A RETRODIRECTIVE DIODE GRID ARRAY USING FOUR-WAVE MIXING

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ABSTRACT

We report retrodirection using quasi-optical diode grid arrays operating at 4 GHz. Phase conjugation is achieved through a process analogous to four-wave mixing. Antiparallel diode pairs provide the third-order nonlinearity. We report retrodirection of beams with incidence angles of up to 60^0 in both the E-plane and the H-plane. Measured antenna patterns are consistent with theoretical predictions.

I. INTRODUCTION

When illuminated by a source, retrodirective antennas will re-direct a signal toward that source without any prior knowledge of its location. Applications of retrodirection include radar transponders and self-tracking wireless communication links.

Retrodirection in antenna arrays will occur when the transmitting phase of each element is the conjugate of the illuminating phase. In general, two types of such arrays have been reported. Van Atta arrays are constructed by connecting pairs of elements with transmission lines of equal length [1]–[4]. The heterodyne method, on the other hand, achieves phase conjugation at each element by mixing the illuminating signal with an external local oscillator [5]–[9]. In this paper, we describe a method of phase conjugation and retrodirection using a microwave process analogous to four-wave mixing in optics.

II. PRINCIPLE OF OPERATION

Phase conjugation through four-wave mixing has long been explored by the nonlinear optics community [10], [11]. A crystal with a high third-order Kerr nonlinearity (χ_3) is required. Attempts to create artificial third-order nonlinear materials suitable for phase conjugation at microwave frequencies have met with limited success [12], [13].

Our approach is illustrated in Fig. 1. Quasi-optical grids loaded with antiparallel diode pairs are used to provide the strong third-order nonlinearity. The grids are pumped by two normally incident microwave beams at frequency f_0. The retrodirected output beam is the phase conjugate of the input. In order to separate the output beam from the pumps and input, the frequency of the input can be offset below the pump frequency f_0 by Δf. The frequency of the retrodirected output will then be $f_0 + \Delta f$.

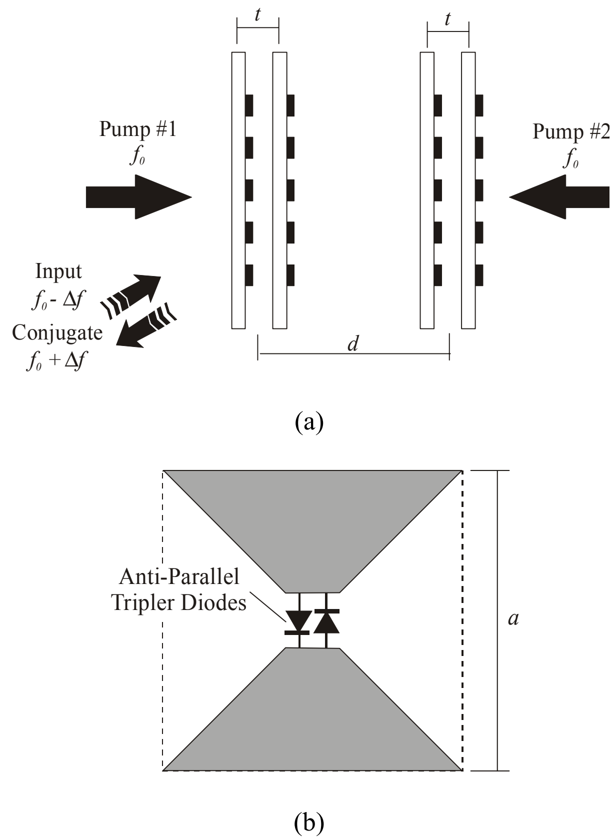

Fig. 1. (a) Four-wave mixing in nonlinear quasi-optical arrays. (b) Array unit cell with a strong third-order nonlinearity.

As a proof of the concept, four 25-element grids were constructed for operation near 4 GHz. A unit cell is shown in Fig. 1(b). A packaged Metelics MSS-30-346-E20 antiparallel diode pair is connected at the apex of a bow-tie antenna. The unit cell size a is 7.7 mm (λ_0/9.8). The grids were constructed on a 15-mil Rogers *RT/Duroid* substrate with $\varepsilon_r = 2.33$. Best simulated and experimental results were obtained with the grid spacing shown in Fig. 1(a), with $t = 5.4$ mm (λ_0/14) and $d = 54$ mm (λ_0/1.4).

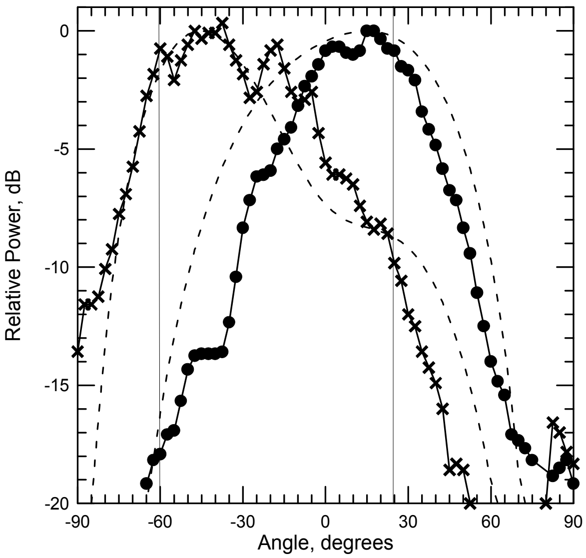

Fig. 2. Measured and theoretical retrodirected power with input beams incident from +25^0 (•) and –60^0 (×) in the E-plane. Dashed lines represent theoretical predictions.

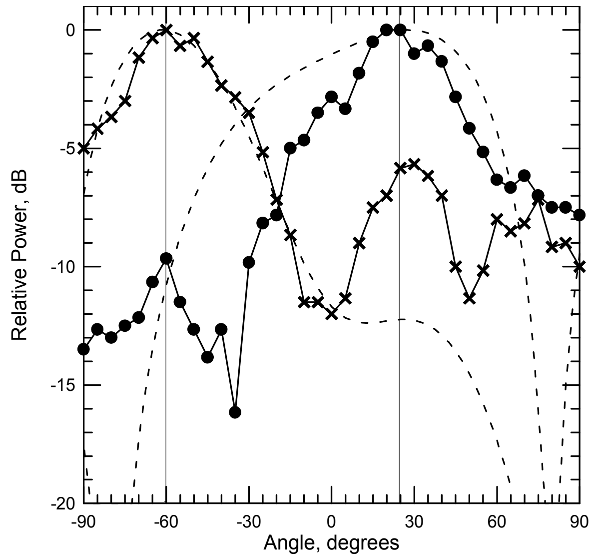

Fig. 3. Measured and theoretical retrodirected power with input beams incident from +25^0 (•) and –60^0 (×) in the H-plane. Dashed lines represent theoretical predictions.

III. Measured Results

The grids were measured in the far field. Fig. 2 plots the measured retrodirected radiation pattern with input beams incident from +25^0 and –60^0. The frequency of the pump beams is 4.0 GHz, the input beam is 3.9 GHz, and the retrodirected beam is 4.1 GHz. These patterns show the array's E-plane pattern, with the illuminating beam incident in the E-plane. Retrodirection is clearly evident. The array can also retrodirect beams incident in the H-plane. H-plane retrodirected patterns are shown in Fig. 3. Fig. 4 shows the measured H-plane power patterns for a full 360^0 span. Note the power in other directions is usually more than 6 dB below the main beam.

Theoretical patterns *U(θ)* are generated using the following expression

$$U(\theta) \propto EF(\theta)\frac{\sin^2(Nk'_x a/2)}{\sin^2(k'_x a/2)}\cos^2(k'_z t/2)\cos^2(k'_z d/2)$$

where *N* is the number of elements per side in each grid (*N* = 5). Furthermore,

$$k'_x = \frac{2\pi}{\lambda_i}\sin\ \theta_i - \frac{2\pi}{\lambda_c}\sin\ \theta$$
$$k'_z = \frac{2\pi}{\lambda_i}\cos\ \theta_i - \frac{2\pi}{\lambda_c}\cos\ \theta$$

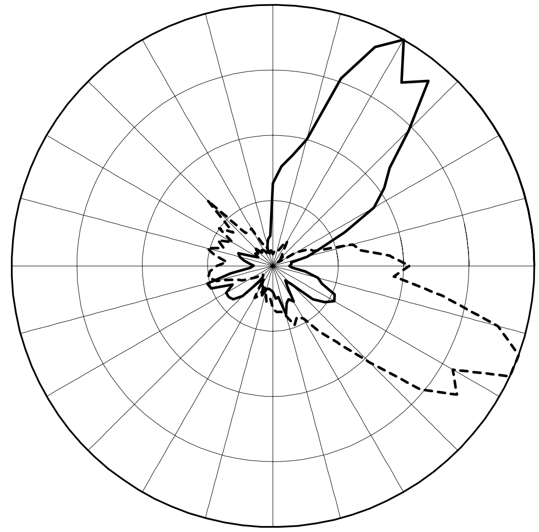

Fig. 4. Measured relative retrodirected power with H-plane input beams incident from +25^0 (dashed lines) and from –60^0 (solid lines). Power is plotted in a linear scale.

where λ_i is the wavelength of the input beam, λ_c is the wavelength of the conjugated beam, and θ_i is the incidence angle of the input beam. *EF(θ)* is an element factor. Because our antennas are short bowties, we assume *EF(θ)* is $\cos^2\theta$ for E-plane incidence and unity for the H-plane. The theoretical patterns are consistent with the measured results. The element factor and the frequency offset of the input and output beams will cause the retrodirected beam

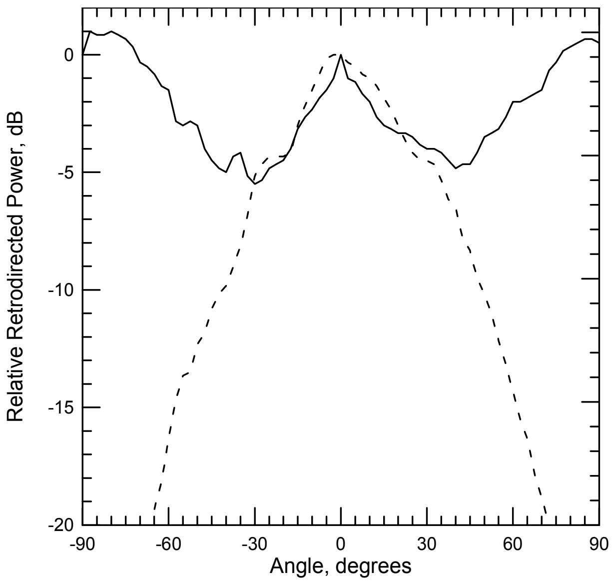

Fig. 5. Relative measured retrodirected EIRP as a function of incidence angle for H-plane (solid line) and E-plane (dashed line) incidence.

to have a slight pointing error; this error can be minimized by minimizing the frequency offset.

Fig. 5 shows the measured retrodirected Effective Isotropic Radiated Power (EIRP) [14] as a function of incidence angle. Both E-plane and H-plane incidences are shown. The element factor causes the retrodirected power for E-plane incidence to fall off rapidly at higher incidence angles. Fig. 6 plots the retrodirected power as a function of offset frequency Δf. The frequency of the pump beams is fixed at 4 GHz. The 3-dB bandwidth is 350 MHz.

Fig. 7 shows the array's linearity. In order to estimate the conversion loss of the retrodirective antenna, we must know its directivity. By measuring the beamwidths in the principal planes, we estimate the directivity to be 10 dB [15]. With an incident input power of 1 µW, we estimate a conversion loss of 24 dB. The power in each pump beam incident on the array is 75 µW. With an incident input power of 150 µW saturating the array, we estimate a conversion loss of 26 dB. These results are roughly consistent with theoretical simulations using a simple nonlinear diode model that predict a conversion loss of 30 dB. We suspect the conversion loss could be improved by increasing the pump power; in some cases, it may be possible to achieve a conversion gain through parametric amplification.

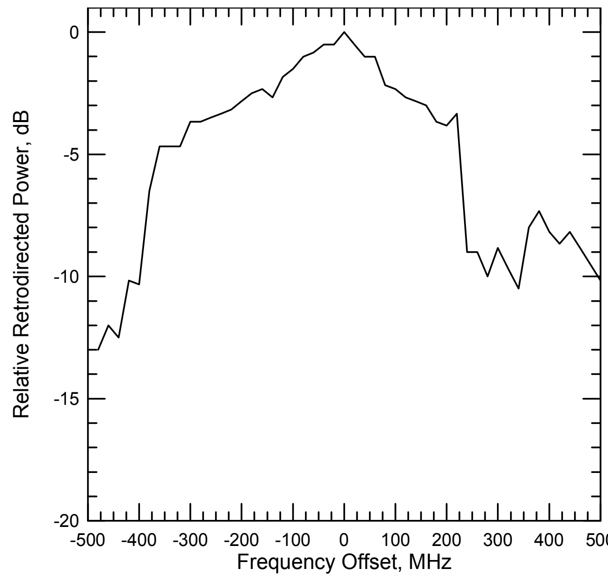

Fig. 6. Relative retrodirected power as a function of frequency offset Δf. The input beam is incident at an angle of 25^0 in the H-plane.

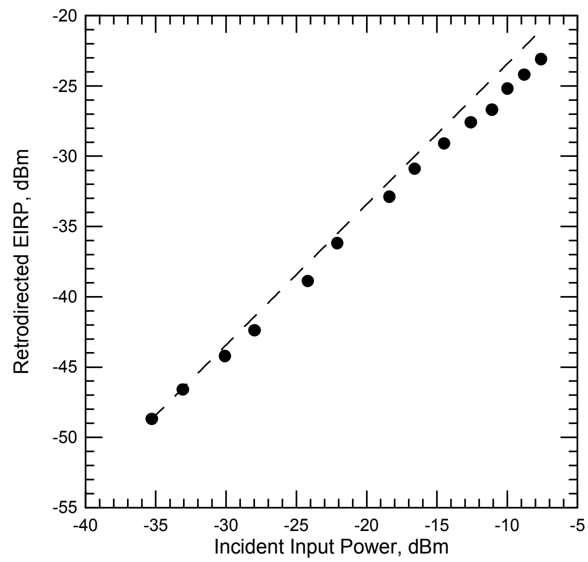

Fig. 7. Retrodirected EIRP as a function of incident input power. The power incident on the array in each pump beam is 75 µW. The input beam is incident at an angle of 20^0 in the H-plane.

IV. CONCLUSION

We have demonstrated retrodirective antennas that achieve phase conjugation through four-wave mixing in quasi-optical diode grid arrays. The arrays will retrodirect power incident at angles up to 60^0 in both the E and H-planes. Although these arrays operated at 4 GHz, the approach should be scalable to higher frequencies.

V. Acknowledgements

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VI. References

[1] L.C. Van Atta, "Electromagnetic reflector," U.S. Patent 2908002, Oct. 6, 1959.

[2] S.N. Aandre, and D.J. Leonard, "An active retro-directive array for satellite communications," *IEEE Trans. Antennas Prop*., vol. 12, pp. 181–186, Mar. 1964.

[3] S.L. Karode, V.F. Fusco, "Self-tracking duplex communication link using planar retrodirective antennas," *IEEE Trans. Antennas Prop*., vol. 47, pp. 993–1000, June 1999.

[4] M.L. Skolnik and D.D. King, "Self-phasing array antennas," *IEEE Trans. Antennas Prop*., vol. 12, pp. 142–149, March 1964.

[5] C.Y. Pon, "Retrodirective array using the heterodyne technique," *IEEE Trans. Antennas Prop*., vol. 12, pp. 176–180, March 1964.

[6] C.W. Pobanz and T. Itoh, "A conformal retrodirective array for radar applications using a heterodyne phased scanning element," in *1995 IEEE MTT-S Int. Microwave Symp. Dig*., Orlando, FL, June 1995, pp. 905–908.

[7] Y. Chang, H.R. Fetterman, I.L. Newberg, S.K. Panaretos, "Microwave phase conjugation using antenna arrays," *IEEE Trans. Microwave Theory Tech*., vol. 46, pp. 1910–1919, Nov. 1998.

[8] R.Y. Miyamoto, Y. Qian, and T. Itoh, "A retrodirective array using balanced quasi-optical FET mixers with conversion gain," in *1999 IEEE MTT-S Int. Microwave Symp. Dig*., Anaheim, CA, June 1999, pp. 655–658.

[9] D.M.K. Ah Yo, W.E. Forsyth, and W.A. Shiroma, "A 360^0 retrodirective self-oscillating mixer array," in *2000 IEEE MTT-S Int. Microwave Symp. Dig*., Boston, MA, June 2000, pp. 813–816.

[10] A. Yariv, *Optical Electronics in Modern Communications*, 5th ed. New York: Oxford University Press, 1997, chapt. 17.

[11] B.E.A. Saleh and M.C. Teich, *Fundamentals of Photonics*. New York: John Wiley and Sons, 1991, chapt. 19.

[12] R. Shih, H.R. Fetterman, W.W. Ho, R. McGraw, *et al*., "Microwave phase conjugation in a liquid suspension of elongated microparticles," *Phys. Rev. Lett*., vol. 65, no. 5, pp. 579–582, 1990.

[13] B. Tasp, K.S.J. Pister, and H.R. Fetterman, "MEMS orientational optomechanical media for microwave nonlinear applications," *IEEE Microwave Guided Wave Lett*., vol. 6, pp. 432–434, Dec. 1996.

[14] M. Gouker, "Toward standard figures-of-merit for spatial and quasi-optical power-combined arrays," *IEEE Trans. Microwave Theory Tech*., vol. 43, pp. 1614–1617, July 1995.

[15] W.L. Stutzman, "Estimating directivity and gain of antennas," *IEEE Antennas Prop. Magazine*, vol. 40, pp. 7–11, Aug. 1998.