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Edge-Mount 1-Watt RF Amplifier for 2-D Waveguide Power Transmission

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Abstract: Two-dimensional waveguide power transmission is a wireless power transmission scheme using a waveguide sheet and receiving proximity couplers. It enables safe, large-area wireless power transmission interfaces on furniture and architectural surfaces including desks, floors, and walls. This paper presents a microwave amplifier board that can be directly attached to an arbitrary position on the waveguide edges and feeds 1-watt power of 2.5-GHz microwave into the sheet. No additional process is required for the sheet to mount the board and the impedance is well-matched. The board comprises some functional blocks of radio frequency (RF) circuits including a phase shifter, RF amplifiers, an RF switch, and an impedance matching structure. A fabricated board was evaluated and the net microwave power available at the output port and the overall dc-to-RF efficiency were estimated to be 0.93 W and 34.8%, respectively.

Keywords: Two-dimensional waveguide power transmission, phased array, RF power amplifier.

1. INTRODUCTION

Two-dimensional waveguide power transmission (2DWPT) is a wireless power transmission (WPT) scheme using a thin waveguide sheet and receiving proximity couplers [1, 2]. It enables a several-watts class safe WPT interface on various surfaces including desks, floors, and walls in general indoor environments. A waveguide sheet used in the system guides a microwave and generates an evanescent filed around its surface. The microwave diffuses over the sheet and a receiving coupler at an arbitrary position on the sheet can extract the microwave across the sheet surface without any electrical contacts.

From a single feeding point, the microwave diffuses over the sheet. If the sheet edges are terminated with microwave absorbers, the microwave not captured by the receiver is dissipated by the absorbers, and the power dissipation reduces the overall power transmission efficiency.

For higher power transmission efficiency, a phased array 2DWPT system has been proposed [3, 4]. It enables focusing microwaves underneath the receiver and the efficiency can be improved. The phased array consists of multiple small edge-mount transmitting couplers attached to an edge of the sheet and of a microwave power source unit with multiple phase-tunable output ports. The ports are individually connected to the couplers with coaxial cables. The power source unit and multiple coaxial cables are bulky and the system is just for experimental use but not for practical use.

This paper presents a radio frequency power amplifier (RFPA) board that is directly attached to sheet edges for compact, practical phased array 2DWPT. It has an impedance matching structure between the 50-Ω microstrip line (MSL) on the board and the sheet. The sheet and the board are connected by just clamping them with metal cases and screws. No additional process is required for the sheet.

The edge-mountable RFPA board enables distributed power source configuration. Fig. 1 shows the comparison between a centralized and a distributed power source configurations.

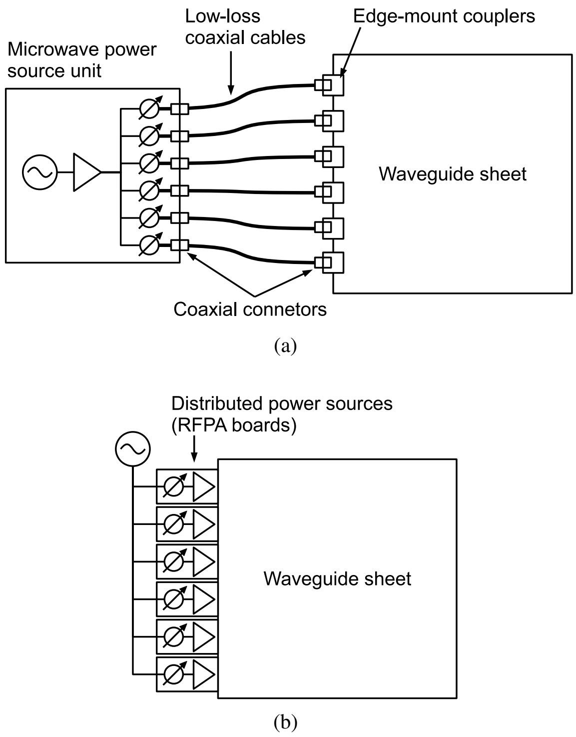

Fig. 1: (a) Centralized and (b) distributed microwave power sources for phased array 2DWPT. In the distributed power source configuration, coaxial cables and connectors at the both ends of the cables are eliminated.

In the centralized configuration, the power source unit has multiple output ports and tends to be bulky. To reduce the power loss in the coaxial cables, less-lossy coaxial cables should be used. Such low-loss cables tend to be thicker and harder. Thus, the system is bulky and is not suitable for practical use.

On the other hand, in the distributed configuration, the

† Akihito Noda is the presenter of this paper.

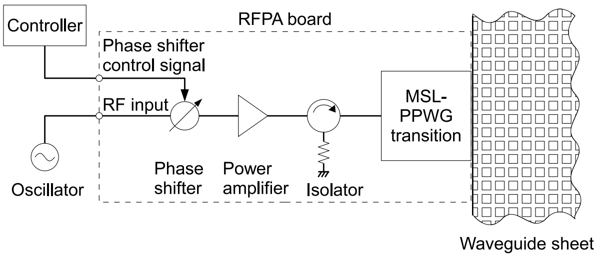

Fig. 2: Block diagram of the RFPA board. MSL-to-PPW mode transition structure is designed so as to suppress the reflection at the port when the board is attached to an anechoic sheet.

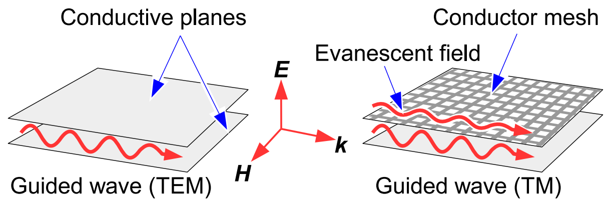

Fig. 3: In an ordinary PPW, a TEM wave can propagate (left). The electric field vector $\boldsymbol{E}$ is normal to the parallel plates, the magnetic field vector $\boldsymbol{H}$ is tangential to them, and the wavenumber vector $\boldsymbol{k}$ is perpendicular to the both of $\boldsymbol{E}$ and $\boldsymbol{H}$. In a 2DWPT sheet, a TM wave similar to the PPW mode can propagate, and an evanescent field is generated above the mesh surface (right).

RFPA boards are directly attached to the sheet edges. The thick and hard coaxial cables and coaxial connectors are eliminated and the system can be more compact. The microwave source signal distribution from single microwave oscillator to each amplifier, thin and soft coaxial cables or other transmission lines including MSL can be used. Although thinner coaxial cables tend to be more lossy, signal attenuations before the final stage amplifiers are not critical in terms of overall power efficiency of 2DWPT system. Thus, the distributed configuration is suitable for compact phased array 2DWPT.

This paper is organized as follows. Section 2 presents the circuit design of the RFPA board. In Section 3, transition structure from MSL to parallel plate waveguide (PPW) is designed for the direct connection between the board and the sheet. A fabricated RFPA board is described in Section 4 and the loss analysis of the board is presented in Section 5. Section 6 concludes this paper.

2. RFPA BOARD CIRCUIT DESIGN

This section describes RFPA board circuit design. A block diagram of the RFPA board is shown in Fig. 2. The circuit consists of four functional blocks: a phase shifter, an RFPA, an isolator, and an MSL-PPW transition.

The RFPA board receives the original RF signal from the oscillator. An electronically controllable phase shifter is required to change the phase of the output microwave and to generate steerable microwave focuses by the phased array. Ideally, the phase shifter should provide arbitrary phase shift ranging from 0 deg to 360 deg. Because of the significant insertion loss of the phase shifter, the phase should be tuned before the final stage amplification for higher power efficiency. Besides, the power handling capacity required for the phase shifter is reduced by tuning the phase before amplifying the RF signal.

The RFPA placed after the phase shifter converts the supplied dc power into the RF power. The overall power transmission efficiency is determined by the product of the dc-to-RF conversion efficiency, the RF transmission efficiency, and the RF-to-dc conversion efficiency. To improve the overall efficiency, higher dc-to-RF conversion efficiency, i.e., power adding efficiency (PAE) of the RFPA is required.

The isolator is required to prevent damaging the RFPA due to the reflected power. The reflection between the RFPA board and the waveguide sheet can be significantly reduced by the MSL-PPW transition structure. However, significant reflection can be generated in the following two cases. First, when the waveguide sheet is open/short ended. Second, when other RFPA boards generate microwaves propagating toward this RFPA. For higher power efficiency, the isolator with a low insertion loss is desired.

As the final stage of the RFPA board, the MSL-PPW transition structure is required. The structure performs impedance matching between the 50-Ω MSL and the sheet guided mode, which is approximated as a PPW guided mode. Unlike the former three components, since this structure is not a commonly used device, it requires a dedicated design. The detail of the design will be presented in the following section.

Thus, the RFPA board consists of the following four components connected in line and in the following order: the phase shifter, the RFPA, the isolator and the MSL-PPW transition.

3. MSL-PPW TRANSITION

This section presents an MSL-PPW transition structure design. The microwave frequency used in the system is assumed as 2.484 GHz. Since it is the center frequency of the IEEE 802.11b 14th channel used only in Japan, the interference risk is reduced, compared to other frequencies in the 2.4-GHz industral, scientific and medical (ISM) band.

The waveguide sheet is approximated as a PPW, as shown in Fig. 3. For direct connection between the 50-Ω MSL in the RFPA circuit and the sheet, an impedance matching transition structure between the MSL and the PPW is required.

Fig. 4 shows an overview of the transition structure realized by copper patterns on the printed circuit board (PCB). The left-hand side end, connected to the isolator, is a 50-Ω MSL. The right-hand side end, attached to the waveguide sheet, is a parallel-plate region, i.e., the both sides of the PCB are covered with solid copper patterns.

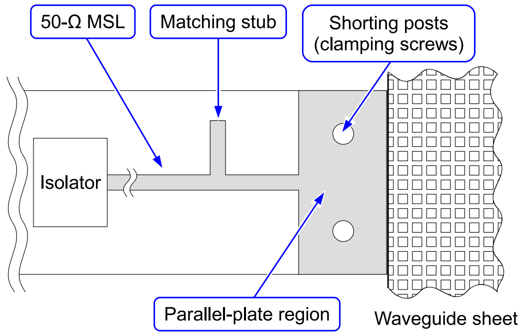

Fig. 4: Overview of the MSL-PPW transition. The transition structure is formed on the PCB with copper patterns.

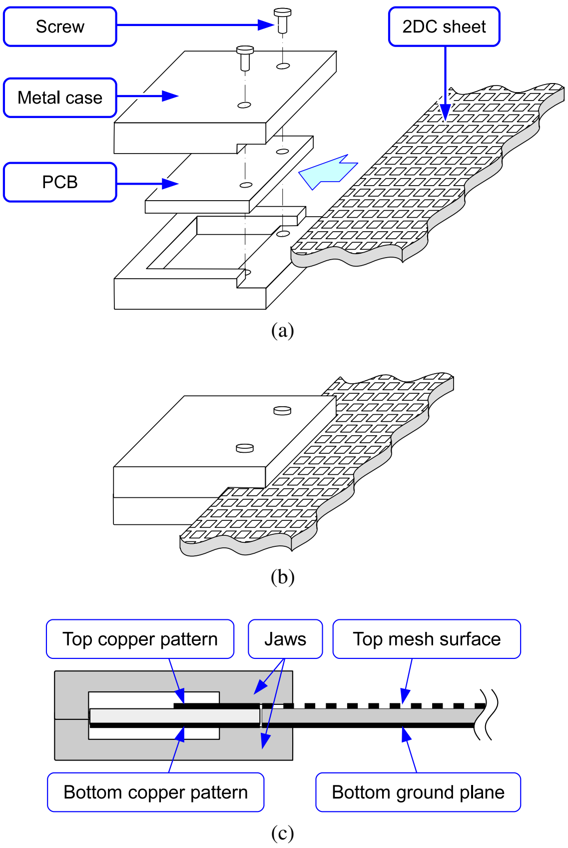

Fig. 5: (a) Exploded view and (b) assembled view of the joint between an RFPA board and a waveguide sheet. (c) Cross sectional view. The PCB edge and the sheet edge are clamped together by the jaws of the metal cases. The top and the bottom copper patterns of the PCB are electrically connected to the top mesh surface and the bottom ground surface of the sheet via the upper and the lower jaws, respectively.

Besides, the parallel-plate is shorted by conductive posts. The posts are metal screws piercing the PCB. The screws fasten the jaws of metal cases of the RFPA board to clamp the board and the sheet together as shown in Fig. 5, for reliable electrical connection between the PCB parallel-plate and the waveguide sheet conductive surfaces.

The distance between the posts was designed as 40 mm, approximately a half-wavelength. If the distance between the posts was significantly smaller than the wavelength, the parallel-plate region would become almost 0 Ω and the impedance matching would be difficult.

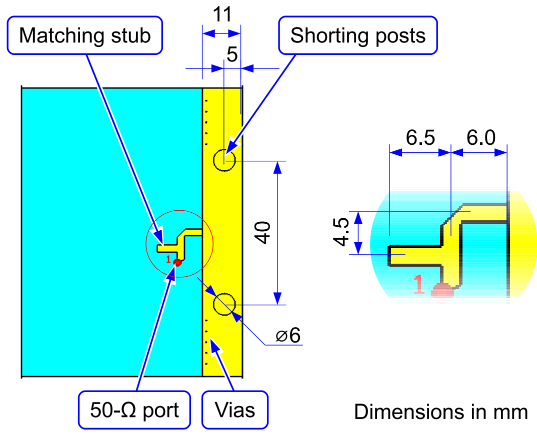

Fig. 6: Finally obtained MSL-PPW transition structure. The MSL is bended for compact implementation. The PCB thickness is 1.0 mm and the other side not shown here is a solid ground plane.

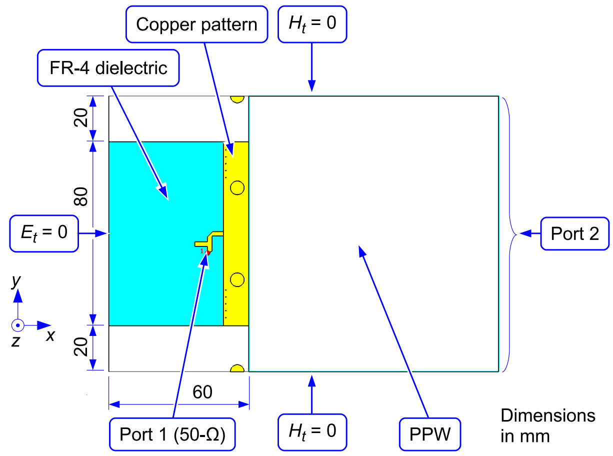

Fig. 7: Simulation model of MSL-PPW transition structure. The left-hand side end boundary condition is $E_t = 0$, i.e., the boundary is a perfect electric conductor wall. The top and the bottom ends boundary conditions are $H_t = 0$, i.e., no electric current flows across the boundary. The copper conductivity, the FR-4 dielectric constant and loss tangent are 5.8×10^7 S/m, 4.4 and 0.02, respectively.

To match the impedance of the parallel-plate with shorting posts to 50 Ω, a matching stub is attached to the MSL. The impedance matching was performed by tuning the stub length and the distance between the stub and the parallel-plate region in an EM field simulation software, CST Microwave Studio.

The structure finally obtained after optimization is shown in Fig. 6. The simulation model and the simulated scattering parameters (S-parameters) are shown in Figs. 7 and 8, respectively. The power loss is due to the lossy nature of the copper and the FR-4 dielectric.

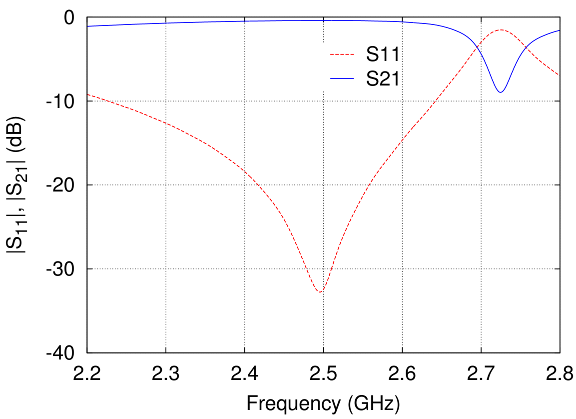

Fig. 8: Simulated S parameters. $|S_{11}| = -31$ dB and $|S_{21}| = -0.4$ dB at 2.484 GHz.

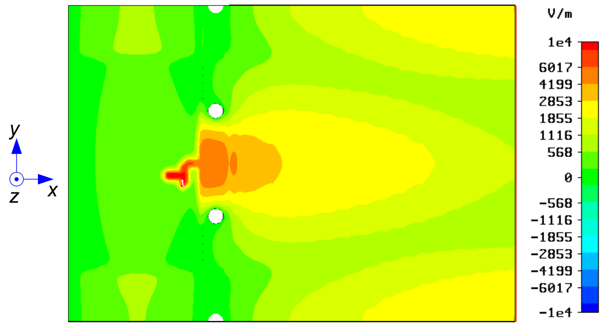

Fig. 9: The amplitude distribution of the z-component of the simulated electric field at 2.484 GHz.

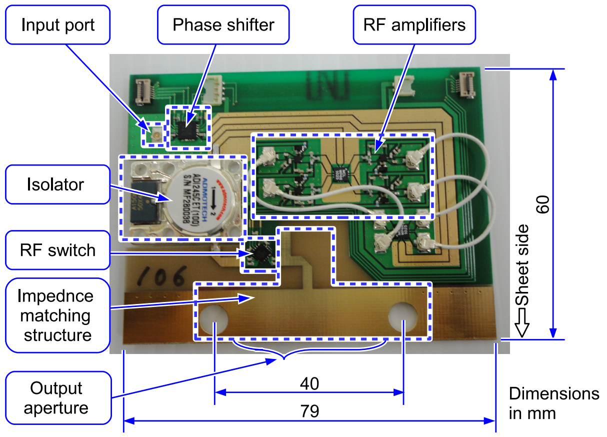

Fig. 10: Fabricated RFPA board.

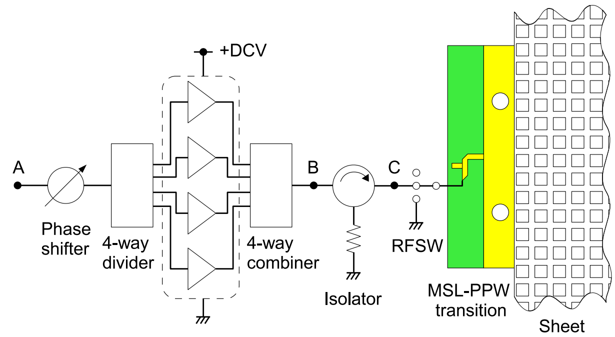

Fig. 11: Schematic diagram of the RFPA board. The RF switch between terminal C and the MSL-PPW structure is used to switch the role of the port between the power source and open/short termination.

Fig. 9 shows a simulated electric field amplitude distribution. The PPW guided wave is generated beyond the transition structure.

Note that the net power flow path from the board is only the direction toward the sheet, because the board is surrounded by $E_t = 0$ (tangential component of the electric field is zero) and $H_t = 0$ (tangential component of the magnetic field is zero) boundaries. These boundary conditions reflect the situation where the metal cases enclose the board for EM emission reduction, and multiple boards are aligned periodically in the y-direction in the same metal cases.

4. FABRICATED BOARD

A fabricated RFPA board and its schematic diagram are shown in Figs. 10 and 11, respectively.

The fabricated board measures 80×60 mm^2. The board thickness is 5 mm and when it is clamped with metal cases, the overall thickness is 8 mm.

In the fabricated board, an RF switch (RFSW) is inserted between the isolator and the MSL-PPW transition. In a phased array system using the boards, when one of them is disabled, the boundary condition at that board seen from the waveguide sheet can be switched to open- or short-terminated from the well-matched absorbing termination, by controlling the RFSW. It increases the degree-of-freedom of the phased array system and can contribute to improve the power transmission efficiency to arbitrary receiver positions.

Input microwave signal is supplied to terminal A shown in the Fig. 11. The signal phase is tuned by the phase shifter, M/A-COM MAPS-010144, which can shift the phase in 360 deg with 16 steps (4-bit control). The phase-tuned signal is divided into 4 channels and individually amplified, and they are combined again. Mini-Circuits BP4U1+ is used as the splitter and the combiner.

The signal of each channel is amplified to approximately 25 dBm by an RFPA IC, CEL μPG2250T5N, with high PAE of approximately 55% [5]. In order to provide 30-dBm (= 1-W) power of microwave at the output port of the board, 4 channels of 25-dBm outputs are combined.

5. LOSS ANALYSIS

In this section, loss analysis of a fabricated RFPA board is presented.

For the board evaluation, approximately 3.5 mW of 2.484-GHz RF signal was applied to the terminal A.

The supplied dc power, P_{dc}, was calculated as 2.67 W, from the measured supply voltage 3.0 V and the current 0.89 A. The RF output power at point B was measured as

Table 1: Loss analysis of the fabricated board.

Component	Power (W)	Ratio (%)
RFPA loss	1.25	46.8
Combiner loss	0.21	7.9
Isolator loss	0.057	2.1
RFSW loss	0.13	4.9
MSL-PPW loss	0.095	3.6
Available RF output	0.93	34.8
Supplied dc power	2.67	100

1.21 W by removing the isolator and connecting an RF power meter, Agilent E4418B.

From the datasheet, the power combiner insertion loss was estimated as 0.7 dB, which corresponded to 0.21 W. The RF power generated by the four RFPAs, P_{RFgen}, was calculated as 1.42 W. Therefore, the power loss at the RFPAs was calculated as $P_{dc} - P_{RFgen} = 1.25$ W.

From the inspection report provided by the manufacturer, the isolator insertion loss was estimated as 0.2 dB, which corresponded to 0.057 W. From the datasheet, the RF switch insertion loss was estimated as 0.5 dB, which corresponded to 0.13 W.

The insertion loss of the MSL-PPW transition was estimated as 0.4 dB from the simulation, as shown in the previous section. It corresponded to 0.095 W.

By subtracting the estimated losses of the isolator, the RFSW and the MSL-PPW transition from the measured output at point B, net available power at the output port, P_{RFnet}, was calculated as 0.93 W. As a result, the overall dc-to-RF efficiency was calculated as $P_{RFnet}/P_{dc} = 34.8\%$.

The analysis summary is shown in Table 1. Thus, the fabricated RFPA board can supply approximately 1-W RF power into the sheet.

6. CONCLUSION

In this paper, we proposed a distributed RF power source configuration for a practical phased-array 2DWPT system. For the proposed configuration, an RFPA board that can be directly attached to the waveguide sheet was developed. The developed board size was $80\times60\times5$ mm^3. The board edge is designed to be clamped together with the sheet by metal cases and screws. By using the developed board, bulky RF power source unit and thick coaxial cables can be eliminated from phased array 2DWPT systems.

Through simulations, measurements and calculations, the net available power at the RFPA board output edge was estimated as 0.93 W. The overall dc-to-RF conversion efficiency of the board was estimated as 34.8%. The output phase can be tuned in the range from 0 deg to 360 deg, via the 4-bit digital input.

The required functions for the distributed RFPA configuration were clarified and were implemented in a compact form. The developed board will enable building a compact, practical phased-array 2DWPT system with a several-watt capacity and with 10% or higher overall dc-to-dc power transmission efficiency.

ACKNOWLEDGMENT

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