A Low-Cost 60-GHz Switched-Beam Patch Antenna Array With Butler Matrix Network

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Abstract—In this letter, a low-cost 60-GHz switched-beam patch antenna array with Butler matrix network is developed and experimentally demonstrated. In order to improve integration with the patch elements, a 4 × 4 planar Butler matrix is implemented in a low-dielectric substrate. The four rectangular patches fed by inset microstrip lines are connected to the outputs of the Butler matrix for the 60-GHz operation. Because of the fabrication tolerances, the operating frequency of the fabricated antenna shifts to 62 GHz. The radiation patterns measured at 62 GHz are in good agreement with the theoretical array factors. The antenna developed in this letter provides a cost-effective approach to implement an adaptive antenna for 60-GHz wireless communications.

Index Terms—Millimeter wave antenna arrays, millimeter wave communication, microstrip antennas, switched-beam antenna.

I. INTRODUCTION

Due to increased demand of high-speed wireless communications, the unlicensed spectrum around 60 GHz has been proposed to provide gigabit broadband services for the wireless local area network (WLAN), video streaming transfer, and short-range multimedia content download. A variety of 60-GHz antennas [1]–[8] has been developed for such applications. However, since the electromagnetic (EM) wave in the 60-GHz range critically suffers from the propagation path loss, the high-gain antennas [2]–[5] are usually employed in the 60-GHz wireless systems to alleviate the high output power requirement of the millimeter-wave power amplifier.

Although the high-gain antenna can improve the system signal-to-noise ratio and then enhance the communication quality, it is not suitable for wireless communication applications due to its property of the high spatial directivity. Therefore, the adaptive antennas [6]–[8] are proposed to overcome this limitation. By judging power levels of detected EM waves, the main beam of the radiation pattern of the adaptive antenna can point to the optimal direction, and then build up the communication link. Except for the approaches to realize adaptive antennas in [6]–[8], the switched-beam antenna with the Butler matrix network [9]–[12] is a cost effective approach to implement an adaptive antenna in microwave and millimeter-wave range.

In this letter, a planar 60-GHz switched-beam antenna shown in Fig. 1 is developed with a 4 × 4 Butler matrix network. As different input ports are excited, the Butler matrix is treated as a beam forming network to provide four output signals with equal power levels and the progressive phases of +45°, −45°, +135°, and −135°, respectively. Hence, one can switch the direction of the radiation main beam by exciting the designated input port as shown in Fig. 1. In addition, in order to reduce the manufacturing cost and effectively integrate the Butler matrix and planar antenna elements, the printed circuit broad (PCB) fabrication process is utilized to realize the switched-beam antenna.

II. IMPLEMENTATION OF SWITCHED-BEAM ANTENNA

As shown in Fig. 1, the switched-beam antenna is integrated by the Butler matrix and antenna elements. The Butler matrix mainly consists of the 90° hybrid coupler, crossover, 45° phase shifter, and phase-adjusting microstrip lines. For easily integrating the antennas on the same substrate, the RT/duroid 5880 substrate with the 5-mil thickness and the dielectric constant $\varepsilon_r = 2.2$ is employed to implement the Butler matrix. Since the line width of the 50-Ω microstrip is too wide to effectively design the components used in the Butler matrix network, the Butler matrix is basically realized by 100-Ω microstrip lines.
Fig. 2 shows the layout of switched-beam antenna designed at 60.5 GHz. The 90° hybrid coupler is realized by two pairs of 100-Ω and 70.7-Ω quarter-wavelength microstrip lines. The crossover is formed by cascading two 90° couplers via two 100-Ω quarter-wavelength microstrip lines. Moreover, the meandered microstrip lines are employed to adjust the output phases of the Butler matrix, and then connected with four rectangular patches operated at 60.5 GHz. The distance between the centers of two adjacent patch antennas is about λ₀/2 at 60.5 GHz. The impedance of input port is transferred to 50 Ω via quarter-wavelength transformer.

The transmission coefficients of the developed Butler matrix network are simulated by Agilent Momentum and shown in Fig. 3. At 60.5 GHz, the transmission coefficients from port 1 to four output ports are in the range from −6 dB to −7.7 dB, while the phase differences between two adjacent output ports are 45.6°, 46°, and 49.3°, respectively. In addition, the simulated return loss of the patch antenna fed by the inset microstrip line is illustrated in Fig. 4. Subject to the design of a planar-type switched-beam antenna, different path lengths of the Butler matrix from the input port to four output ports are inevitable. Hence, it may lead to the output amplitude imbalance and unequal curve slope of the phase response.

III. EXPERIMENTAL RESULTS

The fabricated switched-beam antenna is shown in Fig. 5(a). The circuit size is about 9.75 × 13.1 mm². In order to measure the return losses of input ports, the microstrip-to-CPW (coplanar waveguide) transition pads are mounted on the substrate for on-wafer measurement. The measured return losses are carried out by the Cascade Summit 9000 probe station linked to Agilent E8361A PNA network analyzer. The simulated results in this letter are achieved by the full-wave simulator Agilent Momentum. The measured and simulated return losses of the port 1 are shown in Fig. 5(b). In the entire measurement frequency band, namely from 55 to 65 GHz, one can achieve the return loss of greater than 10 dB. Except that the operating frequency shifts to the higher frequency band, the measured results are in reasonable agreement with the simulated results. The frequency shift is mainly caused by the fabrication etching error. Fig. 5(c) shows the measured and simulated return losses of the port 2. Over the frequency range of 59.7–65 GHz, the return loss of greater than 9.6 dB can be obtained.
In order to demonstrate the switched-beam property, two switched-beam antennas with port 1 and port 2 excitations are fabricated as shown in Figs. 6(a) and 7(a), respectively. Since the developed switched-beam antenna is a symmetrical structure, only two antennas excited by port 1 and port 2 are fabricated for evaluation. Because the unexcited ports of the Butler matrix are isolated from the excited port, only the excitation port is connected with the 1.85-mm coaxial connector. In addition, the antenna is attached to a metallic test fixture to enhance the strength of the antenna structure. The fabrication etching errors not only lead to the frequency shift of the return loss response as described, but also move the radiation performance to the higher frequency band. Hence, the radiation pattern measurement is performed at 62 GHz. Figs. 6(b) and 7(b) present the normalized far-field radiation pattern at 62 GHz in the $x$-$z$ plane defined in Figs. 6(a) and 7(a). As the port 1 is excited, the main beam points to the $14^\circ$. The direction of the main beam switches to $40^\circ$ as the port 2 is excited. Two antennas excited by the port 1 and port 2 give about 8.9 and 7.7 dBi gains, respectively. Besides the conductor loss, the discontinuity effects from the coaxial-to-microstrip transition and the output amplitude imbalance of the Butler matrix also degrade the antenna gain. The theoretical four-element array factors with ideal $45^\circ$ and $-135^\circ$ progressive phase excitations are also depicted for comparison. They are in good agreement with the measured antenna patterns.

**IV. CONCLUSION**

A 60-GHz switched-beam antenna with Butler matrix network is developed for 60-Hz wireless communication applications. The dimension errors from the fabrication process may significantly affect the frequency response of the return
losses, and also lead to the output phase errors of the Butler matrix. Hence, the switched-beam property of the antenna shifts away from the design frequency. Aside from the operating frequency shift, the measured antenna patterns in Section III demonstrated that the developed switched-beam antenna works well as the theoretical prediction. In addition, the Butler matrix is integrated with the antenna elements on the same substrate, it provides a cost-effective approach to implement adaptive antennas for the 60-GHz wireless communications.

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REFERENCES


