IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 15 November 2023, accepted 17 January 2024, date of publication 26 January 2024, date of current version 9 February 2024.
Digital Object Identifier 10.1109/ACCESS.2024.3358895

RESEARCH ARTICLE

Microstrip-Line Sensor for the Estimation of the Fluid Level Inside a Closed Metal Pipe

K. M. LEE, J. CHO, AND M. KIM
Electrical Engineering Department, Korea University, Seoul 02841, South Korea
Corresponding author: M. Kim (mkim@korea.ac.kr)

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government [Ministry of Science and Information Communication Technology (MSIT)] under Grant 2021R1A2C2009528.

ABSTRACT A transmission-line type fluid-level sensor with a low-cost connected oscillator and detector is proposed. The designed physical sensor, applying microwave technology, is a simple fluid-level sensor that relies on changes in radio frequency (RF) signal attenuation based on the fluid's height. The proposed sensor can offer real-time measurements of fluid height inside a closed metal pipe by inserting a microstrip line into the pipe. The fluid level inside the metal pipe can be accurately determined using a portable multimeter, eliminating the need for the complex calibration process typically associated with conventional RF-based measurement instruments. The prototype fluid-level sensor is designed to operate with a dynamic range of 13.1 dB in a 50-mm diameter metal pipe filled with purified water condition. The sensor accommodates microstrip line with a superstrate and a superstrate-to-substrate thickness ratio of 0.236, suitable for sensing water height. The measurement results show a linear relationship between the insertion loss of the transmission line and fluid height at 3.9 GHz, operating within the maximum error range of 2.4 dB.

INDEX TERMS Fluid-level sensor, microstrip line, transmission-line attenuation, superstrate structure, real-time measurement.

I. INTRODUCTION

Liquid-level sensors are commonly used to measure the height of stationary liquids within opaque containers or in pipes with a constant liquid flow. However, there is a growing demand for sensors capable of measuring the level of fluids with irregular or varying flow height in recent years. The accurate real-time measurement of fluid levels inside pipes is crucial in industrial applications for economic reasons. Additionally, it plays a vital role in supporting essential public infrastructure, such as sewage systems during heavy rainfall events, to ensure public safety. Hence, there is a need for straightforward, precise, and real-time fluid-level sensor to gauge fluid level within closed pipe. Existing liquid-level sensors often require expensive hardware and software. Their measurement system is complicated [1], [2], which is disadvantageous for commercialization and industrialization. For this reason, numerous uncomplicated contact and non-contact sensors have been developed. However, these typical liquid-level sensors face challenges when measuring irregular fluid volumes within pipes, as they are primarily designed to measure stationary liquids in large containers.

Microwave sensors, utilizing guided wave radar or capacitors in direct contact with a liquid, can serve as probes to measure the level of a liquid in a container. In wave-based sensors, the probe, featuring a simple structure, measures the reflected waves [3], and these measurements are minimally affected by the surrounding environment, such as the presence of steam, temperature, or pressure [4]. However, this method relies on time-domain reflectometry (TDR), involving the transmission of a rapid and narrow pulse followed by measuring the reflected signal. It demands sophisticated and costly measurement equipment to achieve accurate time measurements on a nanosecond scale [5]. Moreover, obtaining accurate measurement results becomes challenging when the reflected wave is weak due to the low dielectric constant of the fluid or high dielectric losses.

Capacitor-based level sensors measure liquid level directly by detecting changes in capacitance resulting from the presence of two electrodes submerged in the liquid. This approach

The associate editor coordinating the review of this manuscript and approving it for publication was Roberto C. Ambrosio.

has a simple structure and provides highly sensitive level measurement. However, the accuracy of this sensor decreases by the self-inductance problem and by the viscosity and volatility of the liquid, and along with the presence of slurries and bubbles [6]. Additionally, paramagnetic capacitance and the fringe effect also contribute to a reduction in the accuracy of existing capacitor-based level sensors [7]. To overcome these challenges, measuring the capacitance between the sensor plate placing on the liquid surface and the ceiling of the container can be an alternative. However, this method suffers from low sensitivity problem, and the performance of sensor is easily affected by the air environment [7]. Furthermore, capacitor-based sensors may undergo chemical reactions depending on the type of fluid being measured [8] and they exhibit low sensitivity when measuring liquids with high dielectric losses, such as saline water [9]. Microwave resonator-based level sensors have been proposed [10] as an alternative to guided radar, but they are not compatible with closed metal pipes [9]. Contact-type liquid-level sensors have been developed to detect pressure varying with liquid height by utilizing the elastic modulus of optical fibers floating on the liquid's surface. However, this sensor is not suitable for measuring fluids with limited sensitivity [11] and for real-time measurement of fluids under varying pressures. Although a liquid-level sensor based on the refractive index of an optical fiber has been developed, this approach also suffers from limited sensitivity [12]. Moreover, this type of sensor is affected by temperature [13], and often requires specialized optical fiber tips or external parts, increasing the complexity and cost [14], [15].

Pressure-based and reflector-type liquid-level sensors are commonly used to measure the levels of static liquids within containers. These non-contact type level sensors offer the advantage of a longer lifespan compared to contact-type sensors, but the cost of the sensing equipment is high, and the sensing operation time is long [16]. Additionally, they are not suitable for real-time measurement of the level of a fluid flowing through a pipe due to the environmental variation. It is also challenging to measure pressure in such a pipe structure. The reflector-type sensors utilizing acoustic or ultrasonic waves, microwaves, and lasers are highly susceptible to interference from the liquid environment. Additionally, ultrasonic sensors may experience measurement errors due to the effects of surface bubbles, and the signal-to-noise ratio of optical sensors, such as lasers, may be negatively affected by atmospheric conditions such as dust in the empty space within a pipe [17]. Acoustic sensors are also vulnerable to external noise, such as vibration of the instrument and interference noise caused by external acoustic disturbances, leading to potential measurement errors. To address these problems, a microwave wireless radar-based sensor has been proposed. However, microwave radar-based sensors are not well-suited for fluid measurement due to their intrusive structure and the potential for accuracy reduction caused by possible distortion in the progressing mode [18].

In this paper, a fluid-level sensor capable of measuring the level of a fluid inside a closed pipe using a transmission line is proposed. Typically, sensors utilized to measure the state of a substance in industrial settings employ non-contact methods. This type of sensor is widely adopted due to its non-destructive characteristics and ease in satisfying optimal measurement conditions for stationary objects. However, these sensors often necessitate complex technologies and equipment, and their accuracy may be compromised when applied to moving targets. In recent research, there has been an increasing demand for simple sensors, leading to the utilization of simple transmission lines to measure material properties based on insertion loss [19] and return loss [20]. The transmission line can also be implemented as an LC-resonator through printed circuit board (PCB) design. It can be used as a transmission line LC resonator sensor by taking advantage of the change in performance when the test material contacts the resonator. There are also research cases on sensors designed with a split-ring resonator using a transmission line, showing various possibilities for a transmission line sensor.

Recent studies have also measured water levels using a 200 MHz microstrip coupler [21]. However, this approach is susceptible to dielectric loss, resulting in limited transmission performance of up to –10 dB. Predictions of water levels can only be made at very specific frequencies due to resonance periodicity. Furthermore, it has a limited dynamic range, making it challenging to accurately measure liquid levels. The fluid-level sensor presented in this paper utilizes a PCB transmission line, eliminating coupling loss or periodicity. The insertion loss increases solely with rising frequencies. Therefore, measurements can be obtained using simple equipment, and fluid levels can be directly converted based on the insertion loss of the materials employed. Since this method relies on insertion loss, the designed level sensor is minimally affected by other measurement condition, such as movement or flowing condition.

II. FLUID-LEVEL SENSOR MODELING

The proposed fluid-level sensor utilizes a uniform microstrip transmission line. As depicted in Fig. 1 (a), the transmission line is inserted into a metal pipe through which a liquid flows, and the fluid level is measured based on the insertion loss. Simple and low-cost SMA oscillator and power detector modules are connected to either end of the transmission line. Fig. 1 (b) provides a side view of the sensor connected to a metal pipe. When DC bias is applied to the oscillator, it generates an RF signal that flows into the microstrip line. The power detector, connected at the end of sensor, converts the RF signal to a DC voltage output dependent on the height of the fluid. The uniform microstrip line used in the sensor employs a structure where the superstrate covers the metal line. The superstrate ensures the separation of the fluid from the line to prevent chemical reactions between the metal line and the fluid. An image of an actual fluid-level sensor prototype is presented in Fig. 1 (c). In Fig. 1 (c), the uniform microstrip line is installed inside a closed opaque metal pipe, and the voltage output from the power detector is measured using an inexpensive multimeter (costing less than US$400).

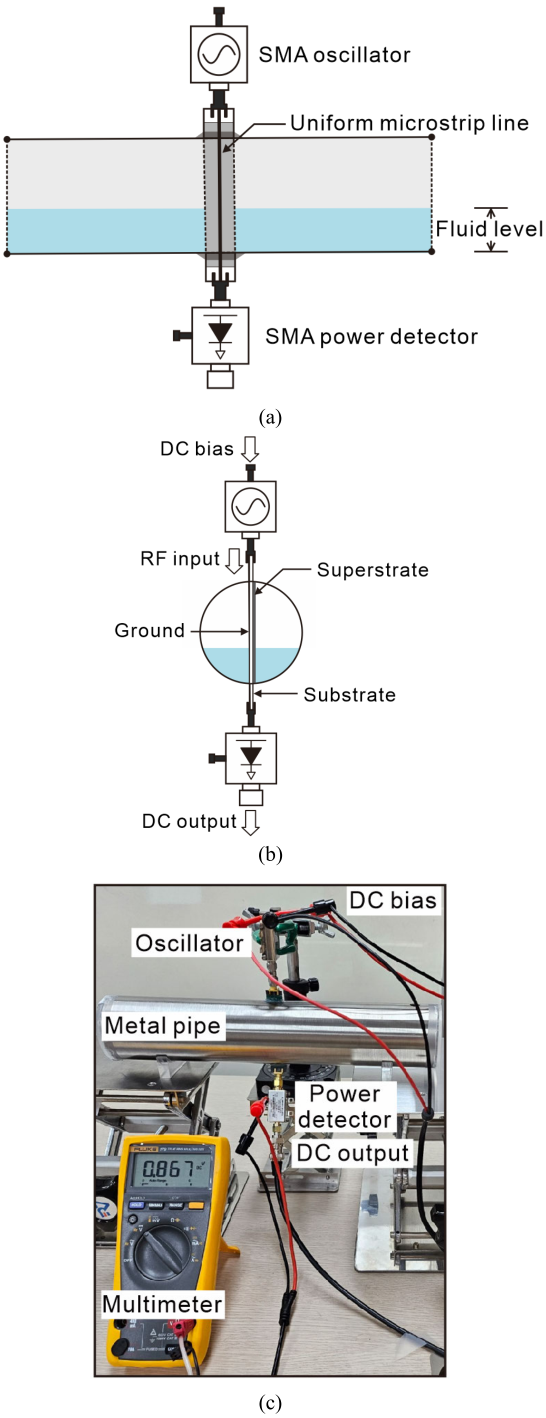

FIGURE 1. (a) Front and (b) side view schematic of the proposed fluid-level sensor system using a low-cost microwave oscillator and detector, and (c) photograph of a prototype fluid-level sensor with simple oscillator and detector modules.

In the proposed sensor system, a uniform microstrip line covered with a dielectric 2 material, as detailed in Fig. 2 (a), is used. This sensor can employ two parameters to determine the height of a fluid in a pipe: the insertion loss and phase delay. Fig. 2 (b) shows the simulation results for the insertion loss (black line) and phase delay (blue line) of 50 mm length microstrip line in fluid according to the superstrate thickness. When the fluid reaches the level sensor, the attenuation constant (α) and phase constant (β) of the microstrip line increase, resulting in a difference in insertion loss and phase delay between the air and fluid. Both parameters can offer a large dynamic range, enabling the observation of changes in the fluid level. However, measuring the phase delay is difficult with a simple measurement setup, as it requires equipment capable of accurate phase calibration at the microstrip line connection terminal and equipment capable of measuring on a very short time scale (e.g., nanoseconds). This equipment is also expensive and bulky, reducing practicality and portability. Therefore, in this study, we design a fluid-level sensor based on the attenuation of the transmission line. The result of simulating the structure shown in Fig. 2 (a) using a High-Frequency Structure Simulation (HFSS) simulator is plotted in Fig. 2 (c). Fig. 2 (c) shows the insertion loss of the transmission line according to the liquid height. The results of microstrip line simulations with different superstrate thicknesses show that the insertion loss decreases as the superstrate thickness increases. It can also be observed that there is a linear relationship between the liquid level and the insertion loss of transmission line, as shown in Fig. 2 (c). The fabricated microstrip line structure simulated as Fig. 2 is explained in section III, and section IV presents the measurement results of the fabricated microstrip line for the fluid-level sensor to verify its performance.

When the microstrip without a superstrate is inserted into a fluid with a high dielectric constant, the characteristic impedance of the microstrip line undergoes significant changes. This leads to a higher impedance mismatch problem between fluid and air condition, reducing the accuracy of the sensor by generating periodic reflection and resonance problem. However, when a superstrate is positioned between the fluid and the microstrip line, this disadvantageous effect of the fluid's dielectric characteristic is suppressed. In the absence of a superstrate ($h2$=0), when the fluid encounters a 50 Ω microstrip line in air environment, the effective dielectric constant increases in accordance with the dielectric constant of the fluid. The high effective dielectric constant results in a very low characteristic impedance. Additionally, with a thin superstrate condition under 10 μm, the dielectric constant of fluid greatly affects to microstrip line, thus the occurrence of ripples caused by standing waves is also confirmed.

When a fluid comes into contact with the microstrip line, a high conductance (G) loss is added to the low-loss transmission line composed of inductance (L) and capacitance (C) as shown in Fig. 3. The conductance of the microstrip line is determined by the capacitance of the parallel plate field and the dielectric of the fringe field [22]. The cited formula in [22] consists of w, the width of the microstrip line, $h1$, the substrate

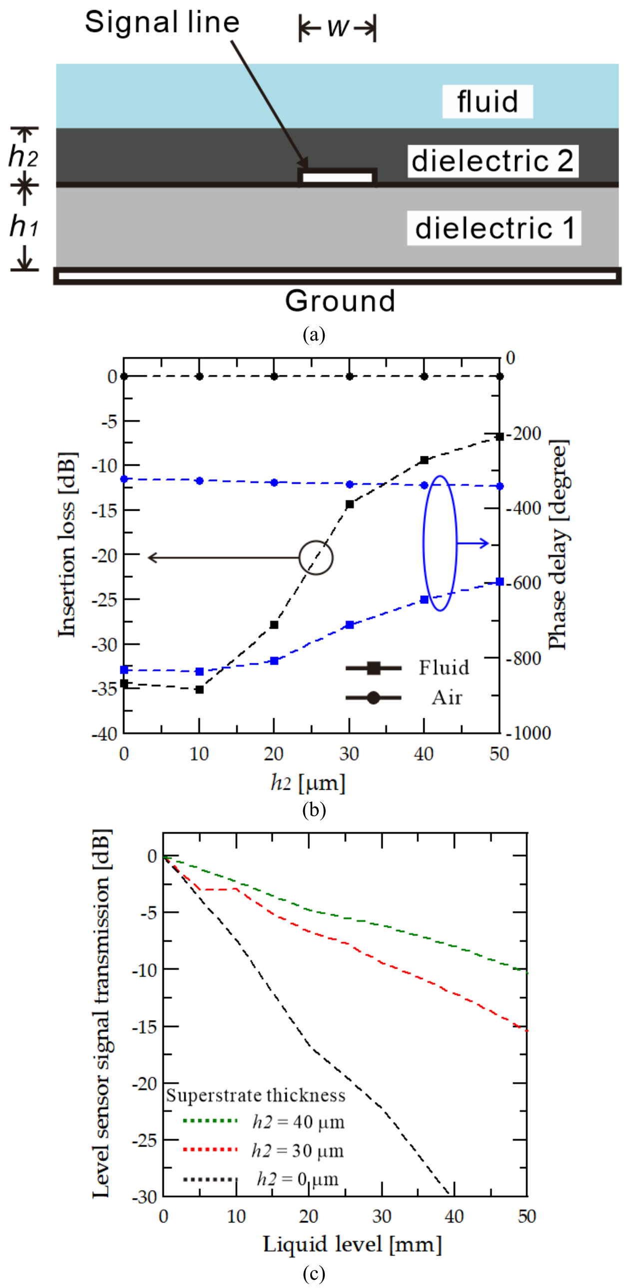

FIGURE 2. **(a) Cross-section of the microstrip line for the proposed sensor system, (b) insertion loss (black line) and phase delay (blue line) as a function of the superstrate height at 3.9 GHz for microstrip lines in the fluid and air, and (c) simulation results for the insertion loss with various superstrate thickness.**

thickness, and σ, the dielectric constant. The variable p represents a minor correction for $h1$ at intermediate values. The first term involving w, $h1$ and σ is determined by the capacitance between the signal line and the ground plane and remains unaffected by external conditions. However, because the second term arises from the fringe field, it is affected by external dielectric loss. Equation in [22] is an expression of a typical microstrip line, but even in a microstrip line with superstrate, the second term can be influenced by the dielectric constant of superstrate and the dielectric constant and loss of external fluid because they involve the fringe effect. Therefore, the thinner the superstate, the more it is affected by the fluid, resulting in increased dielectric loss. The increase in conductance leads to an increase in the attenuation constant due to the proportional relationship $\alpha \propto \sqrt{G}$ within the microstrip line. Fig. 2 (b) presents the simulation results for the insertion loss as a function of the thickness of a superstrate with a dielectric constant of 3.5 on dielectric 1 material substrate $h1$, which has a thickness of 0.127 mm and a dielectric constant of 2.2. As the thickness of superstrate increases, the effect of conductance decreases, and the dielectric loss decreases due to the decrease in α.

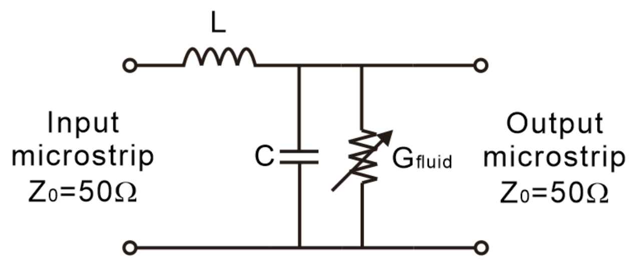

FIGURE 3. **An equivalent circuit model illustrating the conductance of the fluid.**

The low characteristic impedance and dielectric loss problems can be obtained through electromagnetic (EM) simulation. The simulation results in Fig. 4 (a) show the characteristic impedance when a fluid with a high dielectric constant of 81 (e.g., purified water) comes into contact with a transmission line on a substrate with a dielectric constant of 2.2 and a thickness of 0.127 mm. In this simulation setup, without the superstrate, the characteristic impedance is low at 17 Ω. Consequently, the difference in the characteristic impedance in the presence or absence of fluid is high, resulting in inaccuracy due to reflection. However, it is possible to mitigate this fluid effect by using dielectric 2 material as a superstrate, as shown in Fig. 2 (a). As shown in Fig. 4 (a), as the height of the superstrate ($h2$) with a dielectric constant of 3.5 increases, the fluid's effect decreases and the impedance approaches toward 50 Ω. If the height ratio of $h2$ to $h1$ is 0.236, the characteristic impedance is approximately 25 Ω shown as Fig. 4 (a). These simulation results are based on purified water circumstance and can vary depending on the dielectric constant and dielectric loss of the fluid. Fig. 4 shows the simulation results of characteristic impedance using purified water and two other materials for comparison. Material A is a virtual material for comparison, which has the same dielectric loss as purified water and a low dielectric constant of 40. Methanol is similar to material A with a dielectric constant of 33 but has a higher loss than purified water with a tanδ of 0.659. For these two fluids with low dielectric constant, the characteristic impedance is higher than when purified water is used. On the other hand, two materials with similar dielectric constant have similar characteristic impedance. Fig. 4 (b) shows the insertion loss of the three different fluids. Methanol with high dielectric loss exhibits higher insertion loss than material A. Therefore, the proposed sensor can be modified considering the dielectric constant and dielectric loss of fluid, rather than using a fixed superstrate thickness.

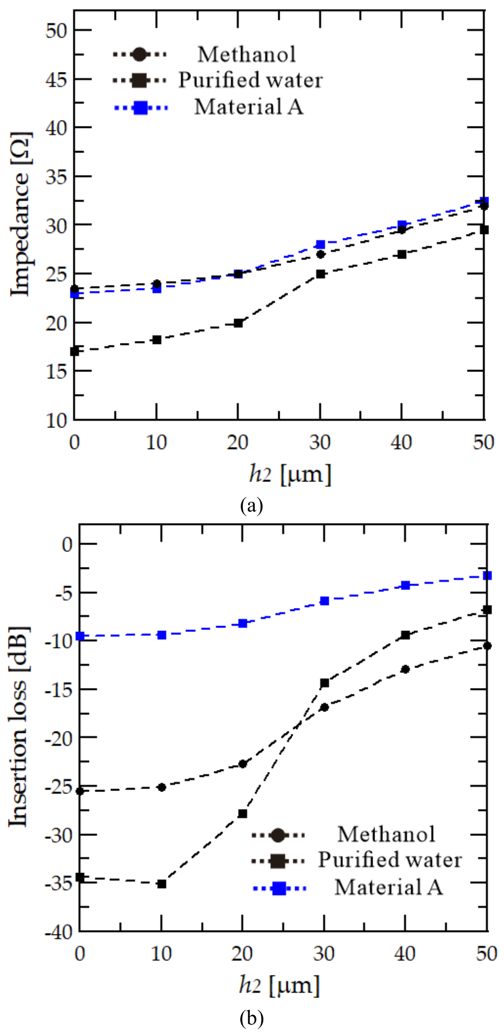

FIGURE 4. (a) Simulated characteristic impedance in a fluid and (b) insertion loss with various material for analysis.

III. DESIGN AND FABRICATION OF A PROTOTYPE FLUID-LEVEL SENSOR

The transmission line for the proposed fluid-level sensor is designed and fabricated to satisfy two conditions based on the modeling presented in Section II. First, standing waves are suppressed by minimizing the change in characteristic impedance. Second, an appropriate attenuation dynamic range is established to detect changes in the transmitted waves. Typically, the limit of insertion loss that can be measured by a simple microwave detector is –20 dB. Therefore, in this design, a level sensor is designed with the aim of achieving a dynamic range capable of covering 20 dB.

The level sensor structure is designed using the HFSS program. The insertion loss of the sensor is predicted by simulator with purified water used as the modeled fluid. The purified water is modeled in HFSS simulation with a dielectric constant of 81 and a conductivity loss of 0.01 siemens/m at 25 °C. The simulation results are plotted together with the measurement results in Section IV for various water levels. Because the insertion loss is low in the low-frequency band, there is a significant reflection effect due to the impedance mismatch problem. However, as the frequency increases, the insertion loss due to fluid increases, resulting in a significant overall increase in the insertion loss. Thus, in the low-frequency band, it is difficult to determine the height of water due to standing waves, while in the high-frequency band, there may be ranges that cannot be detected due to high insertion loss. Therefore, a frequency around 4 GHz is determined to be the most suitable for the sensor.

In Fig. 4 (b), the height ratio of the superstrate to the substrate is set to 0.236, resulting in a dynamic range of 15 dB with the metal pipe filled with purified water condition. The substrate is chosen with a thickness of 0.127 mm to minimize the impact on the flowing fluid. To achieve a height ratio of 0.236, the superstrate thickness is set to 30 μm. To prevent an impedance mismatch problem, the superstrate is a low-loss dielectric film with a similar dielectric constant similar to that of the substrate, achievable through an actual PCB fabricating process.

To verify the design of the proposed fluid-level sensor, a prototype is fabricated using a 0.127-mm Duroid 5880 PCB substrate, as shown in Fig. 5 (a). The total length is 80 mm, with the superstrate not deposited within 5 mm of the end of the microstrip line to ensure a clean connection with the SMA connector. To maintain an impedance of 50 Ω, the section of the transmission line with the superstrate, shown as the green area in Fig. 5 (a), has a width of 0.33 mm, while the section with no superstrate has a width of 0.37 mm. The fluid sensing part of level sensor is a 50-mm length in the center of the microstrip line, with the 10-mm superstrate zone at both ends designed to minimize the effect on the metal pipe and the glue. The thin superstrate material has a dielectric constant of 3.5 and has a tanδ value of 0.001, so it has a lower impedance mismatch problem and dielectric loss. The superstate used in the prototype is made by applying ink coating. This method eliminates the need for an adhesive between the substrate and the superstate, thus eliminating the dielectric constant effects of the adhesive. It also provides ease of production, making it close to the purpose of simple level sensor.

A metal pipe is also manufactured for level sensor verification shown in Fig. 5 (b). The pipe consists of a metal alloy (SUS304), with an inner diameter of 50 mm, a common size for general fluid transfer. The central 50 mm region of the fluid-level sensor is mounted within the pipe. A transparent plate with a scale is installed at one end of the pipe, as shown in Fig. 5 (b), so that fluid level readings can be taken. Since the material of the pipe is metal, there is a problem that the closer the pipe wall and microstrip line are, the more it may affect the performance of the sensor. Therefore, the hole in the metal pipe through which the microstrip line passes is designed and fabricated to be 2 mm apart so that the metal wall does not affect the microstrip line. Fig. 5 (c) shows the simulation results of the return loss based on the gap between the microstrip line and the metal wall. The smith chart shows that a narrower gap results in increased reflection of the microstrip line due to the influence of the metal wall. With a 2-mm gap, the line maintains a 50 Ω characteristic impedance because the metal wall no longer affects it. To accurately analyze the effect of the pipe wall on the microstrip line, we fabricate both a metal pipe and a dielectric pipe with the same structure. The dielectric pipe is made of acrylic and has a dielectric constant of 4. The insertion loss, as measured by connecting the line to each type of pipe, is shown in Fig. 5 (d). It is evident that there is no significant change in insertion loss even when pipes of different materials are connected. This confirms the validity of using the 2 mm gap.

IV. LEVEL SENSOR MEASUREMENTS

Measurements are taken using the fluid-level sensor in the metal pipe via two methods. The first approach uses a 20-GHz vector network analyzer (VNA, N5230A), which is suitable for measuring the frequency characteristics. Basic measurements are taken by connecting ports 1 and 2 to the level sensor connectors. Before measurement, SOLT calibration is conducted using a 3.5-mm 85052D Calibration Kit up to 26.5 GHz. Purified water is used for level sensor testing so that the measurements can be compared with the simulation results. However, S-parameter measurements require a relatively complex calibration process before each measurement, and this calibration is repeated every measurement because its accuracy decreases over time. On the other hand, measurements of insertion loss can avoid complex calibration operations each time.

The second measurement method uses a simple oscillator source and a power detector module. The microstrip line in the fluid-level sensor is directly connected to a low-cost oscillator (ZX95-3800A-S+) and a detector (ZX47-40+), with a True-RMS multimeter (Fluke 179) connected to the detector to display the output voltage. This method offers the advantage of not requiring bulky and expensive VNA equipment, allowing for immediate measurements without intricate calibration. The measurement setups are shown in Fig. 6.

The designed simple fluid-level sensor is measured with the setup shown in Fig. 6 (a). The DC supply (E3646A) applies bias to the oscillator and detector, respectively, as indicated by the numbers in blue letters in Fig. 6 (a). After the bias is applied, the measurement is carried out by changing the liquid height within the metal pipe. Each component is connected by a low-loss cable, as indicated by the green letters in Fig. 6 (a). The measurement setup with VNA is shown in Fig. 6 (b). The VNA and sensor are connected to low-loss 141-1 MSM cable and SMA connector.

Since fabricated sensor uses a fixed loss value, it requires a consistent oscillator power input. Therefore, the oscillator uses a fixed bias voltage of 6 V, and the detector is using

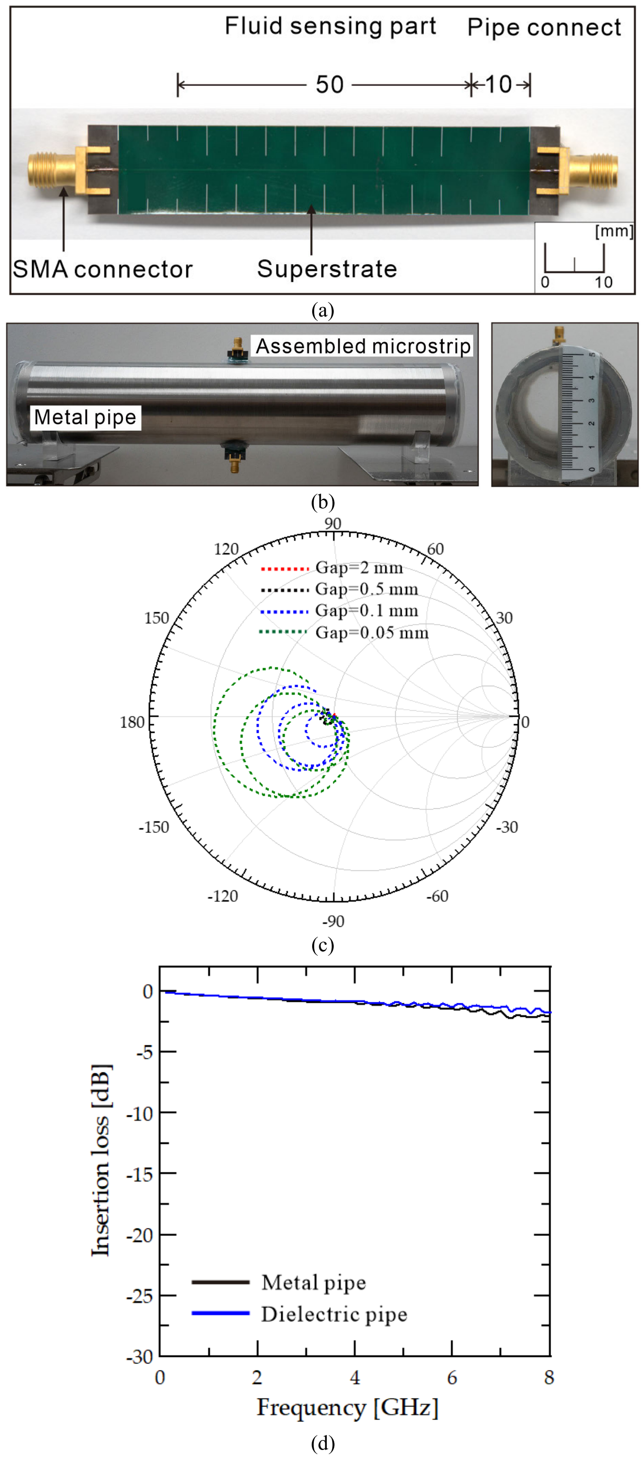

FIGURE 5. **(a) Photograph of the PCB line with the superstrate, (b) the metal pipe used for measurement, (c) smith chart of simulated return loss results up to 8 GHz with gap between line and metal wall, and (d) measured insertion loss with 2 mm gap in metal and dielectric pipe.**

a fixed bias voltage of 5 V shown as Fig. 6. Under this bias condition, the noise floor of the sensor is measured as –50 dBm, and the sensitivity with guaranteed linearity is –40 dBm. Using the simple measurement method with the

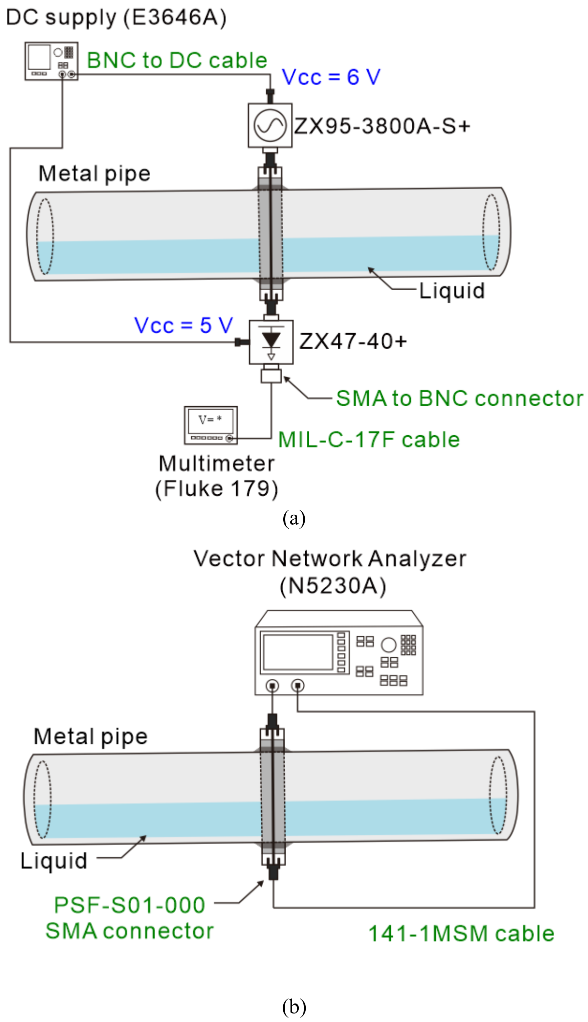

FIGURE 6. **(a) Measurement setup with simple oscillator and detector and (b) with VNA.**

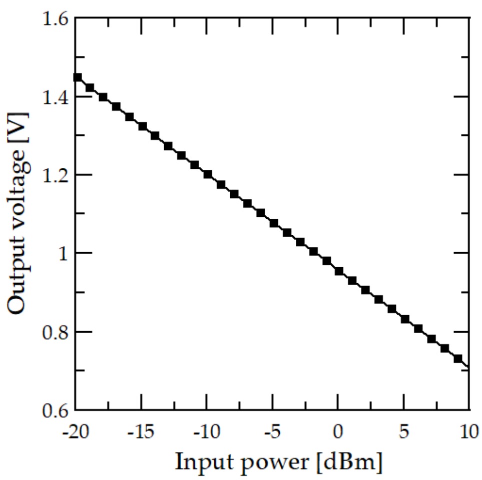

FIGURE 7. **Measurement result of detector output power versus input power.**

oscillator and detector, a linear relationship is observed for the ZX47-40+ detector between the output voltage and the input power over a range of –20 to 10 dBm, as shown in Fig. 7.

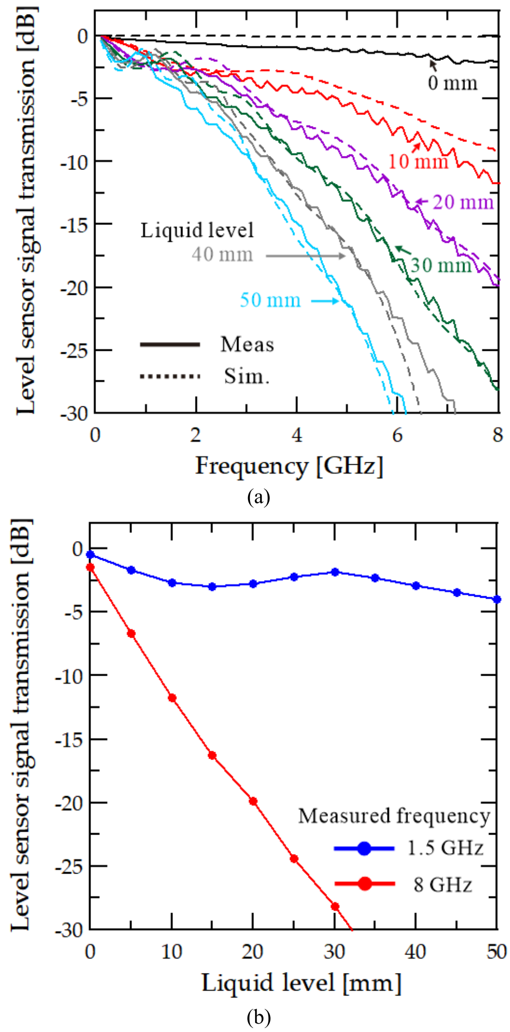

FIGURE 8. **(a) Simulation (dashed line) and measurement (solid line) results for the insertion loss with a 30-um superstrate in accordance with frequency using the VNA, and (b) measurement results for the insertion loss at 1.5 GHz and 8 GHz.**

Thus, this range is used for the measurement. In addition, the ZX95-3800A-S+ oscillator can produce a maximum output power of 4.766 dBm at a frequency of 3.9 GHz. A power level of –20 dBm or more should be entered into the power detector, and the dynamic range is expected to be 15 dB, so the measurements are obtained using the maximum output of the oscillator.

The measurement results using the VNA for the insertion loss according to the frequency for water levels of 0 to 50 mm (in steps of 10 mm) are presented in Fig. 8 (a). The measurement and simulation results are similar, indicating that the purified water modeling is suitably accurate. In the frequency band below 3 GHz, reflection occurs due to the high dielectric constant of water (81), making it difficult to observe the linear insertion loss results due to the height of the water. At frequencies above 3 GHz, the effect of the dielectric loss is higher than the reflection, resulting in a linear trend. However, at higher frequencies above 6 GHz,

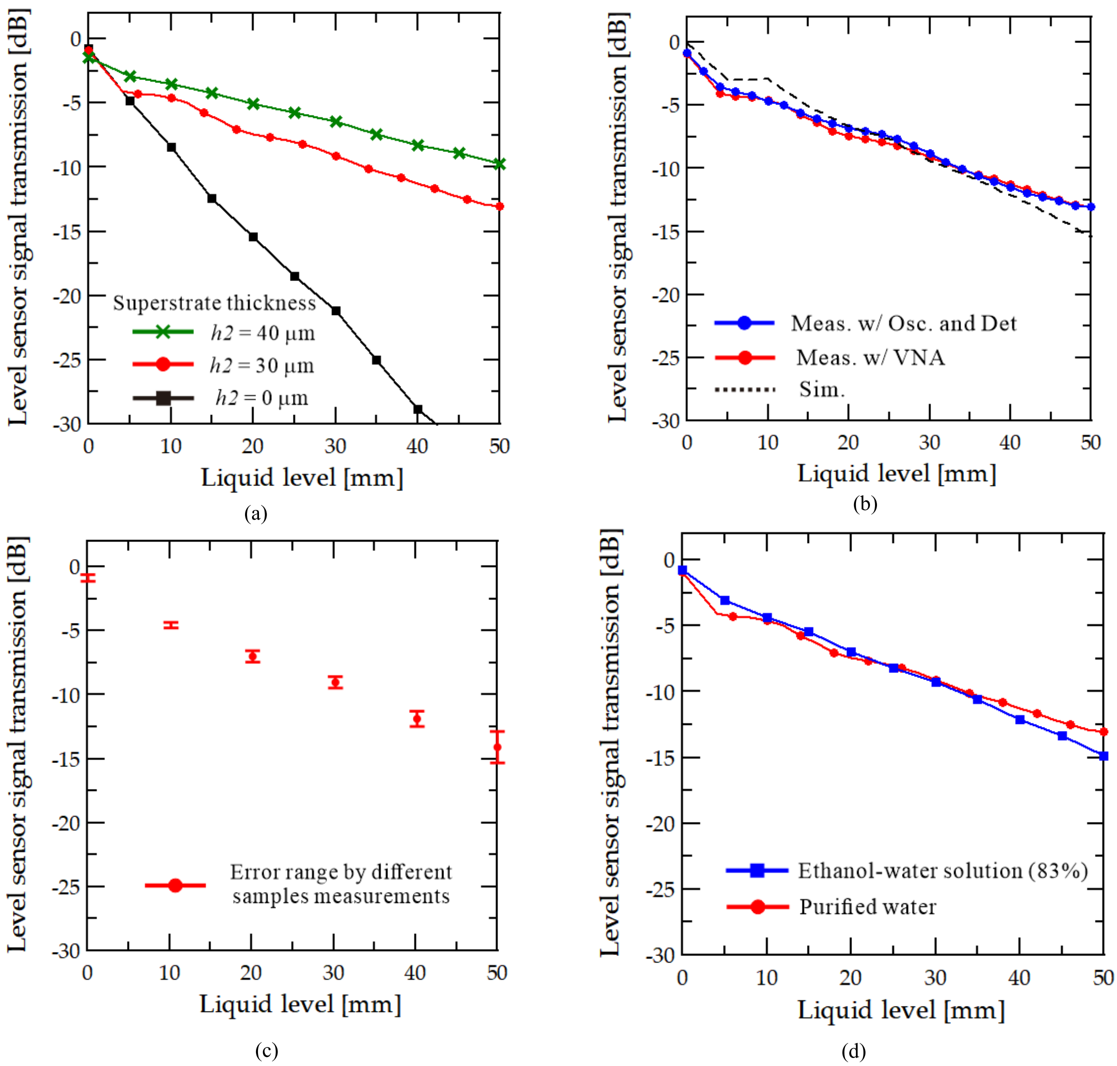

FIGURE 9. **(a) Measurement results for the insertion loss with various superstrate thickness, (b) simulation (dashed line) and measurement results for the insertion loss with a 30-um superstrate using the VNA (red line) and a simple measurement setup (blue line) at 3.9 GHz, (c) error range of designed prototype sensors, and (d) insertion loss measurement result of ethanol-water solution at 3.9 GHz.**

the attenuation constant is higher, leading to a reduction in measurement accuracy. Fig. 8 (b) shows an example of the problem that occurs when the wrong frequency is selected. When a low frequency, such as 1.5 GHz, is used, it becomes challenging to distinguish the liquid level due to a problem caused by reflection. Conversely, when a high frequency, such as 8 GHz, is used, the insertion loss is high, thereby reducing the measurement accuracy. Therefore, 3.9 GHz is selected as the frequency that produces a dynamic range of 20 dB or less in this study.

As the thickness of the superstrate changes, the effect of dielectric loss caused by the fluid also changes. Fig. 9 (a) shows the performance change in insertion loss according to superstrate thickness at 3.9 GHz. It is shown that the thicker the superstrate, the less the slope of the insertion loss change due to the fluid height. Therefore, the microstrip line of fluid-level sensor can be flexibly designed by adjusting the superstrate thickness based on the metal pipe inner diameter and fluid dielectric loss, not on a fixed microstrip line structure. For comparison purposes, a microstrip line without the superstrate is also tested as shown in Fig. 9 (a). The result shows that an insertion loss is higher than 30 dB and the generation of standing waves problem is occurred due to reflection.

The insertion loss according to the fluid level at 3.9 GHz is presented in Fig. 9 (b). The solid red line denotes the results for the sensor with a superstrate thickness of 30 μm, measured using the VNA, with the insertion loss changing linearly depending on the height of water, similar to the simulation results (dotted line). The dynamic range of the fluid-level sensor is 13.1 dB. The measurement results using a simple oscillator and detector are shown in Fig. 9 (b) with blue line. The insertion loss is obtained by converting the voltage output to power and then subtracting the oscillator input power. The insertion loss results of this simple method are similar to those derived from the VNA. Therefore, the proposed fluid-level sensor based on the insertion loss is confirmed to be accurate and cost-efficient.

Fig. 9 (c) shows the error range of the measurement results for different prototype fluid-level sensor samples. While there may be variations in additional loss depending on the connector connection and cable connection state used in the prototype fabrication and measurement, the sensor can operate within the maximum error range of 2.4 dB, and the linearity is maintained.

The designed sensor is not limited to simply measuring the purified water level but can be used for various liquid height measurements. Fig. 9 (d) presents the result of measuring the level of medical ethanol at 3.9 GHz using a measurement condition same to those for purified water. The medical ethanol used for the measurement is a water solution with a concentration of 83%, and the dielectric constant of this ethanol-water solution is less than 28.5. Despite the significant difference in dielectric constant between purified water and the ethanol-water solution, the sensor's insertion loss measurement result shows the linear relationship between the liquid level and the insertion loss. In other words, the designed sensor can measure the liquid level in the metal pipe where insertion loss occurs, regardless of the dielectric constant.

V. CONCLUSION

In this study, a transmission-line type fluid-level sensor comprising a simple oscillator, detector, and transmission line covered with a superstrate is proposed. The measurement results of the prototype sensor verify the linear relationship between insertion loss of designed sensor and fluid height at 3.9 GHz. The sensor demonstrates an operation with 13.1 dB dynamic range in a 50-mm diameter metal pipe filled with purified water condition and with 14.9 dB dynamic range filled with medical ethanol. This type of fluid-level sensor can be manufactured at a low cost, and measurements can achieve the same accuracy as those obtained using expensive and complex VNAs. The proposed strategy can monitor the fluid height inside a closed opaque pipe in real time and obtain fast and accurate results using a simple multimeter without a complicated calibration process. It demonstrates a simple microwave sensor application with potential uses in various future RF implementations. Based on this proposed technology, it is possible to manufacture cost-effective and highly portable fluid-level sensors that can be widely employed in real-time quantity measurement systems for industrial environments and public infrastructure. For instance, the proposed sensor can be applied to measure the amount of fluid in a water transport pipe, where the water level varies depending on the amount of rain. It can also be utilized as a sensor to predict the amount of oil in a pipeline under the same principle. Furthermore, it can be used for level sensing in medical liquid pipes, as demonstrated in this paper. The proposed fluid-level sensor can be easily customized to suit the dielectric constant and dielectric loss of various fluids by adjusting the ratio of the superstrate thickness to the substrate. When dealing with shallow pipes, the superstrate ratio can be decreased, and conversely increased for deeper pipes. This designed sensor can be employed in both fixed and flowing liquid environments. Additionally, the reduced weight of the system, achieved through miniaturized oscillators, detectors, and lines, distinguishes it from existing VNAs or liquid-level sensors, minimizing fatigue in the pipe structure.

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K. M. LEE received the B.S. degree in electrical engineering from Korea University, Seoul, South Korea, in 2015, where he is currently pursuing the Ph.D. degree.

His research interests include development of antenna and passive microwave sensor system for millimeter wave band, and design detector and antenna based on InP DHBT in terahertz region and package integrated circuits in waveguide and lens antenna.

J. CHO received the B.S. degree in electrical engineering from Korea University, Seoul, South Korea, in 2020, where he is currently pursuing the Ph.D. degree. He has been involved in the design and test of phased array system in millimeter wave region and communication analysis with RF front-end components.

M. KIM received the Ph.D. degree from the California Institute of Technology, Pasadena, CA, USA, in 1993.

He was a Member of Technical Staff with the Submillimeter-Wave Advanced Technology Group, Jet Propulsion Laboratory, until 1998, and a Senior Scientist with the Microwave Group, Rockwell Science Center (currently Teledyne Scientific), until 2000. Since 2000, he has been a member of the Faculty of Electrical Engineering, Korea University, Seoul, South Korea. His current research interests include development of both passive and active circuit components required in construction of terahertz communication and imaging systems.