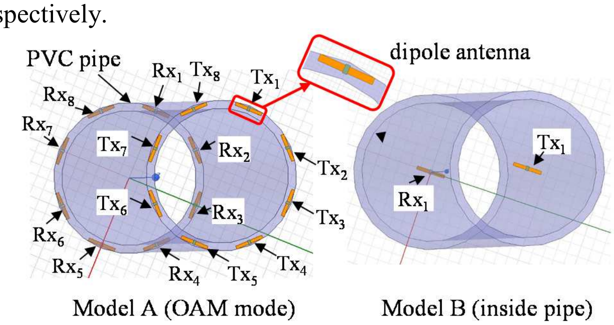

Fig. 1. Simulation model of the OAM mode propagation (Model A) and that of the propagation inside the pipe (Model B).

Figure 2 shows the transmission loss of microwave guided-modes propagating along a 1 m long PVC pipe (Model A). Rx_i-Tx_j indicates the S parameter from Tx_j to Rx_i in Model A. The transmission loss from Tx_1 to Rx_1 was approximately

18.3 dB at 5.0 GHz. Rx_3 and Rx_7, wherein Rx_1 is rotated 90° around the center of the pipe, have almost the same level of received power as Rx_1. The transmission loss from Tx_1 to Rx_5 whose rotation angle from Rx_1 was 180° was approximately 21.8 dB at 5.0 GHz. Conversely, the received power of Rx_2, Rx_4, Rx_6, and Rx_8 whose rotation angles are either 45° or 135° is 12–16 dB lower than that of Rx_1.

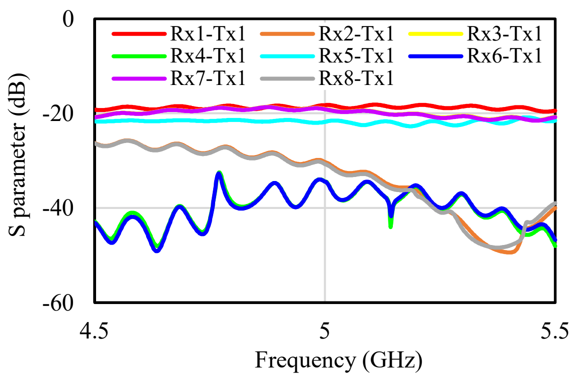

Fig. 2. Simulation results of the S parameter of microwave guided-modes propagating along the 1 m long PVC pipe (Model A).

Figure 3 shows the dependence of the transmission loss of the OAM mode on the transmission distance (Model A). The microwave signal transmitted from the antenna Tx_m in OAM mode l is given by

$$f_{m,l} = \frac{1}{\sqrt{N}} exp\left(j\frac{2\pi l}{N}m\right) \quad (1)$$

where N (=8) is the total number of the transmitter antenna. In three-dimensional electromagnetic simulation, 5 GHz signal is input to Tx_1-Tx_8 with the phase difference expressed in Eq. (1). The received power of Rx_1 was calculated in case the transmission signal of $f_{m,0}$ was applied to Tx_1-Tx_8 (OAM mode l=0). For comparison, the transmission losses were simulated when only Tx_1 and Rx_1 were placed at the center of both ends of the pipe (Model B in Fig. 1). The transmission loss of the OAM mode (l=0) was 22.7 dB, 27.7 dB, and 37.6 dB for transmission distances of 2 m, 4 m, and 8 m, respectively. The transmission loss of Model A are over 20 dB smaller than that of Model B. Figures 4(a) and (b) show the simulation results of the electric field distribution at the 1 m long PVC pipe in case (a) Tx_1 and Rx_1 are installed on the end of the pipe wall (Model A) and (b) Tx_1 and Rx_1 are placed at the center of both ends of the pipe (Model B). When Tx_1 was attached at the cross-section of the pipe wall, the microwave signal was guided by the pipe wall. In case Tx_1 is placed at the center of the end of the pipe, the microwave signal radiated from Tx_1 is not well guided inside the pipe, thereby indicating that the transmission using microwave guided-modes propagating along the pipe wall has lower loss than the propagating microwaves inside the pipe.

Then, it is verified by simulation whether OAM modes can be generated in the microwave signal propagating along the pipe wall by applying a phase difference to the microwave signal input to each transmitting antenna. Figure 5 shows the simulation results of phase distribution in a cross-section 0.85 m away from the end of the pipe, where Tx antennas were installed. The OAM mode number l is -2, -1, 0, +1, and +2. The phase distributions shown in Figs. 5 are spiral, where the l-th mode generates $2\pi l$ phase rotations along the pipe wall. When the mode number is l = 0, a circularly symmetric phase distribution is observed along the pipe wall. When the mode number is $l = \pm 1$, 2π phase rotations are generated along the pipe wall. In modes $+l$ and $-l$, the direction of rotation of the phase is reversed.

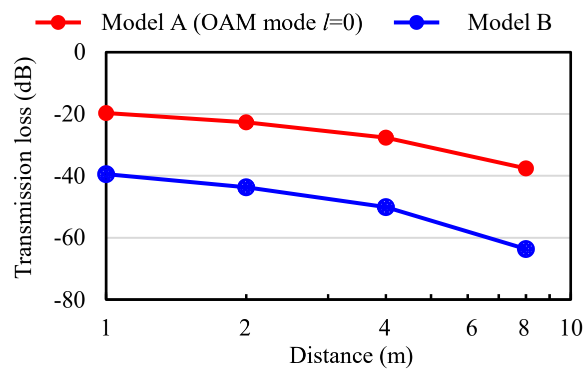

Fig. 3. Simulation results of the transmission loss of the OAM mode propagation (l=0) on the transmission distance (Model A). The simulation results of transmission loss for Model B are also shown.

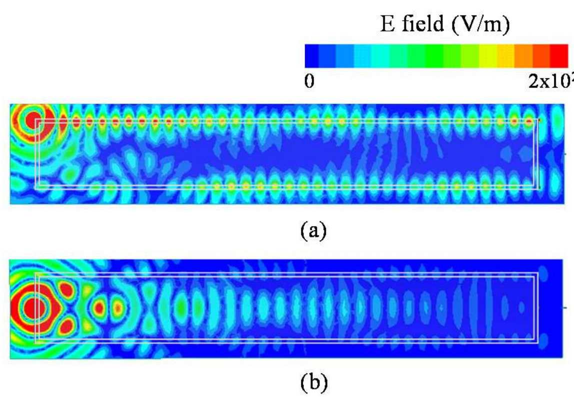

Fig. 4. Simulation results of the electric field distribution at the end of the 1 m long PVC pipe in case (a) Tx_1 and Rx_1 are installed on the end of the pipe wall (Model A) and (b) Tx_1 and Rx_1 are placed at the center of the ends of the pipe (Model B).

Figure 6 shows the simulation results of the electric field distribution at the surface of the 1 m long PVC pipe in case of the OAM mode number l is 0, +1, or +2. At both ends of the pipe, there is coupling with the installed antennas; however, at 0.15 m away from the ends, the microwaves propagate on the pipe wall in the OAM mode. Figure 7 shows the simulation results of electric field vector distribution in a cross-section 0.85 m away from the end of the pipe, where the Tx antennas were installed. Unlike the OAM modes that propagate in free space, the electric field is concentrated around the pipe wall and propagates while rotating along the pipe wall. These results indicate that OAM modes can be generated in the microwave signal that propagates along pipe wall by inputting the signal shown in Eq. (1) to Tx_1-Tx_8.

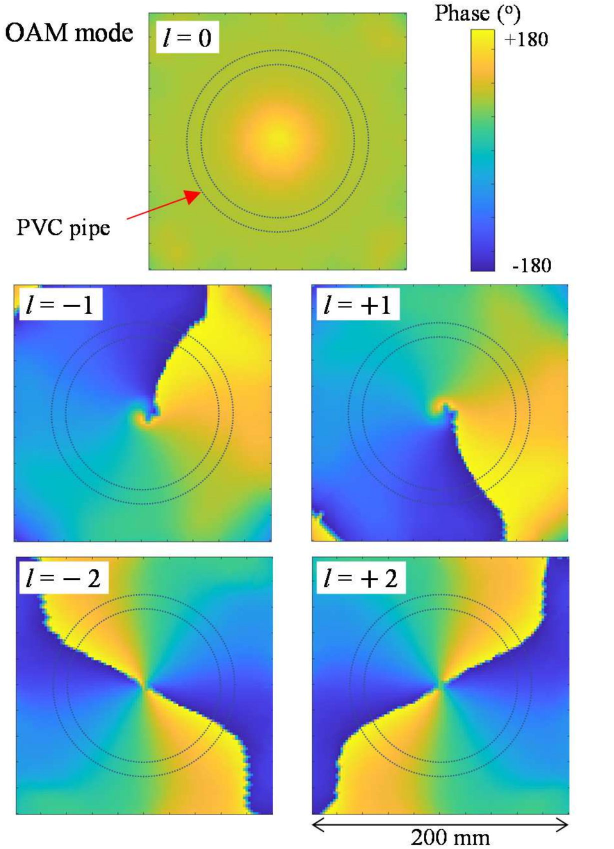

Fig. 5. Simulation results of phase distribution in a cross-section 0.85 m away from the end of the pipe, where the Tx antennas are installed.

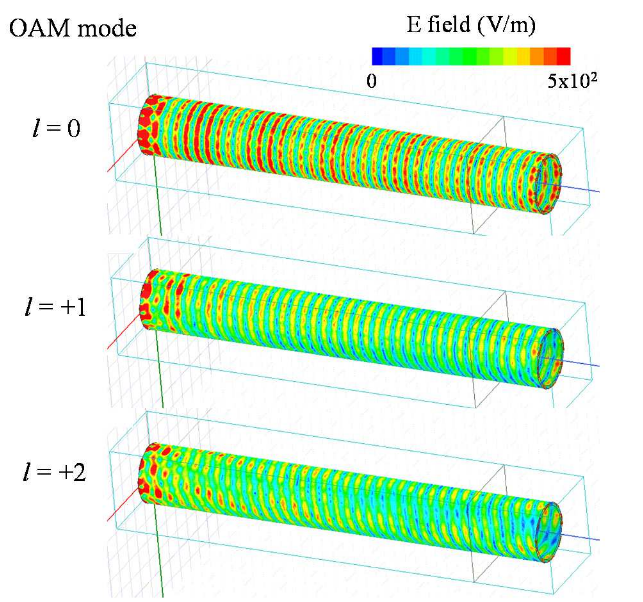

Fig. 6. Simulation results of the electric field distribution at the surface of the 1 m long pipe in case the OAM mode number *l* is 0, +1, and +2.

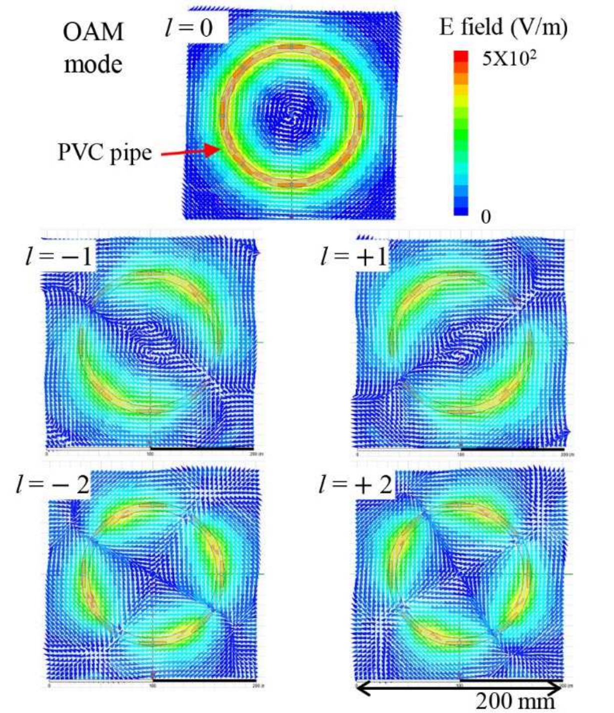

Fig. 7. Simulation results of electric field vector distribution in a cross-section 0.85 m away from the end of the pipe where the Tx antennas are installed.

III. OAM MODE MULTIPLEXING

Section II clarifies that the OAM modes can be generated in the microwave signal that propagates along the pipe wall. Furthermore, this chapter verifies the feasibility of enhancing the capacity of a system using OAM transmission along a pipe wall by multiplexing five OAM modes, (l = -2, -1, 0, +1, +2). The parameter of the OAM system is as follows. The carrier frequency is 5.0 GHz, the channel bandwidth is 20 MHz, and the output power of the transmitter is 5 mW/MHz.

In case OAM modes l = $-L$ to $+L$ are multiplexed, the transmitted signal x_m of the antenna Tx_m is expressed as

$$x_m = \sum_{l=-L}^{+L} s_l \frac{1}{\sqrt{N}} exp\left(j\frac{2\pi l}{N}m\right) \quad (2)$$

where s_l is transmission signal of OAM mode number l. The received signal y_n of Rx_n is expressed as

$$y_n = H_{nm}x_m \quad (3)$$

where H_{nm} is the channel response between Tx_m and Rx_n, which is obtained by the electromagnetic simulation using the simulation model shown in Fig. 1.

When the mode l signal is extracted at the receiver side, each received signal is combined by giving it a phase rotation opposite to that of the transmitted signal. That is, the array output $z_{l,l}$ after synthesis in the case of mode l is expressed as

$$z_{l,l} = \sum_{n=1}^{N} y_n \frac{1}{\sqrt{N}} exp\left(-j\frac{2\pi l}{N}n\right) = s_l \sum_{m=1}^{N} \overline{h_m} \quad (4)$$

The intermodal interference signal $z_{l,l'}$ between modes l and l' is expressed as

$$z_{l,l'} = \sum_{n=1}^{N}\sum_{m=1}^{N} h_{nm} \sum_{l=-L}^{+L} \sum_{l'=-L,l'\neq l}^{+L} \frac{s_{l'}}{N} exp\left(-j\frac{2\pi l n}{N}\right) exp\left(j\frac{2\pi l' m}{N}\right) \quad (5)$$

From these results, the signal-to-interference and noise power ratio (SINR) in mode l γ_l can be expressed as

$$\gamma_l = \frac{E\left[\left|z_{l,l}\right|^2\right]}{E\left[\sum_{l',l'\neq l}\left|z_{l,l'}\right|^2\right] + E[|\tilde{n}_l|^2]} \quad (6)$$

where $\tilde{n}_l$ is the thermal noise in mode l. The system capacity of OAM transmission, C_{sum}, is given by

$$C_{sum} = \sum_{l=-L}^{L} log_2(1+\gamma_l) \quad (7)$$

Figure 8 shows the dependence of SINR γ_l on the OAM mode number as a parameter of the transmission distance. In case the transmission distance is 1 m, the SINR is from 37.5 dB to 43.5 dB. The SINR decreases as the transmission distance increases. The SINR is from 22.1 dB to 28.5 dB when the transmission distance is 8 m. The thermal noise is much smaller than the intermodal interference power; therefore, the decrease in SINR as the transmission distance increases is due to an increase in intermodal interference.

Figure 9 shows the dependence of the system capacity of OAM multiplexing transmission on the transmission distance. For comparison, the system capacity of the wireless transmission system in which only Tx_1 and Rx_1 were placed at the center of both ends of the pipe is shown. In case the transmission distance is 1 m, the capacity of the system is 67.4 bps/Hz, which decreases to 43.4 bps/Hz as the transmission distance becomes 8 m. These values achieve over 2.5 times the capacity over all distances compared to a system that transmits a microwave signal in the pipe with a single pair of dipole antennas, thereby indicating that the capacity of a communication system along the pipe can be enhanced using an OAM multiplexing transmission along pipe wall.

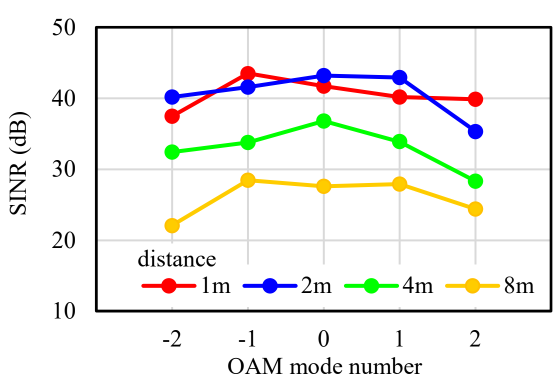

Fig. 8. Dependence of SINR on OAM mode number as a parameter of the transmission distance.

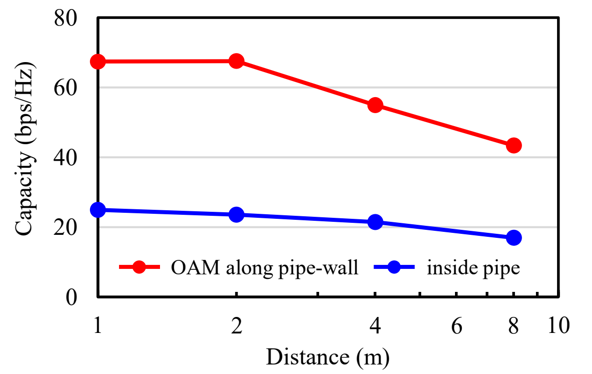

Fig. 9. Dependence of the system capacity of OAM multiplexing transmission on the transmission distance

IV. Conclusion

This study investigated OAM multiplexing transmission along a pipe wall for capacity enhancement of communication for a buried pipe inspection robot. The results showed that OAM modes can be generated in the microwave signal that propagates along the pipe wall by giving a phase rotation to the transmitter antennas. The SINR within the range of 37.5–43.5 dB was obtained when the pipe length was 1 m. The OAM multiplexing system where the microwave signal propagates along the pipe wall achieved 2.5 times the system capacity compared to the system where the microwave signal propagates inside the pipe.

Acknowledgment

Part of this work was supported by MEXT KAKENHI (Grant number JP 21H01328).

References

[1] F. Abate, D. D. Caro, G. D. Leo, A. Pietrosanto and V. Paciello, "Smart meters communication using Gas pipelines as channel: feasibility study," 2019 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), 2019, pp. 1-6, 2019.

[2] V. Doychinov and I. D. Robertson, "Radio Wave Propagation Inside Buried Sewer Pipes for Infrastructure Robotics," 2021 51st European Microwave Conference (EuMC), 2022, pp. 982-985, 2022.

[3] M. Suzuki, K. Fukazawa, A. Hirata, H. Murata, and M. Mizukami, " Study on MIMO Communication using Microwave Guided-Modes Propagating along PVC Pipe Wall," 2022 IEEE International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM2022), POS1.24, 2022.

[4] K. Yoshida, S. Matsukawa, T. Okuda, M. Hazama, S. Kurokawa and H. Murata, "Microwave Time-Domain Analysis for Non-Destructive Inspection of FRPM Pipelines Using Electro-Optic Sensor," 2020 International Topical Meeting on Microwave Photonics (MWP), 2020, pp. 260-263, 2020.

[5] T. Noma, Y. Otagaki, H. Murata, A. Hirata, and M. Mizukami, "Video image transfer using microwave guided-modes propagating along PVC pipe wall," The 2022 IEICE General Conference, C-14-5, 2022. (in Japanese).

[6] Y. Yan et al., "32-Gbit/s 60-GHz millimeter-wave wireless communication using orbital angular momentum and polarization multiplexing," 2016 IEEE International Conference on Communications (ICC), pp. 1-6, 2016.

[7] Y. Yagi, H. Sasaki, T. Yamada and D. Lee, "200 Gbit/s Wireless Transmission Using Dual-Polarized OAM-MIMO Multiplexing on 28 GHz Band," 2019 IEEE Globecom Workshops (GC Wkshps), 2019, pp. 1-4, 2019.