Proc. SICE Annual Conference 2015,
pp.522-527, July 28-30, Hangzhou, China, 2015

Contactless Coupler for 2D Communication Tile Connection

Yuichi MASUDA[1†], Akihito NODA[1], Hiroyuki SHINODA[1]

[1]Department of Complexity Science and Enginnering, University of Tokyo, Chiba, Japan
(Tel : +81-04-7136-3777; E-mail: masuda@hapis.k.u-tokyoac.jp, Akihito_Noda@ipc.i.u-tokyo.ac.jp,
hiroyuki_shinoda@k.u-tokyo.ac.jp)

Abstract: For applying two-dimensional communication (2DC) technology to the entire floor of a room, the concept of 2DC tile have been proposed. In terms of fabrication, delivery, and implementation, the floor should be covered with multiple pieces of 2DC sheets as small as typical carpet tiles. In this paper, we propose a contactless coupler for signal transmission between adjacent 2DC tiles without any electrical contacts. The simulation and measurement results show that the proposed coupler is sufficiently tolerant of positioning error between a pair of couplers.

Keywords: Two-dimensional communication , Contactless coupler.

1. INTRODUCTION

Two-dimensional communication (2DC) or two-dimensional signal transmission (2DST) is a near-field communication scheme using a sheet-like waveguide [1]. The sheet guides electromagnetic waves and generates evanescent (non-radiative) waves above its surface. 2DC enables high speed wireless communication between transceivers laid on the sheet surface without significant radio wave emission into the air.

The goal of this research project is to realize a room-size 2DC system as shown in Fig. 1. There are two ways to realize a room-size 2DC system. One is to use a single piece of waveguide sheet as large as the entire floor of a room as shown in Fig. 2(a). The other one is to use multiple waveguide tiles as large as typical 50 cm × 50 cm carpet tiles, as shown in Fig. 2(b). The waveguide tiles can be produced at lower cost and can be installed more easily than the room-size single piece of sheet. The tiles can be fitted to various sizes and shapes of rooms, including a room with a center column.

In single-sheet 2DC systems, signal attenuation depends on the decay constant of the sheet and the path length. In multi-tile 2DC systems, signals have to be transmitted from one tile to another. Therefore the signal attenuation depends also on the loss at the tile-to-tile connections. The loss obviously increases the signal attenuation and shortens the communication range compared to the single-sheet systems. The communication range can be extended by using amplifiers to compensate the loss.

Recently, we have proposed ultra-wide band (UWB) 2DC tile concept [2]. It has three layers: carpet layer, waveguide sheet layer, and base layer. The waveguide sheet layer works as an interface between transceivers laid on the tile and the underlying base layer. The base layer transmits/receives signals to/from adjacent tiles and it has amplifier circuit to amplify signals.

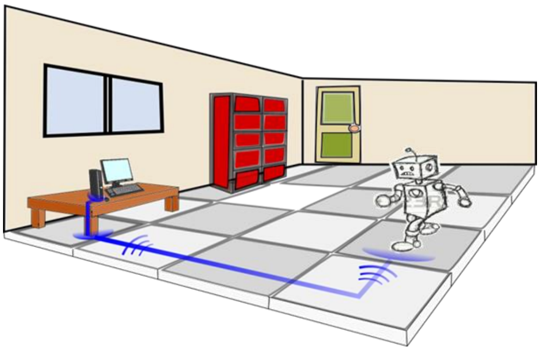

Fig. 1 Overview of 2DC room floor covered by 2DC sheets. Radio waves propagate on the floor, but not in the air.

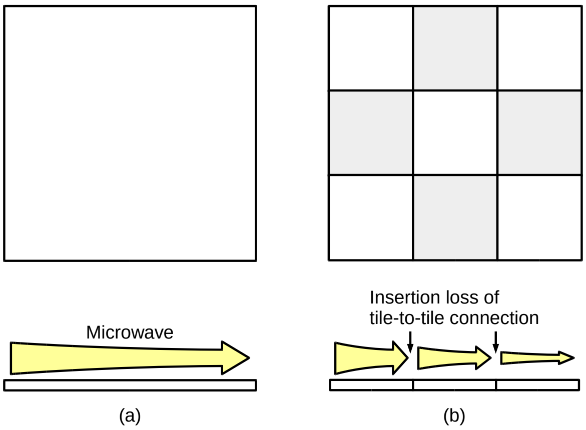

Fig. 2 Overview of (a) a large size 2DC sheet and (b) smaller size 2DC tiles.

Fig. 3 shows the structure of 2DC tiles. A communication device transmits Tx signal into 2DC sheet through the carpet, and this signal is amplified at the base layer. Next, this signal is transferred to a neighboring base layer.

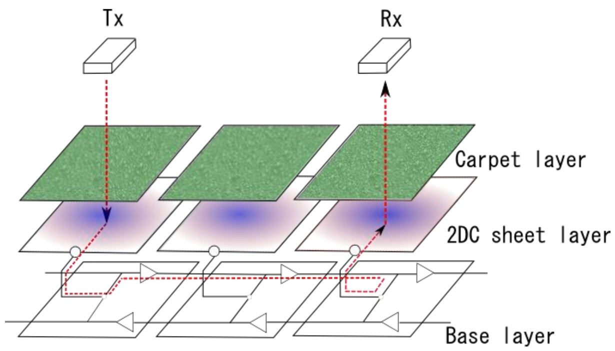

Fig. 3 Structure of 2DC tiles.

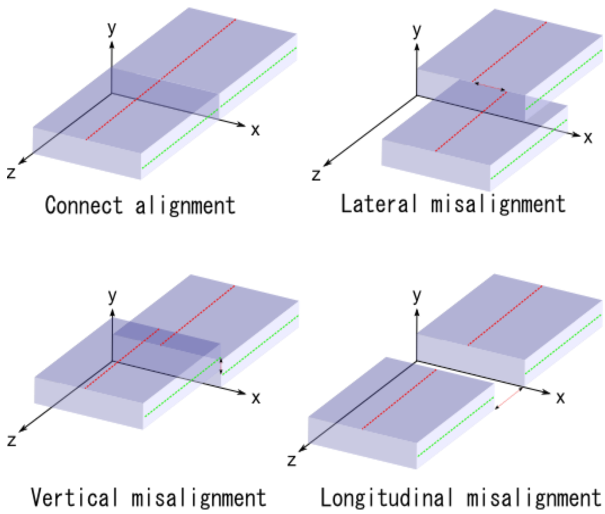

Fig. 4 misalignments between adjacent tiles.

A key technological component of 2DC tile system is, easy connection mechanisms between adjacent tiles, which have not been developed. While installing 2DC tiles on the floor, misalignments between adjacent tiles shown in Fig. 4 will be inevitable. Conventional radio frequency (RF) connectors require screwing (e.g. SMA connectors) or snapping (e.g. SMP connectors). Using screw-type connectors for adjacent tile connection will impair the practicability of the 2DC tiles, because it will increases the workload for installing tiles. Snap-type connectors may be easier than screw-type ones, but precise alignment between connectors is still required. Contactless coupler using capasitive or magnetic couplig methods may be easier than snap-type ones, but those coupler still needs precise alignment [3][4].

In this paper, we propose a contactless RF coupler that provides broadband, low-loss connection as well as easiness of tile installation and reliability. It is tolerant of dust contamination and alignment error between adjacent tiles.

The rest of this paper is organized as follows. In Section 2, the operation of a 2DC tile will be described and the amplifier gain to maximize the scalability of 2DC tile system will be determined. Section 3 will present the coupler design and simulated characteristics. Measured results and discussion will be shown in Sections 4 and 5. Finally Section 6 concludes this paper.

2. 2DC TILE

A 2DC tile system and components of base layer are shown in Fig. 5.

We assume 2DC tile system as multiple tiles connected in a one-dimensional (1-D) chain topology. Two-dimensional area (floor) can be covered with multiple parallel 1-D chains or with a long meander chain. Therefore two of the four edges of the square tile are connected with the adjacent tiles.

In the 1-D chain, signal transmission in two directions, leftward and rightward in Fig. 3, should be supported. To distinguish these two directions, they are refered to as uplink (UL) and downlink (DL) in this system. Because of the separated UL and DL transmission lines, positive feedback loop oscillations are avoided while each tile amplifies signals to compensate signal loss.

2.1 Transition of signal level

According to the spectral mask defined by the Federal Communications Commission (FCC) [5], the upper limit of transmitted signal power density is -41.3 dBm/MHz. The thermal noise at room-temperature is approximately -114 dBm/MHz. Thus, the SNR is inherently lower than 73 dB. The lowest signal power in the communication path from the transmitter to the receiver determines the upper bound of the achievable SNR in the system.

Signal level transition is illustrated in Fig. 6. Once the signal transmitted from the transceiver on a tile, it cannot be amplified until received by the base layer circuit. In the base layer circuit, the signal can be amplified to avoid further SNR degradation. For this purpose, the signal received by the base layer circuit should be amplified immediately by a low noise amplifier (LNA). The amplified signal is fed into the UL transmission line at the combiner. In the UL line, the signal attenuated at the tile-to-tile connection, and amplified to compensate the attenuation.

In the above operation, the achievable SNR is determined by the lowest signal strength at the input of the LNA. It does not depend on the coupler loss. Therefore reducing the insertion loss of the coupler is not the top priority matter. In our UWB 2DC system, the flatness of the insertion loss in the bandwidth of interest will be more important as one of the design criteria.

2.2 The gain of each tiles

UL/DL have an amplifier to compensate signal loss due to passing the contactless coupler and other components including a combiner/divider.

We define the gain of one tile, G_{TILE}, as

$$G_{\mathrm{TILE}} \equiv G_{\mathrm{AMP}} - (L_{\mathrm{CPL}} + L_{\mathrm{OTHERS}})\,, \tag{1}$$

where G_{AMP}, L_{CPL} and L_{OTHERS} respectively represent the amplifier gain, the loss of contactless coupler, and the loss due to other components including cables and the combiner/divider in each tile, and they all are expressed in dB.

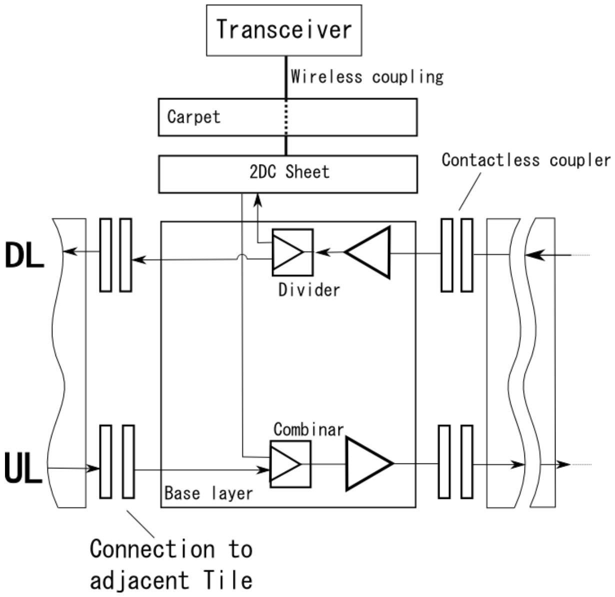

Fig. 5 Block diagram of 2DC tile system.

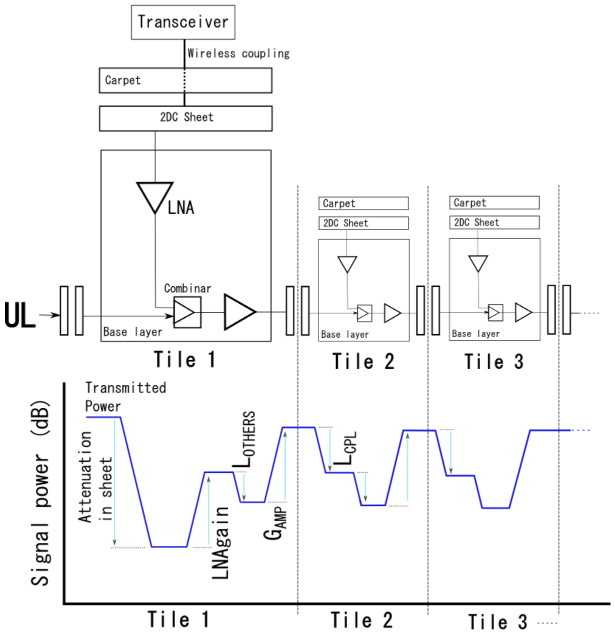

Fig. 6 G_{AMP}, L_{CPL} and L_{OTHERS} respectively represent the amplifier gain, the loss of contactless coupler, and the loss due to other components including cables and the combiner/divider in each tile, and they all are expressed in dB.

To maximize the scalability of the tile chain system, G_{TILE} should be equal to 0 dB. $G_{\mathrm{TILE}} < 0$ dB results in decrease in communication range, and $G_{\mathrm{TILE\_UL}} > 0$ dB can cause signal saturation. Substituting $G_{\mathrm{TILE}} = 0$ dB into Eq. (1) and we obtain

$$G_{\mathrm{AMP}} = L_{\mathrm{CPL}} + L_{\mathrm{OTHERS}} \,. \tag{2}$$

Thus, the optimal amplifier gain is determined.

3. CONTACTLESS COUPLER

In this study, we propose the contactless coupler based on non-resonant waveguide coupling. As described in Section 1, a contactless means of signal transmission is required to be tolerant of misalignments and contaminations.

Since it is not based on resonance, it shows a broader passband in frequency compared to peaky characteristics of resonant circuits. It results in a significant tolerance of the errors in *x*- and *y*- displacement and in the gap between couplers. Although some resonant structure can also achieve broadband characteristics as UWB band pass filters (BPF), such structures will not be enough tolerant of misalignments, because the BPF characteristics sensitively depends on the dimensions of the structure.

The proposed contactless coupler is shown in Fig. 7. Coplanar strip line (CPS) is opposite to another CPS. In Fig. 7, signals fed into transmission line A from port 1 is transferred to transmission line B without electrical contacts.

The behavior of an electromagnetic signal between two transmission lines can be described by coupling mode theory [6] using each transmission line's propagation coefficient.

This theory deal with amplitude of signals propagated between each transmission line with function of length (direction of *x* in Fig. 7). When the amplitude of signals becomes maximum at the opposite coupler, length are called coupling length, as depicted in Fig. 8. We designed the length of transmission line to be equal to the coupling length.

To enlarge the area where significant magnitude of electromagnetic field is caused by the CPS, the width of CPS (direction *y*) is gradually widen from the side of CPS to center of CPS. The more enlarge the area of significant electromagnetic field generated, the more increase the tolerance of each direction's displacement between two couplers. However, the signal loss due to radiation to the outside space will be increased by enlarging the CSP size. Therefore, we searched optimal width by trial and error on simulation.

We simulated the insertion loss from port 1 to port 2 in Fig. 7 in bandwidth 7.75 to 8.25 GHz by using CST Microwave Studio. The absolute value of its insertion loss means L_{CPL} in Section 2. The dielectric constant of the substrates is 4.8, and the loss tangent is 0.02 in this simulation. Results of the simulation are shown in Figs. 9, 10 and 11.

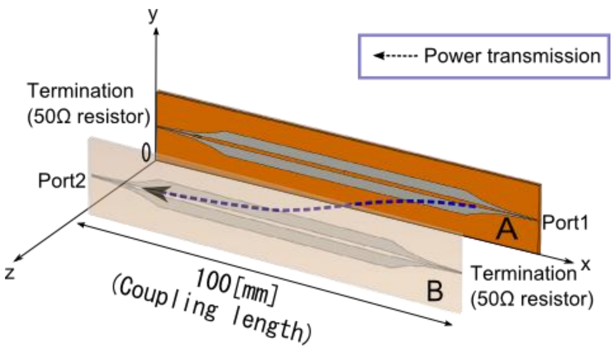

Fig. 7 Contactless coupler.

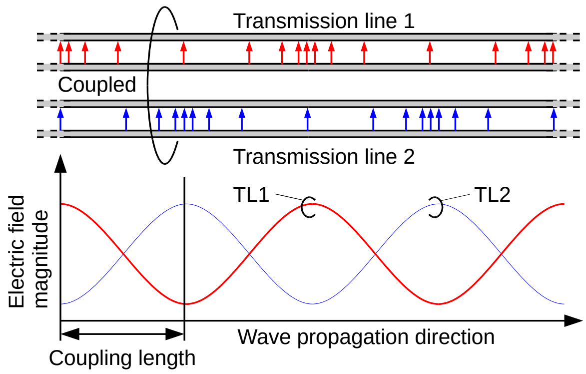

Fig. 8 Power transmission between two coupled guided modes. Electromagnetic wave power is periodically exchanged between two waveguides.

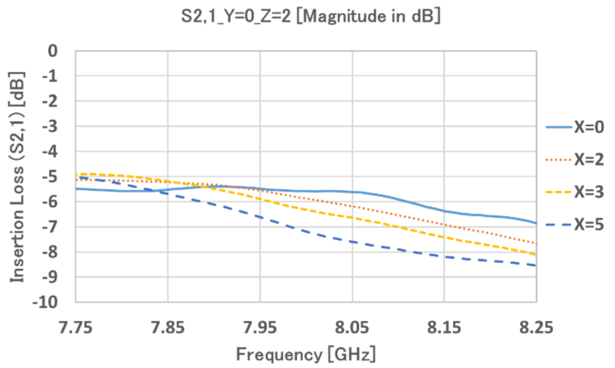

Fig. 9 Insertion loss (S2,1)[dB]   Y=0,Z=2.

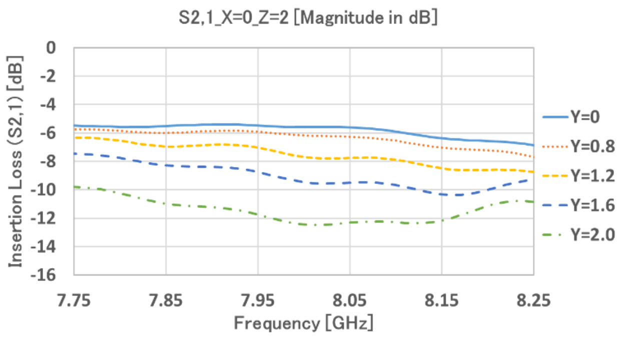

Fig. 10 Insertion loss (S2,1)[dB]   X=0, Z=2.

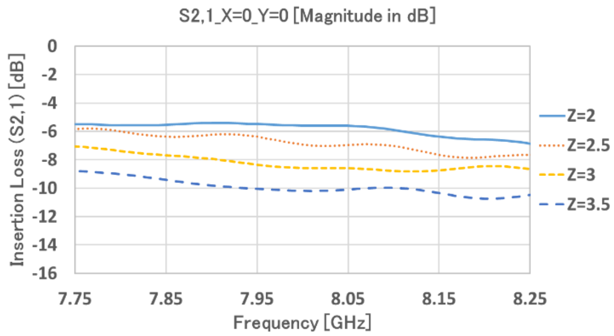

Fig. 11 Insertion loss (S2,1)[dB]   X=0, Y=0.

In Fig. 9, when *x*-displacement is 2 mm, an increment of insertion loss is 1 dB. The difference between the maximum and the minimum in bandwidth increased from 1.5dB to 2.5 dB. In Fig. 10, when *y*- displacement is 1.2 mm, an increment of insertion loss is 1.5 dB and there are no change in the difference between the maximum and the minimum. In Fig. 11, when the gap between couplers is 0.5 mm, an increment of insertion loss is 1 dB and there are no change in the difference between the maximum and the minimum.

The results of Figs. 9-11 show a broader passband in frequency and indicate a significant tolerance of the errors in *x*- and *y*- displacement and in the gap between couplers.

4. EXPERIMENTAL RESULTS

In this section, we show experimental results about Insertion loss of contactless connector.

4.1 2DC tile and measurement system

We made the contactless coupler based on the simulation parameters. The contactless coupler is attached at the one side of base layer as shown in Fig. 12. The figure also shows a 2DC layer and a carpet layer used in an actual use. Substrate of contactless coupler is FR-4 with dielectric constant of 4.8. For measuring the insertion loss of a pair of contactless couplers, two 2DC tiles were connected with the contactless couplers as shown in Fig. 13. We measure it using network analyzer (Fig. 13). A schematic diagram of measurement setup is shown in Fig. 14. The insertion loss was measured with a vector network analyzer (VNA). One of the couplers is connected to VNA port 1 and the other one is connected to VNA port 2. These ports correspond to the ports in the simulation model shown in Fig. 7.

4.2 Results

The results of measured and simulated values of the insertion loss are shown in Fig. 15. Insertion loss of measurement value are lower than simulation value. Possible reasons for the degradation from the simulation are discussed in Section 5. The difference between the maximum and the minimum across the 500-MHz bandwidth we assume to use in the system is 1.5 dB. It is approximately equal to the value obtained with the simulation.

5. DISCUSSION

The measured insertion loss was 3-5-dB lower than the simulated value in the frequency band of interest. There are two possible reasons. First, signals were absorbed by lossy components not modeled in the simulation, including supporting structures. Second, insertion loss of additional coaxial cables were included in the measured value. VNA calibration was performed while a coaxial cable was connected to each port. To measure the insertion loss of the paired couplers, an additional thin coaxial cable, which is shown in Fig. 12, was connected beyond each calibrated cable. Thus, the insertion losses of the paired coupler and of the additional cables were indistinguishable in this measurement.

Figs. 9-11 show that the increment of the insertion loss is less than 2 dB for the *x*-, *y*- and *z*-misalignments of 2 mm, 1.2 mm and 0.5 mm, respectively. The increments of the difference between the maximum insertion loss and the minimum due to the misalignments is also less than 2.5 dB. These values are significantly smaller than a typical path loss in our 2DC system, 20-50 dB, and are insignificant. Thus, this contactless coupler will satisfy our purpose that providing reliable connection as well as easiness of tile installation.

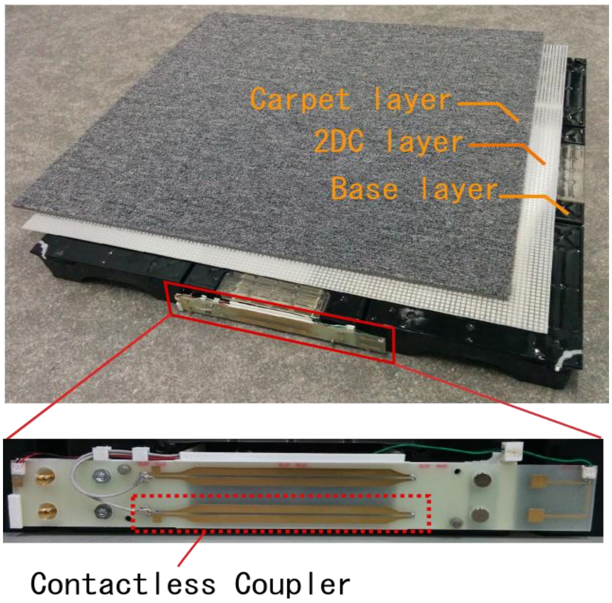

Fig. 12 Overview of 2DC Tile and magnified image of contactless coupler.

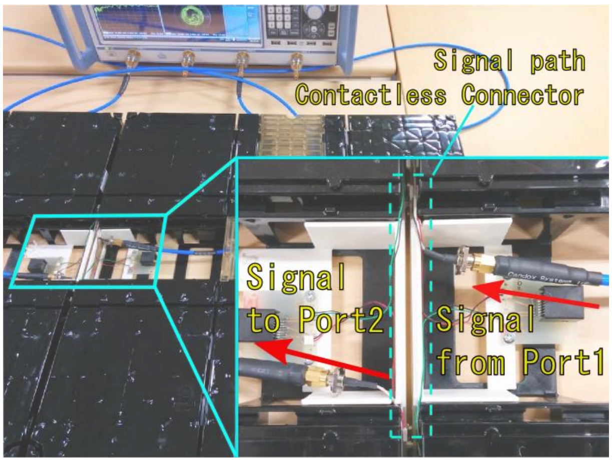

Fig. 13 Overview of measurement setup of contactless coupler using VNA. Magnified view around the coupler pair is also shown.

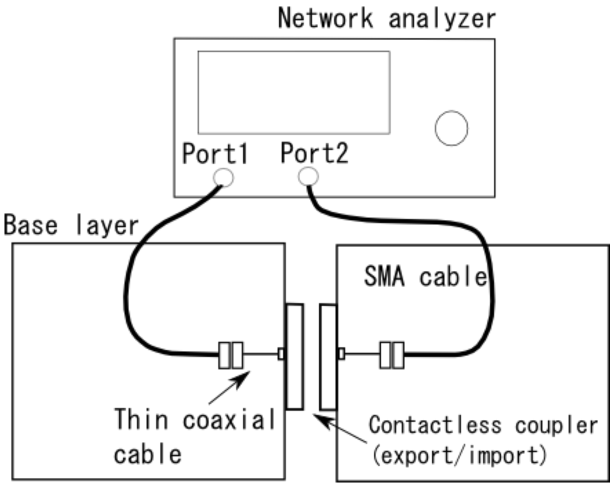

Fig. 14 Schematic diagram of measurement setup of contactless coupler using network analyzer.

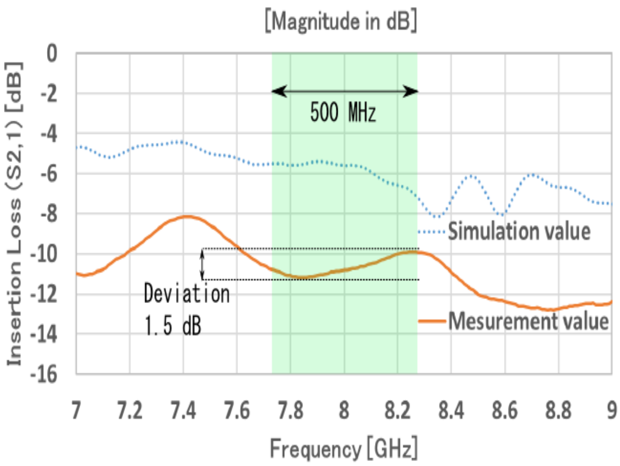

Fig. 15 Measured and simulated values of the insertion loss.

6. CONCLUTION

In this paper, we proposed the contactless coupler to implement the easy connection between adjacent 2DC tiles. It will enable an all over the room floor 2DC system with significantly reduced workload and cost. We evaluated the tolerance of this coupler in numerical simulation by using CST Microwave studio and experimentally confirmed that the coupler's insertion loss is -6 dB in average and with 1.5 dB deviation across 7.75-8.25 GHz in the UWB high band. We also showed that 1-mm order misalignment that can be caused in an actual implementation is acceptable since the increment of the coupler insertion loss is insignificant. The misalignments can be reduced to submillimeter order by using simple mechanical guide structures. Measured result agrees the simulation results.

Although the magnitude of insertion loss can be compensated by amplifiers in the 2DC tiles, the deviation in the insertion loss will be accumulated and increases as the number of tiles connected increases.

Achieving less deviation across wider bandwidth by optimizing the structure will be a future work.

ACKNOWLEDGEMENT

This work was supported in part by the Strategic Information and Communications R&D Promotion Programme (SCOPE) 135003009.

REFERENCES

[1] H.Shinoda, Y. Makino, N. Yamahira, and H. Itai, “Surface sensor network using inductive signal transmission layer,” in Networked Sensing Systems, 2007. INSS’07. Fourth International Conference on, pp. 201–206, IEEE, 2007.

[2] H.Shinoda, A.Okada and A.Noda, “UWB 2D Communication Tiles”, Proceedings of the 2014 IEEE International conference on ultra-wideband, pp. 1-5, Paris, France, September 2014.

[3] S.kawai, H.Ishikuro, and T.Kuroda, “A 2.5 Gb/s/ch 4PAM inductivecoupling transceiver for noncontact memory card,” in IEEE Int. SolidState Circuits Conf. Dig. Tech. Papers, February 2010, pp. 264-265

[4] T.Takeya, , L. Nan, S. Nakano, N. Miura, H. Ishikuro, and T. Kuroda,“A 12 Gb/s noncontact interface with coupled transmission lines,”IEEE J. Solid-State Circuits, vol. 48, no. 3, pp. 790–800, Mar. 2013.

[5] FCC, “First Report and Order in The Matter of Revision of Part 15 of the Commission's Rules Regarding Ultrawideband Transmission Systems,” ET-Docket 98-153, FCC 02-48, 2002.

[6] W. P. Huang, ”Coupled-mode theory for optical waveguides: an overview”, J. Opt. Soc. Am. A 11 (3), pp. 963–983, 1994.