60-GHz Circularly-Polarized Switched-Beam Antenna Module

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1. Introduction

To increase the system capacity and the transmission data rate of wireless communication systems, the smart antenna technologies [1], including the adaptive and the switched beamforming, offer significantly improved solutions. Regarding the circuitry complexity and production cost, the switched beamforming would be currently a better candidate though it can form beams only in the specific predetermined directions based on the received signal strength measurements. In addition, using circularly-polarized (CP) antennas can provide further enhancement due to its capability of reducing multipath reflections and interferences. Therefore, a CP antenna module with the switched beamforming capability is proposed in this paper. The design specifications are as follows: the operating frequency band from 59 to 62 GHz, the input return loss > 10 dB within the band, the in-band axial ratio < 3 dB, and the LHCP peak gain > 10 dBic. The proposed 60-GHz integrated antenna module is composed of four identical CP antennas and a 4×4 Butler matrix as the beamformer. For easier integration, all the components used are in the microstrip configurations, and the RT/Rogers 5880 substrate of 5-mil thickness is chosen as the common dielectric substrate. The design details and the integration considerations are described in the following sections.

2. Width-Reduced Circularly-Polarized Patch Array Antenna

For integration's sake, the microstrip patch antenna came up to our mind. Since the patch antenna is notorious for its narrow bandwidth, the sequential rotation technique [2], [3], which has been demonstrated to be capable of increasing the impedance and axial-ratio bandwidths of a CP array antenna, is applied in our design. In this paper, a sequentially-rotated CP patch array antenna is designed and then used as the element in the switched-beam antenna module. The geometry of the proposed antenna is depicted in Fig. 1. It is composed of two identical rectangular patches edge-fed by microstrip line. Note that a diagonal slot is etched on the rectangular patch to achieve circular polarization for the single patch. The feeding network of the two patches is designed according to the sequential rotation technique. The spatial orientations of the two CP patches are perpendicular to each other, while their feeding phases are in phase quadrature. The two branches are then shunt to a 50-Ω microstrip feed line. In the switched-beam module, four identical pieces of the proposed CP patch array antennas will be placed side by side with the spacing less than $0.75\lambda_0$. Thus the mutual coupling between them should be minimized in order not to degrade the performances of the module. This is accomplished by minimizing the antenna width. As indicated in Fig. 1, the total width of the proposed antenna is approximately 81.5mil, which is less than a half free-space wavelength.

The proposed width-reduced CP patch array antenna designed at 60 GHz was implemented and tested. The measured input return losses and axial ratios compared with those simulated are shown in Figs. 2 and 3, respectively. They exhibit broadband and CP characteristics. The radiation patterns measured and simulated at 60 GHz are plotted in Fig. 4. One can see that, in the x-z plane, the two-element array factor sharpens the main beam and increases the broadside gain, while, in the y-z plane, the pattern is the same as that of a single patch. Also note that the measured and simulated results are in good agreements. All the simulations are carried out using the Zeland IE3D.

3. Integration with Butler Matrix

Since the aforementioned width-reduced CP antenna was designed in the microstrip configuration, one could easily integrate the microstrip Butler matrix with it onto the same substrate. A photo of the 60-GHz CP switched-beam antenna module, which combines the width-reduced antennas and a 4×4 microstrip Butler matrix, is shown in Fig. 5. The progressive phase difference at the upper four output ports of the Butler matrix equals –45° (–135°) when only port 1 (port 3) is excited. Owing to the symmetry of the circuitry, the progressive phase difference equals +45° (+135°) when only port 4 (port 2) is excited. Since each of the output ports is connected to a width-reduced antenna, the switched-beam characteristics can be obtained by feeding through one of the input ports. The switched-beam patterns can be calculated by multiplying the element factor, namely the y-z plane pattern of the width-reduced antenna shown in Fig. 4(b), by the array factor with the antenna spacing d and the output progressive phase of the Butler matrix. However, considering the array factor, the antenna spacing d should be kept less than $0.8\lambda_0$ to avoid the presence of the grating lobes. To trade-off between the spacing and the peak gain of the module, the spacing d is determined to be $0.75\lambda_0$ at 60 GHz. On the other hand, for lower side-lobe levels in the switched-beam pattern, $d = 0.5\lambda_0$ is also used.

The 60-GHz CP switched-beam antenna modules with $d = 0.75\lambda_0$ and $0.5\lambda_0$ were fabricated and tested. The measured switched-beam patterns for the module with $d = 0.75\lambda_0$ as fed via port 1 and port 2 are plotted in Figs. 6(a) and (b), respectively, and similarly, the patterns for the module with $d = 0.5\lambda_0$ are shown in Fig. 7. Since the patterns when fed via port 3 and port 4 are symmetric to those as fed via port 2 and port 1, respectively, they are omitted here for simplicity. In addition, the calculated results based on the principle of pattern multiplication are also shown in the figures for comparison. The calculated results all agree well with those measured. Also, the switched-beam characteristics can be observed from Figs. 6 and 7. As port 1 (port 2) is excited, the main beam of the module with $d = 0.75\lambda_0$ points at $\theta = 9.6°$ ($\theta = –30°$), while that of the module with $d = 0.5\lambda_0$ points at $\theta = 14.5°$ ($\theta = –48.6°$). Note that the module with $d = 0.5\lambda_0$ has a wider scanning range and lower side-lobe levels. Moreover, the measured peak gains of the switched-beam patterns for the two prototype modules are listed in Table 1. They are close to each other and satisfactorily high for practical Wireless Personal Area Network (WPAN) applications.

4. Conclusion

The 60-GHz CP switched-beam antenna module composed of four width-reduced CP patch array antennas and a 4×4 microstrip Butler matrix has been presented in this paper. For broadband CP radiation, the sequential rotation technique has been applied to the patch array antennas. The total width of the antenna has also been taken into account for module integration and minimized during the design process. The performances of the width-reduced antenna have been verified experimentally. The realized 60-GHz CP switched-beam antenna modules with different element spacing both exhibit satisfactorily high gains and tilted main beams as expected. The presented antenna module may find applications in the emerging WPANs.

Acknowledgments
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References
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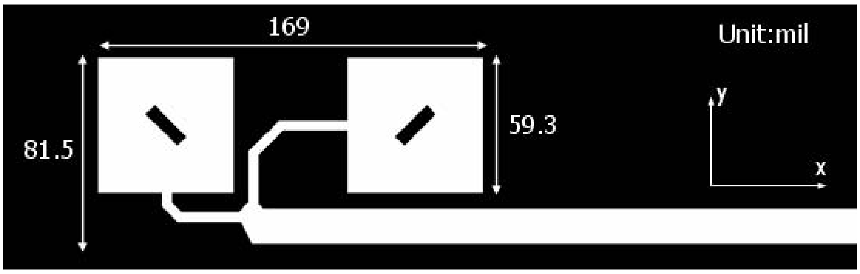


Fig. 1. Geometry of the proposed width-reduced CP patch array antenna.

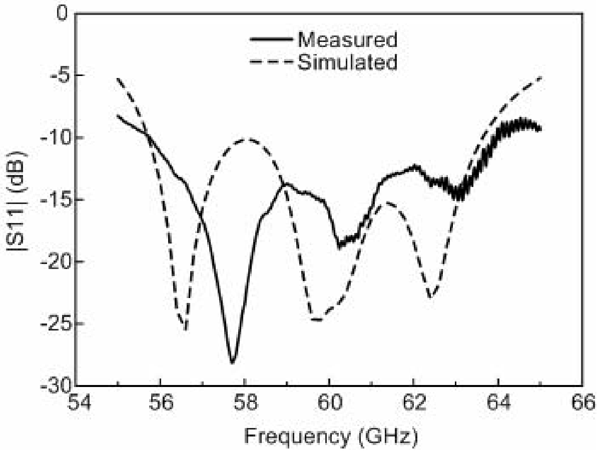


Fig. 2. Return losses of the proposed width-reduced CP patch array antenna.

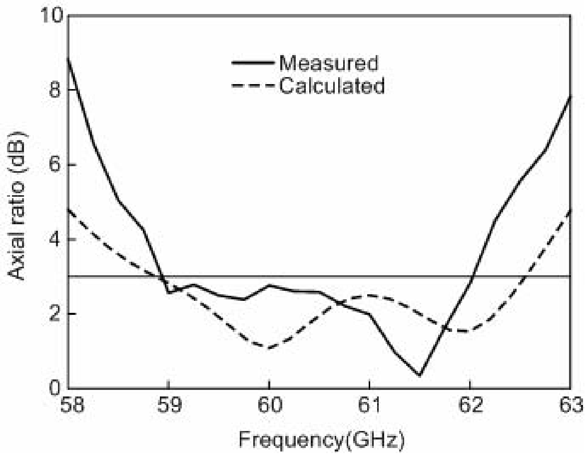


Fig. 3. Axial ratios of the proposed width-reduced CP patch array antenna.

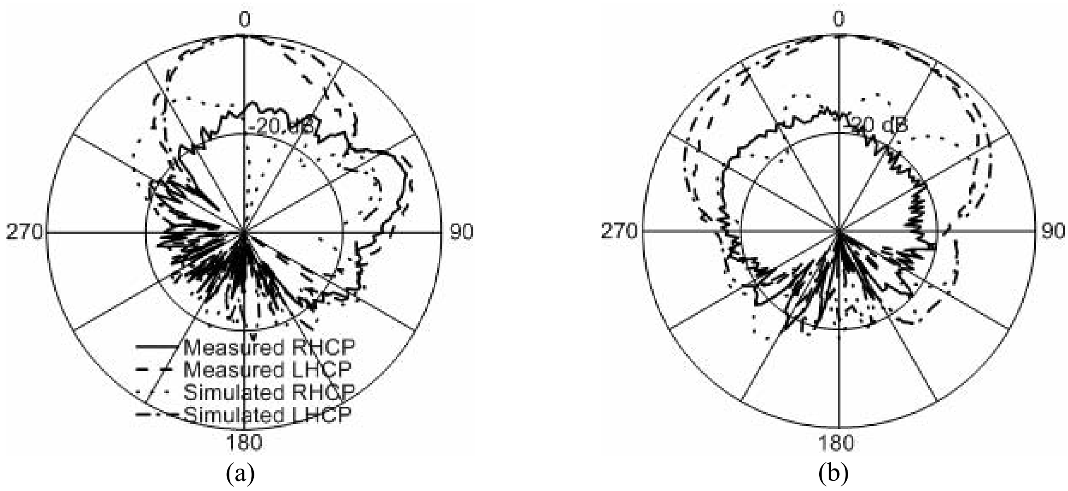


Fig. 4. (a) x-z and (b) y-z plane patterns of the proposed width-reduced CP patch array antenna.

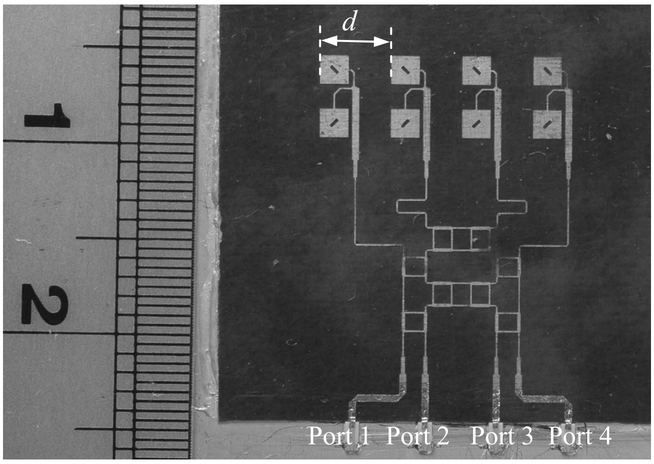
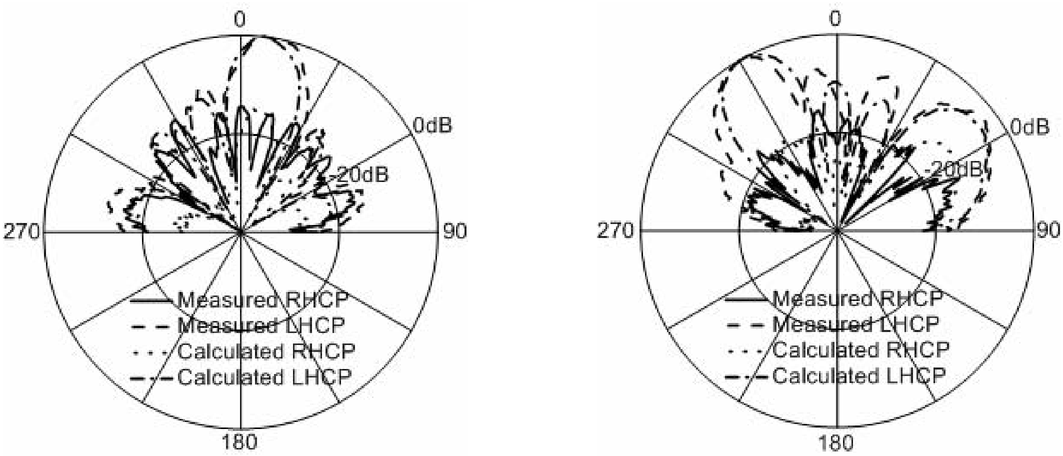
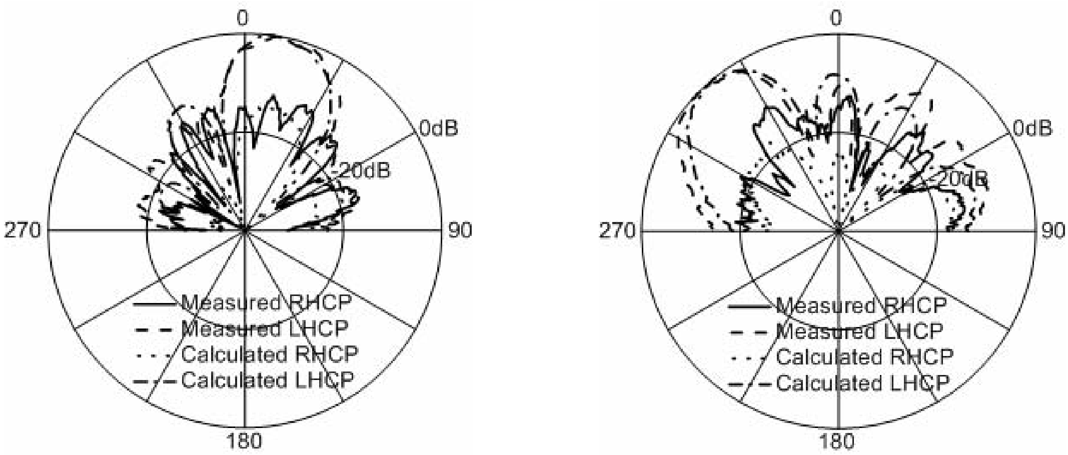


Fig. 5. Photo of the 60-GHz CP switched-beam antenna module with $d = 0.75\lambda_0$.



(a) (b)

Fig. 6. Switched-beam patterns of the module with $d = 0.75\lambda_0$ fed via (a) port 1 and (b) port 2.



(a) (b)

Fig. 7. Switched-beam patterns of the module with $d = 0.5\lambda_0$ fed via (a) port 1 and (b) port 2.

Table 1: Measured Peak Gains of Two Prototype Modules.

(Unit: dBic)	Fed via port 1	Fed via port 2	Fed via port 3	Fed via port 4
$d = 0.75\lambda_0$	11.5	10.1	10.5	11.2
$d = 0.5\lambda_0$	12.1	9.3	10.7	12.3