

Development of Humidity Monitoring System in Greenhouse with Electromagnetic X Band and Artificial Neural Networks

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Abstract—This paper presents a humidity monitoring system with X band electromagnetic transmission. The verification is performed by comparing the gain and phase difference of intermediate frequency between 10.2 GHz and 10.4 GHz. Measurement data are analyzed to classify relative humidity levels and make decisions with ANNs. The system is simulated with electromagnetic field simulation software to analyze the ability of humidity monitoring. The structure from the simulation is developed to be a prototype system, including transmitter and receiver modules. Each module consists of an antenna, a frequency synthesizer, and a frequency mixer. The different operation frequencies of the two modules are -200 MHz and $+200$ MHz. The obtained intermediate frequency by mixing signals from each module is introduced into the circuit to find the gain and phase difference to compare with a relative humidity level. Humidity monitoring experiment is set in a closed plastic box to control the environment. The relative humidity level is from 55% to 95%. The decrease in gain is associated with increased relative humidity. Results found that the phase difference decreases clearly at the relative humidity from 75% to 95%. Both gain and phase difference data are used to train ANNs to optimize ANNs structure. Data are divided into 50% for training and 50% for testing. The proposed ANNs structure with a learning rate of 0.05 provides 98.8% accuracy. The optimized ANNs structure is composed of two input nodes, eight hidden nodes, and four output nodes. Four output nodes represent the relative humidity in 11 levels. The simulated and experimental results show that the system is able to monitor humidity effectively for applying in the greenhouse.

1. INTRODUCTION

The quality and quantity of good agricultural and livestock production are obtained as a result of the appropriate environment conditions [1–4]. Hence, an agriculture production process should be controlled in a greenhouse. The agriculturists who require the agriculture product to meet their goals should manage and control the parameters of environment that affect the growth of yields. Humidity is one of the significant parameters that must be controlled at suitable levels. The humidity control in a greenhouse is an interesting topic for researchers, and many techniques have been presented. Most of the previous systems are based on a commercial humidity sensor. The capabilities of that sensor can only measure a limited area; therefore, it is suitable for small or medium size greenhouse. For example, the monitor and control environment system inside the greenhouse uses a humidity monitor with a DHT11 sensor [5]. The climate control system of an agricultural greenhouse uses a DHT22 sensor [6], and the smart humidity control system in Lingzhi mushroom farm uses a DHT22 sensor to measure humidity [7]. These systems are not a complicated humidity measuring method because they use only a commercial sensor, but they are unsuitable for a large greenhouse. This limitation of the

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sensor in the case of the large greenhouse requires multiple sensors to measure humidity covering the greenhouse area, which are connected as a wireless sensor network. In previous research, the agricultural greenhouse environment monitoring system with wireless LAN (WI-FI) is composed of 5 client sensor modules and a server. Each module is controlled to send data by a microcontroller [8]. The research article [9] used client-server sensor systems. The sensor node uses DTH11 for humidity monitoring which has a limit for a large greenhouse. The system is controlled by a microcontroller and connects to the internet via GPRS. The decision process uses fuzzy-PID [9]. However, client-server sensor systems are complex. Therefore, low complexity systems' design, real-time processing, and humidity measurement of the whole greenhouse are important. The humidity measurement with microwave signal transmission was presented before. This technique is based on the dielectric properties of the medium. The difference of dielectric properties affects amplitude attenuation and changes the phase of the signal differently at each humidity level. The advantage of this technique is the ability to measure humidity in a large area because of microwave signals through the greenhouse and low complexity [10]. However, the previous work uses low frequency (long-wavelength), resulting in an unclear result. Therefore, humidity measurement by microwave frequency with short-wavelength is more responsive to moisture change than long-wavelength. This can be observed by changes in amplitude and phase [11].

This paper presents a humidity monitoring with X band frequency transmission technique at 10.2 GHz and 10.4 GHz. The transmitted frequency is mixed with the other to be intermediate frequencies (IF). The two intermediate frequencies are compared for gain and phase difference versus humidity level. The second part describes the electric properties of a material that affects the attenuation of the signal and principle of a frequency mixer. The third part is a simulation of an antenna structure, the antenna structure improvement, and a system for monitoring humidity analysis. The fourth part presents a prototype system, including two modules of 10.2 GHz and 10.4 GHz. The microcontroller is used for gain and phase difference collection. The fifth part is an experiment that describes comparison results of gain and phase difference versus relative humidity. These results use to train and test artificial neural networks. The last part is the conclusion.

2. THEORIES AND PRINCIPLES

2.1. Dielectric Properties

Permittivity is the property of the medium which affects propagation constant, reflection, and attenuation of electromagnetic wave [12]. Permittivity ϵ includes dielectric constant and dielectric loss factor. Dielectric constant ϵ' describes the amount of electric potential energy that is stored in material under the action of an electric field. ϵ'' is the dielectric loss factor, representing the absorption and attenuation of the power. In dielectric material, the amplitude of the electric field E_0 decreases exponentially along propagates in the z -axis. The attenuation constant depends on the dielectric properties of the material as shown in Equation (1) [13]

$$\alpha = \frac{2\pi}{\lambda_0} \left[\frac{1}{2}\epsilon' \left(\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right) \right]^{1/2} \quad (1)$$

From Equation (1), λ_0 is the wavelength in a vacuum; therefore, frequency affects attenuation. High-frequency signal has the attenuation more than that of the low-frequency. Dielectric properties are a function of frequency, temperature, and humidity. High humid air causes high dielectric properties and high attenuation of the transmission signal. Hence, the presented humidity monitoring system in this paper is on this principle.

2.2. Frequency Mixer

Frequency mixer is an important circuit in a general RF receiver architecture [14]. The mixer converts RF received-signal to intermediate frequency (IF) signal before signal processing. It can reduce the use of high-frequency components because the high-frequency component is costly due to fabrication difficulties [15]. Moreover, converting the frequency to IF reduces the supply voltage of the receiver [16].

A mixer is a three-port network consisting of two input ports and one output port. Two input signals are multiplied by each other to provide output. Input 1 is an RF signal received from the transmitter. Input 2 is a local oscillator (LO) signal. The output of the mixer is IF signal or intermediate frequency that consists of the sum and difference of the input signal frequencies. Then, the output of the circuit is shown in Equation (2) [11].

$$v_{IF} = \frac{V_{RF}V_{LO}}{2} \{ \cos [2\pi (f_{RF} - f_{LO}) t] + \cos [2\pi (f_{RF} + f_{LO}) t] \} \quad (2)$$

When V_{RF} and f_{RF} are amplitude and phase of the RF signal, V_{LO} and f_{LO} are amplitude and phase of the LO signal, and V_{IF} and f_{IF} is the amplitude and phase of the IF signal. A mixer operates like conversion frequency without changing phase of RF signal. Amplitude is halved, causing product to sum trigonometric formula [17]. In the application of a mixer in an RF receiver, IF signal from the mixer is filtered by filter circuit to filter a difference of the input signal frequencies. The advantage of using a low-frequency component makes the system with low attenuation, easy to find equipment, and low cost. Therefore, the presented system is based on IF down-conversion frequency with RF signal and LO at 10.2 GHz and 10.4 GHz with IF of 200 MHz.

3. SYSTEM SIMULATION

The humidity monitoring system is based on microwave transmission, and the system is designed to operate at frequencies of 10.2 GHz and 10.4 GHz. A system development starts with feasibility analysis by simulation in electromagnetic wave simulation program (CST STUDIO SUITE) [18]. The system simulation procedure starts with two antenna model developments operating at 10.2 GHz and 10.4 GHz. The signal transmitting through each humid air level is then simulated to analyze the magnitude and phase of transmission signal changing.

3.1. Antenna Design

A microstrip antenna is designed and developed to obtain an optimal structure by the simulation. The designed antenna is used for receiving and transmitting radio waves of the humidity monitoring system. The antenna performance simulation uses a printed board (FR4) with a dielectric constant of 4.1, substrate thickness of 1.7 mm, and conductor thickness of 0.0795 mm. The geometry of the antenna has a square shape with low complexity as illustrated in Figure 1.

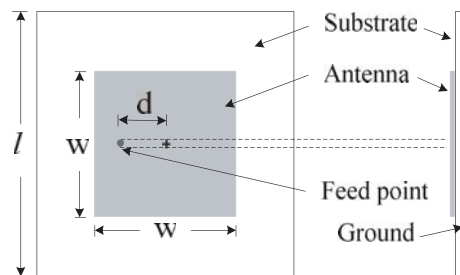


Figure 1. The geometry of a microstrip antenna.

An initial antenna is designed to operate at 10.2 GHz. In Figure 2(a), the antenna width w is varied from 6.7 mm to 7 mm. It is found that the optimal width is 6.9 mm. After that, the feed point is evaluated for optimal value. The length d is varied from 2.3 mm to 2.6 mm to obtain the lowest S_{11} . The simulation result illustrates that the appropriated feed point length is 2.5 mm as shown in Figure 2(b).

The width of the second antenna is adjusted to operate well at a frequency of 10.4 GHz. The width w of the second antenna is simulated by changing w from 6.5 mm to 6.8 mm. When the width of the second antenna is 6.7 mm, the antenna provides the optimal result as shown in Figure 3(a). The feed point length of d is varied from 1.9 mm to 2.2 mm to achieve the lowest S_{22} . It is found in The result

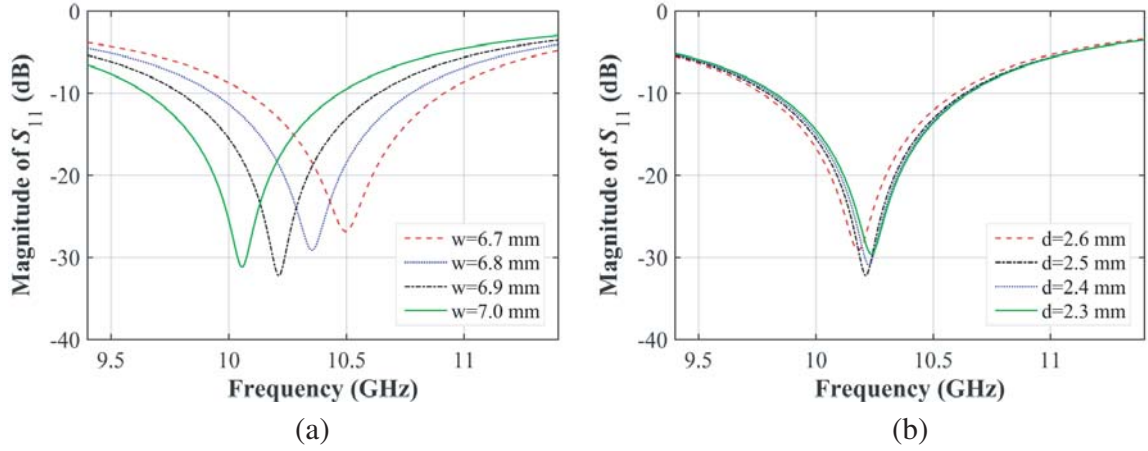


Figure 2. The simulation results of the antenna at 10.2 GHz. (a) Varied width. (b) Varied feed point.

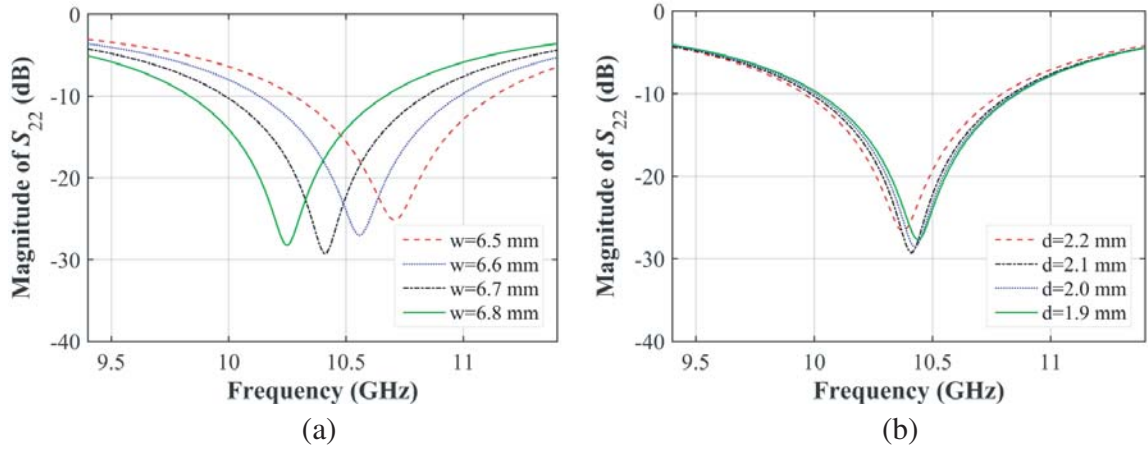


Figure 3. The simulation results of the antenna at 10.4 GHz. (a) Varied width. (b) Varied feed point.

that the appropriated feed point length is 2.1 mm as illustrated in Figure 3(b). l is the length of a ground plane. A ground plane size of two antennas is 16 mm.

From the simulation of the optimized geometry of the first and second antennas, the results illustrate that the simulated S_{11} at the frequency of 10.2 GHz is -31.5 dB, and the S_{22} at the frequency of 10.4 GHz is -29.05 dB. The designed antenna models are applied to the simulation of the humidity determination system.

3.2. Humidity Determination Simulation

The simulated microstrip antenna models are used in the humidity monitoring system for transmitting radio waves at 10.2 GHz and 10.4 GHz. The system is simulated by electromagnetic simulation solvers software (CST STUDIO SUITE). The first step for humidity determination is a simulation of a sample holder modelling for containing a humid air sample. It is made from a material with a dielectric constant of 2.47 [19] and size of $15 \text{ cm} \times 15 \text{ cm} \times 32 \text{ cm}$. To achieve good performance, the simulation is designed realistically. The humid air model is in a sample holder for system performance simulation. The dielectric constant is varied in the range from 1.004 to 1.014 according to a relative humidity increasing [20]. The sample holder comprises a humid air model between the first and second antennas. The distance between the two antennas is 32 cm as shown in Figure 4.

The sample holder is used to maintain and control the relative humidity during testing. The

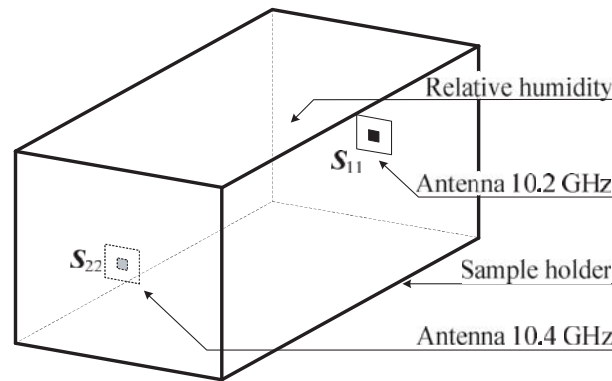


Figure 4. A prototype model of the humidity monitoring system.

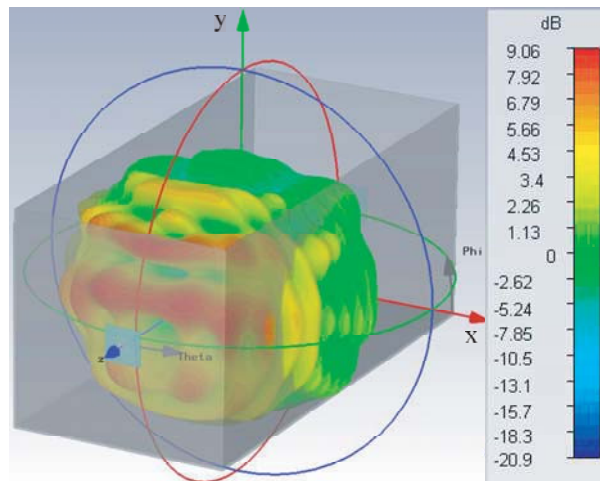


Figure 5. The radiation pattern of the antenna at 10.2 GHz.

simulation of radiation pattern of the first antenna at 10.2 GHz, contained in a sample holder, is performed to test the performance. The result shows that the direction of the main beam directs towards the front with a gain of 6.716 dBi as shown in Figure 5. The main beams considered at 10.4 GHz of the second antenna directs towards the front with a gain of 6.713 dBi.

The designed antennas have low complexity, with appropriated gain; therefore, the proposed antennas are applied in the transmitter and receiver parts in the simulated humidity determination system. Both antennas transmit and receive a signal to measure the different power of transmission power at each humidity level.

The simulation of the humidity uses 11 levels of the sample dielectric constant. The ability of relative humidity classification is analyzed by transmitting radio waves (S_{21} , S_{12}) between 10.2 GHz and 10.4 GHz. The simulation results show that the change in relative humidity affects the amplitude and phase of the transmission signal. In Figure 6(a), the magnitude of S_{21} at every relative humidity level is in range from -32.67 dB to -34.36 dB. On the other hand, the magnitude of the reverse transmitted signal S_{12} ranges from -31.21 dB to -32.65 dB. The changed phase of S_{21} ranges from 148.05 to -24.5 degrees as illustrated in Figure 6(b), and S_{12} ranges from 85.02 to -96.62 degrees.

The simulation results illustrate that when the relative humidity or the dielectric constant of the air changes, it will directly affect the amplitude and phase of transmission signal S_{21} and S_{12} . Thus, humidity determination with the X-band signal becomes an interesting issue.

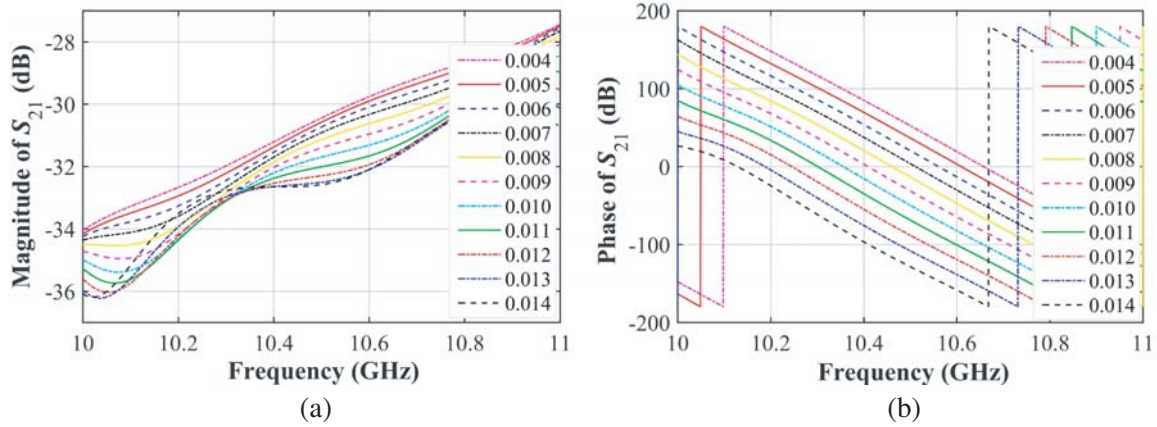


Figure 6. The change of (a) magnitude and (b) phase of S_{21} when dielectric of the relative humidity changes.

4. DESIGN SYSTEM

The simulated results of a humidity monitoring system show that the main characteristics of magnitude and phase change, concerning the humidity level. Thus, the system is developed as a practical application for the humidity monitoring system. The signal transmits through the humid air with the relative humidity from 55% to 95%. After that, the measured magnitude ratio and phase difference of two IF signals are compared with humidity levels.

4.1. System Implementation

The presented humidity measuring system consists of 1) microcontroller (Arduino UNO R3), 2) two transceiver modules with antennas, an oscillator, and a frequency mixer [21], which are integrated into the single board to be a low-cost module, and 3) phase and gain measurement module (AD8302). The designed system uses two transceiver modules. One module operates at 10.2 GHz, and the other operates at 10.4 GHz. Transceiver modules generate and transmit signals from LO inside while receiving a signal from the other transceiver module. After that, the received signal is mixed by a signal from LO, becoming the Intermediate Frequency (IF) at 200 MHz. IF frequencies from two transceiver modules

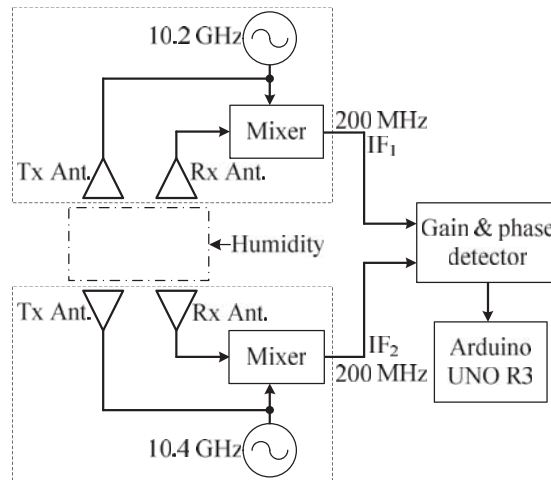


Figure 7. Diagram of the humidity monitoring system.

are the input of gain and phase measurement module. The magnitude ratio and phase difference of 2 IF signals are calculated and converted to DC voltage. System diagram is shown in Figure 7. The structure of a developed prototype system has low complexity. The selected module has a low price but can transmit signal power and process data.

4.2. Prototype System

A prototype system is fabricated according to the diagram in Figure 7. Transmitter and receiver parts are transceiver modules. The module consists of Tx-Rx antennas, LO, and frequency mixer. A transceiver module operates at the 10.2 GHz, and the other operates at 10.4 GHz. The different frequencies of the two transceiver modules are -200 MHz and $+200$ MHz. The received signal of each module is mixed at a frequency mixer inside the module, producing an IF signal as an input of gain and phase measurements. The output of gain and phase measurement is DC voltage that is the ratio of magnitude and phase difference of two IF signals from two transceiver modules at every relative humidity level. DC voltage is converted to a digital signal by an analog to digital converter on the Arduino board that can receive input in the range of 0–5 volts and provide output digital signal with 10 bits. Gain and phase measurements are controlled by the Arduino board. Each relative humidity level measurement is repeated 10 times. The obtained data are averaged. Moreover, there is a standard sensor (DHT22) inside the sample holder for measuring relative humidity compared with the measured data from the proposed system. The received data from the standard sensor are used as reference humidity values to ensure system accuracy. A prototype of the determination humidity system is shown in Figure 8.

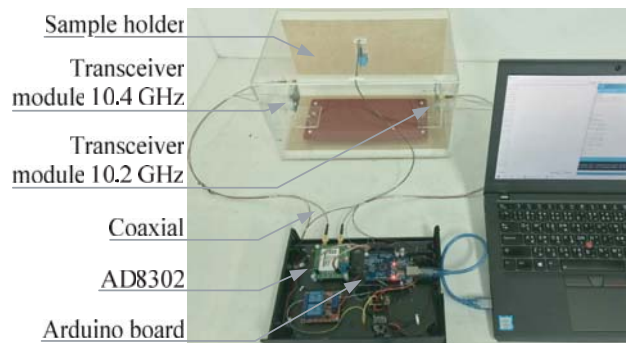


Figure 8. A prototype of the humidity monitoring system.

The system operation is controlled by an Arduino board. The Arduino board is programmed to control the frequency synthesizer for the transmitting, receiving and mixing signal of the transceiver module. Besides, the board is used for processing the data from a humidity measuring system by comparing with the standard sensor and stored humidity data in memory. The obtained data from the system are then used to train the neural network, compared with the reference humidity from the standard sensor.

5. EXPERIMENTAL AND ANALYSIS

The humidity measuring system is tested in an experimental room that controls the temperature at 25°C . The transmission line for sending IF data is an RG316 SMA coaxial cable with 50 ohms [22]. The measured data are processed and averaged by the Arduino board. Next, the averaged data are analyzed to be relative humidity in 11 levels. Finally, the data are transmitted via a USB port to a computer and show the result in a serial monitor function.

5.1. Humidity Monitoring

The transmitter and receiver of the system are securely kept in an acrylic sample holder. The relative humidity is measured with signal transmission between 10.2 GHz and 10.4 GHz in the sample holder. The gain and phase differences of the two IF values are collected from the gain and phase difference detectors. The data from experimental are gain and phase. The measured relative humidity is 11 levels ranging from 55% 59% 63% to 95%. When considering the gain compared with the relative humidity level, it can be noted that the DC voltage is decreased related to the increase of relative humidity. At a relative humidity of 55, the average DC voltage is 0.873 volts. As the relative humidity increases to 59, 63% until 95, the DC voltage of gain is decreased from 0.869, 0.864 to 0.809 volts, respectively as shown in Figure 9(a).

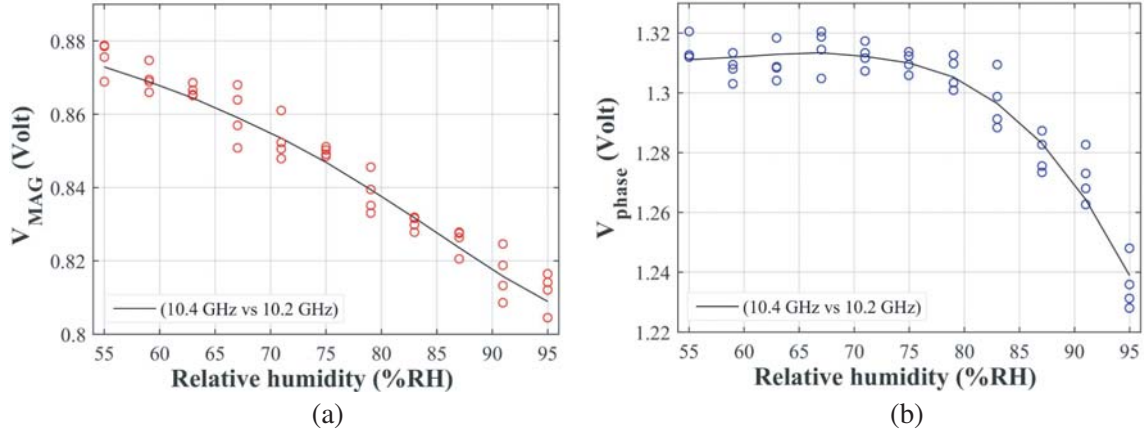


Figure 9. 10.4 GHz and 10.2 GHz modules compare with the relative humidity level. (a) Gain (V_{MAG}). (b) Phase difference (V_{phase}).

The DC voltage of phase difference is in the range from 1.321 to 1.228 volts. It is noted that relative humidity ranges from 55% to 70%, and the voltage is noticeably unchanged with the average value of 1.31 volts. When the relative humidity increases from 70% to 95%, DC voltage is changed in the range from 1.31 to 1.23 volts as shown in Figure 9(b). Comparing the gain and phase difference for each relative humidity level, it can be seen that the gain decreases linearly with increasing relative humidity which is suitable to be a dataset for ANNs training. Phase difference changes slightly when the relative humidity in the range from 55% to 70%. However, when the relative humidity ranges from 75% to 95%, phase differences can be used to classify the relative humidity level. Hence, phase voltage can be used as additional data for ANNs training which make the learning of ANNs better. Therefore, data sets for ANNs training are gain (V_{MAG}) and phase difference (V_{phase}).

5.2. Artificial Neural Network Training and Testing

The collected data from the relative humidity monitoring system include gain and phase difference at each humidity level which is used to train ANNs. There are 2 input nodes in ANNs training using gain (V_{MAG}) as input at node 1 and phase difference (V_{phase}) as input at node 2. To find a suitable structure, the hidden nodes are adjusted into 2 cases which are six nodes and eight nodes. The number of output nodes is 4 nodes that represent 11 levels of relative humidity as shown in Table 1.

In the training method, learning rates are varied from 0.002, 0.005, 0.01, to 0.2, respectively. Each learning rate has a different velocity and the ability for learning. Hence, the testing to find a suitable rate makes the training effective. The condition of training includes the sum of error and epoch which is set to be the sum of error less than 0.01 or epoch more than 10^9 to stop. The training starts at six hidden nodes with a learning rate of 0.002 and epoch over 10^9 cycles. The error rate is 1.051, and the accuracy is 88.2%. The learning rate of 0.01 results in the highest accuracy of 97.8%. ANNs can learn faster, and the error rate decreases to 0.047 at epoch more than 10^9 cycles. When using eight hidden

Table 1. Mapping function of the relative humidity and output nodes.

Relative Humidity	Output node			
	O ₁	O ₂	O ₃	O ₄
55%	0	0	0	0
59%	0	0	0	1
63%	0	0	1	0
67%	0	0	1	1
71%	0	1	0	0
75%	0	1	0	1
79%	0	1	1	0
83%	0	1	1	1
87%	1	0	0	0
91%	1	0	0	1
95%	1	0	1	0

Table 2. Artificial neural network training.

Hidden nodes	Learning rate	Epoch	50% of Data	
			Sum of error	Accuracy
6	0.002	10 ⁹	1.051	88.2%
	0.005		1.029	90.1%
	0.01		0.047	97.8%
	0.05		1.545	86.3%
	0.1		1.508	88.4%
	0.2		1.006	91.1%
8	0.002	10 ⁹	1.047	87.4%
	0.005		1.784	84.8%
	0.01		0.019	98.2%
	0.05		0.014	98.8%
	0.1		1.004	92.7%
	0.2		1.006	90.3%

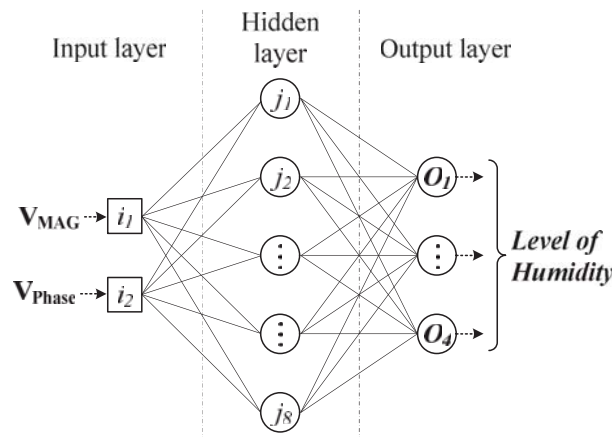


Figure 10. Structure of ANNs for a humidity classification decision.

nodes and epoch more than 10^9 cycles of every learning rate, it is found that a learning rate of 0.002, 0.005, to 0.2 gives the sum of error with 1.047, 1.784, and 1.006, respectively. The accuracy at eight hidden nodes is the highest at 98.8% as shown in Table 2.

The decision process for humidity classification uses the weight from the training process at the learning rate of 0.05. ANNs structure for the system includes two input nodes, eight hidden nodes, and four output nodes to represent 11 relative humidity levels shown in Figure 10.

The optimized ANNs structure has an accuracy of 98.8%. Hence, it is suitable for the decision in humidity measuring application.

6. CONCLUSIONS

A humidity monitoring system uses X band transmission technique. The signal frequencies of 10.2 GHz and 10.4 GHz are transmitted through humid air and received by transceiver modules then converted to an intermediate frequency (IF). The differences of IF_1 from the 10.2 GHz module, and IF_2 from the 10.4 GHz module is compared for humidity determination. The relative humidity level separation capacity of the system is analyzed by simulation. The simulation starts with the antenna design. The simulated antenna models are installed in a testing plastic box that is filled with humid air model. The transmitted and received 10.2 GHz and 10.4 GHz signals are transmitted over the humid air model with the different dielectric constants of air. The simulation results illustrate the possibility of classification of the relative humidity level. The system is then developed in the same way as the simulation for measuring humidity. The prototype system is fabricated with two transceiver modules which include Tx-Rx antennas, local oscillators, and frequency mixers inside. Each module operates both transmitter and receiver parts. IF_1 and IF_2 signals are the output of the transceiver module. Therefore, two IF signals are the input of AD8302 to find their magnitude ratio (gain) and phase difference. The obtained gain and phase difference become inputs of ANNs. The output of ANNs is relative humidity levels from the standard sensor. In the experiment, the relative humidity is varied in the range from 55% to 95% with 88 samples. 50% of all data are for ANNs training and the other 50% for ANNs testing. Thus, the optimized ANNs structure is two input nodes, eight hidden nodes, four output nodes to represent 11 levels of relative humidity. The learning rate is 0.05. The maximum accuracy is 98.8% which is enough and appropriate for measuring and controlling humidity application. This proposed system can be suitably applied to large greenhouse. Because of its low complexity and low cost such as being used for vertical mushroom farming by installing transceivers modules only 2 installation points, the humidity can be measured in the middle between mushroom shelves along the greenhouse line.

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