Sheetlike Waveguide for 2.4 GHz and 5 GHz Bands

Kunsun Eom and Arai Hiroyuki

We present a useful design for a free access mat which supports two frequency bands of 2.4 GHz and 5 GHz. The free access mat is a sheet-shaped waveguide which consists of a tightly coupled double-layered microstrip resonator array. It provides easy access for devices in short-range wireless communications. Interference is a common problem with conventional applications which use free space transmission. Our proposed wireless access system uses a subsidiary waveguide, the free access mat. Wireless devices are proximately coupled to the free access mat through which the coupled electromagnetic (EM) wave transmits. The arrival domain of the EM wave of an application is therefore limited to an area close to the free access mat. Wireless devices can be coupled to the free access mat at an arbitrary position without contact. We previously presented a free access mat for a single frequency band. This paper presents a free access mat for the two frequency bands of 2.4 GHz and 5 GHz. The free access mat uses a ring patch resonator array which is easily excited by typical antennas and is resistant to interference. These characteristics are demonstrated by numerical simulation and confirmed by experiment.

Keywords: Sheetlike waveguide, free access mat, short-range wireless access, smart space.

I. Introduction

1. Congested Wireless Environment

In indoor wireless environments, many wireless devices are used and the frequency resource is congested. To improve the efficient usage of the frequency resource, limits on the arrival domain of an electromagnetic (EM) wave of an application have been sought. Examples include personal area networks (PANs) and body area networks (BANs) which confine the communication area of the radio to the human body. To limit the coverage area of a single radio system, it is essential to reduce the output of the transmitter and to prevent interference from other systems. Several solutions to this problem have been proposed. Bluetooth and ZigBee were developed to provide protocol- or method-based control of free space transmission, while non-license low-power radio applications with low transmission capacities have also appeared. These conventional systems using free space transmission are relatively easy to implement. On the other hand, the wireless LAN has a comparatively small communication area, leading to interference when many users establish independent communication areas.

A new candidate for this purpose is to use a subsidiary waveguide. This approach restrains the transmission power of the wireless device, couples wireless devices to the waveguide, and lowers transmission loss through the waveguide. The coverage area is thereby limited to an area around the subsidiary waveguide. One example of this is a leaky coaxial cable, but this cannot be used for short-range wireless access [1]-[4]. For a coverage area of one or two meters, for example an office desk, a sheet-shaped waveguide would be useful, given that many wireless devices are used on a desk, on a wall, or on the floor.

Our solution to this problem is to use a sheetlike waveguide. This involves placing a sheetlike waveguide on the desk on

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which wireless devices are placed. These wireless devices couple to the sheetlike waveguide at an arbitrary place on the waveguide and are free to move on the waveguide. The coverage area of the radio system is limited to an area close to the waveguide. The sheet-shaped channel enhances the comfort and usability of the working environment.

The sheetlike waveguide concentrates the EM wave to the waveguide, incurring lower transmission loss than free space transmission loss. To eliminate the effect of multipath transmission resulting from the installation of the subsidiary waveguide, transmission loss has to be sufficiently small. The wireless devices couple to the sheetlike waveguide using built-in antennas (resonators). The sheetlike waveguide should provide easy coupling by typical antennas (resonators), and coupling should be able to occur at an arbitrary position or direction. The coverage area of the radio system, that is, the accessible range of the external antennas, should be small enough that there is barely any interference.

In some previous studies, sheetlike waveguides have been presented. One example is the MAGIC-Surface for the infrastructure of sensor networks [5]. Functions such as direction search, communication, power supply, position detection, and orientation are integrated on an intelligent plane, which consists of an array of micro coils and compasses. A disadvantage of this MAGIC-Surface system is its high cost. A second example is the two-dimensional transmission sheet (2DTS) [6]-[9], which has a simple structure of a conductive mesh layer and a ground, between which the insulating layer is sandwiched. Benefits of this system are that it is easy to fabricate and cheap, and it can be applied to PAN and BAN. In addition, power transfer through the sheet is possible. However, a special coupler is necessary to provide sufficient excitation of the sheet, and the coverage area of its radio systems is insufficiently limited. To overcome the limitations of these systems, a new sheetlike waveguide system is needed which is easy to fabricate and can provide easy excitation by typical antennas. Moreover it should be robust against interference. To satisfy these requirements, we propose the use of the free access mat described in next subsection.

In this paper, we focus on the use of wireless LAN-based applications. When the sheetlike waveguide approach is applied to wireless LANs in the office, the use of several waveguides is anticipated; therefore, their resistance to interference is very important. An additional requirement for wireless LAN applications is that the sheetlike waveguide should support both 2.4 GHz and 5 GHz bands.

2. Free Access Mat

In this paper, we propose the use of the free access mat. The free access mat is a type of sheetlike waveguide which provides easy access for devices in short-range wireless communications of one or two meters [10]. It consists of a double-layered array of tightly coupled microstrip resonators and was initially inspired by the ribbon-wire interconnect [11]-[14]. The ribbon-wire interconnect consists of three layers, namely, the ground, the microstrip resonators, and the parasitic element. The dielectric layers are between those three layers as shown in Fig. 1(a). The patch elements are tightly coupled. It is easy to fabricate and has low transmission loss at a certain frequency. The free access mat has a 2D array of ribbon-wire interconnect shown in Fig. 1(b), which also has low transmission loss at a certain frequency band. The predominant parameter in determining the frequency is the size of the patch on the lower layer. By changing the size of the patch resonators, the center frequency can be controlled. A previously reported free access mat has a resonant frequency around 5 GHz [10]. The size of the patch element on the lower layer is about half the wavelength, while that of the patch element on the upper layer is optimized to have a low insertion loss and is also about half the wavelength. The two patch elements are tightly coupled to each other.

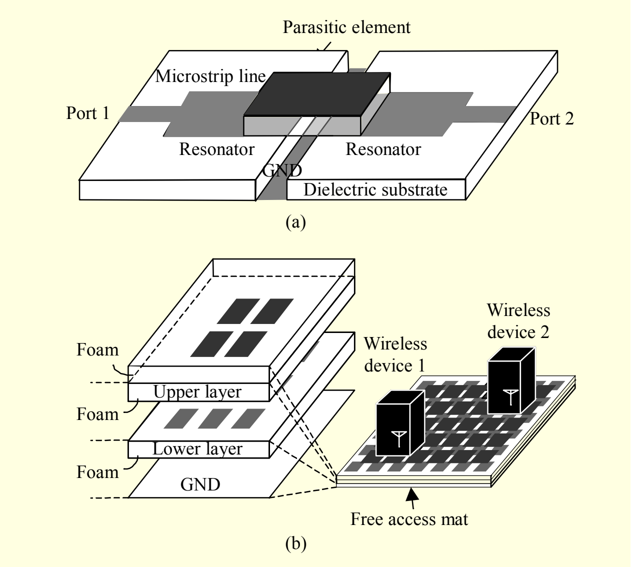


Fig. 1. Configuration of (a) the ribbon-wire interconnect and (b) the free access mat.

The free access mat has a periodic structure. There are other periodic structures, such as frequency selective surfaces (FSSs) and electromagnetic band gap (EBG) structures [15]-[17]. FSS and EBG structures are applied to hybrid radomes to improve the out-band of radar cross section (RCS), band-stop filters, circuit analog absorbers, antenna substrates for surface-wave suppression or for low profile antennas, and so on. They have been also studied as solutions for the interference problem. Most of these FSS and EBG structures consist of a single layer of resonator array. The EM wave reflects from or passes through the structures at a certain frequency. They are installed on a wall or a window; therefore, they prevent leakage of the information to the outside of the room and block the interference which comes through the window. There are also three-dimensional (3D) EBG structures, such as the woodpile structure, which concentrates the EM wave into itself. Some bandpass filters [18], [19] use 3D EBG structures. Most of them are studied for the THz region because of the fabrication problem and the difficulties in constructing a sheet-shaped channel.

The proposed free access mat is a thin sheet-shaped waveguide which enhances the comfort and usability of the working environment. It consists of three layers, namely, two resonator arrays and the ground plane. The EM wave is therefore concentrated into the structure and is transmitted along the free access mat. That is, both the transmitter and the receiver are placed on the same side of the free access mat. We couple wireless devices to the free access mat, and the arrival domain of the radio wave is limited to the area around it. In addition, the free access mat for wideband or dual-band is achievable by optimizing its configuration and size.

The characteristics of the free access mat can be summarized as follows. It incurs low transmission loss of 7.5 dB/λ at a certain frequency band in simulations. The EM wave couples to the free access mat easily using typical dipole antennas at arbitrary positions. The coupling loss of two dipoles is estimated to be less than 6 dB. Symmetrical configuration also allows the easy coupling of antennas regardless of polarization. In addition, the free access mat is robust against interference, allowing coupling with antennas only several millimeters high. Physically independent free access mats do not interfere with each other. As previously mentioned, these are suitable for application in offices using wireless LANs.

II. Free Access Mat with Ring Patch Resonator Array for Dual-Band Operation

In this section, we present the design of the free access mat for dual-band operation in the frequency bands of 2.4 GHz and 5 GHz for wireless LAN. The predominant parameter determining the resonant frequency is the size of the patch on the lower layer. We consider two simple structures. The first connects the patches on the lower layer by thin microstrip lines. The patches on the lower layer and the microstrip lines give resonances at 5 GHz and 2.4 GHz, respectively. This configuration provides low transmission loss at the two desired frequency bands [20]. However, when we coupled dipole antennas to the free access mat, the height of the coupled antenna around 2.4 GHz was too high to restrict the coverage area and to eliminate the effect of interference. Coupling at 2.4 GHz is performed by the microstrip lines which are not covered by the patches on the upper layer. The high accessible height of the external antenna is due to exposure of the resonating part. Therefore, we moved to the second design, which has no uncovered resonating elements. The second design has apertures on the patches on the lower layer. These patches work like ring patch resonators. None of the elements on the bottom layer are fully exposed.

1. Design Providing Two Resonant Frequencies

We first designed a single-patch resonator with an aperture (a ring patch resonator) as shown in Fig. 2(a). The S_{11} characteristics were simulated using the moment method [21]. The simulated S_{11} characteristics are shown in Fig. 2(b). The ring patch resonator has two resonant frequencies at 2.4 GHz and 5.12 GHz. Figure 2(b) also shows the current distribution at each frequency. The resonance at 2.4 GHz is the main resonance of the ring patch resonator, while that at 5.12 GHz is the first harmonic resonance. The ring patch resonator was arrayed on the lower layer. The other parameters, namely, the gap between ring patch resonators, g, and the size of the patch on the upper layer, p, were optimized to have low transmission loss at two frequency bands. The circumference of the ring patch resonators ($4a_{\text{out}}$) was set to one wavelength at 2.45 GHz.

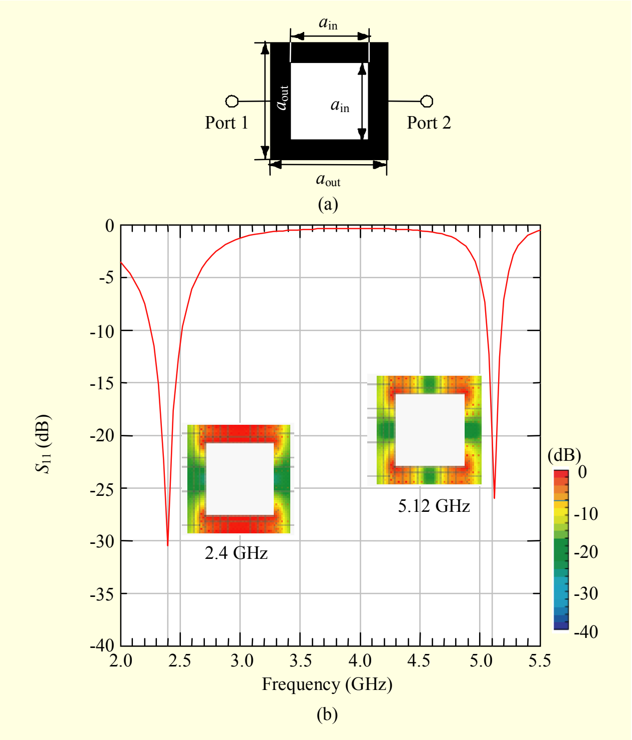
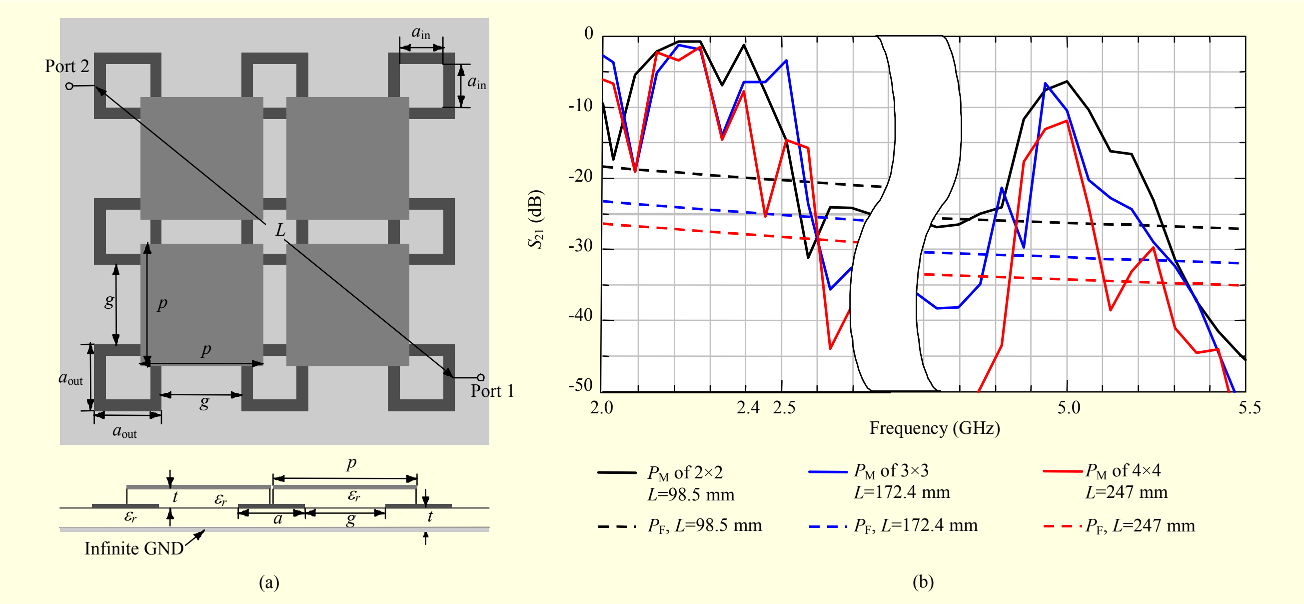


Fig. 2. Single ring patch resonator: (a) configuration of ring patch resonator (a_{out} = 30 mm, a_{in} = 20 mm, ε_r = 2, t = 0.8 mm) and (b) S_{11} characteristics and current distribution.



(a)

(b)

Fig. 3. Free access mat with ring patch resonators: (a) configuration of a free access mat with a 3×3 ring patch resonators array ($a_{out} = 30$ mm, $a_{in} = 20$ mm, $p = 46$ mm, $g = 23$ mm, $\varepsilon_r = 2$, $t = 0.8$ mm) and (b) simulated S_{21} characteristics around 2.4 GHz and 5 GHz, where L is the distance between two ports, P_M is the transmission characteristics through the free access mat, and P_F is the free space transmission loss.

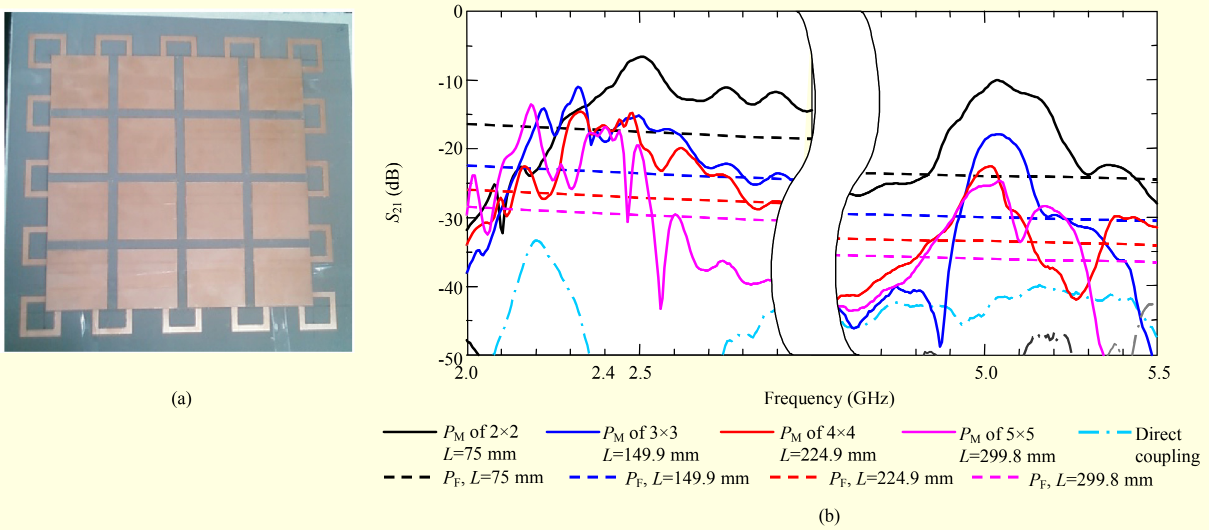
When the size of the inner ring, a_{in}, increased, the resonant frequency around 2.45 GHz decreased. The size of gap g was optimized to incur low insertion loss at both frequency bands. The size of the patch element on the upper layer, b, was optimized to incur low transmission loss at both frequency bands and is about one-half the wavelength at 2.45 GHz. These patch elements were well coupled to each other. All the elements were tightly coupled, requiring the optimization of parameters. Configuration of the free access mat with the ring patch resonator is shown in Fig. 3(a). The input/output ports are assumed to be completely matched to the patch resonator on the lower layer. The distance between ports 1 and 2 is denoted as L. Results with a permittivity of the dielectric substrate of 2.0 fit well with the measured result of the free access mat fabricated using a dielectric substrate of $\varepsilon_r = 2.6$. The dielectric constant changed according to the condition of the bond between the conductor and dielectric body. The resonating element is the ring patch, and sufficient overlapping area is provided by the patch element on the upper layer. This is expected to allow coupling external antennas for both frequency bands to have a low height. Symmetrical configuration provides easy coupling of external antennas at an arbitrary place and direction.

Simulation of transmission characteristics through the free access mat with various numbers of the ring patch resonators and various L values is shown in Fig. 3(b). Transmission loss through the free access mat (P_M) and free space transmission loss (P_F) were simulated. The transmission loss of the concentrated EM wave inside the free access mat is denoted as P_M, while P_F is that of the spherically radiated wave in the free space. When the difference between P_M and P_F ($\Delta L = P_M - P_F$) is greater than 10 dB, the free access mat incurs a transmission loss low enough to eliminate the effect of interference.

Figure 3(b) shows the simulated P_M and P_F with L of 98.5 mm, 172.4 mm, and 247 mm. The P_M values at the two frequency bands of 2.4 GHz and 5 GHz are small. For the frequency band around 2.4 GHz, the smallest P_M is obtained at 2.2 GHz, but ΔL at 2.4 GHz is sufficiently large; therefore, we adopted this model.

The average P_M per wavelength was 3.4 dB/λ at 2.4 GHz and 3.5 dB/λ at 5 GHz. These values are much smaller than the P_F per wavelength of 22 dB/λ because the EM wave is concentrated at the free access mat, while P_F shows the transmission loss of the radiated wave in free space. The P_M for one meter was estimated as 18.4 dB at 2.4 GHz and 20.9 dB at 5 GHz, while the P_F for one meter was estimated as 40.1 dB at 2.4 GHz and 46.4 dB at 5 GHz. The ΔL for one meter was more than 21 dB at both frequencies. In addition, ΔL increased as L increased because of the concentrated wave inside the free access mat. These results demonstrate that the free access mat incurs a transmission loss which is low enough to exclude the effect of multipath interference caused by the free access mat itself.

Transmission loss with the free access mat with a ring patch



(a)

(b)

Fig. 4. Free access mat with ring patch resonator array: (a) fabricated free access mat with a 5×5 ring patch resonator array and (b) measured S_{21} characteristics around 2.4 GHz and 5 GHz when standard dipole antennas at 5 mm height are coupled to the free access mat. "Direct coupling" indicates the measured S_{21} using a reflector instead of the free access mat.

resonator array at two frequency bands of 2.4 GHz and 5 GHz was low. We obtained large ΔL at both frequency bands, making it possible to ignore the effect of the multipath transmission arising from the free access mat and interference.

Coupling between external antennas and the free access mat in practical usage requires further investigation. Experiments using the coupling of standard dipole antennas to the free access mat with ring patch resonators are described in the next subsection.

2. Measured Small Transmission Loss and Easy Coupling by External Antennas

We fabricated the free access mat using a commercial dielectric substrate as shown in Fig. 4(a). It has ring patch resonators arrayed in a 5×5 configuration on the lower layer and 16 patches on the upper layer. The parameters were the same as those in the simulated model shown in Fig. 3(a). Patches on the upper layer were set in place in the middle of the four ring patch resonators on the lower layer and affixed using scotch tape.

We prepared two pairs of standard dipoles, one with a resonant frequency around 2.4 GHz and the second at around 5 GHz. Transmission characteristics were measured with various distances between two dipole antennas (L) at the height of 5 mm. One pair of dipoles was coupled to the free access mat, and the EM wave transmitted through the free access mat. The S_{21} characteristics were measured using a network analyzer with L changed from 75 mm to 299.8 mm. We moved the dipoles over the same free access mat. We then changed to another pair of antennas with the same resonant frequency.

The measured S_{21} characteristics around 2.4 GHz and 5 GHz are shown in Fig. 4(b). This figure also shows P_F for the same L and the mutual coupling between two dipole antennas over the reflector instead of the free access mat (shown as direct coupling). The measured P_M included the coupling loss of the two dipoles. The P_M was small at both 2.4 GHz and 5 GHz, even when the direct coupling was less than –40 dB. The small transmission loss therefore originated from the concentration of the wave into the free access mat. Because L with 2×2 was about a half wavelength, the P_M with 2×2 was much smaller than that of the other array. This indicates that the direct coupling was stronger than that of the other array. In addition, the variation in P_M was smaller than the variation in P_F as L changes. This was caused by the concentration of the EM wave into the free access mat. The ΔL for each L was larger than 10 dB at 2.4 GHz and 11 dB at 5 GHz. A large ΔL was also obtained when the coupling loss of two dipole antennas was included.

The average P_M per wavelength was also small, measuring 9.5 dB/λ at 2.4 GHz and 6.9 dB/ λ at 5 GHz. The P_M for one meter was estimated as 28.7 dB at 2.4 GHz; the P_F for one meter was 40.1 dB. The P_M at 5 GHz for one meter was estimated as 34.6 dB; the P_F for one meter was 46.4 dB. The P_M at both frequencies was much smaller than the P_F. The ΔL for one meter, including the coupling loss of two antennas, was larger than 11 dB at both frequencies. The effect of multipath transmission caused by the free access mat could therefore be ignored.

These measured results show the strong coupling between external antennas and the free access mat. The difference between the simulated and measured transmission losses was due to the coupling loss of the two dipoles used in measurement, which was estimated to be smaller than 6 dB.

The free access mat allows easy coupling with a typical antenna. The measured P_M and ΔL indicate reasonable constraint of the arrival domain of the radio wave of the antennas which are coupled to the free access mat. In addition, antennas on the free access mat were able to access it at arbitrary positions and directions because of the symmetry of the structure. The coupled signal at an arbitrary position travels freely inside the free access mat from point to point.

3. Small Accessible Range and Freedom from Interference

The free access mat is designed to limit the coverage area of radio systems. The first dual-band design was reported in [20]. However, the accessible range of this design is too large to limit the coverage area of the radio wave. The accessible range of the external antenna using the design proposed in this paper therefore requires confirmation. Coupling height should be kept low to maintain security, limit the communication area, and reduce the effect of interference.

Standard dipole antennas were configured over the free access mat as shown in Fig. 5(a), and L was fixed at 149 mm. The height of the two antennas (h) was changed from 5 mm to 40 mm. Transmission characteristics for h at 2.4 GHz and 5 GHz are shown in Fig. 5(b) and (c), respectively. Direct coupling between the two dipoles over the reflector instead of the free access mat was also measured but was too small and therefore was not plotted. For this experiment, we defined the accessible height as that at which ΔL was more than 10 dB.

When h increased, P_M increased because the free space transmission loss between the antenna and the free access mat increased, and the coupling between the antenna and free access mat was weakened. At around 2.4 GHz, the dipoles coupled strongly to the free access mat at the height of 5 mm. When h was higher than 10 mm, however, P_M at 2.4 GHz increased significantly, and the center frequency shifted to the lower frequency bands. The accessible range of external antennas is therefore limited to less than 10 mm at 2.4 GHz where ΔL is more than 10 dB. At 5 GHz also, P_M increased when h increased. The accessible range was the same as that with 2.4 GHz. This low accessible height for external antennas indicates that only wireless devices on the free access mat would be able to couple with it, a characteristic likely to be welcomed by many users. Moreover, undesired wireless devices outside of the free access mat would not affect those coupled to it.

Interference between several adjacent free access mats is an important consideration when two or more free access mats are used together in a small space such as an office. When free access mats are placed on adjacent desks, interference between them should be low. To measure interference, we prepared two free access mats with the same resonant frequency around 5 GHz. Two standard dipoles whose resonant frequencies were around 5 GHz were coupled to the free access mats, and h and L were fixed to 5 mm and 150 mm, respectively.

Transmission characteristics in the four cases shown in Fig. 6 were investigated. In the first two cases, both dipoles were coupled to a single free access mat, mat 1 or mat 2. In

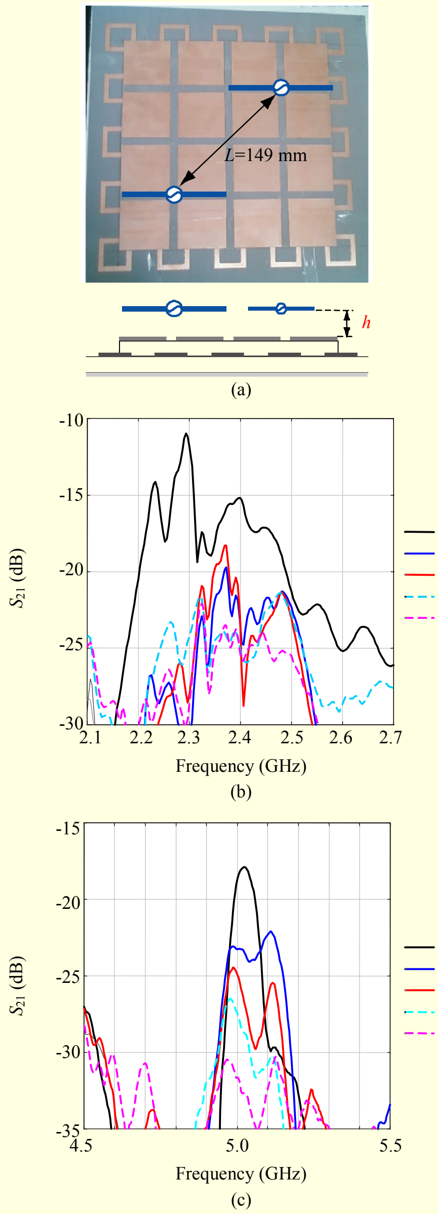


Fig. 5. Accessible height of external antennas: (a) measurement, and S_{21} characteristics with various h values at (b) around 2.4 GHz and (c) 5 GHz.

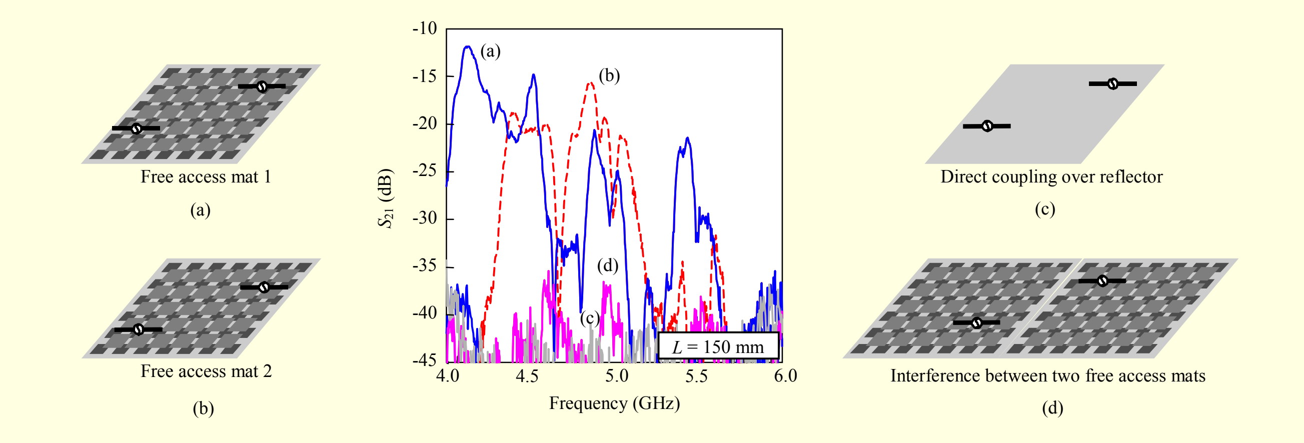


Fig. 6. Interference between two adjacent free access mats. S_{21} characteristics when two dipoles couple to (a) free access mat 1, (b) free access mat 2, and (c) a reflector instead of a free access mat. (d) Interference between two adjacent free access mats without changing L.

the third case, they were located over a reflector instead of a free access mat with the mutual coupling of two antennas taking place through the free space rather than through the free access mat. In the last case, two free access mats were located next to each other, and each dipole was coupled to a free access mat without any change in L. The distance between the two free access mats was negligibly small, although they did not have any point of electrical contact. This last configuration was used to test for interference between two adjacent free access mats.

In the first two cases, when two dipoles were coupled to the same single mat, transmission loss was small at around 4.9 GHz. In the last case, however, the transmission loss was very large, reaching almost that of the third case, which involved direct coupling between antennas. This difference between S_{21}s of the last case and the first two cases was larger than 15.9 dB. Interference between two adjacent mats was markedly small and was considered negligible. These findings show that no interference would occur if many users operated their own physically independent free access mats in close proximity.

When the power of wireless devices was reduced, the coverage areas of several users were confined to near each free access mat. Coverage areas could be allotted by individual free access mats. Even when close to each other, each user could have an independent communication area of one segment per free access mat.

III. Conclusion

We presented a novel method to limit the arrival domain of radio systems using a sheetlike waveguide, the free access mat. The free access mat with a ring patch resonator was newly designed to provide two frequency bands for wireless LANs. Findings demonstrated that this design achieves low transmission loss, easy coupling with typical antennas, small accessible range, and interference free zone.

The free access mat with a ring patch resonator array incurs small transmission loss around 2.4 GHz and 5 GHz. Transmission loss through the free access mat was much smaller than the free space transmission loss, with a difference between them of more than 10 dB. This design thus avoids the effect of multipath transmission caused by installation of the free access mat itself.

The free access mat was easily excited by typical antennas at arbitrary positions and directions. The EM wave of the coupled antennas was concentrated into the free access mat and transmitted at a small loss. The coupling loss of two standard dipoles was less than 6 dB.

The accessible height of external antennas was limited to several millimeters. Interference between adjacent physically independent free access mats was negligible; therefore, only wireless devices on the free access mat are able to couple to the free access mat, allowing the possibility of using multiple free access mats in a confined space.

The free access mat with a ring patch resonator array can be used for wireless LAN applications. Small transmission loss, easy coupling with typical antennas, small accessible range of external antennas, and negligible interference between adjacent free access mats make it possible to limit the coverage area of wireless LANs in offices and facilitate the efficient use of frequency resources in indoor wireless networks.

A square ring resonator array was used for simplicity in this study, and the transmission loss is sufficiently small. When a wider bandwidth is required, varying the shape of these ring resonators would be effective. This will be the subject of a future work.

References

[1] A.S. Hu, "Leaky Coaxial Cable Characteristics at 900 MHz," *IEEE Trans. Vehicular Technol.*, vol. VT-26, no. 4, Nov. 1977.

[2] S.P. Morgan, "Prediction of Indoor Wireless Coverage by Leaky Coaxial Cable Using Ray Tracing," *IEEE Trans. Vehicular Technol.*, vol. 48, no. 6, Nov. 1999.

[3] J.H. Wang and K.K. Mei, "Theory and Analysis of Leaky Coaxial Cables with Periodic Slots," *IEEE Trans. Antennas Propag.*, vol. 49, no. 12, Dec. 2001.

[4] D.H. Kim and H.J. Eom, "Radiation of a Leaky Coaxial Cable with Narrow Transverse Slots," *IEEE Trans. Antennas Propag.*, vol. 55, no. 1, Jan. 2007, pp. 107-110.

[5] M. Minami et al., "MAGIC-Surfaces: Magnetically Interfaced Surfaces for Smart Space Applications," *Adjunct Proc. the 3rd Int. Conf. Pervasive Comput.*, Munich, Germany, May 2005, pp. 59-64.

[6] Y. Makino and H. Shinoda, "Selective Stimulation to Superficial Mechanoreceptors by Temporal Control of Suction Pressure," *Proc. World Haptics*, Italy, Mar. 2005, pp. 229-234.

[7] Y. Makino, K. Minamizawa, and H. Shinoda, "Sensor Networking Using Two-Dimensional Electromagnetic Wave," *Proc. IEEJ 22nd Sensor Symp.*, 2005, pp. 83-88.

[8] H. Chigusa, Y. Makino, and H. Shinoda, "Large Area Sensor Skin Based on Two-Dimensional Signal Transmission Technology," *Proc. World Haptics*, Tsukuba, Japan, Mar. 2007, pp. 151-156.

[9] H. Shinoda et al., "Surface Sensor Network Using Inductive Signal Transmission Layer," *Proc. Fourth Int. Conf. Networked Sensing System (INSS)*, June 6-8, Braunschweig, Germany, 2007, pp. 201-206.

[10] K. Eom and H. Arai, "A Free Access Mat by Tightly Coupled Patch Array for Short Range Wireless Access," *IEICE Trans. Electron.*, vol. E90-C, no. 12, Dec. 2007, pp. 2254-2260.

[11] H. Izumi, H. Arai, and T. Itoh, "Ribbon-Wire Interconnect Using Parasitic Element," *IEICE Trans. Electron.*, vol. E82-C. no. 4, Apr. 1999, pp. 662-664.

[12] H. Izumi, H. Arai, and T. Itoh, *Electromagnetically Coupled Contact-less Structure and Its Applications for RF Circuit Elements*, Doctoral Dissertation, Yokohama National University, Mar. 2007.

[13] H. Izumi and H. Arai, "Electromagnetically Coupled Power Divider Using Parasitic Element," *IEICE Trans. Electron.*, vol. E84-C, no. 10, Oct. 2001, pp. 1597-1601.

[14] H. Izumi and H. Arai, "Dielectric Phase Shifter (DSP) Using Contact-less Connector," *IEICE Trans. Commun.*, vol. E86-B, no. 10, Oct. 2003, pp. 2982-2986.

[15] John C. Vardaxoglou, *Frequency Selective Surfaces – Analysis and Design*, Research Studies Press, England, 1997.

[16] Ben A. Munk, *Frequency Selective Surfaces – Theory and Design*, Wiley-Interscience, New York, 2000.

[17] Yang Fan, *Electromagnetic Band Gap Structures in Antenna Engineering*, Cambridge University Press, New York, 2008.

[18] N. Delhote et al., "Large Experimental Bandpass Waveguide in 3D EBG Woodpile Manufactured by Layer-by-Layer Ceramic Stereolithography," *IEEE/MTT-S Int. Microw. Symp.*, vol. 4, June 2007, pp. 1431-1434.

[19] Z. Wu et al., "Rapid and Inexpensive Fabrication of Terahertz Electromagnetic Bandgap Structures," *Optics Lett.*, vol. 16, no. 21, Oct. 2008, pp. 16442-16451.

[20] K. Eom and H. Arai, "Dual Band Free Access Mat for Short Range Wireless Access," *IEEE PIMRC*, vol. 390, Athens, Greece, Sept. 2007.

[21] http://www.zeland.com.

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