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Compact Feeding Circuit for an Antenna That Achieves Three-Way Switchable Beam Directions Using Lumped Parameter Elements

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Abstract: There have been a number of studies on phased array antennas and adaptive antennas as directional antennas that can be scanned electronically. However, these antenna systems require expensive phase shifters and power controllers, and their construction is complex. Small and relatively inexpensive antenna system, in which the beam is scanned or the beam direction is switched electronically, are expected for consumer applications. This research presents a compact feeding circuit for an antenna which enables its beam to be switched in three directions using lumped parameter elements. The circuit was designed and constructed in such a way that the transmission lines of two conventional rat-race circuits were replaced with phase shifters which utilize lumped elements. The proposed circuit has a single input port and four output ports for connection to the antennas, and can obtain phase differences of ±90° and 0° between antennas. The prototype was fabricated and evaluated at 1 GHz. The measured values were very consistent with the theory. The phase difference and magnitude errors between the antennas were -2.5 ~ +2.6°, -0.4.8 ~ +0.45dB with the SW1-setting, and -1.8 ~ +7.1°, -0.54 ~ +0.45dB with the SW3-setting. The area of the prototype fabricated this time was 8 × 7 mm, and reduced to 1/216 in comparison with the conventional circuit.

Keywords: Rat-Race Circuit, Hybrid Ring, Phase Shifter, Array Antenna, Multi Beam Antenna, Butler Matrix, Feeding Circuit, Phased Array antenna

1. Introduction

Simple, small, and relatively inexpensive antenna sistems, in which the beam is scanned or the beam direction is switched electronically, are expected for consumer applications [1]. There have been a number of studies on phased array antennas and adaptive antennas as directional antennas that can be scanned electronically [2-11]. However, these antenna systems require expensive phase shifters and power controllers, and their construction is complex. As a result, these antenna systems are both expensive and large, and so are unsuitable for consumer applications.

Multibeam antennas can switch beams, and are simple and relatively inexpensive since they do not require the use of expensive phase shifters. The Butler Matrix is a well-known network used for multibeam antennas [12]. Butler Matrices are rather large since they consist of four hybrid circuits. The main problem of these systems is that they cannot direct the beam in the boresight direction, and a boresight beam is important for some systems. In 2005, M. Koubeissi proposed a feeding matrix capable of controlling the beam in three directions, including boresight [13]. However, the feeding matrix is larger than the Butler Matrix since it consists of eight hybrid circuits. In 2007, a compact feeding matrix capable of controlling the beam in three directions with two hybrid circuits (hybrid three-direction beam matrix: HTBM) was proposed. HTBM has a single input port and four output ports for connection to the antennas, and can obtain phase differences of ±90° and 0° between antennas [14].

Thus, many studies have been conducted so far to reduce the size and cost of beam switching antennas. In 2011 an RTBM (Rat-race three direction Beam Matrix) circuit was reported as a feeding matrix circuit which realize a compact beam switching antenna, having same phase differences as HTBM [15]. This circuit, characterized by the ability to switch its beam in three directions using two rat race circuits and one three-contact switch, was in fact fabricated in 2015 [16]. Then, a rat race circuit—also reported in the same year—was significantly downsized by being replaced with a lumped constant circuit [17, 18]. This research has aimed to develop a miniaturized RTBM circuit which replaced transmission lines with lumped constant elements and which yet has the performance equivalent to conventional RTBM circuits. Its operating frequency was set at 1 GHz in consideration of the self-resonant frequency of the coil.

2. Design and Fabrication

Figure 1 shows the RTBM circuit which replaced transmission lines Ta, Tb, HB1 and HB2 of the RTBM circuit proposed in Reference [15] with lumped constant elements. Its transmission lines were replaced with π phase shifters using LC elements. By switching the three-contact switch in the signal input section to SW1, SW2, and SW3, this circuit can shift the phases between the four antenna terminals ANT1–ANT4 to 0°, -90°, and +90°. The transmission lines (To) having a characteristic impedance of 50Ω and an electrical length of λ/4 were used to connect ANT1–ANT4 and the output ports (B1, B2, D1, D2) of the feeding circuit. The substrate used in the design were characterized by its dielectric constant ε_r = 3.3, dielectric thickness h = 0.8 mm, conductor thickness t = 18 μm, and dielectric loss tangent tan δ = 0.006 [16]. The designed center frequency was 1 GHz. The length (Lo) and width (Wo) of the transmission lines (To) were calculated using an RF simulator, S-NAP (modified nodal analysis, MEL), which determined Lo = 46.03 mm and Wo = 1.871 mm.

The substrate was fabricated through cutting processes. After the front- and back-side patterns were formed on one side of the two layers for double-sided board, their two ground planes were joined together by applying solder paste to each ground plane and then applying the heat for reflow soldering. Via holes were made by drilling a ϕ1 mm hole in the substrate and passing a ϕ 0.5 mm tin-plated wire through it. To insulate the tin-plated wire from the ground of the intermediate layer, the metal around the via holes was scraped off by ϕ3 mm. An SMA connector was used for attaching to the output ports.

Since the purpose of this paper is to validate the miniaturization of the RTBM using the transmission lines proposed in Reference [16], the input signal was input directly to each port as in Reference [16]. Figure 2 shows the fabricated SW1 setting circuit. The symbol '○' denotes GND, and the symbol '△' denotes a Via connected to the opposite surface. The areas enclosed by the dotted line in Figures 2(a) and (b) are the RTBM circuits, and the enlarged views are shown in Figures 2(c) and (d). In Figures 2(a) and (b), the white letters with black outline show the ports mounted on the opposite sides. In the case of SW3 setting, Tb (SW1) shown in Figure 2(c) was not mounted on the back side. Instead, Tb was mounted in the area enclosed by the dotted line as shown in Figure 2(d), where signals were input from Port1 (SW3).

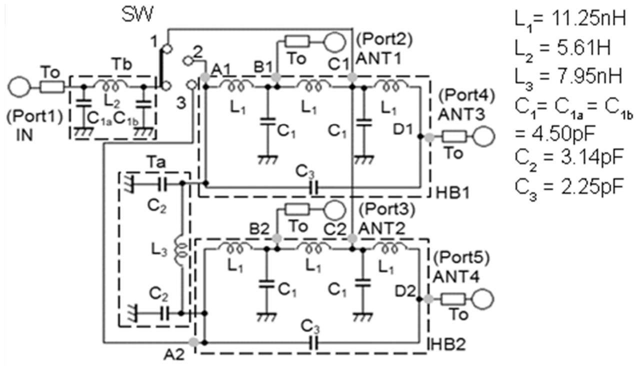
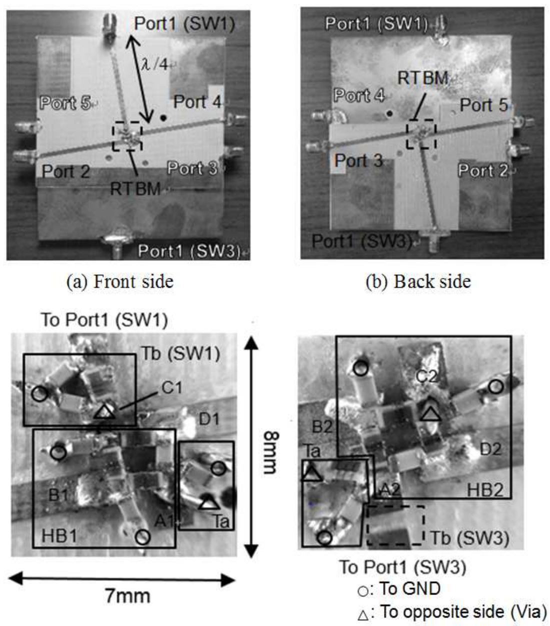


Figure 1. *RTBM circuit using lumped parameter elements.*



(a) Front side (b) Back side

(c) Enlarged view of front side (d) Enlarged view of back side

Figure 2. *Constructed RTBM circuit.*

The values of elements used for fabricating the actual devices were L_1: 11nH, L_2: 5.6 nH, L_3: 6.2 nH, C_1: 4.3 pF, C_{1a}: 3.3 pF, C_{1b}: 3.6 pF, C_2: 4.3 pF, and C_3: 2.2 pF. The values C_{1a} and C_{1b} used for the phase shifter Tb were modified from their theoretical values in order to adjust the deviation in the input impedance of the RTBM caused by stray capacitance or the effect of vias. The value L_3 for Ta was also modified in consideration of the effect of vias.

3. Simulation and Measurement

In the simulation, the circuit in Figure 1 was analyzed using an RF circuit simulator, S-NAP (MEL). In the analysis, the reflection characteristics S_{11} and the transmission characteristics S_{21} to S_{51} were obtained with the input port IN as Port1 and the antenna ports ANT1–ANT4 as Port2–Port5. The reflection characteristics and transmission characteristics were measured using a vector network analyzer (HP8752). The circuit was evaluated for only SW1 and SW3 settings, while the evaluation of SW2 setting was omitted because the operation of the circuit is the same as that for SW3 setting. Unused ports were terminated with 50Ω terminating resistors. The measurement was made at a center frequency of 1 GHz and a span of 50 MHz. The SOLT method was selected for the calibration of the vector network analyzer.

4. Results and Consideration

Figure 3(a) shows the measurement results of the transmission characteristics on the polar chart when signals were input from Port1 (SW1) in the case of SW1 setting. Figure 3(b) shows the measurement results of the transmission characteristics when signals were input from Port1 (SW3) in the case of SW3 setting. The black lines drawn on the charts denote the measured values; the round dots denote 1GHz points; and the symbols '×' denote 1GHz points of simulation values.

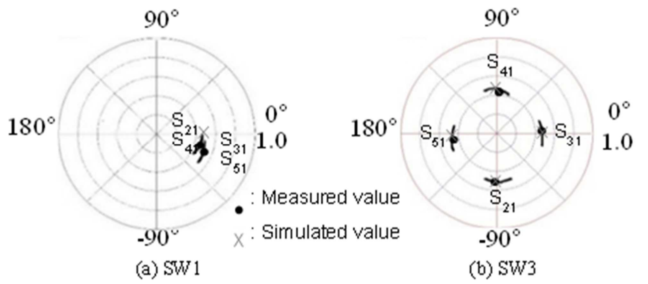


Figure 3. *Measured S-parameter of RTBM.*

The simulation values with SW1 setting were as follows: Phases (Port2, Port3, Port4, Port5): 0.9°, 0.9°, 1.5°, and 1.5°; Output levels: -6.44 dB, -6.44 dB, -6.34 dB, and -6.34 dB.

The simulation values with SW3 setting were as follows: Phases: -87.7°, 1.1°, 91.6°, and -178.8°; Output levels: -6.40 dB, -6.45 dB, -6.42 dB, and -6.35 dB.

The measured values with SW1 setting were as follows: Phases: -10.3°, -12.8°, -10.2°, and -12.1°; Output levels: -6.66 dB, -6.33 dB, -6.81 dB, and -6.36 dB. The errors between antennas were -2.5 ~ 2.6°, and -0.48 ~ +0.45 dB.

The measured values with SW3 setting were as follows: Phases: -90.8°, -2.60°, 87.9°, and -175.0°; Output levels: -6.45 dB, -6.24 dB, -6.78 dB, and -6.33 dB. The errors between antennas were -1.8 ~ 7.1°, and -0.54 ~ +0.45 dB.

The desired values of the phase difference between each antenna element are 0° with SW1 setting, 90° with the SW3 setting; and the desired values of the output level are 0 dB with both settings. The maximum measurement errors for these desired values are 2.6° in phase and 0.48 dB in output level with SW1 setting; and 7.1° in phase and 0.54 dB in output level with SW3 setting.

As for the circuit reported in Reference [16], the maximum error between each antenna element was 8.5° in phase and 0.71 dB in output level for SW1 setting, and 10.9° in phase and 1.98 dB in output level for SW3 setting. These results of characteristics are better than those of the previously reported circuit. The reflection characteristic S_{11} was -25.70 dB or less, and thus demonstrated proper matching at the input port of this circuit. The above errors were mainly caused by the dielectric constant error of the substrate, the element error, the line width and line length error generated by the substrate processing and the influence of vias.

The size of the conventional RTBM circuit was estimated to be 135 × 90 mm for 1 GHz operation, while the size of the RTBM circuit fabricated this time was 8 × 7 mm, thus reducing the area to 1/216.

Table 1. *The measured values for each port and the error between the antennas for each setting at 1GHz.*

Setup Name		Port2 ANT1	Port3 ANT2	Port4 ANT3	Port5 ANT4	Error between antennas
SW1	Ph. [deg]	-10.3	-12.8	-10.2	-12.1	-2.5 ~ +2.6
	Mag. [dB]	-6.66	-6.33	-6.81	-6.36	-0.48 ~ +0.45
SW2	Ph. [deg]	-90.8	-2.6	87.9	-175	-1.8 ~ +7.1
	Mag. [dB]	-6.45	-6.24	-6.78	-6.33	-0.54 ~ +0.45

5. Conclusion

A compact antenna feeding circuit which consisted of two rat-race circuit using the lumped constant elements was proposed in this report. The proposed circuit had a single input port and four output ports for connection to the antennas. The phase differences between antennas could be switched to +90°, –90° or 0° using a switch, and the beams could be controlled in three directions, including boresight. The prototype was fabricated and evaluated for 1GHz operation. As a result, the return losses of the input port were more than 25.7 dB. The phase difference and magnitude errors between the antennas were -2.5 ~ +2.6°, -0.48 ~ +0.45dB with the SW1-setting, and -1.8 ~ +7.1°, -0. 54 ~ +0.45dB with the SW3-setting. The Circuit performance was very consistent with the theory. The fabricated feeding circuit was extremely compact. The size was 8 × 7 mm, and reduced to 1/216 in comparison with the conventional circuit. This novel feeding circuit is promising as an inexpensive and small-sized multi-beam antenna.

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