Dual-Polarized Slot-Coupled Patch Antennas on Duroid with Teflon Lenses for 76.5-GHz Automotive Radar Systems

Bradley G. Porter, *Member, IEEE*, Leonard L. Rauth, *Member, IEEE*, John R. Mura, and Steven S. Gearhart, *Member, IEEE*

***Abstract*— A dual-polarized 76.5-GHz microstrip patch and teflon lens antenna system was designed, constructed, and tested. A receiver (RX) array of three dual-polarized microstrip patches was coupled through a 10-cm-diameter lens to produce radiation patterns with 3° beamwidths and beam crossovers of −3 dB. The transmitter (TX) consisted of a single dual-polarized microstrip patch coupled through a 2.5-cm-diameter lens to produce a 10° beamwidth. Slot-coupled patches were used to isolate the microstrip feed circuit from the radiating elements. The antennas and feeds were fabricated on commercially available 5880 Duriod substrates. Cross-polarization levels were less than −20 dB and were typically less than −30 dB over the entire beam at the design frequency. First sidelobe levels were no greater than −15 dB and were typically closer to −20 dB. Stepped and unstepped versions of the 10-cm-diameter receive lens were designed and fabricated. Antenna system sidelobes levels were lower with the stepped lens while the cross-polarization levels were comparable.**

***Index Terms*—Aperture coupling, polarization, printed antennas, road vehicle radar.**

I. Introduction

THERE have been significant efforts in recent years to design a low-cost millimeter-wave radar system for use in automobiles for collision warning and intelligent cruise control systems. Much of the research to date has been on single polarized systems [1]–[3]. There have been a few efforts on dual-polarized systems for automotive radar [4], [5], but none to our knowledge that use slot-coupled patches and none with polarization isolation as high as 30 dB. A dual-polarized system has the potential of detecting road surface conditions such as black ice or wet surfaces [6], [7]. Typically, the single-polarized automotive antenna systems consist of a small low-directivity antenna feeding a lens, the low-directivity antenna being a waveguide aperture [1], or a slot-coupled patch on semiconductor substrates [2]. We propose the use of commercially available teflon-based substrates (Rogers Duroid) on which antenna and microstrip designs are patterned. This paper reports on the design and construction of dual-polarized slot-coupled patch antennas on 5880 Rogers Duroid. The design uses surface mount components on 1-μm-thick gold microstrip line. High directivity is achieved with teflon lenses.

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B. G. Porter was with the Microwave and Millimeter Wave Communications Laboratory, Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706 USA. He is now with Microwave Systems Design, Raytheon Electronic Systems, Sudbury, MA 01776 USA.

L. L. Rauth was with the Microwave and Millimeter Wave Communications Laboratory, Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706 USA. He is now with Plexus Technology Group, Neenah, WI USA.

J. R. Mura was with the Microwave and Millimeter Wave Communications Laboratory, Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706 USA. He is now with Motorola, Libertyville, IL USA.

S. S. Gearhart is with the Microwave and Millimeter Wave Communications Laboratory, Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706 USA.

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II. Design and Fabrication

Most automotive radar systems scan a 10° wide region in front of the the automobile using a single transmit (TX) beam with 10° half power (−3 dB) beamwidth to transmit a radar signal and three receive (RX) beams with half power beamwidths of 3° to independently measure radar scatter from three lanes of traffic ahead of an automobile [1]. Beam crossover is typically in the −4 to −5 dB range. We sought to design a polarimetric microstrip patch antenna system with teflon lenses that would have a 3° RX beam, a 10° TX beam, sidelobe levels less than −20 dB for the central beam and less than −17 dB for the off-axis beams, and polarization isolation greater that 20 dB. The entire system was to be fabricated on commercially available substrates.

A. Dual-Polarized Slot-Coupled Patches

A slot-coupled patch antenna consists of two substrates and three metallization layers, as shown in Fig. 1. The metallized patch radiators are located on the top substrate while the millimeter-wave microstrip circuitry is located on the bottom substrate. A ground plane between the substrates isolates the radiators from the microstrip circuitry. Slots in this ground plane are used to electromagnetically couple signals from the microstrip circuitry to the radiating patch antennas. We have used a 5-mil-thick patch substrate and a 3.5-mil-thick feed-slot substrate, as shown in the sideview of Fig. 1. We used the thinnest possible standard 5880 Duriod substrate (3.5 mil) for the microstrip line to allow the feedlines to be as narrow as possible. Narrow lines reduce the cross coupling between the two polarizations and thus reduce the cross polarization. Furthermore, since a resonant patch on 5880 Duroid $(\epsilon_r = 2.2)$ is only slightly larger than 1 mm square, the microstrip lines

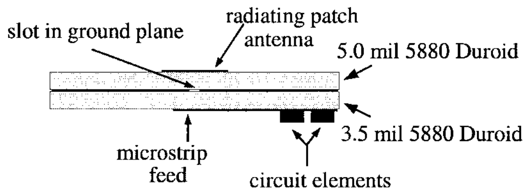


Fig. 1. Sideview of a slot-coupled patch antenna.

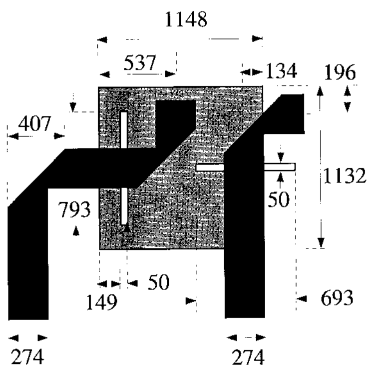


Fig. 2. Slot-coupled patch antenna. Dimensions are given in micrometers (μm).

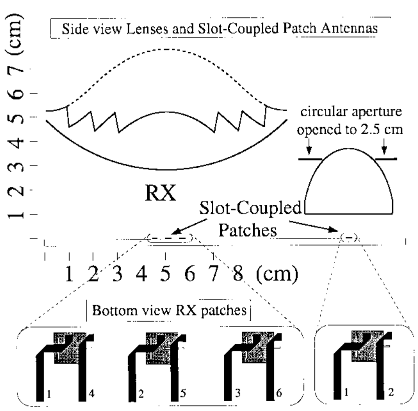


Fig. 3. Automobile radar antenna system employing teflon lenses over slot-coupled microstrip patch antennas.

must be significantly less than 1 mm wide in order to fit dual-polarized slots under the patch. For the patch layer, a thick substrate maximizes bandwidth, while a thin substrate minimizes undesirable surface waves. A 5-mil-thick Duroid 5880 substrate was chosen as the best compromise.

A single dual-polarized patch was first designed using HP-Momentum moment method software. The dimensions are shown in Fig. 2. A calculated input impedance of 50 Ω at 76.5 GHz and a calculated return loss of greater than 20 dB over a bandwidth of 0.9 GHz was achieved for the horizontal polarization and 0.8 GHz for the vertical polarization.

Traditionally, dual-polarized slot-coupled patch designs placed slots under the patch in an "L" (|__) configuration [8]. However, consistent with our previous results [9] and based on symmetry arguments, we find that there is better polarization isolation if the slots are placed in a "T" (|—) configuration under the patch, with one slot under the main body of the patch and the other along an edge. Brachet *et al.* had similar results using an "H" (|—|) configuration under the patch [10]. The "H" is desirable only to make radiation patterns perfectly symmetric. Since our feedlines were too wide to allow usage of the "H" feed, the "T" feed was chosen. The slight radiation pattern asymmetries due to the "T" feed configuration should not be detrimental to the operation of the radar.

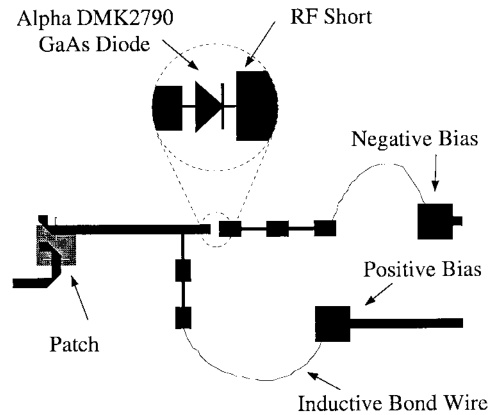


Fig. 4. Bias network shown with slots and a patch.

Fig. 3 shows the overall design of the radar system at 76.5 GHz. With this patch configuration, HP-Momentum results over the entire 76–77 automotive radar band show that there is less than −34 dB coupling between any two perpendicular slots and less than −23 dB coupling between any two parallel slots. Coupling between parallel slots under different patches is higher than coupling between perpendicular slots under the same patch, which shows how effective the "T" slot configuration is in reducing cross-polar coupling. Calculated cross-polarization levels of all the slots were −29 dB or less at the center frequency of 76.5 GHz.

A single TX patch is used to transmit the 76.5-GHz signal. The addition of two identical patches spaced 2.7 mm center-to-center on either side of the original single patch had a very minimal effect on coupling and input impedance and, therefore, the same microstrip patch element design was used for the three receive (RX) patches, as shown in Fig. 3.

B. Teflon Lenses

Teflon lenses were designed to focus the microstrip patch beams into the 3° RX and 10° TX beamwidths. For the RX lens, the inner surface was chosen to be spherical while the outer surface was calculated to be that surface which is required to produce a planar phase front in front of the lens—commonly called a Friedlander surface [11].

Rays radiated from the patch (as calculated by HP-Momentum) were then traced through the lens to determine aperture distributions and Fourier analysis was used to determine the far-field radiation pattern from the aperture distribution. Since it is difficult to generate two-dimensional radiation patterns in HP-Momentum, we calculated only the E- and H-plane patterns for each slot. For the RX lens, each pattern from $\theta = 0°$ to $\theta = 45°$ was traced through the RX lens to determine the aperture distribution. Fourier analysis was then used to

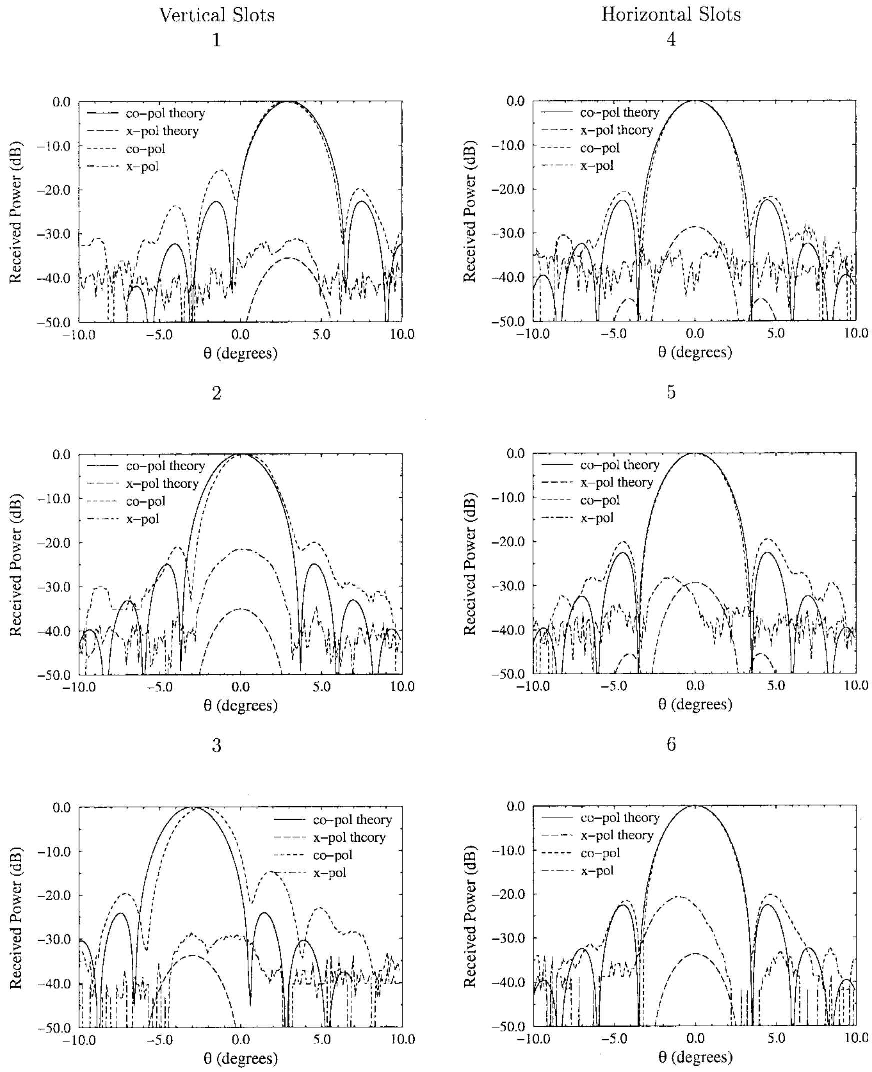


Fig. 5. Normalized E-plane radiation patterns of unstepped RX lens at 76.5 GHz.

determine the far field assuming that each E-plane or H-plane distribution was circularly symmetric. The circularly symmetric approximation gave very good results for on axis beams as will be seen in the next section. As might be expected, the circularly symmetric distribution approximation was less accurate for off-axis beams (slots 1 and 3 E-plane, slots 4 and 6 H-plane), however, they were adequate for our purposes.

We also note that the the lens was positioned over the patches such that rays from the patches at the edges of the RX lens surface are nearly parallel to the lens and are therefore highly reflected. The large reflections at the lens edge create a sharper taper in the electric field distribution at the edges of the lens, reducing the antenna sidelobe levels.

The outer surface of the RX lens was stepped to decrease its thickness and weight. Fig. 3 shows a sideview of the stepped RX lens with a dashed line above the stepped lens contour indicating the unstepped lens contour. The step length was

$$L_s = \frac{\lambda_o}{n-1} \tag{1}$$

in which n is the index of refraction of teflon $(n = \sqrt{2.2})$.

The TX lens was designed in the same manner as the RX lens except that a spherical surface was not necessary for the inner surface, which was chosen to be flat. It was 2.5 cm in diameter and was placed very close (1 cm) to the microstrip patch antenna to maximize beam transfer forward of the automobile. A side view of the TX lens designs is also shown in Fig. 3.

Lenses were constructed on computerized numerical control (CNC) lathes at the University of Wisconsin-Madison. Both stepped and unstepped RX lenses were constructed.

III. Results

Lenses and patch antennas were aligned in an Aerotech dual-axis rotary micropositioner. A tunable Gunn oscillator with an attenuator and high-gain horn was positioned 5 m from the lens. The tunable Gunn source was placed on a manual rotary stage so it could easily be turned 90° for cross-polarization measurements. Alpha GaAs DMK2790 detector diodes were placed in series in the microstrip line and biased at 130 μA. The diodes were RF shorted at the cathode and the anode was connected to the antenna microstrip, as shown in

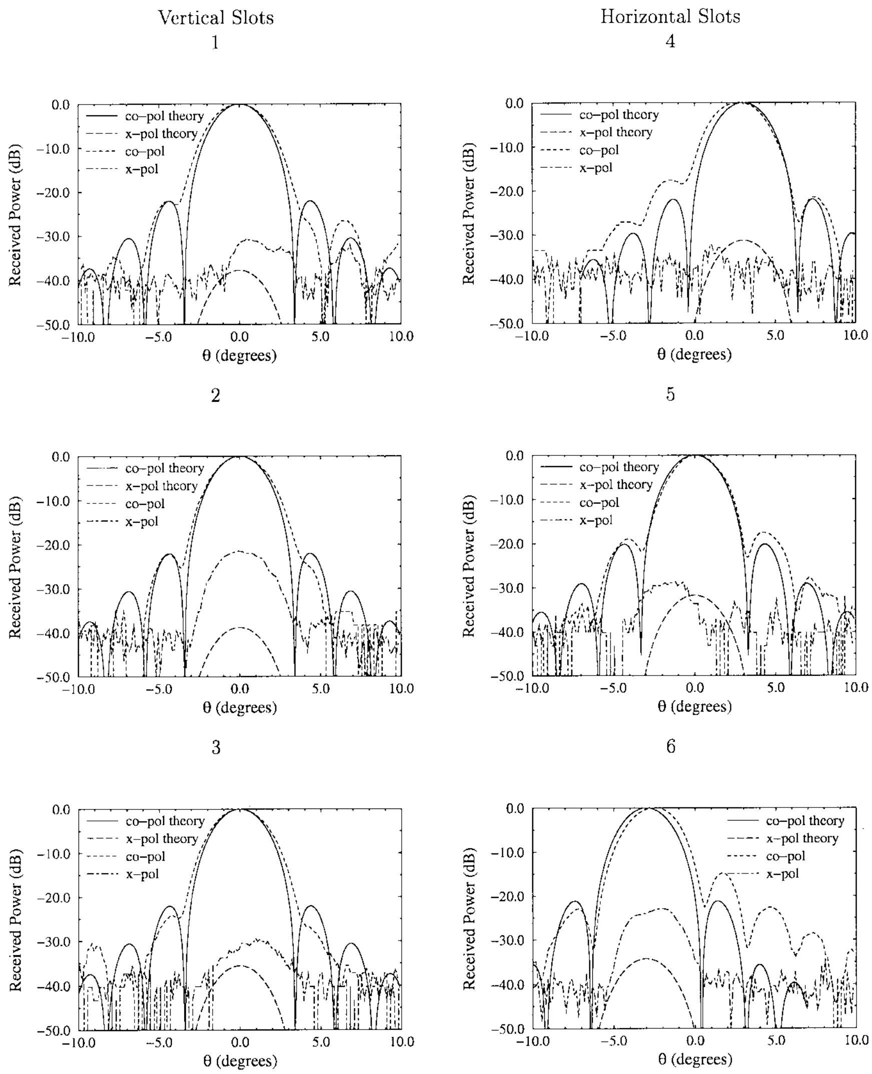


Fig. 6. Normalized H-plane radiation patterns of unstepped RX lens at 76.5 GHz.

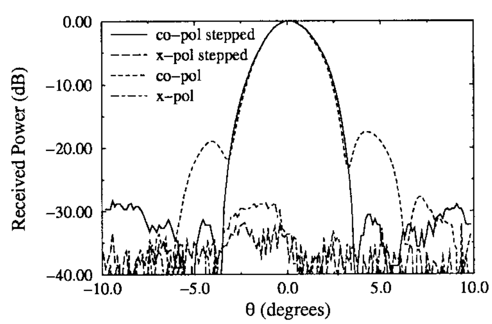


Fig. 7. RX H-plane slots 5 showing comparison of stepped/unstepped lens measurements.

Fig. 4. The waveguide attenuator was adjusted to ensure that the received signal remained in the diodes' square law region.

Measured and theoretical radiation patterns of the patch antennas and unstepped RX lens are shown in Figs. 5 and 6. Numbers above each plot in the figures indicate the port numbers which are detailed on Fig. 3. Table I summarizes the information in the plots. While some sidelobe levels were slightly higher than expected, most were well within specifications of −20 dB for on axis beams. There was excellent agreement between specified and measured beamwidths. E-plane beamwidths were all about 2.7–2.8° and H-plane beamwidths were slightly higher at 2.8–3.1° with the exception of slot 5 which had a beamwidth of 2.6°. Cross-polarization levels were all less than −20 dB most were closer to −30 dB.

TABLE I
SUMMARY OF RESULTS FOR UNSTEPPED 10-cm DIAMETER LENS. DIRECTIVITY MEASUREMENTS ASSUME A CONSTANT INTENSITY LEVEL OF -40 dB AND -50 dB OUTSIDE OF $-10^\circ \leq \theta \leq 10^\circ$

	3 dB beamwidth degrees		max sidelobe level dB		Max x-pol dB		Directivity dB	
	E-plane	H-plane	E-plane	H-plane	E-plane	H-plane	-40 dB ($\|\theta\| \geq 10^\circ$)	-50 dB ($\|\theta\| \geq 10^\circ$)
slot 1	2.77	3.05	-15.6	-22.0	-31.3	-30.7	36.3	36.8
slot 2	2.73	2.84	-20.0	-22.2	-21.6	-21.5	35.5	35.9
slot 3	2.73	2.93	-14.7	-24.1	-28.8	-29.4	34.1	34.4
slot 4	2.80	2.98	-20.6	-17.6	-32.1	-32.3	37.3	37.9
slot 5	2.78	2.56	-19.5	-17.5	-28.0	-28.7	35.2	35.5
slot 6	2.76	2.86	-20.2	-14.9	-20.7	-22.9	33.3	33.5

TABLE II
SUMMARY OF RESULTS FOR STEPPED 10-cm DIAMETER LENS. DIRECTIVITY MEASUREMENTS ASSUME A CONSTANT INTENSITY LEVEL OF -40 dB AND -50 dB OUTSIDE OF $-10^\circ \leq \theta \leq 10^\circ$

	3 dB beamwidth degrees		max sidelobe level dB		Max x-pol dB		Directivity dB	
	E-plane	H-plane	E-plane	H-plane	E-plane	H-plane	-40 dB ($\|\theta\| \geq 10^\circ$)	-50 dB ($\|\theta\| \geq 10^\circ$)
slot 1	2.84	3.15	-16.9	-21.7	-30.3	-31.1	36.7	37.2
slot 2	2.88	2.86	-24.5	-19.6	-26.7	-27.6	35.6	35.9
slot 3	2.82	2.93	-23.6	-24.6	-20.1	-20.1	34.5	34.8
slot 4	2.89	2.67	-26.0	-28.3	-29.4	-31.8	38.0	38.7
slot 5	2.88	2.96	-13.7	-25.0	-27.9	-29.8	35.5	35.8
slot 6	2.84	2.97	-24.1	-15.7	-21.9	-23.8	33.4	33.7

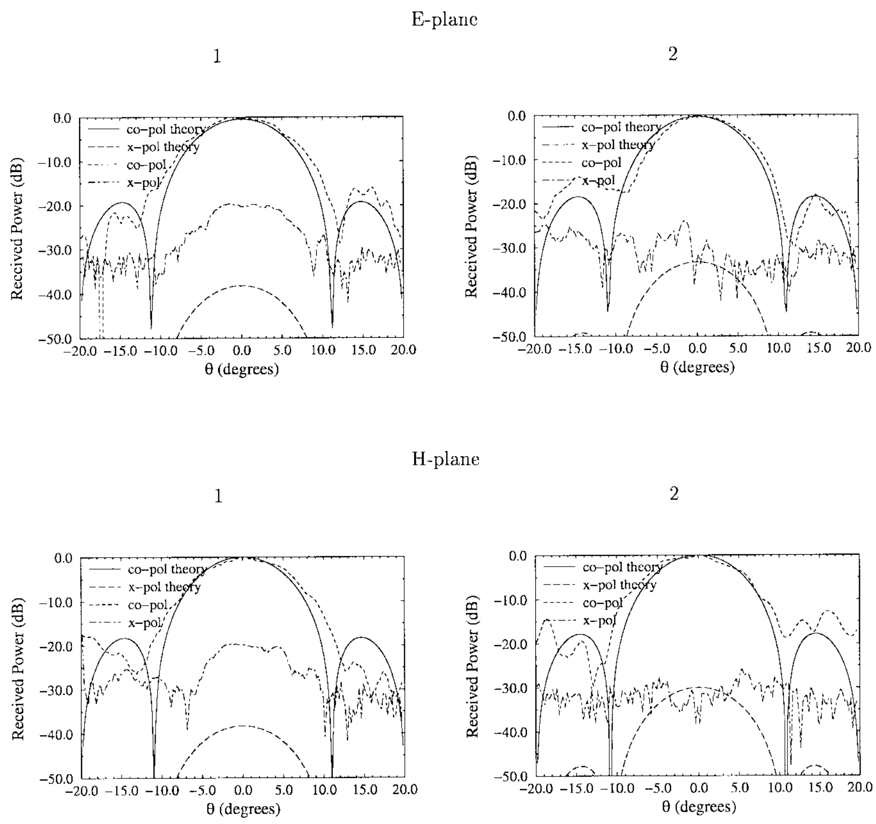
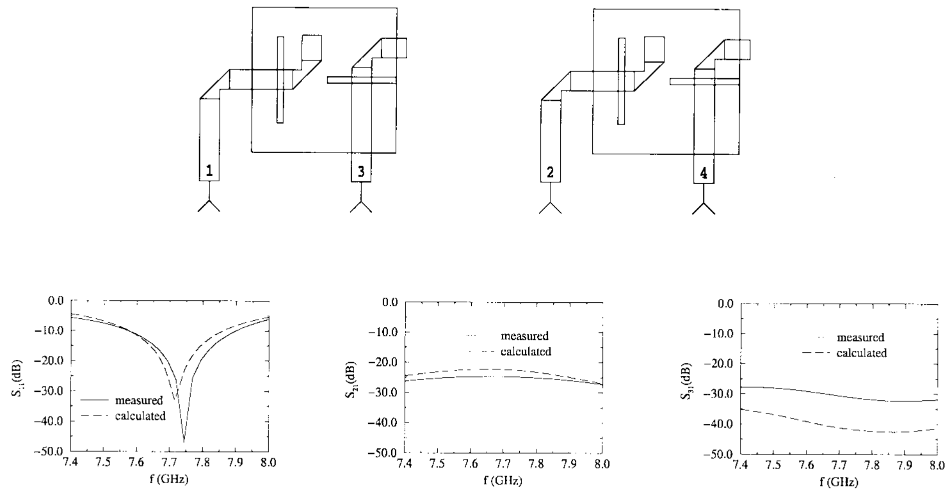


Fig. 8. Normalized TX lens radiation patterns.

Adjacent beams of the E-planes of slots 1, 2, and 3 and the H-planes of slots 4, 5, and 6 were all separated by 2.4–2.7° at their peaks and beam crossover was at the -2.7-dB level.

Directivity was estimated from copolar and cross-polar measurements in the angular sector $-10^\circ \leq \theta \leq 10^\circ$ in the E- and H-planes. The portion of the E-plane pattern laying in $\phi = 0^\circ$ half-plane was assumed to be the same throughout the region $-45^\circ \leq \phi \leq 45^\circ$ and the E-plane pattern laying in $\phi = 180^\circ$ half-plane was assumed to be the same throughout $225^\circ \leq \phi \leq 135^\circ$ and, similarly, the H-plane pattern at $\phi = 90^\circ$ was assumed to be the same in the region $45^\circ \leq \phi \leq 135^\circ$ and the H-plane pattern at $\phi = 270^\circ$ was assumed to be the same throughout the region $225^\circ \leq \phi \leq 315^\circ$. A constant intensity outside of $-10^\circ \leq \theta \leq 10^\circ$ was also assumed for the half-space $0 \leq \theta \leq 90^\circ$. Directivity was computed for two different values of this intensity: -40 dB and -50 dB. Since the difference between directivity calculations for these two intensity levels was 0.5 dB or less, we conclude that



	Coupling at Center Frequency of 7.7 GHz in dB					
	S_{12}	S_{13}	S_{14}	S_{32}	S_{34}	S_{24}
calculated	-22.4	-30.7	-40.0	-34.0	-28.3	-29.4
measured	-22.3	-41.3	-64.0	-54.7	-23.3	-41.3

Fig. 9. S-parameters for 7.7-GHz 10X model of slot-coupled patches.

the radiation outside of $-10° \leq \theta \leq 10°$ is insignificant in directivity calculations. Measured cross polarization was included in the calculations. Directivity calculations for the unstepped lens were between 33–38 dB and are shown in Table I.

Fig. 7 shows measurements with the stepped lens on slot 5. There is a slight increase in 3-dB beamwidth and a larger increase in the first null beamwidth. However, The first sidelobe level is significantly lower with the stepped lens. The results in Fig. 7 are typical of other comparisons as well. Table II summarizes the results for all the slots measured with the stepped lens. There is no significant increase in cross-polarization levels above the -30 dB level for any of the slot-coupled patches and frequently there is a decrease in the maximum sidelobe level. The directivity of the stepped lens-patch system was slightly higher (less than 1 dB higher) than that of the unstepped lens-patch system.

Results from the TX lens are shown in Fig. 8. Beamwidths were all very close to 10° (9.5–10.0) except for the E-plane TX port 2 which was 8.2°. Sidelobe levels varied from -13 dB to -22 dB.

We designed and constructed two low frequency 7.7-GHz 10X approximately scaled slot-coupled patches side by side in order to measure input reflection levels and element-to-element coupling which we are unable to do at 76.5 GHz. It was impossible to scale all dimensions by exactly 10X because of the availability of substrates. The antennas were redesigned using available substrates to approximately 10X for the primary purpose of checking the accuracy of HP-Momentum, so that we might have some confidence in a successful 76.5-GHz design. Fig. 9 shows the results. In fig. 9, S_{nn} represents the input reflection coefficient at the antenna feed n and S_{mn} represents the coupling from the feed of antenna n to the feed of antenna m. Obviously, we would like for S_{nn} and S_{mn} to be as small as possible for all ports at the design frequency. Although only S_{11} of the reflection coefficients is shown, all measured and calculated reflection coefficients were in close agreement, the measured resonant frequency being at the target frequency within ±50 MHz. The highest measured coupling was between slots of the same polarization under different patches and was -25 dB. A small table in Fig. 9 summarizes coupling results.

IV. CONCLUSION

We have demonstrated highly decoupled low cross-polarization dual-polarized slot-coupled patch antennas for automotive radar. These antennas can be fabricated successfully on standard commercially available substrates. The use of our stepped lens, generally lowered the sidelobe levels and did not significantly increase cross-polarization levels.

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REFERENCES

[1] H. H. Meinel, "Commercial applications of millimeter waves: History, present status, and future trends," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1639–1653, July 1995.

[2] M. Stotz, G. Gottwald, H. Haspeklo, and J. Wenger, "Planar millimeter-wave antennas using SiN_x-membranes on GaAs," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1593–1595, Sept. 1996.

[3] Millitech Corporation, "Crash avoidance FLR sensors," *Microwave J.*, vol. 37, pp. 122–126, July 1994.

[4] M. O. Thieme, R. H. Rasshofer, A. Stiller, and E. M. Biebl, "A novel circularly polarized w-band direct detection receiver for six-port

polarimetric radar systems," *IEEE-MTT-S Int. Microwave Symp. Dig.*, 1997, vol. 3, p. 1269.
[5] G. P. Gauthier, N. Dib, L. P. Katehi, and G. M. Rebeiz, "77-GHz dual-polarized microstrip antennas on thin dielectric membranes," in *IEEE Antennas Propagat. Soc. Int. Symp. Dig.*, Montreal, Canada, July 1997, vol. 3, pp. 1874–1877.
[6] K. Sarabandi, E. S. Li, and A. Nashashibi, "Modeling and measurements of scattering from road surfaces at millimeter-wave frequencies," *IEEE Trans. Antennas Propagat.*, vol. 45, pp. 1679–1688, Nov. 1997.
[7] K. Sarabandi and E. S. Li, "Characterization of optimum polarization for multiple target discrimination using genetic algorithms," *IEEE Trans. Antennas Propagat.*, vol. 45, pp. 1810–1817, Dec. 1997.
[8] A. Adrian and D. H. Schaubert, "Dual aperture-coupled microstrip antenna for dual or circular polarization," *Electron. Lett.*, vol. 23, pp. 1226–1228, Nov. 1987.
[9] B. G. Porter and S. S. Gearhart, "Theoretical analysis of coupling and cross-polarization of perpendicular slot antennas on a dielectric half-space," *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 383–390, Mar. 1998.
[10] P. Brachat and J. M. Baracco, "Printed radiating elements with two highly decoupled input ports," *Electron. Lett.*, vol. 31, no. 4, pp. 245–246, Feb. 1995.
[11] C. J. Sletten, Ed., *Reflector and Lens Antennas*. Norwood, MA: Artech House, 1988.

Brad Porter (S'90–M'99) received the A.S.E.E. degree from Ricks College, Rexburg, ID, in 1990, the B.S.E.E. degree from Brigham Young University, Provo, UT, in 1992, and the M.S.E.E. degree from the University of Wisconsin-Madison, in 1996. He is currently working toward the Ph.D. degree from the University of Wisconsin.

He is currently a Senior Engineer at Raytheon Company in Sudbury, MA. His interests are in computational electromagnetics and high-efficiency array radiators for ground-based radar and satellite communications.

Leonard L. Rauth (S'93–M'97) received the B.S.E.E. and M.S.E.E. degrees from the University of Wisconsin, Madison, in 1996 and 1997, respectively.

His Master's research was in the area of passive power divison as well as fabrication of antennas and circuit elements on Duroid. Since 1998 he has been with Plexus Technology Group, Neenah, WI. His current research interests include GaAs monolithic microwave integrated circuits design and layout. Development has been concentrated in the recently allocated 5-GHz UNII band.

John R. Mura received the M.S.E.E. degree from the University of Wisconsin, Madison, in 1997.

His is currently with Motorola, Libertyville, IL, as a Senior RF Design Engineer developing CDMA single-band and dual-band handsets. His current interests are in RF circuit design and simulation for CDMA receivers and transmitters.

Steven S. Gearhart (S'91–M'95) received the B.S.E.E. degree from the Virginia Polytechnic Institute and State University, Blacksburg, in 1988, and the M.S.E.E. and Ph.D. degrees from the University of Michigan at Ann Arbor, in 1990 and 1994, respectively.

Since 1994, he has been an Assistant Professor in the Department of Electrical and Computer Engineering at the University of Wisconsin, Madison. His research interests include micromachined integrated circuits and antennas, polarization-agile and multiresonant antenna elements, automotive radar systems, and silicon ultrashallow CMOS junctions.

Dr. Gearhart was the recipient of a Student Paper Award at the 1994 IEEE Microwave Theory and Techniques International Symposium in 1994 and was the advisor of a Student Paper Award winner in 1996. In 1998 he received the Army Research Office Young Investigator Award.