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LETTER

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Paper-based frequency selective surface for stable angle of incidence

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Abstract: In this letter, a paper-based frequency selective surface (FSS) attachable to building walls using the ink-jet printing technique is presented using the novel type of FSS at Ku-band. The proposed paper-based FSS has frequency stability for different incidence angles and polarizations and wide band-stop bandwidth. Simulation was performed using a commercial EM software to obtain the transmission loss of the structure and then the measurement results of the fabricated one were compared. The comparisons between the simulation and measured results show good agreements.

Keywords: frequency selective surface, ink-jet printing, stable angle of incidence

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

The exponential growth in wireless communication, results in heavy usage of the radio spectrum, especially the unlicensed bands, which increasingly leads to a degradation in wireless communication particularly with channel congestion in

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indoor environments. For the communication environment in a secure building, a conference room, or in the intensive care unit of a hospital where life-supporting medical instruments are installed, providing limited radio communication service coverage and achieving wireless security from outside the building or room using complete electromagnetic wave shielding structure are required [1]. Therefore, it is necessary to find a way to ensure both the efficiency and security of limited radio resources by preventing the leakage of radio waves inside the building or the infiltration of unwanted wireless signal from outside at relatively low cost. The conventional approach to block intentional wireless communication is to install a solid metallic-shielded enclosure. However, this approach can be costly and labor-intensive.

In recent years, ink-jet printing is an inevitable process to fabricate variable electronic components. Conventional chemically etching technique, which is time-consuming, expensive, and involves very complicated processes, has been widely adopted in the printed circuit board (PCB) industry to manufacture many circuits [2]. The ink-jet printing technology has very several advantages, including low cost and a cleanable process other than the conventional lithographic technology. Therefore, the ink-jet technology may be cost-effective means of production for certain scales of production of frequency selective surfaces (FSS) [3]. Paper-based FSS can reduce the above-mentioned problems with recent proposals to provide band-selective screening within buildings to reduce co-channel interference and to increase the signal-to-interference ratio by rejecting interfering signals from adjacent buildings. Recent studies have been mainly conducted with focus on implementing FSS on windows [4], and there have also been studies that attempted to install FSS structures on the walls [5]. An FSS is a surface that exhibits reflection or transmission properties as a function of frequency. The frequency response of the FSS is determined by several design parameters, such as conduction element length, inter-element spacing, and substrate thickness. Depending on the geometry of the surface's shape, an FSS can efficiently control the transmission and reflection of the incident wave, and it also has a spatial filter behaviour [6]. Traditional FSS consists of periodic patch elements or slot arrays of simple elements backed by a supporting dielectric layer. These planar FSS structures are easy to fabricate but have performance limitations in terms of being susceptible to changes of polarization and sensitive to angle incidence [7].

In this letter we designed a new type of FSS for angle of incidence for paper substrate and demonstrated the use of inkjet printing to realize band-stop FSSs for low cost manufacturing that can be easily applied as wallpaper on the walls of a room without the structural loading issue to existing architecture.

2 Simulation and measurements

To obtain stable angle of incidence for paper substrate, we designed a novel type of frequency selective pattern. The unit cell of geometry of the frequency selective pattern in the proposed FSSs is illustrated in Fig. 1. The square patch array and the loaded patch on center of four patches are combined to realize a wide band-stop bandwidth due to dual resonance.

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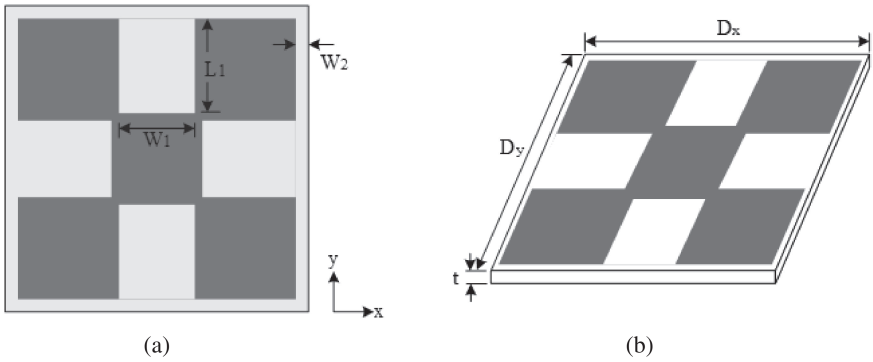

Fig. 1. Unit cell of geometry of the proposed FSS (a) Top view (b) Perspective view

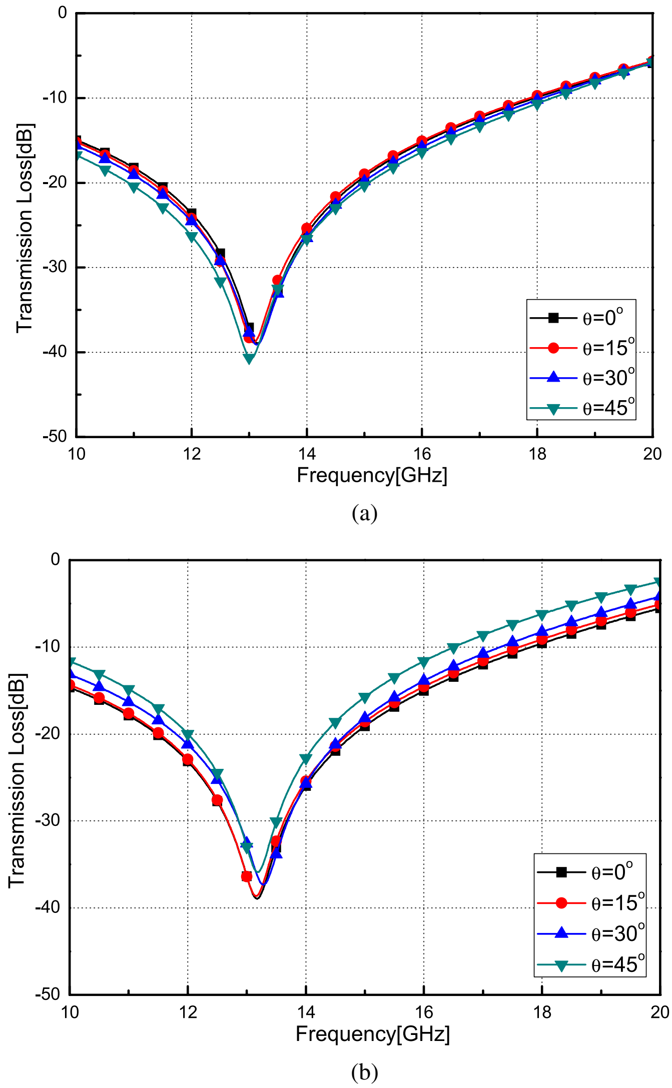

Fig. 2. Simulated results (a) TE mode (b) TM mode

Simulation was done using Ansoft HFSS, which is a commercial electromagnetic (EM) software that utilizes a Finite Element Method to determine the electromagnetic behaviour of the structure and the optimized design parameters. Floquet's ports were used to determine the transmission loss of the proposed FSSs.

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The designed FSS has operating band-stop properties at 13 GHz for Ku band application. The special coated paper with dielectric constant of $\varepsilon_r = 3.0$, dielectric loss tangent of $\delta = 0.02$, and thickness of 180 µm was used as substrate.

Fig. 2(a) and Fig. 2(b) show the simulated results for the angular stability of the resonant frequency of the proposed FSSs at normal incidence (0°), 15°, 30°, and 45° for TE and TM polarizations, respectively. Results also showed that the proposed FSSs have the expected band-stop characteristic centered at 13.2 GHz and are very stable, with only 0.9% difference for resonant frequency, for each different polarization and different incidence angle. For a −20 dB bandwidth, which means 99% band rejection, the simulation showed a wide bandwidth, with 26% for both polarizations.

(a) (b)

Fig. 3. Fabricated paper-based FSS (a) Printed FSS on paper (b) Installed paper-based FSS for measurement

To evaluate the effectiveness of the proposed FSSs at Ku-band, we fabricated the proposed paper-based FSSs as shown in Fig. 3 with the unit cell dimension shown in Fig. 1. The size of the unit cell was 7.4 mm(Dx) × 7.4 mm(Dy) and the height of the paper substrate was 180 µm(t). The designed parameters were $W_1 = 1.6$ mm, $W_2 = 0.1$ mm, and $L_1 = 2.4$ mm. A well-known commercial inkjet printer, MFC-J5910DW of Brother Industries Ltd, USA was used using a disposable piezo ink-jet cartridge. This printer can create and define patterns over an area of about A3 paper size and has a resolution of up to 1200 × 6000 dpi. A silver nanoparticle conducting ink in ethylene glycol and ethanol of AGIC-AN01, which was provided by AgIC Inc. of Japan, was used for ink-jet printing. It was characterized as having 15% silver, surface resistance of 0.2 Ω/□, viscosity of 2–3 mPa·s and surface tension of 30–35 mN/m at 25°C. The specially coated paper from AgIC Inc., with a dielectric constant of $\varepsilon_r = 3.0$, loss tangent of $\delta = 0.02$, and thickness of 180 µm was used for FSS printing during the simulation.

The transmission loss of the proposed FSS was measured by the Ku-band free-space measurement system consisting of standard horn antennas. The prototype was placed in an anechoic chamber where transmitting and receiving horn antennas on opposite sides were placed facing the proposed FSSs surrounded by the absorbers to mitigate any scattering effect of the fixture holding the proposed structure as shown in Fig. 3(b).

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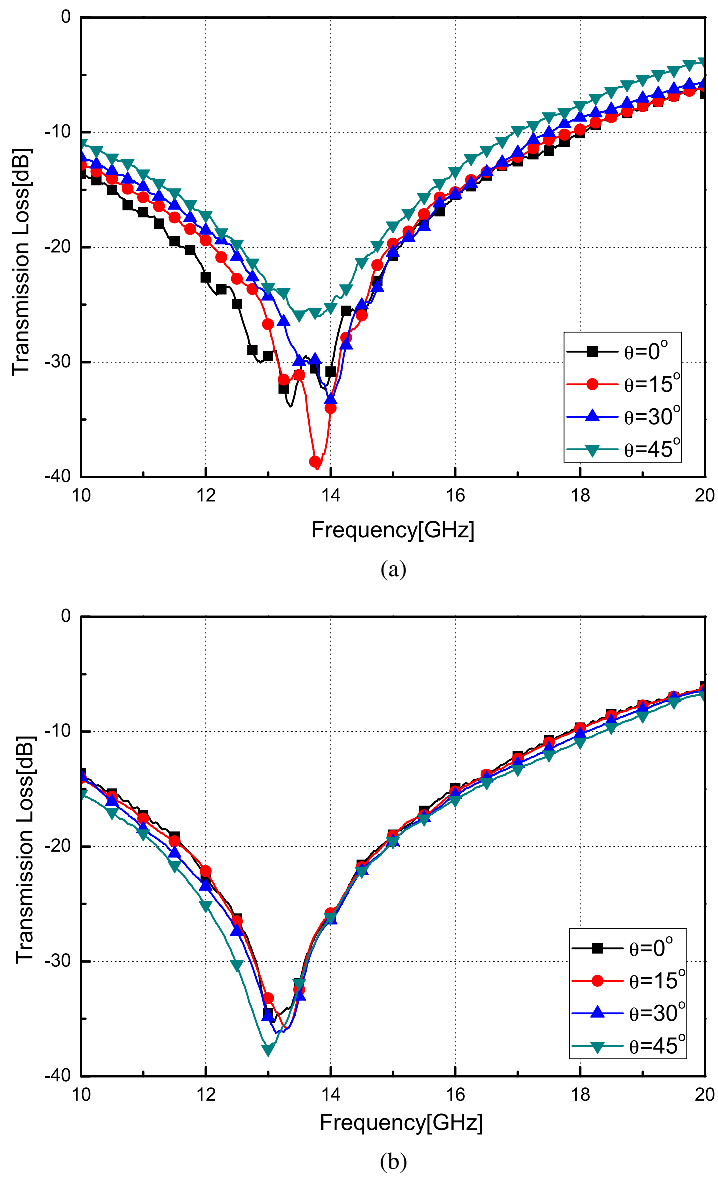

Fig. 4. Measured results (a) TE mode (b) TM mode

The measured angular independent operation of the proposed FSSs for TE and TM modes of polarization is depicted in Fig. 4(a) and Fig. 4(b), respectively, in which transmission loss for varying angles of incidence was substantiated. From the measurement results, it was observed that the proposed design at normal incidence (0°), 15°, 30°, and 45° for both TE and TM polarizations provides a very stable resonant frequency of 13.3 GHz. For TE and TM modes of normal incidence, the results showed that the measured −20 dB bandwidth for 99% power absorption for both modes are 3.43 GHz and 3.15 GHz at the resonant frequency, respectively. Additionally, all characteristics of the measurement results agree with those of the simulation at target frequency. The results implicitly mean that the transmission property of the proposed FSS is independent for both TE and TM modes of polarization of the incident plane wave.

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3 Conclusion

This letter presents the simulation, fabrication and measurement results of the paper-based FSS attachable to building walls using the ink-jet printing technique. The proposed paper-based FSS has frequency stability for different incidence angles and polarizations and wide band-stop bandwidth. Simulation was performed using a commercial EM software to obtain the transmission loss of the structure and then the measurement results of the fabricated one were compared. The proposed FSS was fabricated using a commercial ink-jet printer and silver nano conductive ink. It was observed that the design provides stable resonant frequency characteristics for polarization and different angles of incidence as well as a wide band-stop bandwidth as expected. The possibility of directly printing onto the paper substrate also means the possibility of mass product by roll-to-roll printing method, which is an attractive option for frequency selective control that occupies a large surface area.

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