VI. Conclusion

We have investigated the performance of microstrip and coplanar lines up to a frequency of 20 GHz. Model parameters are deduced from measurements and compared with their physical meaning. For both microwave-line types, the attenuation decreases with decreasing linewidth. The smallest attenuation, 0.5 dB/mm, will be achieved for a coplanar waveguide with only 4.2-μm center conductor width. Less than 30 μm in overall width will be necessary for such a CPW, which is acceptable for the application in silicon-based MMIC's. Both line types do not need backside metallization or backside via holes. Due to the small line dimensions, both line types are very attractive for low-cost MMIC designs up to 20 GHz because of minimizing the real estate on wafer.

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Circularly Polarized Millimeter-Wave Rectenna on Silicon Substrate

Ralph H. Rasshofer, Markus O. Thieme, and Erwin M. Biebl

***Abstract*— A circularly polarized (CP) silicon-integrated W-band rectenna (rectifying antenna) for use in six-port polarimetric radar systems was designed, numerically optimized, and fabricated. A rigorous numerical optimization was performed by using the supergrid method (SGM). The rectenna applies a novel low-loss purely planar dual-patch antenna (DPA) layout, which allows the receiver to be manufactured using monolithic integration. The measurement results for the receiver demonstrate an excellent cross-polarization discrimination (XPD) >14 dB @ 76 GHz over a wide range of the scan angle (12 dB @ $\pm 20^\circ$).**

***Index Terms*—Active antenna, automotive radar, circular polarization, circularly polarized antenna.**

I. Introduction

Prototypes of millimeter-wave polarimetric radar systems have successfully demonstrated their capability in automotive applications, e.g., measurement of the lateral and longitudinal velocity [1], evaluation of the road condition [2], and collision avoidance [3]. However, the availability of miniaturized low-cost components is a prerequisite for serving the high-volume automotive market. To reduce manufacturing costs, monolithically integrated components can be conveniently employed.

Though a variety of designs for linearly polarized (LP) integrated direct-detection receivers were developed [4], existing designs for circularly polarized (CP) antennas do not comply with monolithic integration since they do not employ a purely planar circuit layout [5], [6]. We, therefore, propose a novel purely planar dual-patch rectenna, which is fully compatible with monolithic integration. The use of two almost-quadratic patches eliminates the need of phase shifters, resulting in a smaller chip size and higher sensitivity of the receiver. We applied a generic two-step approach, comprising a simple transmission-line equivalent-circuit model of the antenna and full-wave electromagnetic (EM) simulation and optimization tools to dimension the layout and optimize the receiver's cross-polarization discrimination (XPD) and sensitivity. We fabricated the rectenna on a high-resistivity silicon substrate with backside metallization using a flip-chip technique to integrate the detector diode. Experiments demonstrate the efficiency of this receiver conception. Although primarily intended for use in six-port polarimetric radar systems [7], [8], the rectenna can find many applications in short-haul communication systems as well. In this paper, we present design and fabrication as well as measurement results of this novel silicon-based receiver chip.

II. Physical Condition for Circular Polarization

CP operation requires phase quadrature and equal magnitude of the antenna's orthogonal current components. This can be accomplished by feeding the radiating elements of the antenna with a phase shifter, e.g., a 90° hybrid. However, for millimeter-wave integrated antennas, this approach has several drawbacks. The use of a phase shifter increases the chip size and causes additional ohmic losses.

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The authors are with the Institut für Hochfrequenztechnik der Technischen Universität München, 80333 München, Germany.

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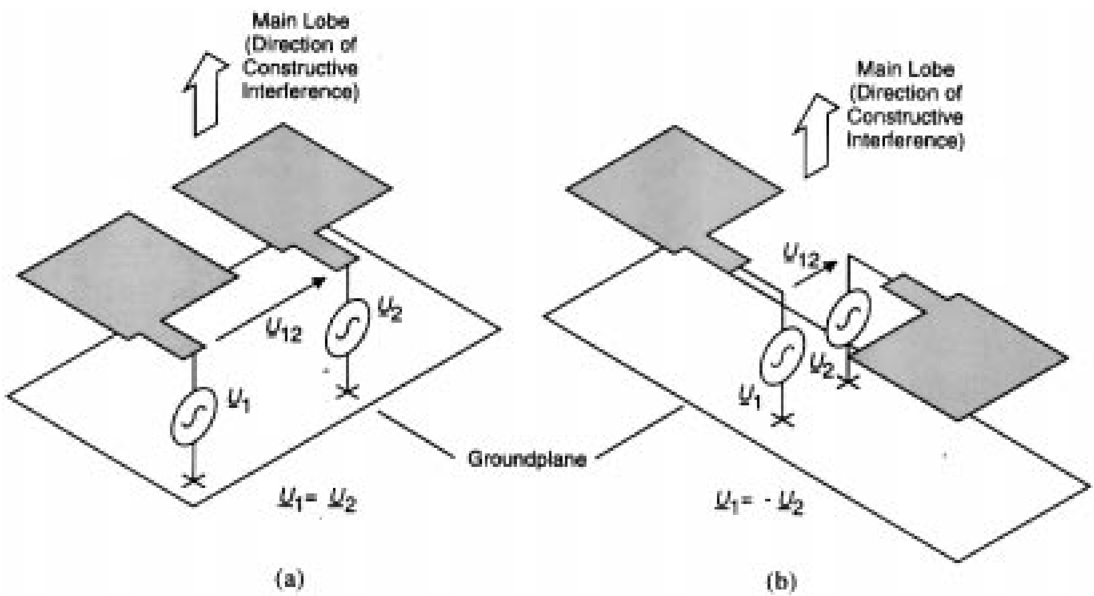

Fig. 1. Two antenna configurations producing the same radiation pattern in the far field in direction of the main lobe. (a) Common mode: $\underline{U}_{12} = 0$. (b) Differential mode: $\underline{U}_{12} = \underline{U}_1 + \underline{U}_2$.

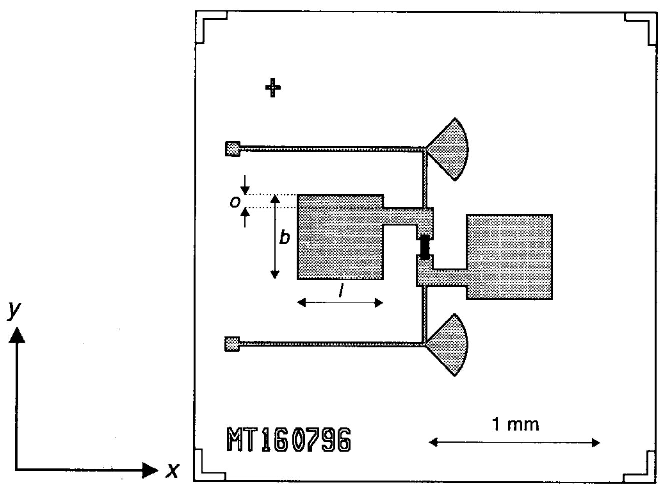

Fig. 2. Layout of the dual-patch antenna (DPA): $o = 60$ μm, $b = 550$ μm, $l = 500$ μm.

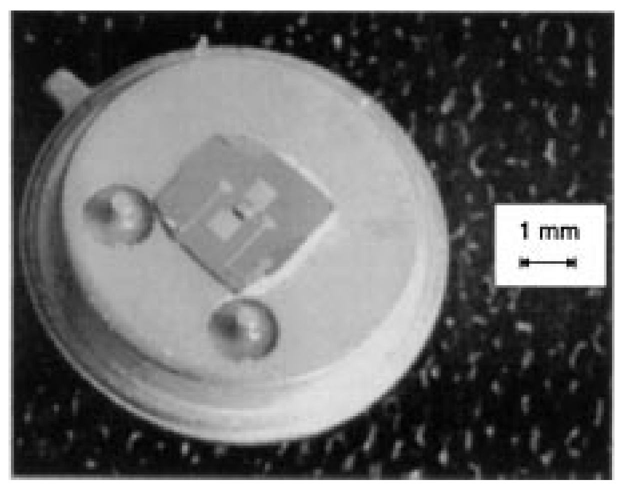

Fig. 3. Photograph of the DPA, mounted on a TO 39 package.

Furthermore, matching of the detector diode is difficult due to the highly reflective character of Schottky detector diodes at millimeter-wave frequencies.

A different promising concept is the use of an almost-quadratic patch antenna. In the antenna patch (size $l \times b$ with $l \approx b$), two orthogonal fundamental modes TM_{01} and TM_{10} are excited. Due to the deviation from the perfect quadratic shape of the patch, the resonant frequencies of both modes differ slightly. By properly adjusting the patch size, a 90° phase shift between the two modes can be achieved at the design frequency. As the modes radiate orthogonal linear polarization with phase quadrature, a circular polarized EM field emerges.

The patch element may either be excited through the ground plane or by a feeding network. While the first solution is incompatible with monolithic integration, the latter significantly deteriorates the rectenna's XPD due to parasitic radiation of the feeding network. Thus, a new planar feeding concept was employed. It took advantage of the fact that two identical patch elements contribute evenly to the far field in a direction perpendicular to the substrate surface when excited in phase at the same magnitude [see Fig. 1(a)]. The same holds true when one patch element is rotated 180° in the plane of the substrate surface and both patches are excited in differential mode [see Fig. 1(b)]. Thus, both voltage sources in the configuration of Fig. 1(b) can be replaced by a single one, connecting both feeding lines in the surface of the substrate.

Matching the diode's and the antenna's impedance is achieved by off-center feeding. The feeding point is shifted by an offset o from the border of the patch, increasing the imaginary part to the antenna's input impedance while only slightly changing the real part (see Fig. 2).

III. Design Procedure

A silicon P-Schottky diode, fabricated at Daimler-Benz, Ulm, Germany, is employed as a detector. The diode has a small-signal impedance of $9.5 - j58\ \Omega$ at a dc operation point of 60 μA.

To dimension the antenna layout, a two-step approach proved to be most efficient. In a first step, we employed a simple transmission-line

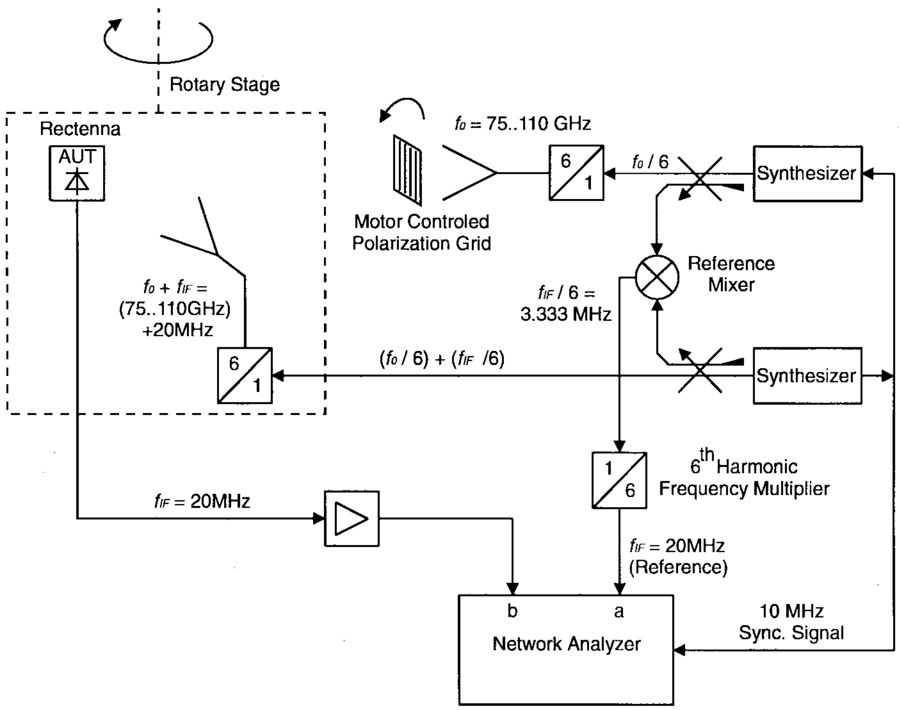

Fig. 4. Functional diagram of the heterodyne measurement setup used to characterize the CP rectenna.

equivalent-circuit model of the antenna to obtain a rough estimate for the antenna's dimensions. In a second step, this was used as an initial guess for EM simulation and optimization based on the combination of a method of moments (MoM) code and a nonlinear simplex optimization scheme.

This scheme employs the supergrid method (SGM), a novel tool for an efficient solution of the moment matrix equation. The SGM takes advantage of a special matrix element-sorting scheme, which produces a block-toeplitz structure in the moment matrix. Matrices of a block-toeplitz structure can be solved very efficiently. Moreover, SGM takes advantage of reusing matrix solutions in the optimization process, again saving a considerable amount of computing time. In combination, SGM saves up to 80% computational time and approximately 90% of computer memory [9].

The objective function of the optimization embraces the XPD and the matching of the detector diode, thus focusing on the receiver's sensitivity. The optimization includes the dimensions of the patches, the position of the feeding point of the patches, and the dimensions of the impedance transformer. The optimization accounts for the parasitic radiation of the impedance transformer and the biasing network. After the optimization, a simulated XPD >19 dB @ 76.5 GHz was achieved (without optimization: 4.8 dB).

IV. Fabrication

The rectenna was fabricated on a 100-μm-thick high-resistivity silicon substrate with backside metallization. The detector diode was integrated using flip-chip technique. Monolithic integration of the diode is possible with only minor changes of the layout. Fig. 3 shows a photograph of the rectenna chip, mounted on a TO 39 package.

V. Measurement Results

To verify the performance of the CP rectenna, a novel heterodyne measurement setup was used [10]. The antenna under test (AUT) and a horn antenna radiating the local oscillator (LO) signal are mounted on a rotary stage (see Fig. 4). Thus, signal strength and phase of the LO signal applied to the AUT are kept constant. A second horn antenna with a fixed position (i.e., not mounted on the rotary stage) radiates an RF signal with a frequency offset of 20 MHz relative to the LO signal. A reflector grid mounted in the aperture of the RF horn antenna shifts the polarization of the RF signal from horizontal to vertical without changing its phase. Mixing of the RF and LO signal in the direct detection AUT yields a 20-MHz IF signal. From the magnitude and the phase of the IF signal, the polarization of the receiver is calculated.

Fig. 5 shows the measured XPD in the frequency range 71–84 GHz. The rectenna exhibits an XPD of 12 dB @ 76.5 GHz (nominal frequency). The relative deviation from the optimum frequency is as low as 0.65%. The noisy parts of the curve above and below the design frequency result from the decreasing sensitivity of the antenna. The asymmetry of these noisy parts with respect to the maximum of the curve indicates the fact that maximal sensitivity of the antenna is obtained for a frequency of 77.0 GHz. Obviously, the optimizer could not simultaneously maximize sensitivity and XPD and, thus, found a compromise between both optimization goals.

The diagrams in Figs. 6 and 7 show the calculated and measured characteristics of the AUT for an angular scan of azimuth and elevation. As can be seen, calculated and measured curves agree very well. For large values of the elevation and the azimuth angle, imperfect matching of measurement results and calculated data is observed, which can be contributed to the finite lateral extension of the substrate. A minimum 12-dB XPD is maintained over a scan angle range of $\pm 20^\circ$. The figures demonstrate the impressively large dynamic range and high polarization purity of the used measurement setup. The dynamic range of the setup was calculated to be at least 56 dB.

VI. Conclusion

We developed a CP silicon-integrated direct-detection receiver for a six-port polarimetric millimeter-wave radar system. We used a novel DPA layout, which includes a matching network and a biasing

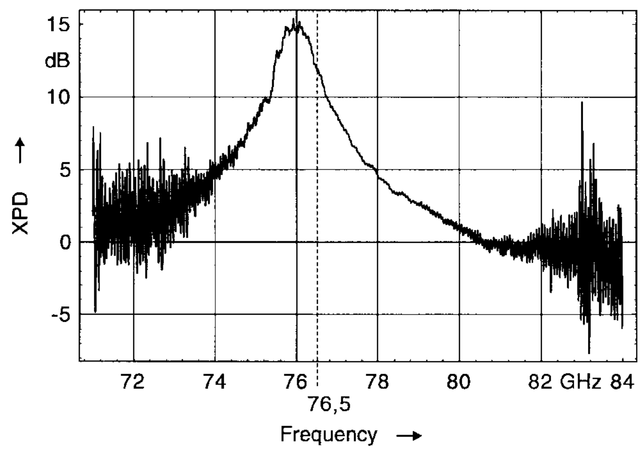

Fig. 5. Measured XPD of the CP receiver chip versus frequency.

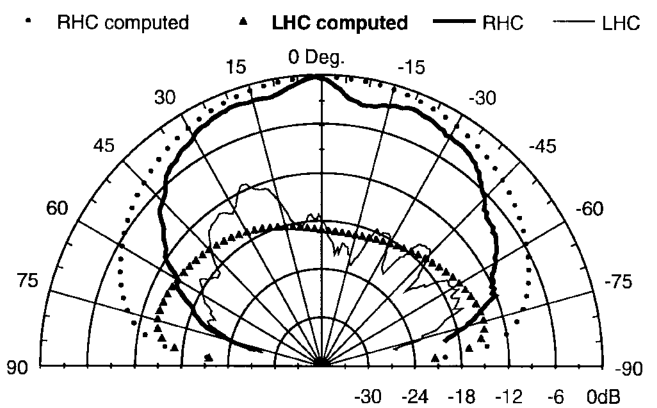

Fig. 6. Computed and measured normalized detection of incident LHC and RHC polarized waves, plotted over an angular scan in the x–z plane at the design frequency of 76.5 GHz.

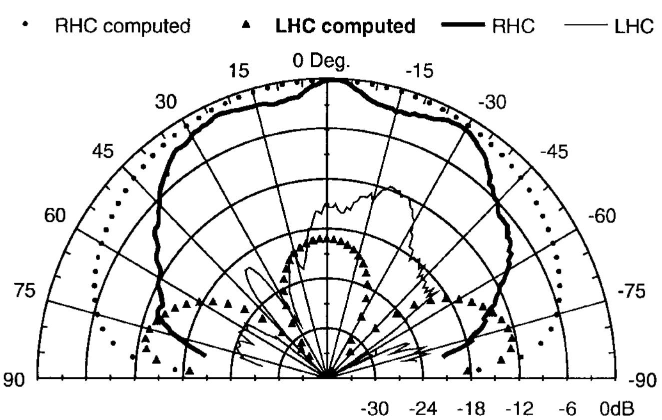

Fig. 7. Computed and measured normalized detection of incident left-hand circularly polarized (LHC) and right-hand circularly polarized (RHC) waves, plotted over an angular scan in the y–z plane at the design frequency of 76.5 GHz.

network to operate the Schottky detector. The major advantage of this novel type of antenna is a small-size purely planar circuit layout, which permits a monolithically integrated fabrication of the receiver. The DPA requires no phase-shifting network, resulting in a high-sensitivity small-size receiver with good polarization discrimination. We used a generic two-step approach to design the layout. In a first step, we applied an approximate transmission-line equivalent-circuit model of the antenna to obtain an initial guess for the dimensions of the antenna layout. In a second step, employing a sophisticated EM simulation and optimization process leads to an optimized layout with enhanced XPD and sensitivity of the receiver. The rectenna was fabricated on a high-resistivity silicon substrate using flip-chip technique to integrate the Schottky diode. To get accurate measurement results, a novel heterodyne measurement system was employed. Measurement results demonstrate a good cross-polarization discrimination (XPD) >14 dB @ 76 GHz over a wide range of the scan angle (12 dB @ $\pm 20°$). While intended for use in six-port polarimetric radar systems, the rectenna is also well-suited for short-haul communication systems, taking advantage of the unique properties of the CP radiation pattern.

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