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Development of Transmitter/Receiver Front-End Module with Automatic Tx/Rx Switching Scheme for Retro-Reflective Beamforming

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Abstract

In this work, a transmitter/receiver front-end module (T/R FEM) with an automatic Tx/Rx switching scheme for a 2.4 GHz microwave power transfer is developed for a retro-reflective beamforming scheme. Recently, research on wireless power transfer techniques has moved to wireless charging systems for mobile devices. Retro-reflective beamforming is a good candidate for tracking the spatial position of a mobile device to be charged. In Tx mode, the T/R FEM generates a minimum of 1 W. It also comprises an amplitude and phase monitoring port for transmitting RF power. In Rx mode, it passes an Rx pilot signal from a mobile device to a digital baseband subsystem to recognize the position of the mobile device. The insertion loss of the Rx signal path is 4.5 dB. The Tx and Rx modes are automatically switched by detecting the Tx input power. This T/R FEM is a design example of T/R FEMs for wireless charging systems based on a retro-reflective beamforming scheme.

Index Terms: Automatic switching, Beamforming, Microwave power transfer, Retro-reflective, Wireless charging

I. INTRODUCTION

Various portable electronic devices, such as laptop computers, smart phones, digital cameras, and smart watches must be periodically charged by chargers connected to a power outlet. However, the wireless power transfer (WPT) technique, patented by N. Tesla [1] in 1914, is now considered a feasible solution to remove wired chargers, after a 60 W light bulb was lit wirelessly by a resonant inductive coupling scheme developed by a research team at the Massachusetts Institute of Technology (MIT) [2].

WPT techniques are categorized into two types: non-radiative or near-field, and radiative or far-field. Resonant inductive coupling is a near-field WPT technique. An example of a far-field WPT technique is microwave power transfer (MPT), developed for transmitting large amounts of power to unmanned aerial vehicles, and for the concept of space solar power [3].

Recently, MPT has attracted attention for charging mobile devices. Zhai et al. suggested a retro-reflective beamforming scheme for a wireless charging system [4]. A generic schematic of retro-reflective beamforming is illustrated in Fig. 1. In this scheme, a receiver, such as a mobile device to be charged, informs the RF power transmitter of the location where it resides by sending a pilot signal. When the transmitter recognizes the location of the receiver, it steers an RF power beam toward the receiver.

The retro-reflective beamforming scheme was devised by L. C. Van Atta in 1959 [5] and was demonstrated with a 4 × 4 Van Atta array of 16 dipoles by Sharp and Diab in 1960 [6]. An experimental study on wireless power delivery to low-power mobile devices based on retro-reflective beam-

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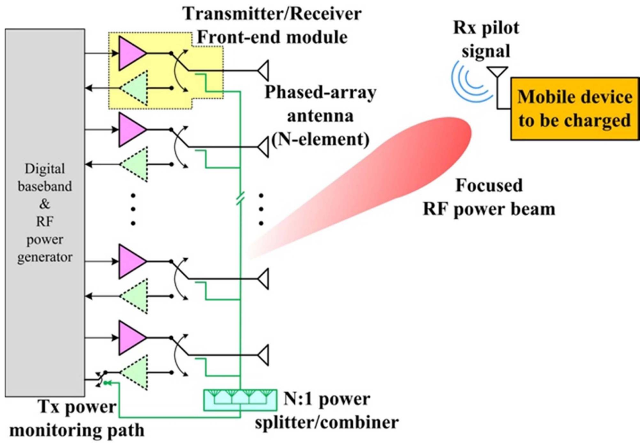

Fig. 1. Schematic of retro-reflective beamforming for microwave power transfer.

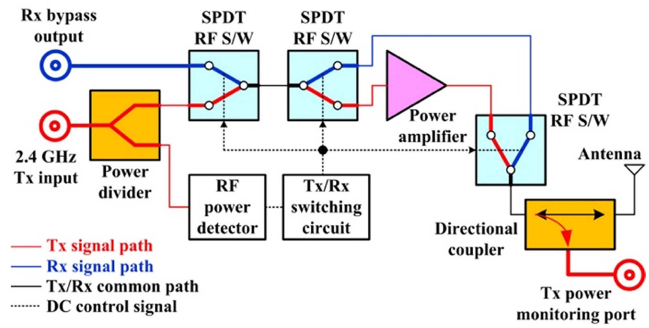

Fig. 2. Tx/Rx signal path in the transmitter/receiver front-end module.

forming was reported in [7].

A more sophisticated design is needed for wirelessly transmitting a large amount of RF power. In addition to the phased-array antenna, the transmitter and receiver front-end module (T/R FEM) is a key component in the retro-reflective beamforming scheme. The T/R FEM must be capable of passing a pilot signal from a receiver to the digital baseband subsystem and amplifying the RF power fed into the phased-array antenna. It also needs a transmitting-power monitoring path to monitor the amplitude and phase of its transmitting power.

In this work, a T/R FEM with an automatic transmitter and receiver (Tx/Rx) switching scheme was designed, fabricated, and characterized. The design aspects of the T/R FEM are explained in Section II. Its characteristics are shown in Section III, followed by the conclusion in Section IV.

II. DESIGN OF TRANSMITTER AND RECEIVER FRONT-END MODULE WITH AUTOMATIC Tx/Rx SWITCHING SCHEME

Several design elements must be considered when implementing a T/R FEM with a Tx/Rx automatic switching scheme. In the following subsections, specific design considerations are presented: the Tx/Rx signal path and RF power budget, the automatic switching scheme between Tx and Rx modes, distributing DC power supplies, and the layout of various RF and DC components on a multi-layered printed circuit board (PCB).

A. Tx/Rx Signal Path and RF Power Budget

The Tx/Rx signal paths are shown in Fig. 2. To switch between the Tx and Rx signal paths, three single-pole double-throw (SPDT) switches are required in this design. To divide the Tx and Rx signal paths, two SPDT switches are placed at the input and output ports of the power amplifier. Without the third SPDT switch, the Rx bypass output port and the power divider output port would share the input RF port of the second SPDT switch in Fig. 2, which must be avoided in RF signal path design. The third SPDT switch is placed to isolate the Tx and Rx signal paths.

These SPDT switches are controlled by the RF power detector with a Tx/Rx switching circuit. When Tx power is applied to the 3-dB power divider, as shown in Fig. 2, half of the Tx power goes to the power detector. If the Tx power generates sufficient voltage for the RF power detector to turn on the Tx/Rx switching circuit, the three SPDT switches are aligned to enable the Tx signal path. Otherwise, the SPDT switches are aligned to enable the Rx signal path.

Because the purpose of this work is to design a T/R FEM for retro-reflective beamforming, Tx power-budget analysis is the most important design aspect. The RF output power goal from the T/R FEM is at least 30 dBm (=1 W). The insertion losses (ILs) of the power divider, SPDT switch, and directional coupler selected for the T/R FEM design are typically 3.0 dB, 0.7 dB, and 0.1 dB, respectively. Therefore, the cascade IL from the power divider input to the power amplifier input is typically 4.4 dB.

The power amplifier selected for this work has 33 dB of small signal gain. From the power amplifier output to the directional coupler output, the cascade IL is typically 0.8 dB. Thus, a typical total gain of the Tx signal path would be 27.8 dB. An RF output power of 30 dBm can be achieved when the power at the power divider input is 2.2 dBm.

B. Automatic Tx/Rx Switching Scheme

A popular method for implementing automatic switching between a transmitter and a receiver is to adopt a microcontroller and a software control scheme. However, even a small lightweight microcontroller would require extra circuitry between the microcontroller and the transceiver, additional power consumption, and software. In this work, the auto-

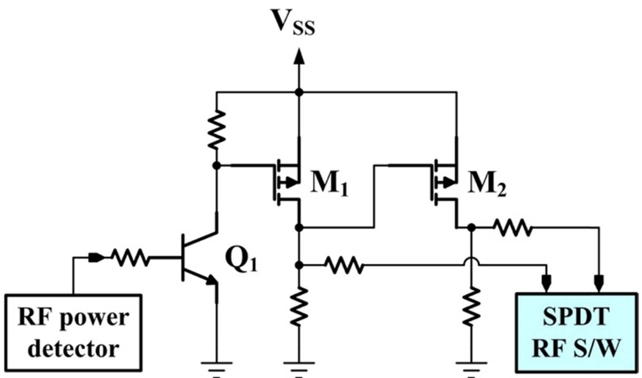

Fig. 3. Schematic of the automatic Tx/Rx switching circuit.

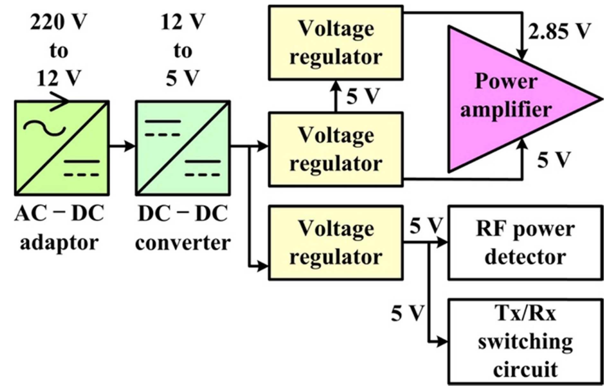

Fig. 4. Block diagram of the DC power-supply distribution.

matic Tx/Rx switching scheme is designed and implemented without being controlled by a microcontroller.

As shown in Fig. 3, an RF power detector and a level-shifting circuit using two p-channel FETs (M_1 and M_2) and a bipolar junction transistor (BJT) (Q_1) are used to implement the automatic Tx/Rx switching scheme.

The RF power detector converts the RF input power to DC voltage. When the DC voltage from the RF power detector is greater than Q_1's turn-on voltage, Q_1 turns on. This makes M_1 turn on, and the V_{ss} voltage is applied to one control pin of the SPDT RF switch. When Q_1 is turned off, M_1 turns off, but M_2 turns on to supply the V_{ss} voltage to another control pin of the SPDT RF switch. The input RF power vs. the output voltage from the RF power detector will be discussed in the following section.

C. Design of DC Power-Supply Distribution

When developing a T/R FEM, the DC power-supply distribution is an important part of the design process. Firstly, the input DC power to the T/R FEM is 12 V from an AC–DC adaptor. The 12 V from the AC–DC adaptor need to be converted to 5 V by a DC–DC converter on the module. Secondly, the 5 V from the DC–DC converter is distributed to two 5-V voltage regulators to supply DC power for an RF power amplifier, an RF power detector, and an automatic Tx/Rx switching circuit. The third voltage regulator supplies a 2.85 V reference voltage for the RF power amplifier. Fig. 4 shows a block diagram of the DC power-supply distribution.

D. PCB Layout

The PCB layout design and a fabricated PCB sample are shown in Fig. 5. In a four-layer PCB, the RF paths were routed on the top layer. The second and third layers were used for a ground plane and power-line routing, respectively. The fourth layer was used as a heat sink to dissipate the heat from the power amplifier. The major components and their manufacturers for the T/R FEM are listed in Table 1.

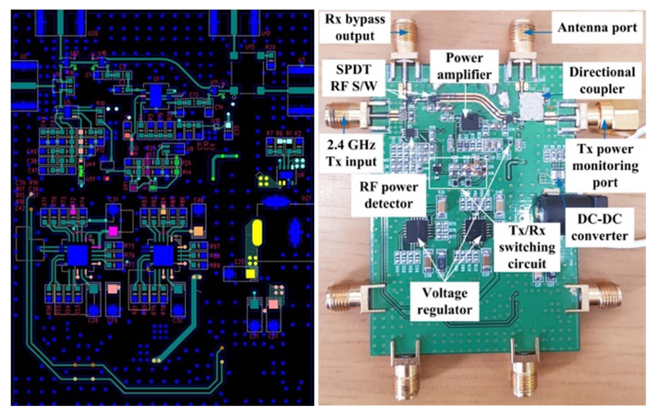

Fig. 5. PCB layout design (left) and the fabricated PCB (right).

Table 1. Major components and their manufacturers

Component	Manufacturer	Part number
Power amplifier	Skyworks Solutions, Inc	SKY65174-21
SPDT RF switch	Skyworks Solutions, Inc	SKY13370-374LF
Power detector	Analog Devices	ADL5903
Directional coupler	Anaren	XEC24P3-30G
Power divider	Anaren	PD2328J5050S2HF
DC–DC converter	Texas Instruments	TPS82130SILR
Voltage regulator	Texas Instruments	TPS7A4701RGWR

III. RESULTS

A. Measurement Set-up

The circuit performance of the power amplifier and the Tx and Rx signal paths on the T/R FEM are measured by a vec-

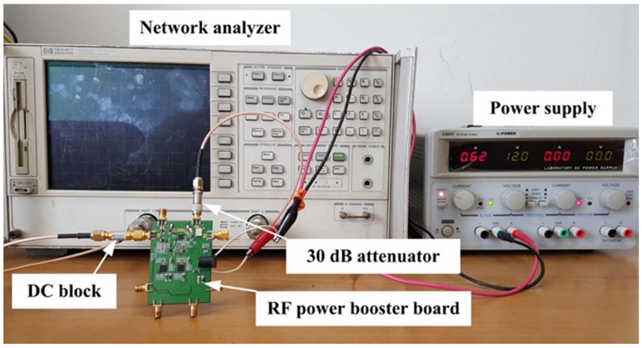

Fig. 6. Measurement setup for the transmitter/receiver front-end module.

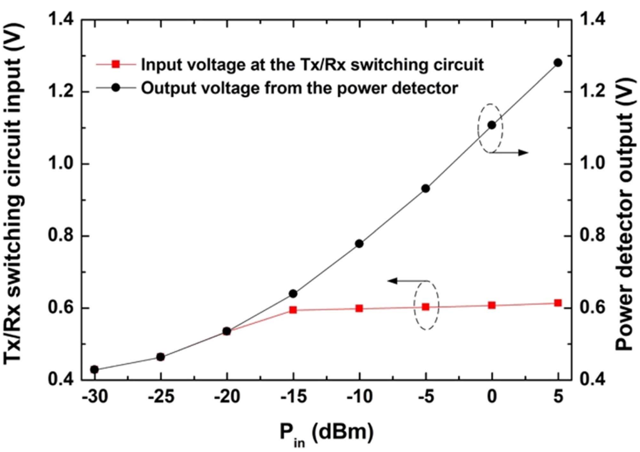

Fig. 7. Measured results of the voltage at the Tx/Rx switching circuit input and the output voltage of the power detector.

tor network analyzer, HP8753E, manufactured by Hewlett-Packard Company, with a DC power supply. To avoid any damage to the network analyzer, a coaxial DC block and 30-dB attenuator are placed at the input and output ports of the network analyzer, respectively. Fig. 6 shows a picture of the measurement setup.

B. Tx/Rx Switching Circuit

The automatic Tx/Rx switching function is performed by detecting the 2.4 GHz RF power level at the input of the RF power detector. The 2.4 GHz RF input power (P_{in} in horizontal axis in Fig. 7) applied to the Tx input port is converted to voltage by the power detector. Voltage is measured at the power detector output port (black circle symbol in Fig. 7) and the base of Q_1 in Fig. 3 (red square symbol in Fig. 7).

It can be seen that the voltage increment is fairly linear after -15 dBm of P_{in}, and the output voltage from the power detector is greater than 0.6 V when P_{in} is greater than -15 dBm. Fig. 7 also shows the input voltage at the Tx/Rx switching circuit, which corresponds to the voltage at the base of Q_1. When

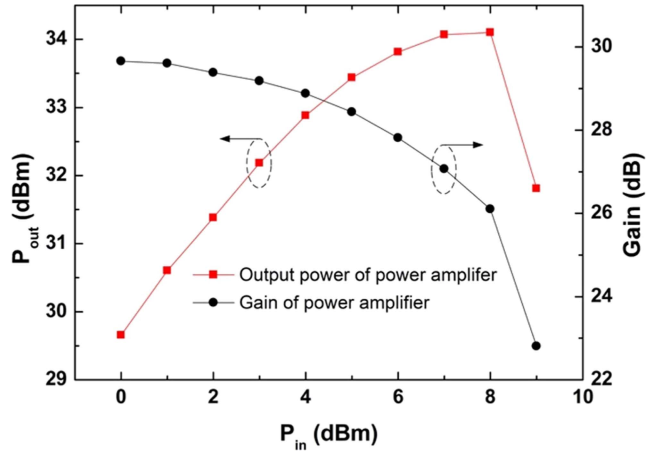

Fig. 8. Measured results of the output power and gain of the power amplifier.

P_{in} is greater than -15 dBm, Q_1 is turned on, because its turn-on voltage is 0.6 V. When a BJT is turned on, the base voltage maintains its turn-on voltage as shown in Fig. 7. As mentioned in Section II-B, when Q_1 is turned on, the SPDT RF switches are turned on to activate the Tx path. Thus, the Tx path is activated when the P_{in} at the Tx input port is greater than -15 dBm.

C. Tx and Rx Signal Path

In T/R FEM development, the power amplifier is an essential part of the module. The measured performance of the power amplifier is shown in Fig. 8. As indicated in the manufacturer's specification sheet, the output P_{1dB} (output 1 dB power compression point) is confirmed to be 31 dBm in Fig. 8. Even though the output power is gradually saturated above 31 dBm, the maximum power generated by the power amplifier is 34 dBm, which is enough to acquire more than 30 dBm of output RF power from the T/R FEM.

The measured S-parameters for the Tx signal path, from the Tx input port to the power amplifier input, are shown in Fig. 9(a). At 2.4 GHz, the return and insertion losses are 13.7 and 7.3 dB, respectively. A return loss of more than 10 dB indicates a fairly good match. However, the insertion loss of 7.3 dB is 2.1 dB more than the calculated insertion loss of 5.2 dB in Section II-A. The additional 2.1 dB loss would come from the three SPDT RF switches and the transmission lines between the devices.

The measured S-parameters for the Rx signal path, from the antenna port to Rx bypass output port, are shown in Fig. 9(b). At 2.4 GHz, the return and insertion losses are 13.0 and 4.5 dB, respectively. Again, the return loss of more than 10 dB indicates a fairly good match. The insertion loss of 4.5 dB in the Rx signal path is good enough to recover the pilot signal from a mobile device that is less than 5 m from the transmitter.

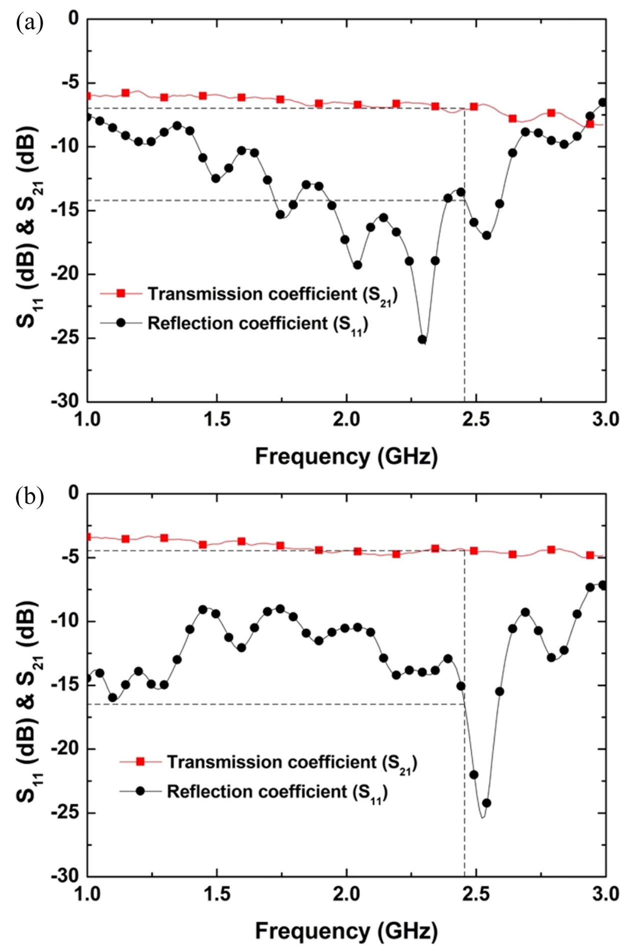

Fig. 9. Measured S-parameters for (a) the Tx signal path from the power divider to the power amplifier input and (b) the entire Rx signal path from the antenna port to the Rx bypass output port.

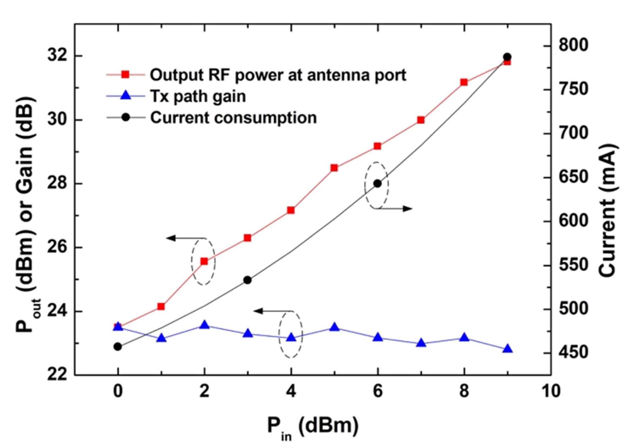

Fig. 10. Measured results of the output power, gain, and current consumption of the entire Tx path.

The actual performance of the entire Tx signal path is shown in Fig. 10. When the input RF power is no less than 7 dBm, the output power at the antenna port is more than 30 dBm. The Tx signal path gain is around 22-23 dB, which means the gain of the power amplifier is around 31 dB. When the RF output power is 30 dBm, the current consumption is measured to be around 715 mA.

IV. CONCLUSIONS

A transmitter/receiver front-end module (T/R FEM) with automatic transmitter and receiver switching capability was developed and characterized for a microwave power transfer based on retro-reflective beamforming. When the Tx power applied to the Tx input port is more than -15 dBm, the Tx signal path is turned on; otherwise, the Rx signal path is established to receive a pilot signal from a mobile device. The RF output power of the module is a minimum of 1 W and the insertion loss of the Rx signal path is 4.5 dB, which is sufficient to recover the pilot signal from a mobile device. The T/R FEM with automatic Tx/Rx switching capability is a design example of a wireless charging system based on retro-reflective beamforming.

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