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Research Article

Security Paper Design with Frequency-Selective Structure for X-Band Electromagnetic Detection System

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This study designed and fabricated a frequency-selective structure-based security paper for the electromagnetic detection system of a security gate, which aims to prevent leakage of confidential documents. When a functional paper embedded with a frequency-selective pattern that selectively reflects a specific frequency is being leaked out of a security zone, the electromagnetic detection system receives and detects the intensity of the electromagnetic wave reflected from the security paper passing through an antenna gate, which transmits/receives RF signals. A stable detection performance of the security paper can be ensured by improving the incidence angle stability for incident waves and reducing the reflection loss. This study designed a frequency-selective structure with stable frequency reflection properties at the X-band by utilizing a Jerusalem cross structure. The proposed design was realized using the screen printing technique, which could implement a circuit, to print silver ink on a plain paper. To verify the applicability of the frequency-selective structure-based security paper, an RF detection system with a multiple antenna array was constructed and the intensity of the received signals was measured. The measurement was performed for various scenarios, and the result showed that the proposed security paper was well detected.

1. Introduction

Our information society is being sustained by intense technology competition for taking the initiative in high-tech development. To assure fair competition and rights, each country enacts legal regulations for intellectual property rights that assign values to inventions, knowledge, and techniques. With the recent increase in the number of industry crimes, an increasing number of national industrial technologies and original high-tech inventions are being leaked out overseas, which not only causes great property damage but also retards industrial progress. This is a great loss to the country [1, 2].

State secrets or industrial technology are mostly leaked by insiders using diverse media and channels. Government organizations and private companies have adopted digital or electronic documentation systems, which are optimized for information management and security in each group, to prevent any document leakage through online channels such as electronic mail or messenger. However, such electronic documents are easy to modify and fabricate, and forgeries are difficult to identify. Therefore, electronic documents cannot perfectly replace paper documents, whose forgeries can be identified because of the physical properties of paper. Important information is still stored in paper documents. Accordingly, the security of paper documents is also essential to prevent leakage of secrets or technology information, and thus, various attempts are being made to enhance offline security [3, 4]. A representative technique in this regard is the electronic article surveillance system, which uses functional papers embedded with security function. An electromagnetic induction sensor is embedded in a paper, and when this paper is taken out of a security zone, an antenna gate installed at the boundary of the security zone detects the paper. This security paper is an electromagnetic-sensing paper and can be detected using either electromagnetic

(EM) or radio frequency (RF) method. In the EM method, when a paper embedded with a soft magnetic material such as permalloy and ferrite passes through a magnetic gate, an AC magnetic field changes, which generates a harmonic. The paper is detected due to this harmonic. On the other hand, in the RF method, when a paper embedded with a resonator, which is a conductive material with a particular LC value, passes through an antenna gate, a resonant frequency is detected, thereby identifying the paper [5, 6]. The EM method is typically applied in the form of a microwire and fabricates security papers by installing a tag on each sheet of the document. However, it has a short recognition distance and, thus, low efficiency of document detection. The RF method, especially the RFID technique, ensures a long recognition distance of the tag, and as an ID is granted to the IC chip of the tag, document management becomes efficient. However, for the application of this technique to security papers, each document sheet needs to be equipped with an IC chip, which is both difficult and expensive. If a single RFID tag is used, to save cost, documents can be stolen with a little damage caused to the tag. Recently, chipless RFID technology has been studied to overcome the disadvantages of using this RFID chip [7, 8]. In [7], the miniaturized chipless RFID was proposed for identification sensor using millimeter wave and designed by applying cavity structure. The miniaturized RFID tag proposed in this study can be applied to various applications such as identification, tracking, and management of arbitrary objects. However, in order to realize a cavity effect, a via hole process is required together with a substrate having a certain thickness, so that it can be applied only to a limited physical range of documents where security is required. Another study of chipless RFID is [8]. In this paper, chipless RFID with split ring resonator (SRR) structure was designed and printed by printing conductive ink on A4 paper. Chipless RFID can confirm the resonance at the point where the tag and the leader of the SRR manufactured by printing method are aligned, because it is recognizable at the very close distance between the reader and the tag and is difficult to recognize at the point where the alignment is out of alignment. Chipless RFID technology can be applied to efficient document management by assigning IDs to books, file binders, and document bundles, but it is difficult to apply to the theft and leakage management of a piece of paper documents.

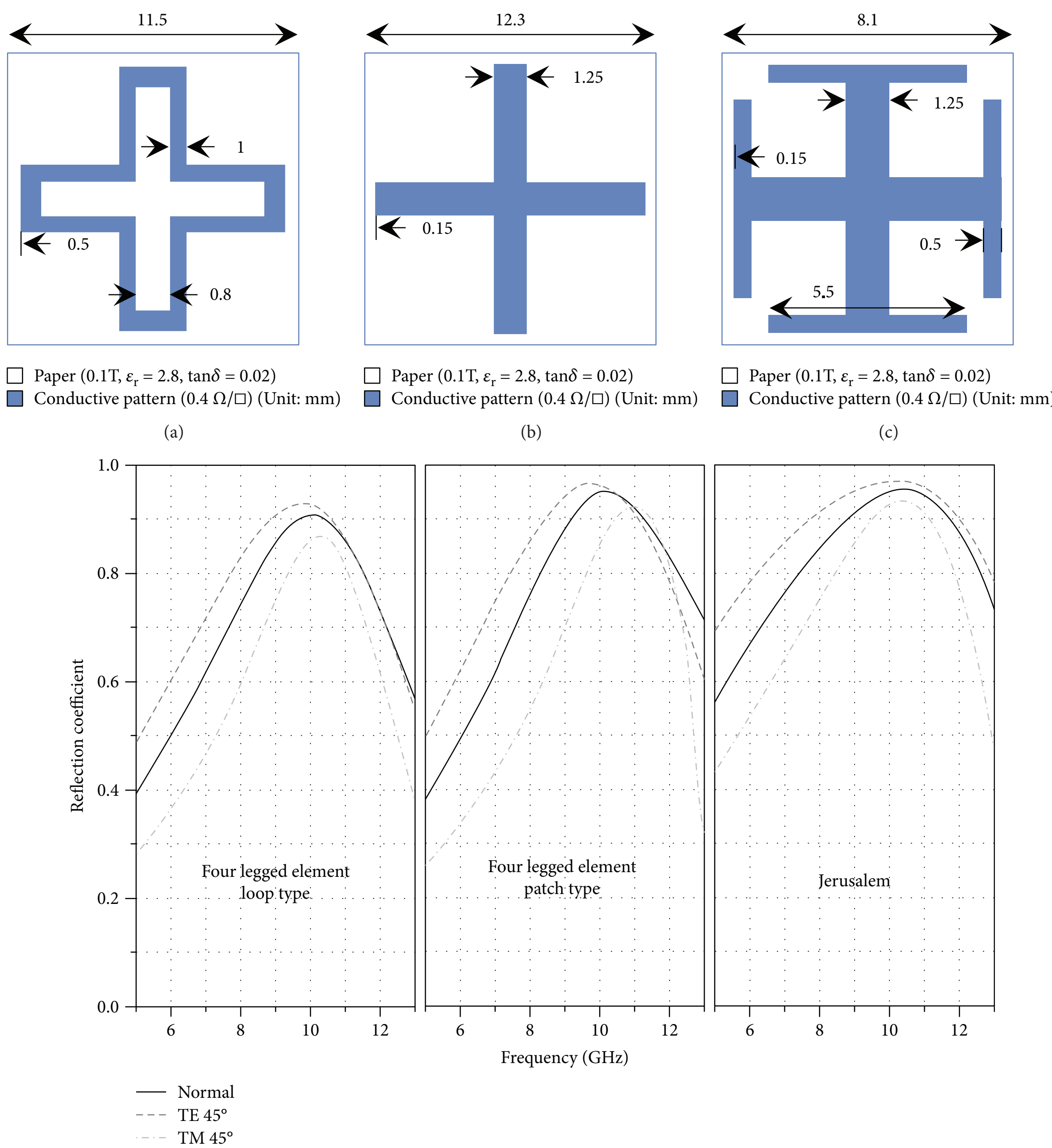
To address the above limitations, this study fabricates a security paper by applying the frequency-selective surface (FSS) technology, which is available at the microwave band. An FSS is developed by arraying a pattern of conductive materials periodically and infinitely on a dielectric substrate. This surface functions as a spatial filter and is mainly applied to radome, main/secondary reflectors, and the frequency control of indoor environments [9–11]. The frequency-selective surface structure is a structure that acts as a spatial filter that selectively transmits or reflects the incident frequency. This characteristic is applied to the object detection sensor, and it is possible to design the structure in a coplanar plane, which is applied to paper to detect leaked documents.

An FSS is traditionally fabricated in the form of a printed circuit board. However, this method is complex and has low efficiency. Besides, as harmful substances are generated during the fabrication, the application is limited. To fabricate each sheet of a document as FSS-based security paper, a new method that considers issues such as applicability in paper, workability, mass production, and cost needs to be developed [12]. This study attempted to prevent the leakage of paper documents by applying the FSS technology to fabricate an electromagnetic security paper. Conductive silver ink was printed on a sheet of A4 paper by using the screen printing technique. The electromagnetic security paper thus was fabricated and operated at X-band. The screen printing technique is easy and incurs low production costs. In addition, a gate system with a transmitter-receiver system that can detect X-band RF signals was fabricated to verify the performance of the security paper with a frequency-selective structure. Detection distances for a person carrying the security paper were measured according to the number of folds. In this way, the applicability of the proposed security paper to a real security system could be examined.

2. Design and Fabrication of Security Paper

When an electronic detection system using RF signals is installed in a space, each document needs to pass an antenna gate before being carried out of the security zone. To detect papers without any recognition error, a security paper that exhibits good performance in terms of frequency reflection and is stable against incidence angles and polarization of incident wave needs to be designed. In addition, folded or crumpled security papers can be detected by downsizing the unit structure such that a single sheet of A4 paper can hold as many unit structures as possible.

To meet these performance requirements, this study designed a loop structure that can cut off frequency at the X-band by using a four-legged element structure with narrow-band property. Incidence angles of 0°and 45°at TE and TM polarizations were applied to observe the stability for polarization and incidence angles. The incidence angle stability was 2.6% (261 MHz), and the reflected power at normal incidence exhibited a reflectivity of 82.3%. Next, a cross-shaped patch structure was designed to ensure 90% or more reflection performance. The reflection performance of the patch structure at normal incidence was improved to 90.3%, but the incidence angle stability was 7.1% (732 MHz), which corresponded to a 4.5% decrease from the four-legged element structure. To address this problem, a Jerusalem structure was designed by adding an end-loading element, which is a capacitance element, to the patch structure. HFSS, a commercial electromagnetic analysis software, was used to verify the electromagnetic performance of the designed pattern. For the structural analysis and simulation, a paper with 0.1 mm thickness ($\varepsilon_r = 2.8$, $\tan\delta = 0.02$) was used as the dielectric substrate and a sheet resistance of 0.4 Ω/□ was assumed to design a conductive pattern satisfying the reflected power of 80% or higher. The electromagnetic property simulation of the Jerusalem structure, which was finally adopted for the security paper, showed an incidence angle stability of 2.2% (232 MHz) and a reflection performance of 90.7% at normal incidence, indicating the

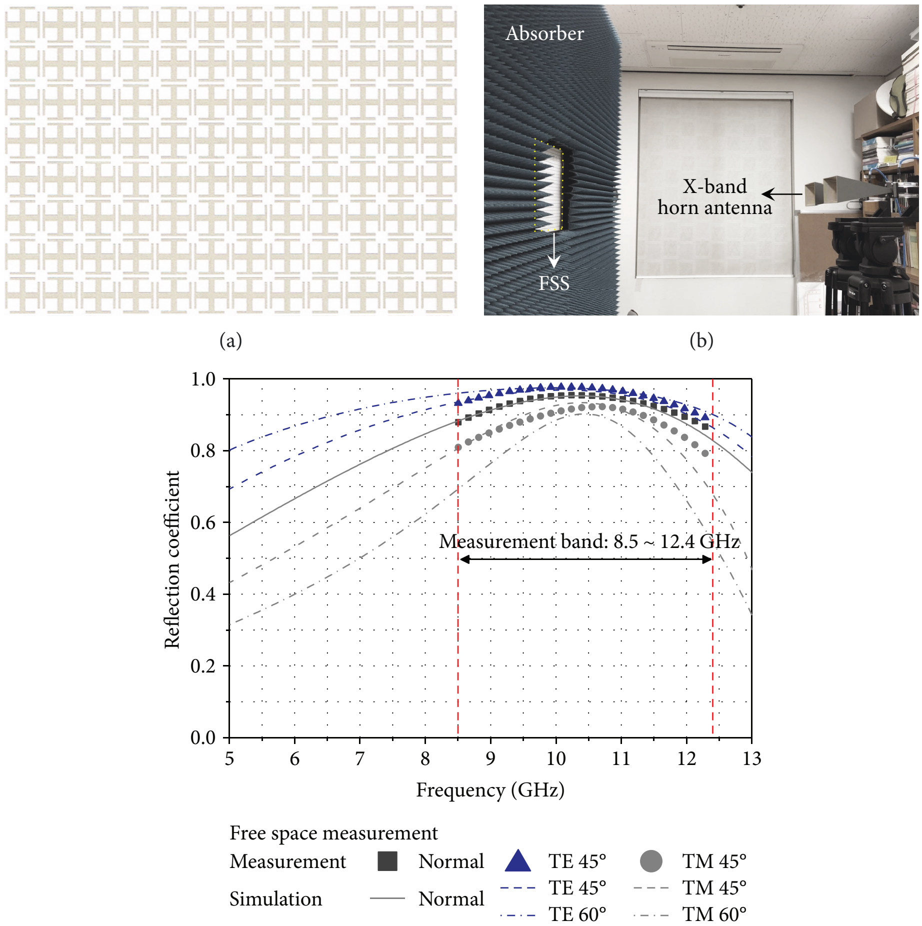


(d)

Figure 1: Proposed FSS unit cell and simulation results: (a) loop type; (b) patch type; (c) Jerusalem cross type; (d) free space measurement results.

applicability to the security paper. The FSS unit structure proposed in this paper is shown in Figures 1(a)–1(c). The frequency reflection properties of the proposed structure are depicted in Figure 1(d).

Based on the simulation result, the Jerusalem structure exhibiting the best values of incidence angle and reflectivity was applied to fabricate a security paper, as shown in Figure 2(a). The security paper was developed by printing conductive silver ink on an A4 paper using the screen printing method. In case a conductive pattern is printed on an ordinary paper, the ink is absorbed, the sheet resistance is lowered, and thus conductivity decreases. This makes it difficult to achieve the designed electromagnetic performance. Accordingly, this study used silver ink with a high viscosity of 28000 cPs at 20°C to form a conductive pattern on an ordinary paper, where 1 cPs is the viscosity of water at 20°C. The screen printing technique was applied to print high-viscosity silver ink on an ordinary paper, and a thermal curing process was conducted for 20 min at 150°C to improve the sheet resistance after printing. Consequently, a conductive pattern with



(a) (b) (c)

Figure 2: Fabricated security paper and measurement results: (a) fabricated security paper; (b) free space measurement setup; (c) reflection characteristics.

a 6 μm thick ink layer and 20.1 mΩ/□ sheet resistance was formed, and the security paper had a thick conductive ink layer and good conductivity. As shown in Figure 2(b), the free space method was used to measure the electromagnetic wave reflection property of the fabricated security paper. Figure 2(c) shows the measurement result. The resonance frequency was 10 GHz, showing 1.12% (117 MHz) error for the design value and 0.5% (50 MHz) and 2.1% (220 MHz) errors at an incidence angle of 45° for the TE and TM modes, respectively. Thus, the measurement result agreed well with the simulation result. The surface resistance is proportional to the resistivity of the material and is inversely proportional to the thickness and linewidth. The frequency-selective surface is printed with a thin ink layer to produce a uniform sheet of security paper; we designed a Jerusalem structure with a thick line width. In frequency-selecting surface unit structure by miniaturization, the number of unit structures arranged on A4 paper size can be increased to improve detection performance and to design a security paper with stable polarization and incident angle. There is a convoluted element structure as a way to minimize the frequency-selective surface applicable to security paper. The convoluted element method uses a complicated shape to form a dense pattern inside the unit structure, thereby increasing the reactance component and miniaturizing the structure. In the future, it is possible to design a miniaturized unit structure with minimum linewidth that guarantees the surface resistance performance and to realize more reliable security paper through printing technique capable of thin line width printing.

3. Measurement of Signal Strength of Security Paper

The RF-based detection system for the security paper was integrated into the gate located in the boundary of the security zone. As shown in Figure 3, the system comprises an RF signal generator, a transmit/receive antenna, and a measuring device for received signals. The signal generator applied 10 GHz signals of the X-band and 0 dBm power to a transmitting antenna, and signals from this antenna were reflected from the security paper with 10 GHz reflectivity and input into a receiving antenna. Six receiving antennae were used and configured in a 2×3 array to receive signals in any direction, and six received signals were averaged. One sample was collected every 10 ms, and thus, 100 datasets

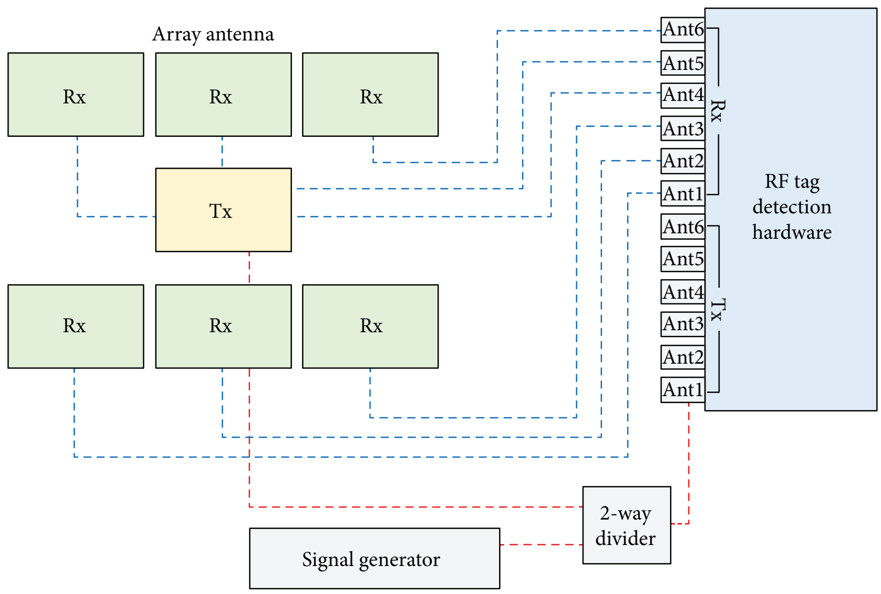


Figure 3: RF security paper detection system block diagram.

were analyzed within 1 s. The received signal strength indication (RSSI) was measured, and data were collected in a nonreflection environment, where no reflecting object exists. After this environment was prepared, the antenna gate was opened and the above data collection was performed when a person passed through the antenna gate. In comparison with the existing data collected from a nonreflection environment, if the measured data were equal or lower than the signal strength of the nonreflection environment, it was concluded that there was no reflecting object and, thus, the security paper was not leaked. Otherwise, it was concluded that the security paper was being leaked on the basis of selective reflecting of a 10 GHz signal. In this case, alert should be given to a security staff and the leakage of security paper can be prevented in advance. Figure 4 presents the detection algorithm of the designed security paper detection system. To verify the detection distance performance of the fabricated security paper, the proposed system was implemented as a measurement environment, as shown in Figure 5(a), and the received signal strength was measured according to the detection distance. Figure 5(a) shows a diagram of the security paper detection environment. The RF tag detection hardware on the back of the transmitting and receiving antenna consists of the RF measurement device for RSSI detection and the detection algorithm shown in Figure 4. In this measurement system, the measurement sample is applied to the front of the antenna, and the maximum distance between the antenna and the sample is 1 m. In addition, it can be applied like an antenna gate by applying the transmission/reception antenna facing to the measurement environment. As mentioned above, the RF measuring system comprises one transmission horn antenna, six receiving horn antennae, one signal generator, and one spectrum analyzer. The transmission antenna sends 10 GHz signals of 0 dBm magnitude. Figure 5(b) shows the image of the gate for the fabricated security detection system.

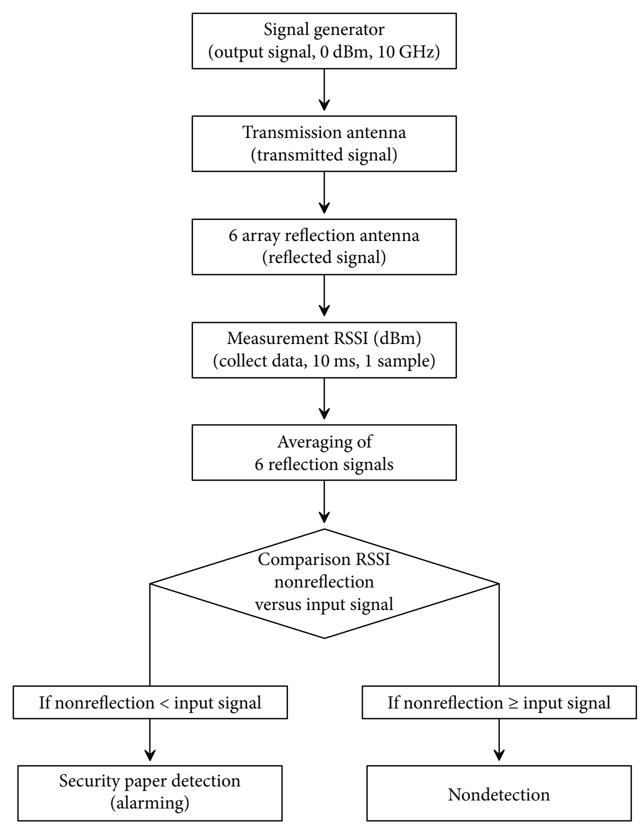
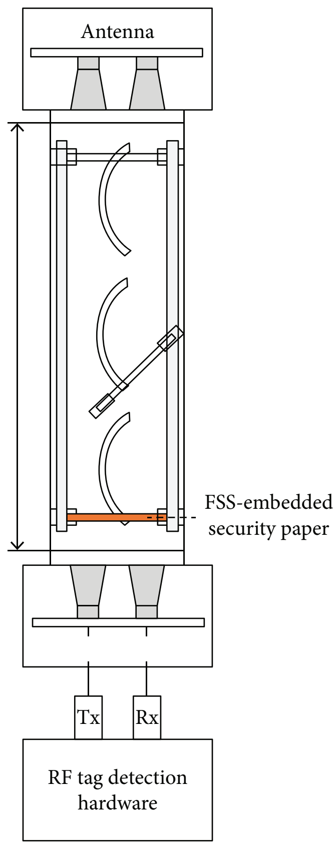
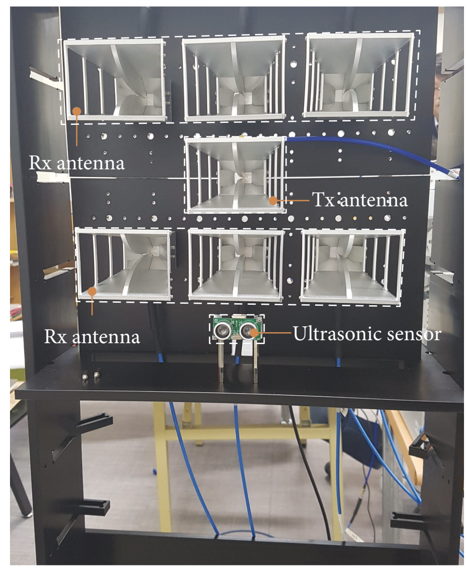


Figure 4: Algorithm of security paper detection.

The detection distance was measured according to the number of folds in the security paper. This measurement aimed to verify the performance of the paper in a case where someone leaks the paper by folding or crumpling it, to damage the embedded electronic sensor. This paper is a concept to detect the leakage of security paper by measuring the magnitude of received signal for transmission signal, and it is



(a)



(b)

Figure 5: Security paper detection system setup: (a) security paper detection system setup (top view); (b) fabricated security paper detection antenna setup.

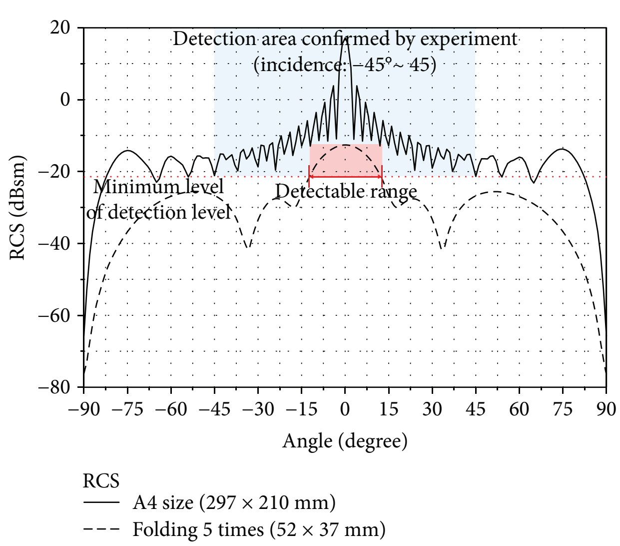


Figure 6: Simulated results of RCS analysis on PEC plate size change.

theoretically related to radar cross section (RCS). RCS analysis was performed to theoretically explain the reason why we measured A4 size 5 times folded security paper up to 1 m as shown in Figure 6. Assuming a PEC plate of A4 paper size (290 × 210 mm) and a PEC plate of size 52 × 37 mm (A4 size) folded five times, the RCS at 1 m was analyzed to calculate the reflection area for the size change of security paper. In this paper, we measured the incident angle of 45° by measuring the frequency reflection characteristics of A4 size security paper and confirmed the stable performance. Based on this, we assume that the RCS level when the incident wave enters the A4-size PEC plate at a distance of 1 m to 45° is the minimum detection area and compared the RCS level of the PEC plate folded five times on A4 paper. RCS performance is smaller than that of A4 size PEC plate when A4 paper is vertically incident on PEC plate of 5 times fold size, but RCS performance is improved than when it is incident at 45° on A4 size PEC plate. Therefore, in the case of vertical incidence, the maximum detection distance of security paper that folded A4 size paper 5 times was determined as 1 m. For an A4-size security paper folded in half five times, the detection distance was measured from 30 to 100 cm at 5 cm intervals. The number of unit structures for each fold is listed in Table 1.

As shown in Figure 7, the measurement results were compared between the nonreflection environment without FSS specimen and RSSI of FSS-embedded security paper.

As a result, the A4 paper folded three times was well detected at 1 m distance; the 1/16 size paper, which was folded four times, could be detected as far as 0.9 m away; and the 1/32 size paper, which was folded five times, was

Table 1: Number of unit cell for folding paper.

Count	Folding, cutting Size (mm)	Number of unit cell Jerusalem
0	A4 (297 × 210)	35 × 25
1	A4/2 (210 × 148)	25 × 17
2	A4/4 (148 × 105)	17 × 12
3	A4/8 (105 × 74)	12 × 8
4	A4/16 (74 × 52)	8 × 6
5	A4/32 (52 × 37)	6 × 4

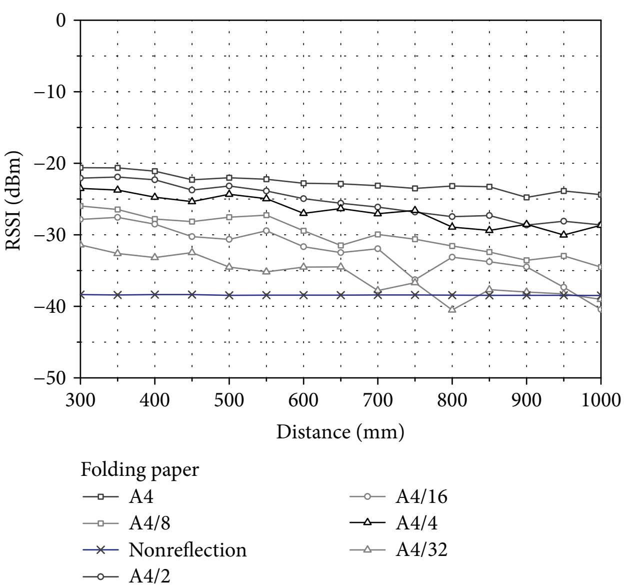


Figure 7: Measurement results of detection distance for folding paper.

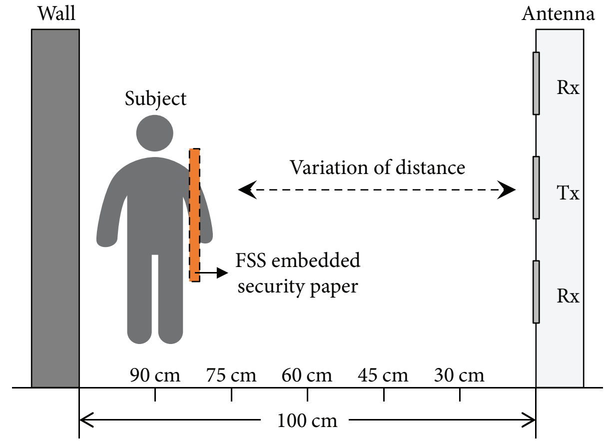
Table 2: Specification of security paper tester.

Subject	Height (cm)	Weight (kg)	Body shape
A	179	90	Fat
B	179	64	Slim

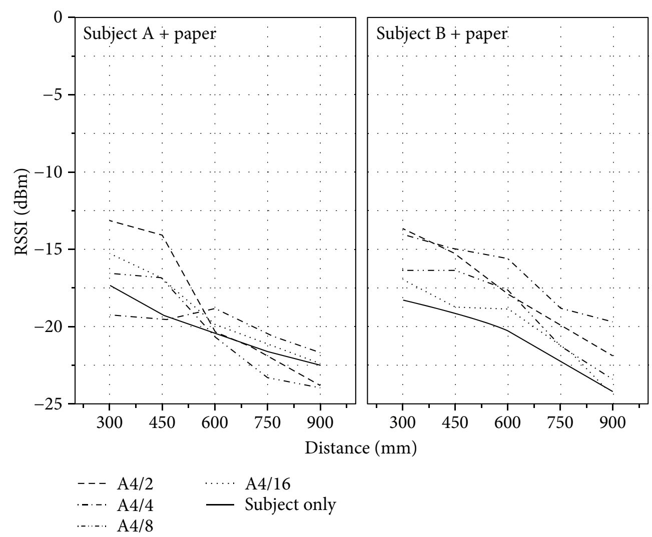
detected at 0.65 m. Thus, even if the proposed security paper was taken out, folded, or crumpled, it could be detected.

As security papers are stolen by persons in reality, the electrical impact of an antenna gate on a person who is passing through it needs to be considered. In this study, another measurement of detection distance was conducted for persons carrying a folded security paper. To observe the electrical influence according to different physiques, the measurement was performed for two persons: subject A with robust frame and subject B with thin frame. Table 2 provides detailed information of the subjects.

Persons of the same height were selected to ensure the same measurement condition, and each subject attached a security paper on the chest. The subjects are facing toward the front of the antenna. Reflected signals from the tester were measured for vertical incidence. By the security paper



(a)



(b)

Figure 8: Measurement of when a human has security paper: (a) measurement scenario when a human has security paper; (b) measurement results of when a human has security paper.

detection algorithm in Figure 4, the RSSI for the subject can be compared to the RSSI for when the subjects has the security paper in the body, and the security paper can be detected if it is measured higher than the tester's RSSI. Through the RSSI measurement of the subject, the electrical influence on the change of the body was analyzed and the stronger physique of subject A by the RSSI comparison of subjects A and B confirmed that the RSSI is higher at the distance of more than 0.6 m. While subjects A and B were carrying folded security papers, the detection distance was measured. As shown in Figure 8, when subject A was located further than 0.6 m, the reflection of the body was larger than that of the paper, and thus, detection was not successful. In contrast, when subject B stood 1 m away, the paper was well detected. This result indicates the necessity of considering various scenarios in an experiment before applying the proposed electromagnetic security paper to real security gate systems. Nevertheless, the proposed security paper has turned out to an effective security solution.

4. Conclusions

This study used an FSS for designing and fabricating a security paper in order to prevent the leakage of classified documents. A security gate with transmitting and receiving antennae, which could detect RF signals at the X-band, was also fabricated to verify the performance of the fabricated security paper. Since a security paper needs to have stability for incidence angle and excellent reflection performance, the well-known Jerusalem structure was adopted as the unit structure for the design of FSS security paper. Based on the simulation results, the security paper was fabricated by printing highly viscous conductive silver ink on an ordinary A4 sheet by the screen printing method and then conducting a thermal curing process. To verify the electromagnetic security paper thus fabricated for a security system, the fabricated gate system embedded with X-band RF transmitter and receiver was used. The detection distance was observed by measuring the strength of the received signal according to distance. To verify the applicability of the security paper, the measurement was conducted for two cases. In the first case, the paper was folded, and in the second case, the subjects were advised to carry such folded papers. When an A4 sheet was folded to 1/32 of its original size, it could be detected as far as 0.65 m away. In case a person was carrying the security paper, the subject with a robust build was electrically more affected by the detection system, and hence, the security paper was difficult to be identified. Consequently, further studies need to focus on minimizing the effect of the antenna gate on the human body and consider various scenarios. However, it is still obvious that the proposed electromagnetic security paper is applicable as a security solution.

Data Availability

The simulated and experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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