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Feeding Matrix Placed on a Single Layer with Hybrid Coupler Controlling Beams in Three Directions Including Boresight

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1. Introduction

Simple, small, and relatively inexpensive microwave sensors, in which the beam is scanned or the beam direction is switched electronically, are expected to be useful as large-area intruder sensors [1]. There have been a number of studies of phased array antennas and adaptive antennas as directional antennas that can be scanned electronically [2], [3]. 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 they are therefore unsuitable for consumer applications.

Parasitic beam antenna systems are inexpensive antennas in which some elements obtain radio energy by induction or radiation from the driven element [4]. In these systems, the beam is wide and has a high side lobe, making it difficult to determine the direction of targets. Therefore, they are not available for use as antennas for microwave sensors or radar systems. Narrow beam, compact and inexpensive phased array antennas with bidirectional feeds were proposed in 2006 [5].

Multibeam antennas can switch beams, and are both simple and relatively inexpensive as they do not require the use of expensive phase shifters. The Butler Matrix is a well-known network type used for multibeam antennas [6]. Butler Matrices are rather large as 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 microwave sensors. In 2005, Koubeissi proposed a feeding matrix capable of controlling the beam in three directions, including boresight [7]. However, the feeding matrix is larger than the Butler Matrix as it consists of eight hybrid circuits.

Here, a compact feeding matrix capable of controlling the beam in three directions with two hybrid circuits (hybrid three-direction beam matrix: HTBM) is 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. The components of HTBM dependent on the phase differences between antennas are placed on a single layer, and the pattern can be designed and calculated with a 2D EM simulator. First, we describe the construction and theoretical underpinnings of HTBM, and then report confirmation of the characteristics of HTBM with an EM simulator. Finally, the radiation characteristics of the system consisting of HTBM and a four-element patch array antenna were calculated with the EM simulator.

2. Theory and Design

Fig. 1 shows the circuit diagram of HTBM (hybrid three-direction beam matrix), which consists of two hybrid couplers, λ/4 transmission lines, and three switches (SW1~SW3). The components shown in Fig. 1(a) and Fig. 1(b) are located on the front (A-plane) and the rear (B-plane) of the unit, respectively. HTBM has a single input port (IN) and four output ports (ANT1~ANT4) to connect to the antennas. Components T_1~T_5 indicate the λ/4 transformer to match the input impedance to that of the source. In Fig. 1, all transmission lines are λ/4 in length. HTBM shown in Fig. 1 can be designed easily as the characteristic impedance of transmission lines is of only two types (Z0, $Z0/\sqrt{2}$) and the pattern is symmetrical. The phase differences between antennas are dependent on M_1~M_4 and the hybrid coupler placed on the A-plane, and the components including the bend and the junction can be designed using the 2D-EM simulator.

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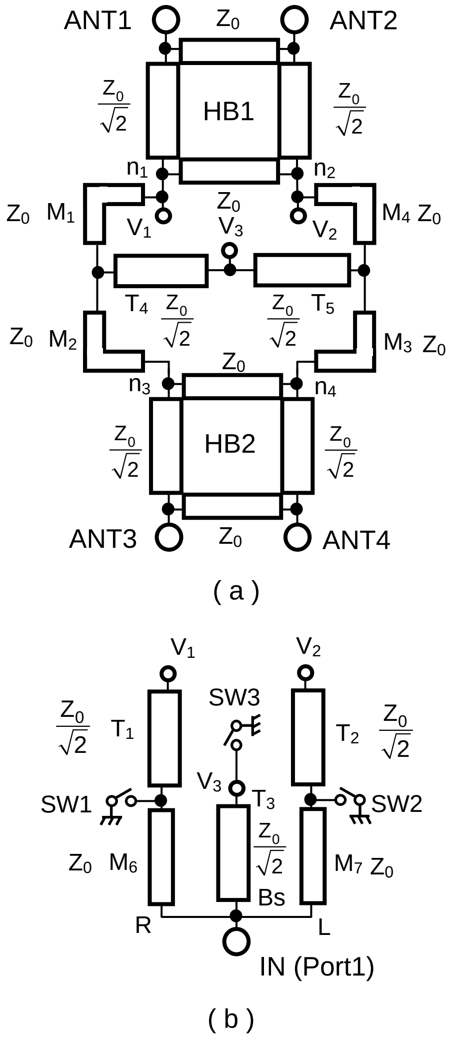
Table 1. Switch condition and phase of the output port for each setting of HTBM.

Setup Name	Beam Direction	SW1	SW2	SW3	ANT1	ANT2	ANT3	ANT4
R	Right	OFF	ON	ON	90°	0°	-90°	-180°
L	Left	ON	OFF	ON	0°	90°	180°	270°
Bs	Boresight	ON	ON	OFF	-45°	-45°	-45°	-45°



(a)

(b)

Fig. 1 Circuit diagram of HTBM.

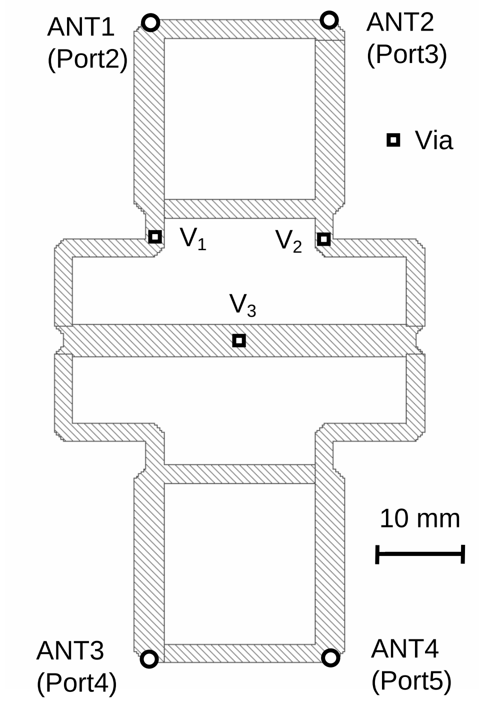


Fig. 2. Pattern of HTBM.

SW1~SW3 are switches with $\lambda/4$ lines. When these switches are ON, the two $\lambda/4$ lines connected to the switch become short stubs, and are isolated from the remainder of the circuit. When the switches SW1, SW2, and SW3 are set to OFF, ON, ON, the input signal passes through the R-side at the trifurcation point and then *via* (V_1); this is named the R-setting. The phases of the signals at each node n_1, n_2, n_3, and n_4 are 180°, *, 0°, and *, where "*" indicates no signal. In addition, the phases fed to each antenna ANT1, ANT2, ANT3, and ANT4 are 90°, 0°, –90°, and –180°. The phase difference between the antennas is –90° as the basis for ANT1, and the beam is directed to the right for the array antenna arranged in the order: ANT1, ANT2, ANT3, ANT4. When the switches SW1, SW2, and SW3 are set to ON, OFF, and ON, the input signal passes through the L-side at the trifurcation point and then *via* (V_2); this is named the L-setting. The phases of the signals at each node n_1, n_2, n_3, and n_4 are *, 180°, *, and 0°. The phases fed to each antenna ANT1, ANT2, ANT3, and ANT4 are 0°, 90°, 180°, and 270°. The phase difference between antennas is +90°, and the beam is directed to the left.

When the switches SW1, SW2, and SW3, are set to ON, ON, and OFF, the input signal passes through the Bs-side at the trifurcation point and then *via* (V_3); this is named the Bs-setting. The phases of the signals at each node n_1, n_2, n_3, and n_4 are the same. The phase of ANT1 is the synthesis of output signals for n_1 and n_2, and is –45°. The phases of the other output ports can be obtained as described for ANT1. The phase difference between antennas is 0°, and the beam is

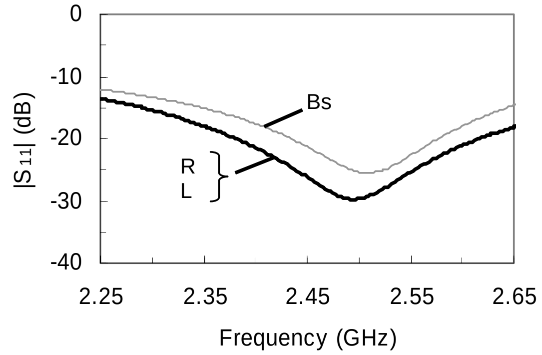


Fig. 3. $|S_{11}|$ frequency characteristics of HTBM for each setting.

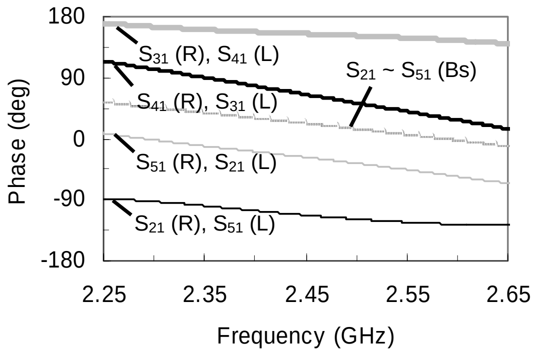


Fig. 4. Phase of S-parameter frequency characteristic for each setting of HTBM.

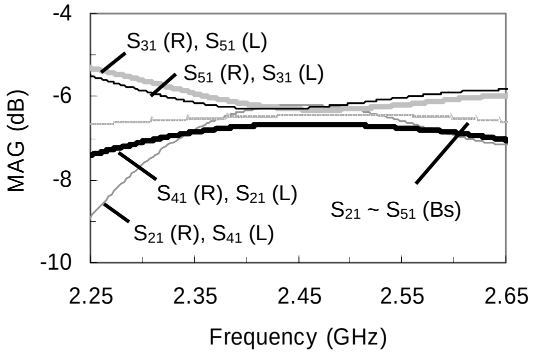


Fig. 5. Magnitude of S-parameter frequency characteristic for each setting of HTBM.

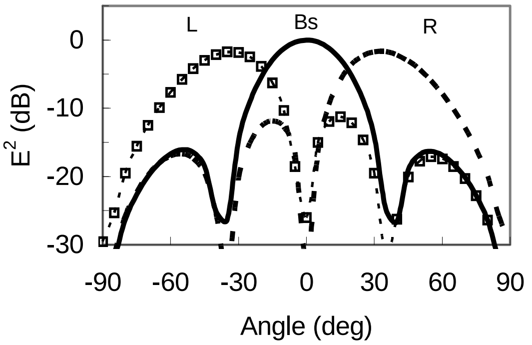


Fig. 6. Radiation characteristics for each setting.

directed to boresight. Table 1 summarizes the switch settings (R, L, Bs) and the phases of the output ports.

The input impedance of HTBM and the antenna are set as Z_0 in Fig. 1. The characteristic impedances (Z_{T1}~Z_{T5}) of T_1~T_5 can be obtained as follows. The input impedance of n_1 in the R-setting, n_2 in the L-setting, and n_3 in the Bs-setting are $Z_0/2$, when $Z_{T4} = Z_{T5} = Z_0/\sqrt{2}$. In addition, the input impedances of n_1~n_3 are transformed to Z_0 by the λ/4 transformer (T_1, T_2, T_3) of characteristic impedance ($Z_0/\sqrt{2}$).

The design conditions were as follows: $Z_0 = 50\ \Omega$; substrate characteristics, $\varepsilon_r = 3.3$, $\tan\delta = 0.006$, thickness = 0.8 mm; and frequency = 2.45 GHz. Each transmission line was calculated by the EM simulator: SONNET (moment method [9]). The widths of transmission lines of Z_0 and $Z_0/\sqrt{2}$ were 2.0 mm and 3.25 mm, respectively. The λ/4 line length was 18.5 mm. The λ/16 transmission lines were inserted into the input ports of hybrid couplers to avoid analysis of the junction of the hybrid coupler. The layout based on these conditions is shown in Fig. 2; HTBM is compact, and measures 75 (H) × 45 (W) × 3 (T) mm.

3. Simulations

The S-parameter in Fig. 2 was simulated with SONNET under the following simulation conditions for each setting. In the R-setting, the signal is input from via (V_1), with via (V_2) set to open and via (V_3) set to short. In the Bs-setting, the signal is input from via (V_3), and via (V_1 and V_2) are both set to open. The S-parameter of the L-setting is the same as the values for the R-setting with the exchange of Port 2 ↔ Port 3 and Port 4 ↔ Port 5. The via input signal is set to Port 1 and output ports (ANT1~ANT4) are set to Port 2~Port 5, and the frequency range is 2.25~2.65 GHz.

Fig.3 shows the results of simulated $|S_{11}|$ frequency characteristics for each setting. The return losses are less than –21 dB for 2.45 GHz, and the input impedance of HTBM showed a good match to 50 Ω. Fig. 4 shows the phase of the S-parameter for each setting. In the R-setting, the phase difference of the S-parameter is –90° from S_{21} toward S_{51}. In the L-setting, the phase difference of the S-parameter is +90°. The phases of all S-parameters are identical in the Bs-setting. In the R-setting, the simulated phases of the S-parameter are $S_{21} = -115.2°$, $S_{31} = 153.4°$, $S_{41} = 63.6°$, and $S_{51} = -29.8°$ for 2.45 GHz. These values represent those with subtraction of the line length (λ/2) on the B-plane from the phases shown in Table 1 and addition of the line length (λ/16) into the hybrid coupler. Fig. 5 shows the magnitude of the S-parameter for each setting. In the R-setting and the L-setting, the values are –6.5 dB ± 0.3 dB, and the values in the Bs-setting are –6.5 dB for 2.45GHz.

Next, we considered the radiation characteristics. The applied array antenna is a four-element patch array antenna with a distance of 0.4λ between antenna elements, each of which measured 18.7 × 18.7 mm. The feeding method was coaxial feeding. The characteristics of the substrate were as follows: $\varepsilon_r = 10.23$, $\tan\delta = 0.004$, thickness = 0.8 mm. A substrate with high dielectric constant was used for miniaturization of the antenna elements. The S-parameters obtained in Fig. 4 and Fig. 5 were applied as sources of each antenna, and the radiation characteristics were calculated by SONNET. Fig. 6 shows the radiation characteristics for each setting. The calculated values were: beam angle, ±34°; side lobe, –11 dB; and beam width, 30°.

4. Conclusions

We propose a novel feeding matrix, consisting of two hybrid couplers, λ/4 transmission lines, and three switches (hybrid three-direction beam matrix: HTBM). Phase differences between antennas of ±90° and 0° can be obtained using the HTBM, and the beams can be controlled in three directions, including boresight. HTBM was designed for ISM band and the S-parameters were calculated with an EM simulator. The calculated propagation characteristics between the input and output ports agreed well with the theoretical values, and the return losses of the input port were less than –21 dB. The radiation characteristics of the system consisting of HTBM and a four-element patch array antenna were calculated with the EM simulator. The calculated values are: beam angle, ±34°; side lobe, –11 dB: and beam width, 30°. The HTBM is compact, measuring 75 (H) × 45 (W) × 3 (T) mm. This novel feeding matrix is promising as an inexpensive, small-sized, narrow beam multibeam antenna for ISM band.

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