A K-Band Full-Duplex Transmit-Receive Lens Array

Michael Forman, James Vian, and Zoya Popović

University of Colorado
Boulder, CO 80309-0425 USA
Michael.Forman@Colorado.EDU

Abstract— **A K-band full-duplex transmit-receive lens antenna array using uniplanar circuitry is reported. The array transmits at 19 GHz and receives at 21 GHz by means of two independent unit cells. Orthogonal antenna polarization and bandpass circuitry provide a simulated isolation of 42 dB between transmit and receive channels. The measured gains of the active array are 3.0 and 8.3 dB above passive with an on-off ratio of 10 and 15 dB for transmit and receive modes respectively.**

I. Introduction

Active-antenna array technology combines printed antennas and active devices with the goal of improving performance, increasing functionality, and reducing size relative to alternative architectures. Such arrays show potential for use in millimeter-wave applications such as wireless local-area networks, electronic identification systems, and vehicle collision-avoidance radar. This work builds upon a large body of research in transmit-only active-antenna arrays [1]; utilizes a lens feed to improve feed efficiency and eliminate the bulk of a Gaussian or wave-guide feed [2-4]; and improves upon the results of previous half- and full-duplex transmit-receive arrays [5-8]. In [5], the transmit and receive channels are at the same frequency with isolation provided using orthogonal antenna polarization (25 dB), but due to the saturation of the input amplifier by the output, simultaneous transmission and reception is not possible. The goal of this work is to achieve full-duplex operation by the introduction of multiple levels of isolation between the transmit and receive channels.

This work is supported by the Army Research Office MURI Program on Quasi-Optical power Combining under contract DAAH04-98-0-0001 and ONR and the office of Secretary of Defense under a MURI grant N00014-97-1-1006.

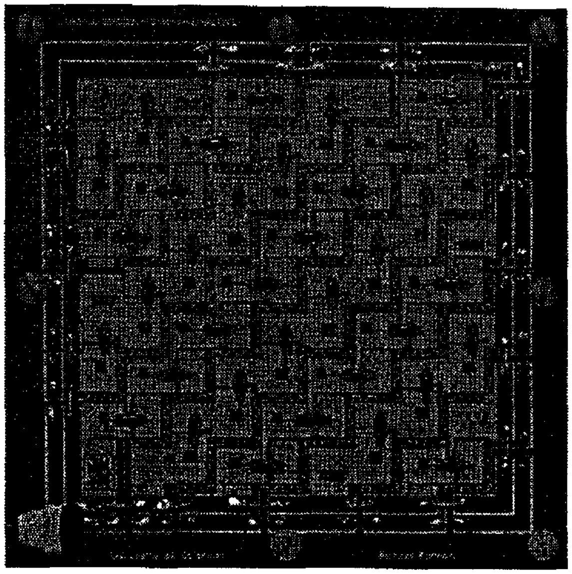

Fig. 1. The K-band full-duplex transmit-receive active-antenna array shown from the feed side. Antennas on the feed side replace a corporate feed, while the opposite (non-feed) side contains the main radiators. The array is 10.5 cm square.

II. Design

A. Array Element

A single full-duplex transmit-receive unit cell is comprised of two independent orthogonal unit cells, one for each channel (Figure 2). A single channel's unit cell contains a patch antenna, a coplanar-waveguide section with amplifier, and a slot-fed patch antenna. A unit cell measures 8.5 × 17 mm ($0.538 \times 1.077\,\lambda_{19\,\mathrm{GHz}}$ or $0.595 \times 1.190\,\lambda_{21\,\mathrm{GHz}}$).

The full-duplex transmit-receive array is designed for uniplanar multilayer processing. Vias and air bridges are eliminated by integrating microstrip line (MSL) and finite-width ground-backed coplanar waveguide (fCPW) within a single unit cell. The MSL provides the connection to the standard patch an-

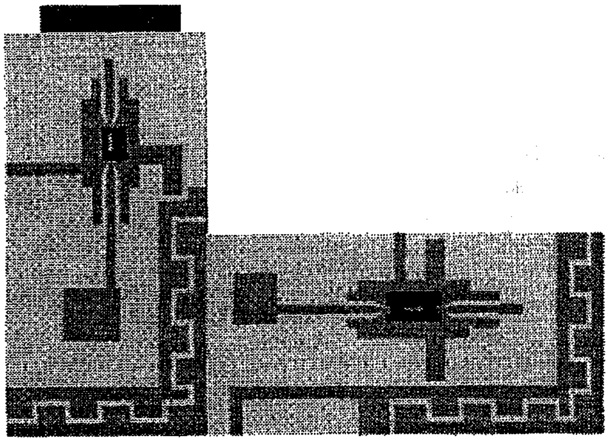

Fig. 2. The 19-GHz transmit (*left*) and 21-GHz receive (*right*) unit cells as seen from the feed side.

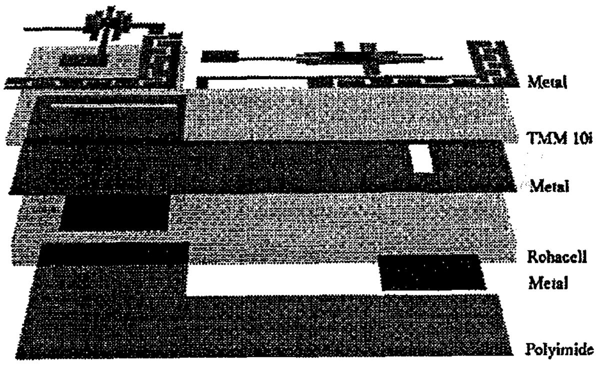

Fig. 3. Assembly drawing of the transmit and receive unit cells. Substrates are shown partially transparent for clarity.

tenna on the feed side of the array; the fCPW provides a transition to the amplifier, which eliminates the vias required with MSL. Transitions between MSL and fCPW occurs in a section of three coupled microstrip transmission lines of length $\lambda_{ms}/4$ at the unit cell's frequency of operation [9]. This transition also feeds a patch antenna on rigid foam through a slot in the ground plane on the opposite side of the MMIC (Figure 3). The integrated slot-transition feed reduces space consumption and improves the front-to-back ratio (36 dB) of the slot-fed patch relative to a standard MSL feed. The slot-fed patch is polarized orthogonally to the microstrip-fed patch antenna which eliminates a 90° bend in the unit-cell transmission line.

Amplification is performed in transmission (19 GHz) by an HP HMMC-5620 single-bias power amplifier (PA) with a maximum small-signal gain of 17 dB from

TABLE I

SIMULATED COUPLING BETWEEN UNIT CELLS FOR EACH CHANNEL IN THE PASSIVE ARRAY.

Coupling Path	Side	Freq (GHz)	Coupling (dB)
$\mathbf{PA_{19}} \Rightarrow LNA_{19}$	Non-Feed	19	**-50**
$PA_{21} \Rightarrow \mathbf{LNA_{21}}$	Non-Feed	21	**-42**
$LNA_{19} \Rightarrow \mathbf{PA_{19}}$	Feed	19	-29
$\mathbf{LNA_{21}} \Rightarrow PA_{21}$	Feed	21	-21

6 to 20 GHz. Amplification is performed in reception (21 GHz) by an Alpha AA022N1-00 single-bias low noise amplifier (LNA) with a maximum small-signal gain of 22 dB from 20 to 24 GHz and a noise figure of 2.5 dB. To improve channel isolation and array stability, the amplifiers are chosen to provide reduced gain in the frequency range outside their respective channels.

Coupling simulations performed on the passive unit cells with Zeland IE3D place the channel isolation at -42 dB at 21 GHz. Results of the simulations are summarized in Table I. The second row in the table indicates coupling, which contributes to noise seen by the LNAs generated by the PAs.

B. *Full-Duplex Quasi-Optical Array*

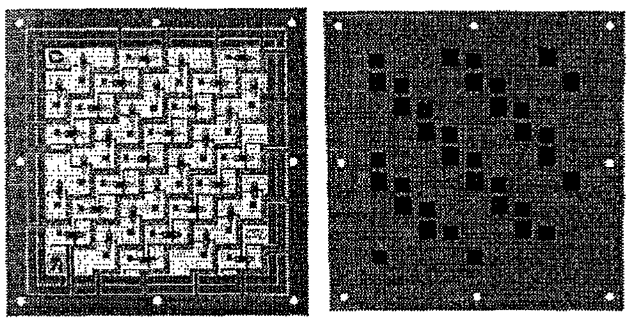

Fig. 4. The *K*-band full-duplex transmit-receive active antenna array shown from the feed side (*left*) and the non-feed side (*right*). The array is 10.5 cm square.

The array contains 18 transmitting and 18 receiving unit cells arranged in alternating diagonal rows (Figure 4). The distance between neighboring antennas on the non-feed side for a given frequency is 12 × 24 mm (0.76 × 1.52 $\lambda_{19\,GHz}$ or 0.84 × 1.68 $\lambda_{21\,GHz}$). This unit-cell spacing generates two grating lobes approximately 55° off boresight in the diagonal plane corresponding to the largest row separation. Equivalently, a single

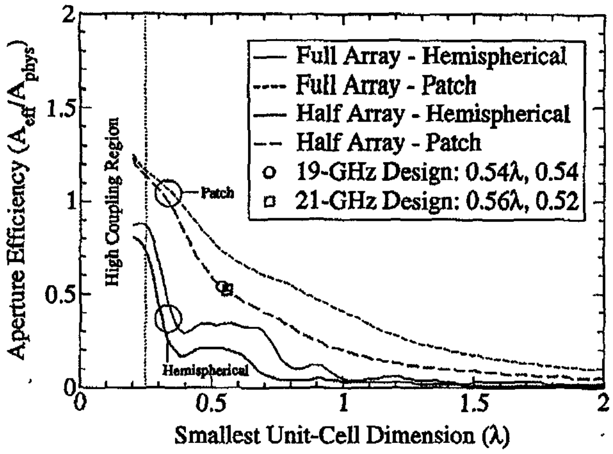

Fig. 5. Aperture efficiency versus the smallest unit-cell dimension for the transmit-receive active-antenna array.

transmitter in the far field generates three maxima on the focal surface with similar angular separation. In communication applications, the aliasing of the main-beam can be used to increase received and transmitted power by employing multiple receivers or transmitters on the focal surface. Additional receivers may also be used to improve angular diversity [6].

A one-degree-of-freedom true-time-delay lens array [4] with a focal distance, F, of 166.5 mm and an aperture diameter, D, of 90 mm ($F/D = 1.85$) is implemented. Lensing is provided by the variation in length of the microstrip lines which feed the standard patch antennas. The maximum delay-line length near the center of the array is 2 mm or 143° at 20 GHz.

Aperture efficiency as a function of the smallest unit-cell dimension (a unit cell has a 2:1 length-to-width ratio) is shown in Figure 5. For an array populated with a single unit cell operating at a single frequency, the aperture efficiency is 0.73 at 19 GHz and 0.71 at 21 GHz. The aperture efficiency for the full-duplex array is 0.54 at 19 GHz and 0.52 at 21 GHz. The net effect of populating the array with two independent unit-cells is a 27% drop in aperture efficiency. The high directivity (9 dB) of the slot-fed patch antenna reduces the effect of the grating lobes on aperture efficiency relative to the simulation based on an array of hemispherical radiators.

III. Uniplanar Multilayer Fabrication

The array is fabricated using low-cost materials on three layers of dielectric: Rogers TMM 10i substrate, Rohm Rohacell 31 HF rigid foam, and Sheldahl Novaclad G2300 copper-cladded polyimide. The substrate layers are summarized in Table II and directly correspond to the layers shown in Figure 3 on the preceding page. The TMM 10i substrate is chosen for its thermal properties, high permittivity, and resistance to compression necessary for wire bonding. To minimize loss due to substrate modes, the substrate thickness is selected to be a fraction of a wavelength in the dielectric ($\lambda_d/13$ at 20 GHz).

TABLE II

Array substrate values shown in order of assembly with feed side first.

Product	Material Description	ϵ_r	$\tan\delta$	h (μm)
Rogers TMM 10i	Metal	1.0	–	17.5
	Substrate	9.8	0.002	381
	Metal	1.0	–	17.5
Rohm Rohacell 31 HF	Foam	1.07	0.004	1000
Sheldahl Novaclad G2300	Metal	1.0	–	17.5
	Polyimide	3.3	0.011	50.8

Fabrication is performed in multiple photolithographic steps on TMM 10i for the circuits and slots, and on Novaclad G2300 for the slot-fed patch antennas. Alignment between the features on opposite substrate sides is maintained during fabrication by the use of an aluminum holder with alignment pins. The fabrication process achieves measured alignment accuracies of $\pm 50\,\mu$m between circuits and slots on opposite substrate sides. Simulations show that transition-to-slot alignment must be within $\pm 200\,\mu$m to ensure low insertion loss. The slot-to-patch alignment is more forgiving, allowing a simulated and experimentally verified tolerance of $\pm 600\,\mu$m.

TABLE III

Active array measurements.

Channel	Freq (GHz)	On/Off (dB)	Gain (dB)	G_a (dB)
Transmit	18.9	10.0	-3.3	3.0
Receive	21.1	15.0	3.6	8.3

IV. Measurements

The array is placed between a 5.3-dB radiating waveguide aperture at the focal point and a 20.8-dB

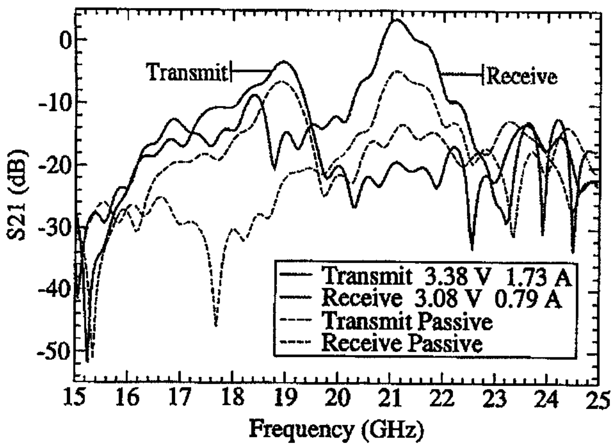

Fig. 6. Measurement of the passive and active array showing transmission response through the array as a function of frequency.

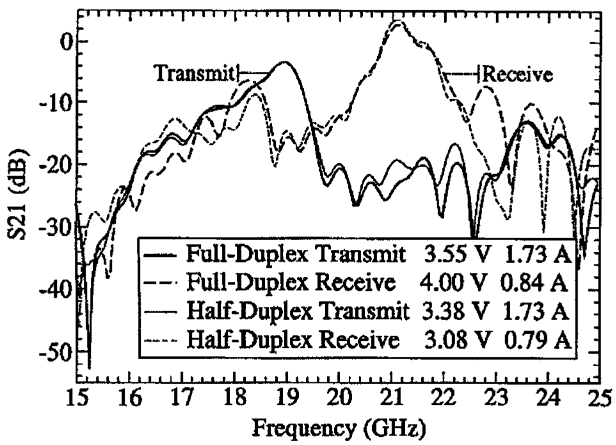

Fig. 7. Comparison of the active array operating in half- and full-duplex mode showing transmission response through the array as a function of frequency.

pyramidal horn in the far field. Small-signal measurements are performed with an HP 8510C vector network analyzer and are normalized to a corrected free-space through calibration.

Passive-array measurements are shown in Figure 6. The transmit and receive channels have a through gain of -6.3 dB at 18.9 GHz and -4.7 dB at 21.1 GHz respectively. Measured center frequencies are within a fraction of a percent of the simulated values. Active small-signal gain measurements are performed initially in half-duplex mode, where only a single channel is on at a given time. The transmit and receive half-duplex small-signal active measurements are shown in Figure 6 and summarized in Table III. The transmit array channel provides -3.3 dB of gain at 18.9 GHz which is 3.0 dB above the passive array at 3.38 V and 1.73 A. The receive channel provides 3.6 dB of gain at 21.1 GHz which is 8.3 dB above the passive array at 3.08 V and 0.79 A.

Active small-signal full-duplex measurements are presented with the half-duplex measurements in Figure 7 for comparison. The presence or absence of bias to the devices of one channel has little effect on the gain of the other channel. The difference in bias level between half- and full-duplex modes is attributed to gain suppression of the MMICs due to the increased temperature at full-duplex operation.

The maximum gain of the MMICs is limited by amplifier stability. The bias levels at which oscillations occur in one MMIC are unaffected by the bias level or state of the other MMIC. It is believed that the oscillations are due to an impedance mismatch presented to the amplifier by wirebond inductance or the wirebond-fCPW interface.

References

[1] R. A. York, "Quasi-optical power combining," in *Active and quasi-optical arrays for solid-state power combining*, R. A. York and Z. B. Popović, Eds., chapter 1. John Wiley, New York, 1997.

[2] W. A. Shiroma, E. W. Bryerton, S. Hollung, and Z. B. Popović, "A quasi-optical receiver with angle diversity," in *IEEE MTT-S International Microwave Symposium Digest*, San Francisco, CA, June 1996, pp. 1131–1134.

[3] J. Schoenberg, S. C. Bundy, and Z. Popović, "Two-level power combining using a lens amplifier," *IEEE Transactions on Microwave Theory and Techniques*, vol. 42, no. 12, pp. 2480–2485, Dec. 1994.

[4] D. T. McGrath, "Planar three-dimensional constrained lenses," *IEEE Transactions on Antennas and Propagation*, vol. 34, no. 1, pp. 46–50, Jan. 1986.

[5] S. Ortiz, T. Ivanov, and A. Mortazawi, "A transmit-receive spatial amplifier array," *IEEE MTT-S International Microwave Symposium Digest*, vol. 2, pp. 679–682, Jun. 1997.

[6] S. Hollung, A. E. Cox, and Z. B. Popović, "A quasi-optical bi-directional lens amplifier," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, pp. 2352–2357, Dec. 1997.

[7] Z. Popović and A. Mortazawi, "Quasi-optical transmit-receive front ends," *IEEE Transactions on Microwave Theory and Techniques*, vol. 46, no. 11, pp. 1964–1975, Nov. 1998.

[8] J. Vian and Z. Popović, "A transmit/receive active antenna with fast low-power optical switching," *IEEE Transactions on Microwave Theory and Techniques*, vol. 2, pp. 847–852, June 2000.

[9] M. Forman and Z. Popović, "A K-band ground-backed cpw balanced coupler and integrated antenna feed," *European Microwave Conference*, vol. 1, pp. 216–219, Oct. 2000.