A Bi-Directional Quasi-Optical Lens Amplifier

Stein Hollung, Amanda E. Cox, and Zoya Basta Popović, *Member, IEEE*

***Abstract*—A 24-element bi-directional quasi-optical lens amplifier array is presented. The lens amplifier array is designed for X-band, and operates in transmission mode. Single-pole double-throw (SPDT) switches are used to switch between transmit and receive amplifiers. The lens amplifier array demonstrates gains of 5.5 dB at 10.1 GHz in receive mode, and 2 dB at 10.2 GHz in transmit mode, with more than 15-dB ON/OFF isolation. Several applications for the lens amplifier array are demonstrated: a quasi-optical transceiver front-end, reduction of multipath fading, and a multiuser frequency reuse application.**

I. Introduction

Several transmission-mode plane-wave-fed quasi-optical amplifiers for microwave and millimeter-wave power combining have been presented to date [1]–[3]. Each of these amplifiers is fed with a plane wave from a source in the far field. In order to improve feed efficiency without using external lenses, lens amplifier arrays were developed [4], [5]. In a transmission-mode lens amplifier, the feed is placed in the near field along the focal surface, thereby minimizing diffraction loss. In transmission, a lens amplifier can provide high effective radiated power. A lens amplifier can also be used in reception, offering high dynamic range because the noises contributed from the individual amplifiers are uncorrelated [6]. In reception, a plane wave is received, amplified, and focused onto a receiver [7]. The transmit and receive functions of a lens amplifier can be combined to form a quasi-optical T/R module, as shown in Fig. 1. In this paper, we present a 24-element bi-directional quasi-optical lens amplifier with a unit cell, as shown in Fig. 2. Section II describes the unit cell, Section III discusses the array, and Section IV describes some applications for this lens array.

II. Single Array Element

A bi-directional transmission amplifier element, designed to operate around 10 GHz, was fabricated on a 0.507-mm-thick Duroid substrate with $\epsilon_r = 2.2$. A circuit schematic of the array element is shown in Fig. 3. Orthogonally polarized antiresonant slot antennas were used at the input and output because of their wide-bandwidth and ease of fabrication with

Manuscript received April 1, 1997; revised July 31, 1997. This work was supported by the U.S. Army Research Office under grant DAAH 04-96-1-0343, by the National Science Foundation under a Presidential Faculty Fellow Award, and by the DOD (ARO) DURID program under Grant DAAH 04-95-1-0444 and Grant DAAG 55-97-1-0027.

The authors are with the Department of Electrical and Computer Engineering, University of Colorado at Boulder, CO 80309 USA.

Publisher Item Identifier S 0018-9480(97)08331-2.

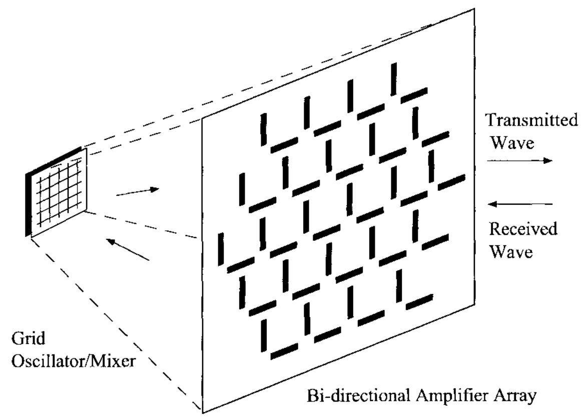


Fig. 1. A quasi-optical T/R module consisting of a bi-directional amplifier and a grid oscillator/mixer.

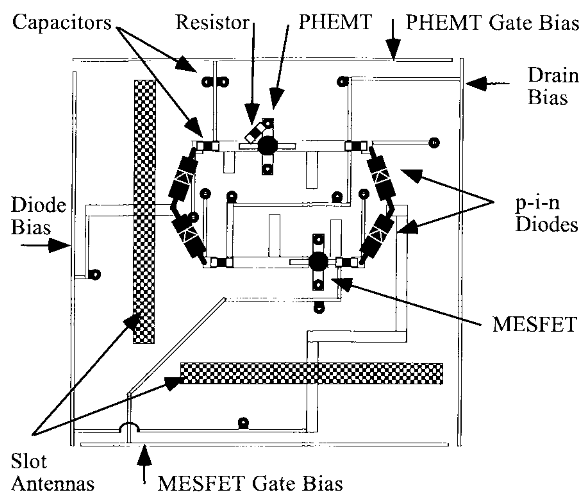


Fig. 2. A bi-directional X-band quasi-optical array amplifier element. The slot antennas are 2.5 cm long and 2 mm wide, and the unit cell dimensions are 3.5 cm $\times$ 3.7 cm.

microstrip feed lines. Fig. 4 shows the measured and simulated return loss for a single slot antenna. A 2:1 VSWR bandwidth of about 40% was measured. The measured E- and H-plane radiation patterns for a single slot antenna are shown in Fig. 5. The H-plane pattern shows a null in the boresight direction as expected for a center-fed second resonance slot. Both the characteristic impedance of the microstrip and the antenna input impedance are 65 Ω, to avoid additional matching sections for the antennas. Two single-pole double-throw (SPDT) switches are used to switch between a general-purpose MESFET amplifier stage for transmit mode and

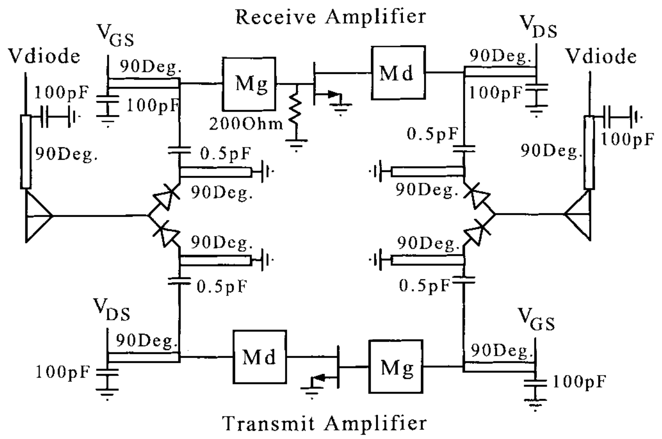


Fig. 3. Circuit schematic of the unit cell. Both amplifiers are matched for gain with matching circuits Mg at the gates and Md at the drains.

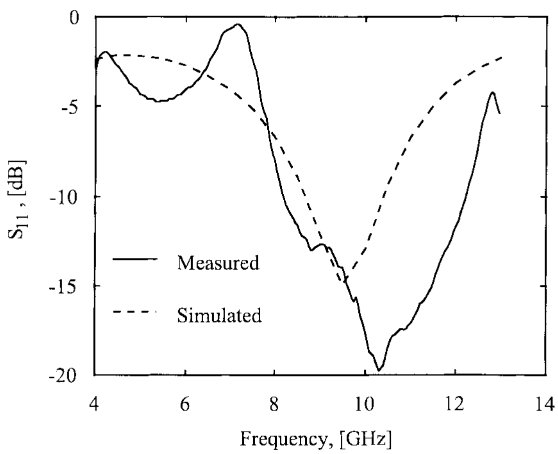


Fig. 4. Measured (–) and simulated (- -) return loss for a single slot antenna. The simulations were performed with the computer-aided design (CAD) package *Ensemble*.

a pseudomorphic high-electron-mobility transistor (PHEMT) amplifier stage for receive mode. Both amplifiers are matched for gain in this unit cell. The receive amplifier is stabilized with a 200-Ω chip resistor from gate to source. Two p-i-n diodes are used for each switch. The dc bias for the diodes is supplied through the slot antenna feed lines. Both transistors share the same drain bias to reduce the number of bias lines.

Measurements for the unit cell are conducted using E-plane horns placed in the far field and connected to an HP 70 820A Microwave Transition Analyzer. In transmission, an incoming plane wave from a vertically polarized horn is amplified by the transmit amplifier, reradiated as a horizontally polarized plane wave, and received by a horizontally polarized horn. In reception, an incoming plane wave from the horizontally polarized horn is amplified by the receive amplifier, reradiated as a vertically polarized plane wave, and received by the vertically polarized horn. Polarizers are inserted at a quarter-wavelength on each side of the unit cell to improve the gain. The received power is measured for both the transmit and receive amplifiers over a range of frequencies. The gains contributed by the amplifiers are approximately calculated

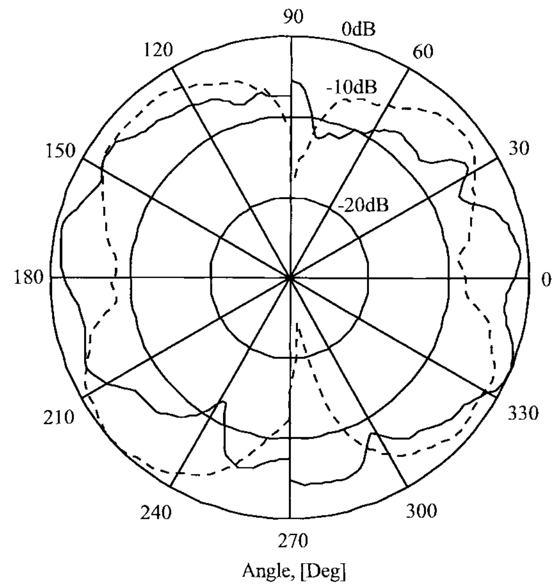


Fig. 5. Measured radiation patterns for a single antiresonant slot antenna at 10 GHz. 0° represents the circuit side and 180° represents the ground plane. E-plane (–) and H-plane (- -).

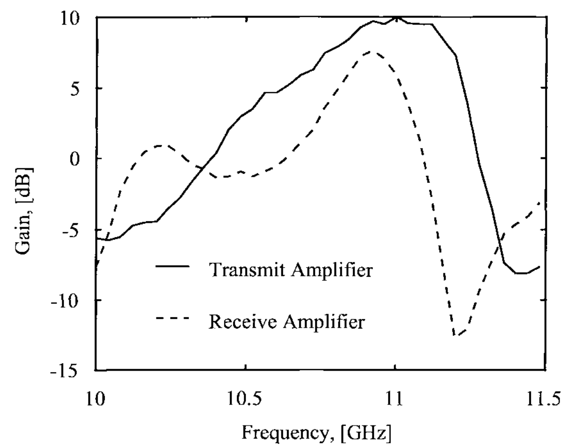


Fig. 6. Measured gain of the transmit (–) and receive (- -) amplifier in a unit cell.

from the Friis formula and plotted in Fig. 6. A gain of 5.5 dB for the slot antennas with polarizers was used for the calculations, based on the measurement shown in Fig. 5. The transmit amplifier has a maximum measured gain of 10 dB at 11 GHz. The receive amplifier has a measured gain of 7.5 dB at 10.8 GHz. Measured ON/OFF isolation of approximately 10 and 20 dB are seen for the receive and transmit amplifiers, respectively.

III. BI-DIRECTIONAL LENS AMPLIFIER ARRAY

The bi-directional lens amplifier array consists of 24 elements in a triangular lattice with four elements in the first and fifth row, five elements in the second and fourth row, and six elements in the third row, as shown in Fig. 7. Lensing delay lines are incorporated between the antenna pairs in each unit cell. The delay-line lengths were calculated using

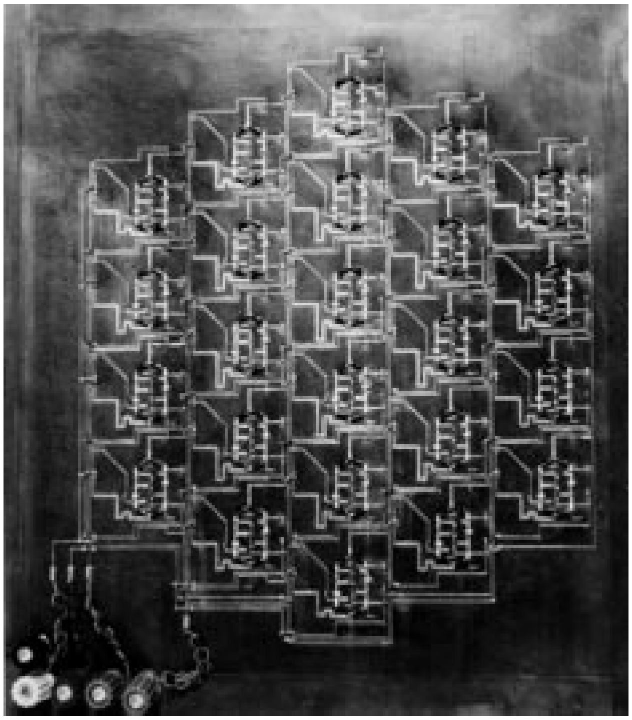


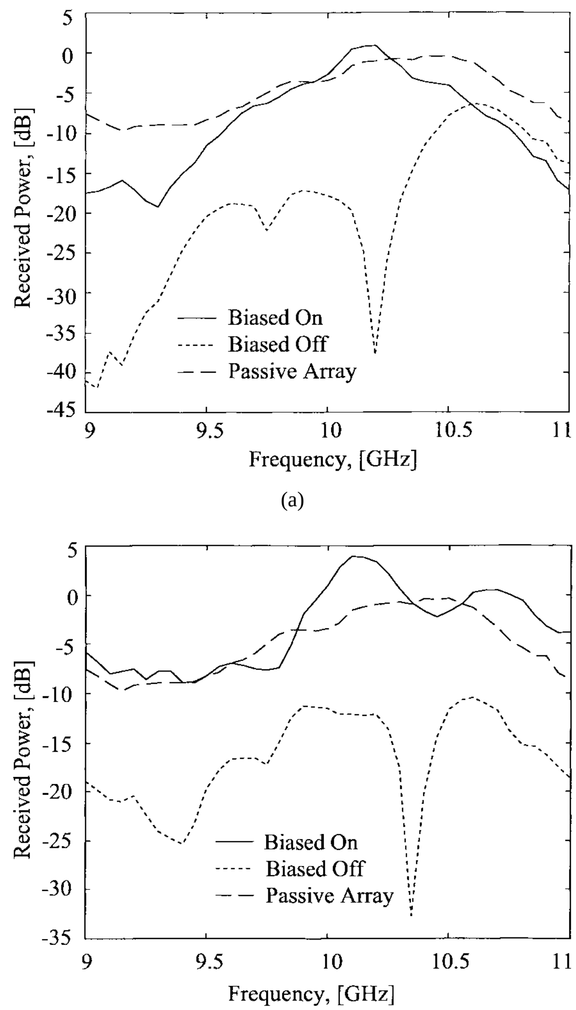
Fig. 7. Photograph of the circuit side of the 24-element bi-directional amplifier array. Orthogonally polarized slot antennas are located in the ground plane, as indicated in Fig. 2.

the design equations for a lens with one degree of freedom [8]. The focal distance of the array is 27.5 cm and the corresponding F-number is 1.5. Each element in the array measures 3.5 cm $\times$ 3.7 cm. The gate bias lines are horizontal, while the drain and diode bias lines are diagonally distributed. An identical passive array, with the amplifiers replaced by 65-Ω through lines between the two slots, is used for calibration.

For reception, a transmit horn antenna, located in the far field of the array, provides a horizontally polarized incident plane wave to the array. The array receives, amplifies, and reradiates a vertically polarized wave to a receive horn located at the focal point. For transmission, the signal path is reversed. Two polarizers are inserted at a quarter-wavelength distance on each side of the array. The passive array is measured to provide a reference for the measurements. The measurements are normalized to a through measurement with the transmit and receive horns co-polarized. A 22 cm $\times$ 26 cm aperture cut out of absorbing material is used for this calibration.

Measurements were first performed with the ten central elements populated. A measured ON/OFF isolation of 25 dB for both receive and transmit modes with ten elements is seen. In receive mode, a maximum power gain of about 10 dB relative to the passive array with ten elements connected is measured at 9.4 GHz. In transmit mode, the measured power gain is about 5 dB at 10.2 GHz.

These measurements were repeated with the 24 elements populated (the results are plotted in Fig. 8). In receive mode, a maximum power gain of 5.5 dB relative to the passive array with all 24 elements connected is measured at 10.1 GHz. In transmit mode, the measured power gain is 2 dB at 10.2 GHz.

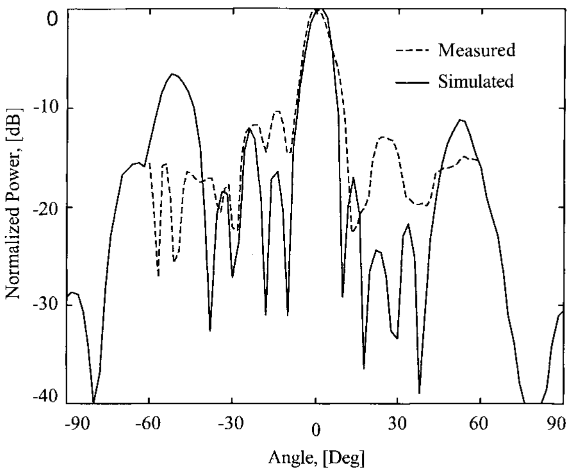


(b)

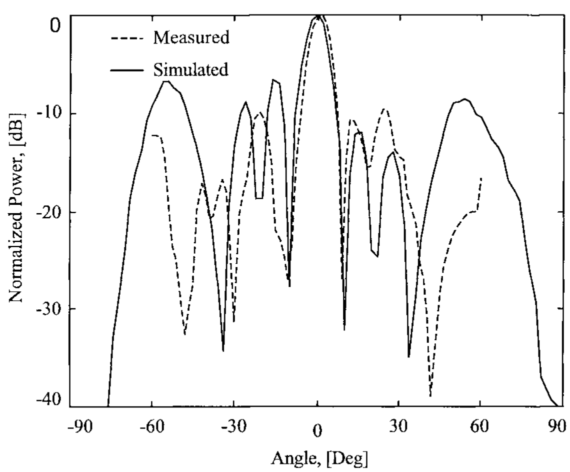
Fig. 8. (a) Measured ON/OFF ratio of the 24-element active and passive array in transmit mode, with polarizers at input and output. (b) Measured ON/OFF ratio of the 24-element active and passive array in receive mode, with polarizers at input and output. The measurements are normalized to a through measurement with a rectangular aperture surrounded by absorbing material. The solid lines represents the biased on state, the dotted lines the biased off state, and the dashed lines shows the measured results for the passive array.

A possible explanation for reduction in gain when increasing the size of the array from 10 to 24 elements is increased nonuniformity of the amplifiers across the array. This could be due to fabrication, unmatched devices, and coupling between unit cells, as well as a larger fraction of edge elements in the 24-element array as compared to the ten-element array. The absolute power gain relative to the rectangular aperture is 3.9 dB in reception and 0.9 dB in transmission. Measured ON/OFF isolation ratios of approximately 15 dB in receive mode, and more than 20 dB in transmit mode are seen. Notice that the physical area of the active antenna array covers only 55% of the aperture, so the absolute power gains are expected to be higher than those measured. Also note that due to the limited performance bandwidth of the amplifiers, the active array is lossy compared to the passive array outside the amplifier gain range.

The 24-element lens amplifier has a measured beamwidth of about 10° in both E- and H-plane, with sidelobe levels of less



(a)



(b)

Fig. 9. (a) Measured (- -) and simulated (—) H-plane radiation pattern for the receive amplifier at 10.1 GHz. (b) Measured (- -) and simulated (—) E-plane radiation pattern for the receive amplifier at 10.1 GHz. The theoretical patterns were calculated using the measured antenna pattern of a single slot antenna.

than -10 dB, as shown in Fig. 9. The theoretical patterns were calculated using the measured radiation pattern of a single slot antenna.

IV. Applications

A. A Quasi-Optical Receiver

A complete quasi-optical receiver front end can be formed by cascading the lens amplifier with a 10.39-GHz grid oscillator/mixer, as shown in Fig. 1. A transmitted 10.10-GHz carrier, amplitude modulated with a 10-kHz square wave, is amplified and focused by the ten-element lens amplifier toward the self-oscillating mixer located at the focal point. The 290-MHz IF present on the bias lines of the grid oscillator is demodulated using an HP 89441A Vector Signal Analyzer. The recovered 10-kHz square wave is shown in Fig. 10. The quasi-optical grid oscillator is just one example of a feed type. Possible advantages of using a grid oscillator are: 1) power combining at the source level; 2) reduced phase noise as more devices in the grid lock [9]; and 3) self-oscillating fundamental or harmonic mixing in reception [7].

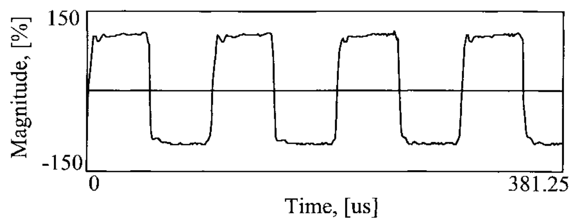


Fig. 10. A 10-kHz square-wave signal received by a quasi-optical receiver front-end and demodulated. A transmitted amplitude modulated 10.1-GHz carrier is received, mixed to a 290-MHz IF, and demodulated using a vector signal analyzer.

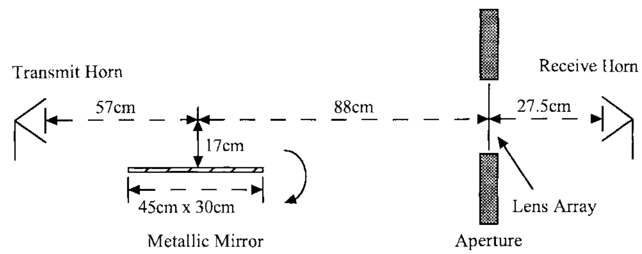


Fig. 11. Test setup for the multipath experiment. A 45 cm $\times$ 30 cm metallic mirror located parallel to the optical axis in front of the 24-element lens amplifier is translated in 3-mm steps from the axis. For each step, the mirror was rotated through a set of angles.

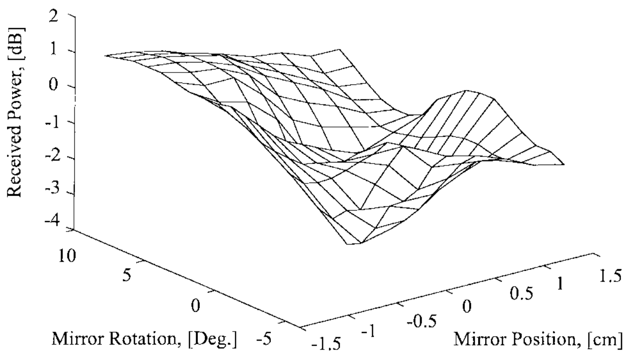
B. Multipath Fading Reduction

Reduction of multipath fading using a lens amplifier array can be demonstrated by a simple measurement. A 45 cm $\times$ 30 cm metallic mirror located parallel to the optical axis in front of the amplifier array was translated in 3-mm steps perpendicular to the optical axis, as shown in Fig. 11. For each step, the mirror was rotated through a set of angles. The received power was measured for all mirror positions with and without the lens amplifier.

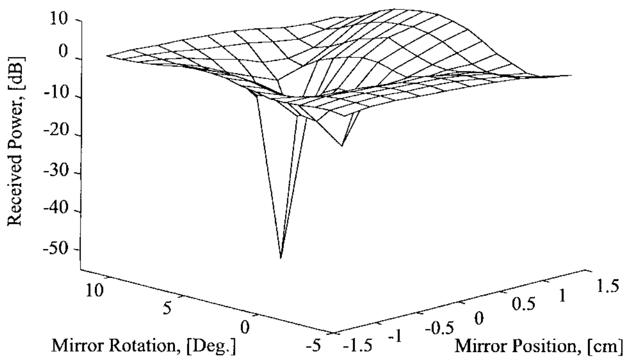
The measured maximum fades of a 10.1-GHz carrier signal, with and without the 24-element lens amplifier, and normalized to the received signal without the mirror inserted, are shown in Fig. 12. Maximum fading nulls of less than -4 dB and greater than -50 dB were measured with and without the lens amplifier, respectively. This simple measurement show that a lens amplifier can also provide a significant improvement of multipath fading effects due to the increased directivity of the receiver [10].

C. A Multiuser Application

A multiuser frequency reuse experiment demonstrates how two separate signals incident from different angles can be received independently at different locations along the focal surface of the 24-element lens amplifier array. Beamsteering patterns are measured at 10.1 GHz for receive locations at $-20°$, $0°$, and $+20°$ along the focal surface in the E-plane of the array, as shown in Fig. 13. The normalizing power levels of the main lobes are within 2 dB. The measured sidelobe levels for the $0°$ and $20°$ receive locations are below -10 dB.



(a)



(b)

Fig. 12. Measured maximum multipath fading nulls of a 10.1-GHz carrier signal. The received power is normalized to through measurements without the mirror inserted. (a) With and (b) without the 24-element lens amplifier array inserted. Notice the different vertical scales.

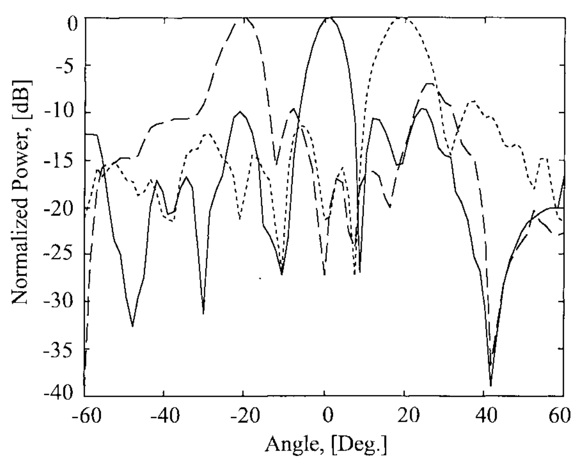


Fig. 13. Beamscanning in E-plane at 10.1 GHz for the 24-element lens amplifier array in receive mode. Receive horn at (–) 0°, (- -) $-20°$, and $(\cdots)$ 20° locations are shown. The normalizing power levels of the main lobes are within 2 dB.

A multiuser experiment, with two incident signals at 0° and 20° and with the same incident power levels is performed, as shown in Fig. 14. The received power of an interfering signal originating 20° from the desired signal has a measured relative power of about -10 dB in this setup. Square-wave signals at $f_A = 50$ kHz and $f_B = 150$ kHz are frequency modulated on a 10.1-GHz carrier and incident from 0° and 20°, respectively. The demodulated signals received at the 0° and 20° positions on the focal surface are shown in Fig. 15.

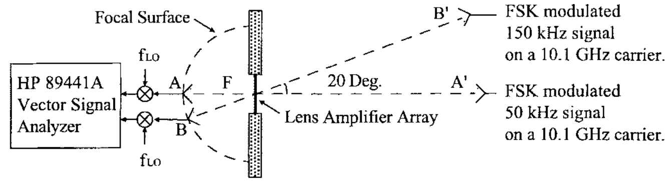
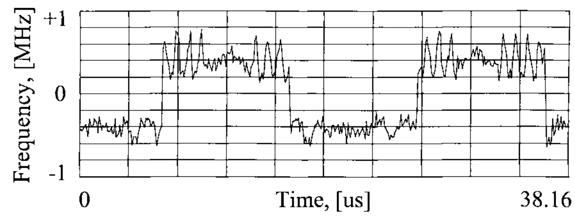
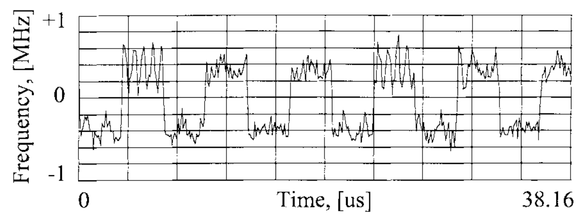


Fig. 14. Test setup for the multiuser experiment. Square-wave signals at $f_A = 50$ kHz and $f_B = 150$ kHz are frequency modulated on a 10.1-GHz carrier and input at 0° and 20° from the optical axis, respectively. The two signals are received by horns located on the focal surface behind the 24-element lens amplifier array, and demodulated using a vector signal analyzer.



(a)



(b)

Fig. 15. (a) Received and frequency shift-keying (FSK) demodulated 50-kHz signal for a receiver located at 0°. (b) Received and FSK demodulated 150-kHz signal for a receiver located at 20°. The signals are demodulated using a vector signal analyzer.

The interfering signal appears as an additional ripple in the demodulated signal.

V. Conclusion

A bi-directional quasi-optical lens amplifier array is presented. In transmit mode, the vertically polarized antiresonant slot antennas receive an input wave from a focal point and SPDT switches route it through transmit amplifiers to the horizontally polarized output slots. In reception, the horizontally polarized slots couple the input signal through the receive amplifiers to the vertically polarized slots. Amplifier gains of 5.5 dB at 10.1 GHz in receive mode, and 2 dB at 10.2 GHz in transmit mode are measured. The functionality of this quasi-optical approach is demonstrated by: 1) a quasi-optical T/R module; 2) a quasi-optical AM receiver; 3) significant multipath fading null reduction; and 4) a multiuser with frequency reuse FSK data link.

Acknowledgment

The authors wish to thank Rogers Corporation, Chandler, AZ, for substrate donations, and Boulder Microwave Technologies, Inc., Boulder, CO, for use of *Ensemble*. The authors also thank the DOD (ARO) DURID program that enabled the purchase of most of the equipment used for this work.

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Stein Hollung was born in Oslo, Norway, on March 7, 1970. He received the electrical engineering degree from Oslo College of Engineering, Oslo, Norway, in 1992, the B.S. and M.S. degrees in electrical engineering from the University of Colorado at Boulder, in 1994 and 1995, respectively, and is currently working toward the Ph.D. degree in electrical engineering.

Amanda E. Cox received the B.S. degree in electrical engineering, the M.S. degree in aerospace engineering sciences from the University of Colorado at Boulder in 1983 and 1996, respectively, and is currently working toward the Ph.D. degree in electrical engineering.

She served as a Project Engineer at both Teledyne MEC, Palo Alto, CA, developing traveling-wave tube amplifiers for satellite communications and radar applications, and at TIW Systems, Sunnyvale, CA, developing microwave subsystems for satellite communications and radio astronomy. Her research interests include remote sensing, radio astronomy, GPS, and satellite systems.

Zoya Basta Popović (S'86–M'90), for a photograph and biography, see this issue, p. 2174.