Reduction of Substrate-Mode Effects in Power-Combining Arrays

Ayman Al-Zayed, *Student Member, IEEE*, Robert R. Swisher, *Student Member, IEEE*, Frédéric Lécuyer, *Student Member, IEEE*, Andrew C. Guyette, *Student Member, IEEE*, Qi Sun, *Member, IEEE*, and Michael P. De Lisio, *Member, IEEE*

***Abstract*—We report a simple theory for the reduction of substrate modes in quasi-optical power-combining arrays. This qualitative theory predicts that detrimental substrate-mode effects can be greatly reduced through a judicious choice of the array unit cell size. Experimental evidence from quasi-optical tripler grids is presented to confirm the theory. Measured results show a dramatic improvement in the radiation pattern and effective radiated power of arrays with both grounded and ungrounded substrates.**

***Index Terms*—Power combining, quasi-optics, substrate modes.**

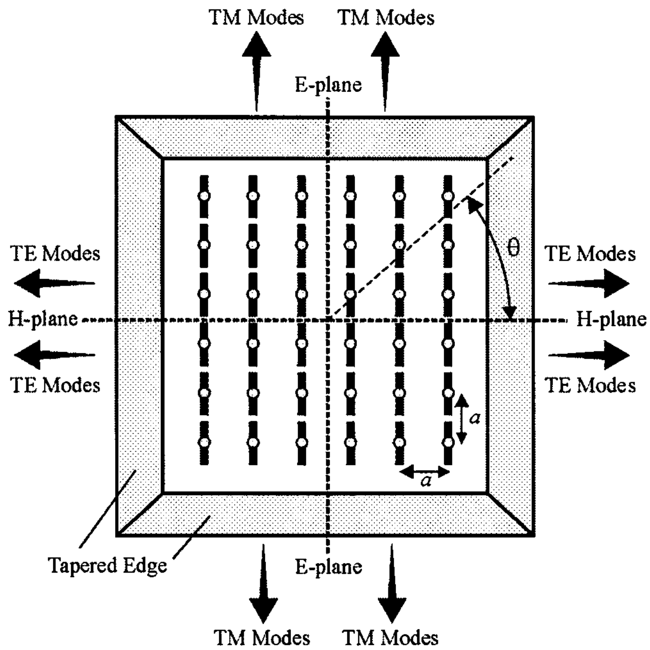
I. INTRODUCTION

QUASI-OPTICAL grids are intended to combine the outputs of many solid state-devices in free space. Some grid oscillators [1] have been quite successful. A 100-MESFET oscillator radiated 10 W at 10 GHz [2]. Other grid oscillators, on the other hand, have suffered from low-output powers and poor radiation patterns. The measured radiation pattern from a 36-MESFET grid revealed 4-dB sidelobes [3]. A 35-GHz monolithic oscillator had sidelobes only 2 dB less than the main beam [4]. Griffin [5] pointed out that these poor patterns are due to substrate modes that radiate through the edges of the array. Substrate-mode excitation could also be the cause of poor performance in other quasi-optical devices, including amplifiers and multipliers.

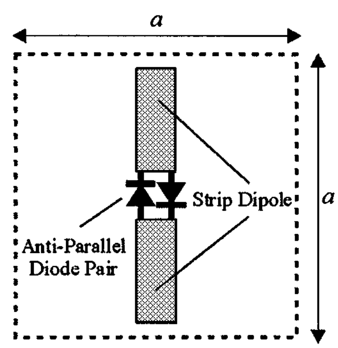
Substrate-mode power in grids can be reduced by choosing electrically thin substrates [6]. Monolithic grids, however, would be constructed on electrically thick high-dielectric-constant substrates. In this paper, we present a simple qualitative approach to minimize the effect of substrate modes through a careful choice of unit cell size. We confirm our theory with measurements from quasi-optical tripler arrays built on high-ε_r substrates.

II. THEORY

Our theory is based on the work of Rutledge *et al.* [7], Preventza [8], and Pozar [9], [10]. We begin by considering a quasi-optical grid as an array of short dipoles on a substrate, as shown in Fig. 1(a). For simplicity, we assume a square array, where the dipole spacing is a in both directions and there are N elements on each side. For a given substrate thickness and dielectric constant, the effective dielectric constant $\varepsilon_r^{\text{eff}}$ and the propagation constant β of the various dielectric slab waveguide modes can readily be determined [11]. The orientation of the dipoles is such that TE slab modes will propagate perpendicular to the dipole axis; these TE modes will degrade the grid's H-plane pattern



(a)



(b)

Fig. 1. (a) Square dipole array layout. The element spacing is in both directions. (b) Unit cell detail. We have used packaged Metelics MS30-346-E20 diodes.

Manuscript received July 25, 2000. This work was supported by the U.S. Army Research Office Quasi-Optic Multidisciplinary University Research Initiative Program through the California Institute of Technology under a grant.

A. Al-Zayed is with the Department of Electrical Engineering, North Carolina State University, Raleigh, NC 27695 USA.

R. R. Swisher is with the RF Sensor Division, Naval Air Warfare Center, Barking Sands Pacific Missile Range Facility, Kauai, HI 96752 USA.

F. Lécuyer is with Radio Frequency Systems Inc., Meriden, CT 06450 USA.

A. C. Guyette and M. P. De Lisio are with the Department of Electrical Engineering, University of Hawaii at Manoa, Manoa, HI 96822 USA.

Q. Sun is with Space System/Loral, Palo Alto, CA 94303 USA.

Publisher Item Identifier S 0018-9480(01)04001-7.

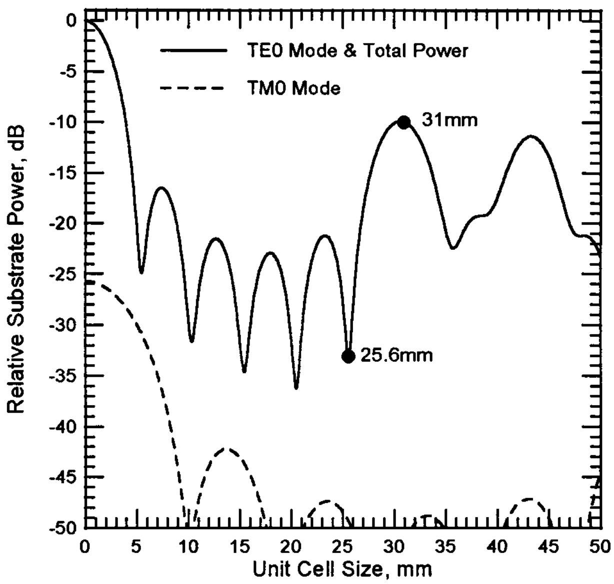


Fig. 2. Relative substrate-mode power as a function of unit cell size a for a 36-element array at 5.2 GHz on an ungrounded substrate. The guided wavelength of the TE mode is 31 mm.

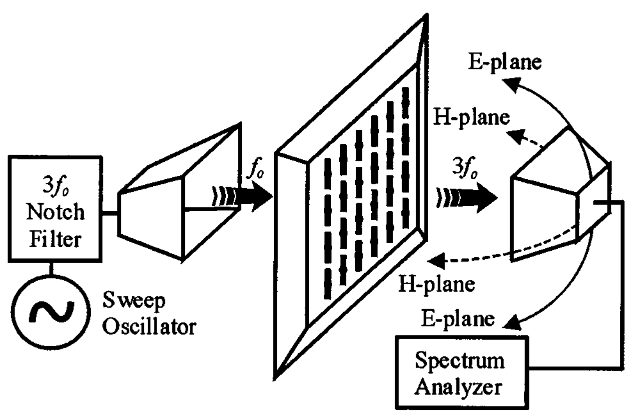
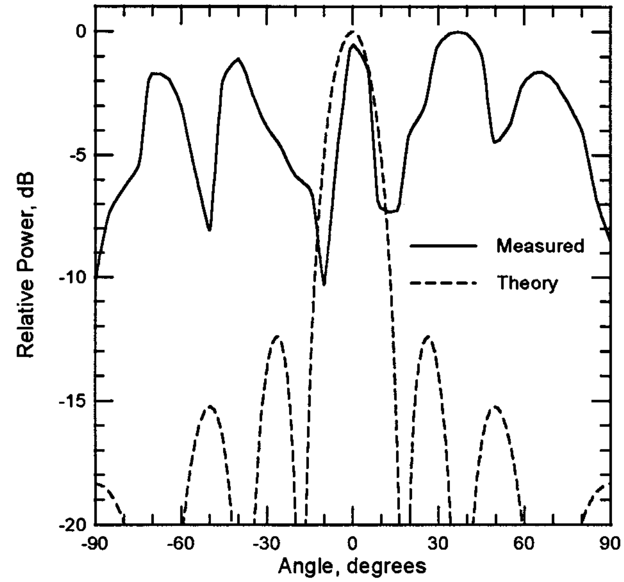
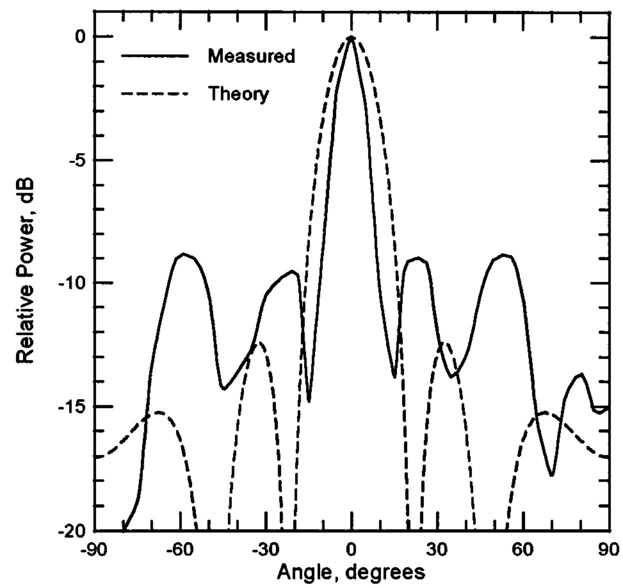


Fig. 3. Schematic of the far-field measurement setup. Measurements on grounded arrays are performed in reflection.



(a)



(b)

Fig. 4. H-plane radiation patterns at an output frequency of 5.2 GHz on ungrounded substrate. (a) Larger (31 mm) unit cell. (b) Smaller (25.6 mm) unit cell. The theoretical patterns were generated assuming a uniform array of short dipoles.

by radiating from the edges of the array. TM slab modes, on the other hand, will propagate parallel to the dipole axis and thus cause poor E-plane patterns.

We next assume that each dipole in the array is excited with a uniform amplitude and phase. This is a clear oversimplification, especially for oscillator arrays where the phase between elements may be determined by the dynamics of the locking mechanism. Our uniform assumption is more valid for quasi-optical amplifiers and mixers, where the illumination can control the element excitation to a great extent. Nevertheless, the slab-mode power that the entire array excites can be calculated by integrating in the plane of the substrate. The power in a single-slab mode P will be given by the expression

$$P = K\int_0^{2\pi} \frac{\sin^2(N\beta a\cos\theta/2)}{\sin^2(\beta a\cos\theta/2)}\frac{\sin^2(N\beta a\sin\theta/2)}{\sin^2(\beta a\sin\theta/2)} \times \mathrm{EF}(\theta)d\theta. \quad (1)$$

The coefficient K is used to relate the power levels in different slab modes and can be calculated using the reciprocity approach developed by Rutledge *et al.* [7]. The first two terms in the integrand are familiar from antenna array theory. The function $\mathrm{EF}(\theta)$ is the element factor for the short dipoles and is $\cos^2\theta$ for TE modes and $\sin^2\theta$ for TM modes, with θ defined in Fig. 1(a). The mode power in (1) is a function of the element spacing a; the slab mode power will be large for certain spacings (e.g., spacings near a full guided wavelength) and will be small for other spacings.

III. Measurements—Ungrounded Substrate

To test this approach, we fabricated quasi-optical tripler arrays using antiparallel diode pairs in each unit cell, as shown in Fig. 1(b). The arrays were constructed on an ungrounded Rogers

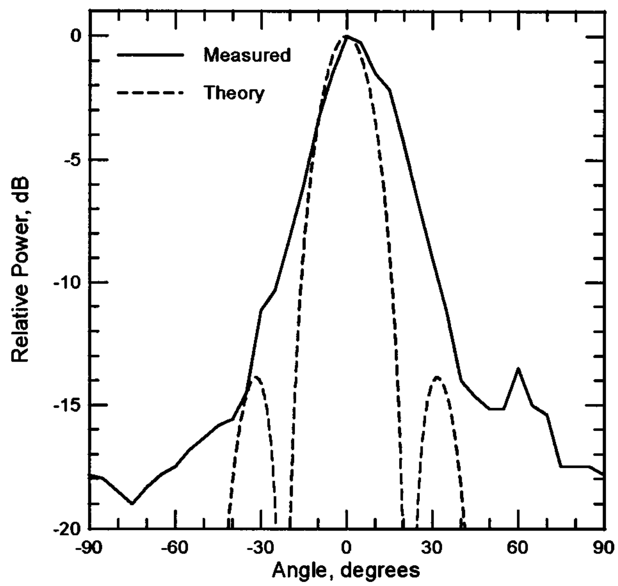


Fig. 5. E-plane radiation pattern for the smaller (25.6 mm) array at an output frequency of 5.2 GHz on ungrounded substrate.

TABLE I
SUMMARY OF MEASURED RESULTS—5.2-GHz ARRAY ON UNGROUNDED SUBSTRATE

Cell Size (mm)	H-plane Sidelobe Level (dB)	Relative Peak ERP (dB)
25.6	−9	0
31	0	−13

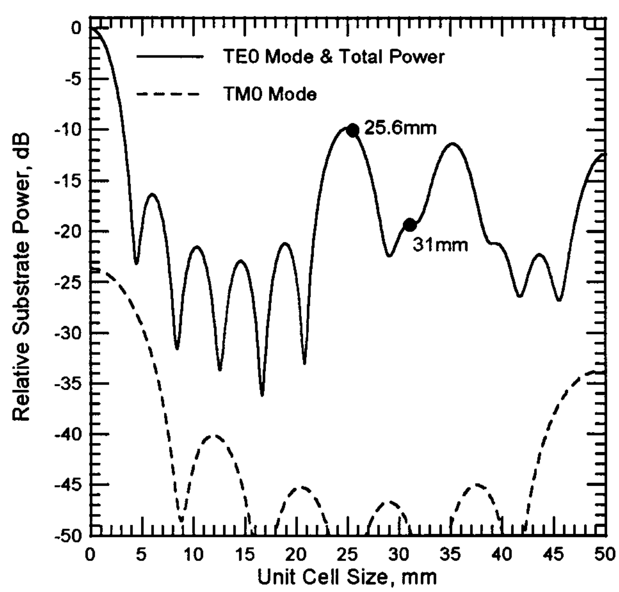
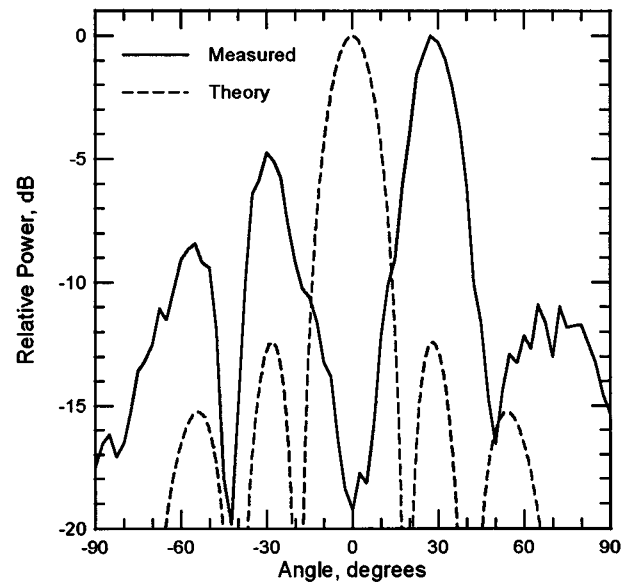
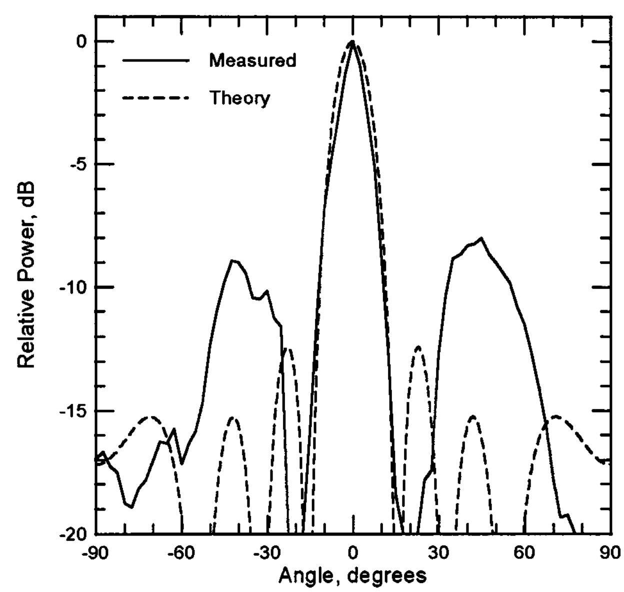


Fig. 6. Relative substrate-mode power as a function of unit cell size a for a 36-element array at 6.0 GHz on an ungrounded substrate. The guided wavelength of the TE mode is 25 mm.

RT/Duroid 6010 substrate with a nominal relative dielectric constant of 10.5. For our calculations, we use a higher dielectric constant to account for the anisotropy of the substrate [12]. The edges of the arrays were tapered to reduce standing waves in the slab. At an output frequency of 5.2 GHz, two modes can propagate in the substrate: the TE_0 and TM_0 modes. Fig. 2 shows the relative substrate-mode power as a function of unit cell size for these modes. A single dipole will excite 26 dB more power into the TE mode than into the TM mode, which means the TE mode dominates the total substrate power. Furthermore, the TE mode power excited by a lone dipole is about 12 dB greater than the power that dipole will radiate into the air. We fabricated two arrays with unit cell sizes of 25.6 and 31 mm. The larger grid should excite over 20 dB more substrate power than the smaller array. These substrate effects should be evident in the grid's H-plane radiation pattern.



(a)



(b)

Fig. 7. H-plane radiation patterns at an output frequency of 6.0 GHz on ungrounded substrate. (a) Smaller (25.6 mm) unit cell. (b) Larger (31 mm) unit cell. The theoretical patterns were generated assuming a uniform array of short dipoles.

We measured the radiation patterns by illuminating the grids with power at one-third of the 5.2-GHz output frequency. The illuminating source's third harmonic was removed with a notch

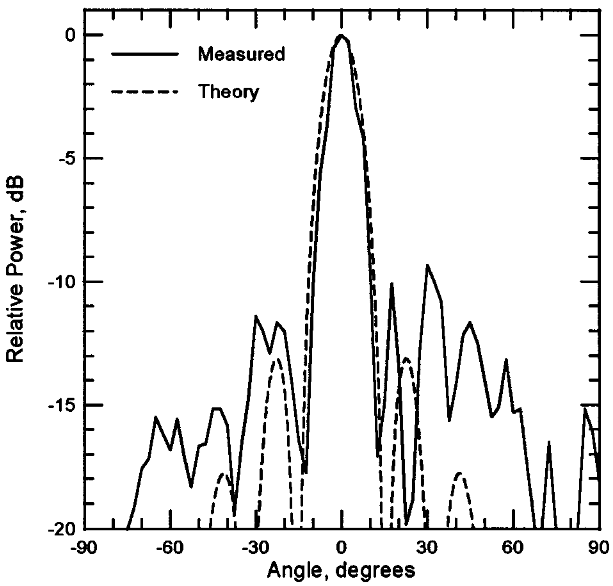


Fig. 8. E-plane radiation pattern for the larger (31 mm) array at an output frequency of 6.0 GHz on ungrounded substrate.

TABLE II
SUMMARY OF MEASURED RESULTS—6.0-GHz ARRAY ON UNGROUNDED SUBSTRATE

Cell Size (mm)	H-plane Sidelobe Level (dB)	Relative Peak ERP (dB)
25.6	N/A (Monopulse)	−11
31	−8	0

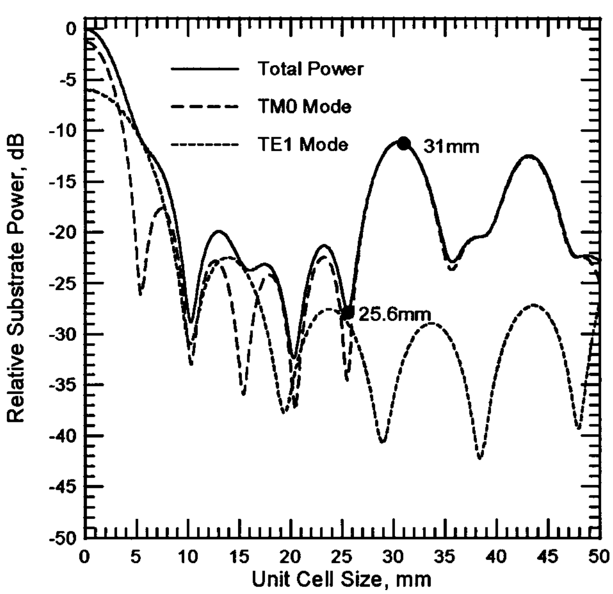
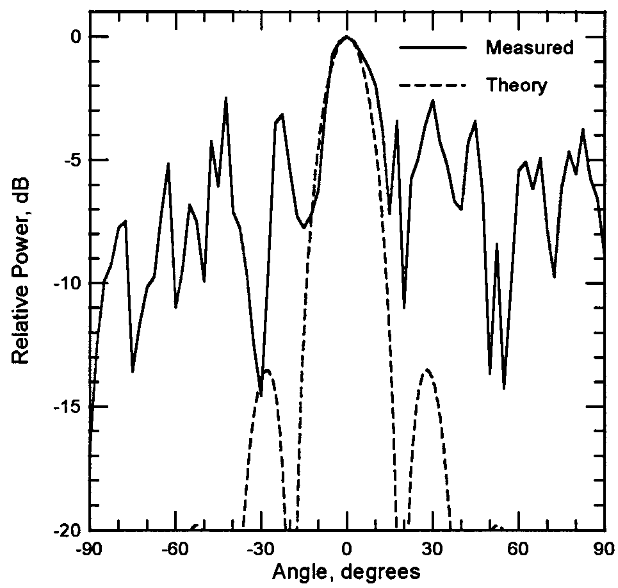


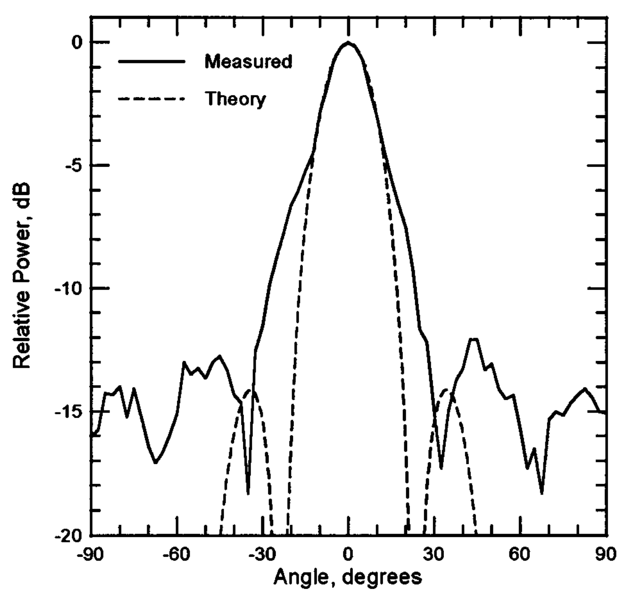
Fig. 9. Relative substrate-mode power as a function of unit cell size a for a 36-element array at 4.9 GHz on a grounded substrate. The guided wavelength for the TM mode is 30.5 mm.

filter to eliminate confounding effects. Fig. 3 illustrates the measurement setup. The radiated power from the tripler grids could then be separated from the input power with a spectrum analyzer. Fig. 4 shows the H-plane radiation patterns for both arrays. The larger array has very high sidelobes, which are indicative of substrate-mode excitation. The smaller grid has a much better radiation pattern, with a 9-dB sidelobe level. We conclude that the substrate moding effects are greatly reduced. The E-plane pattern of the smaller array was good and showed no evidence of substrate modes, as shown in Fig. 5. A nonuniform current distribution may be the cause of the beam broadening. In addition, the peak effective radiated power (ERP) measured by our receiving antenna was 13 dB higher for the smaller grid. Our measurements are summarized in Table I. These results indicate that a small change in cell size can have a dramatic effect.

To further validate our theory, we tested the same grids at an output frequency of 6.0 GHz. In this case, we predict the smaller (25.6 mm) grid will excite more substrate-mode power than the



(a)



(b)

Fig. 10. E-plane radiation patterns at an output frequency of 4.9 GHz on grounded substrate. (a) Larger (31 mm) unit cell. (b) Smaller (25.6 mm) unit cell. The theoretical patterns were generated assuming a uniform array of short dipoles.

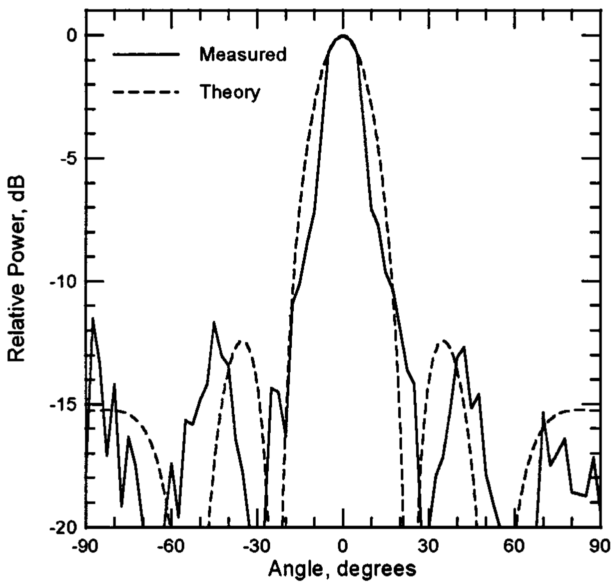


Fig. 11. H-plane radiation patterns for the smaller (25.6 mm) array at an output frequency of 4.9 GHz on grounded substrate.

TABLE III
SUMMARY OF MEASURED RESULTS—4.9-GHz ARRAY ON GROUNDED SUBSTRATE

Cell Size (mm)	E-plane Sidelobe Level (dB)	Relative Peak ERP (dB)
25.6	−12	0
31	−3	−16

larger (31 mm) array, as shown in Fig. 6. In this case, the difference in substrate power is 9 dB. The H-plane radiation patterns confirm our prediction, as shown in Fig. 7. The smaller grid's radiation pattern is poor, resembling a monopulse pattern, with no main beam at all. The larger grid has a much better pattern, with 8-dB sidelobes. The larger grid's E-plane pattern is very good, with no evidence of substrate moding, as shown in Fig. 8. The peak ERP radiated from the smaller grid was 11 dB lower than the power from the larger grid. These results are summarized in Table II. Again, we see the unit cell size can greatly affect the grid's performance.

IV. MEASUREMENTS—GROUNDED SUBSTRATE

To further validate our theory, we tested the performance of our arrays when placed on a thicker grounded substrate. Two slab modes can propagate in the substrate at a frequency of 4.9 GHz: the TM_0 and TE_1 modes. A single short dipole on this grounded substrate will excite 5 dB more power into the TM mode than into the TE mode. Furthermore, the TM mode power excited by a single dipole will be about 6 dB greater than the power this dipole will radiate into the air. Fig. 9 shows the predicted substrate power as a function of unit cell size. At larger cell sizes, the TM power dominates. We would, therefore, expect a degradation in the array's E-plane pattern. We predict that the larger (31 mm) grid will excite 16 dB more substrate power than the smaller (25.6 mm) grid. We measured the radiation patterns reflected from the array. Fig. 10 shows the E-plane radiation patterns for both arrays. The larger array has high sidelobes—only 3 dB below the peak—which indicate significant substrate-mode excitation. The smaller grid had a much better radiation pattern, with a 12-dB sidelobe level. The H-plane pattern of the smaller array showed no evidence of substrate modes, as shown in Fig. 11. In addition, the peak ERP measured by our receiving antenna was 16 dB higher for the smaller grid. Our measurements are summarized in Table III. Again, these results confirm our predictions.

V. CONCLUSION

In this paper, we have presented a simple qualitative theory for predicting the substrate-mode power in grid arrays. This theory predicts that the deleterious effects of substrate modes can be greatly reduced through a careful choice of the grid's unit cell size. We verified these predictions with experimental results from multiplier grids on both grounded and ungrounded substrates. We found that small changes in the unit cell size can have a dramatic effect on the grid's radiation patterns and ERP.

This technique may be useful in the design of monolithic quasi-optical components constructed on electrically thick substrates. This approach is most applicable to amplifiers, mixers, and other arrays with a quasi-optical input, as the incident beam will largely control the amplitude and phase distribution of the elements.

ACKNOWLEDGMENT

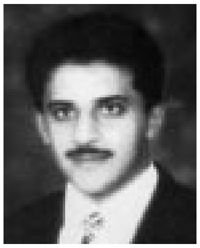
The authors would like to thank D. Landry, Art Department, University of Hawaii at Manoa, and M. Sindelar, Art Department, University of Hawaii at Manoa, for assistance with constructing this paper's measurement system. The authors would also like to thank the reviewers for many helpful suggestions.

REFERENCES

[1] Z. B. Popović, R. M. Weikle, II, M. Kim, and D. B. Rutledge, "A 100-MESFET planar grid oscillator," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 193–200, Feb. 1991.
[2] J. B. Hacker, M. P. De Lisio, M. Kim, C.-M. Liu, S.-J. Li, S. W. Wedge, and D. B. Rutledge, "A 10-W X-band grid oscillator," in *IEEE MTT-S Int. Microwave Symp. Dig.*, San Diego, CA, June 1994, pp. 823–826.
[3] R. M. Weikle, II, M. Kim, J. B. Hacker, M. P. De Lisio, and D. B. Rutledge, "Planar MESFET grid oscillators using gate feedback," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 1997–2003, Nov. 1992.
[4] M. Kim, E. A. Sovero, R. M. Weikle, II, J. B. Hacker, M. P. De Lisio, and D. B. Rutledge, "A 35 GHz HBT monolithic grid oscillator," in *Proc. 17th SPIE Int. Infrared Millimeter Waves Conf.* , R. J. Temkin, Ed., Pasadena, CA, Dec. 1992, pp. 402–403.
[5] D. W. Griffin, "Monolithic active array limitation due to substrate modes," in *IEEE AP-S Int. Symp. Dig.*, Newport Beach, CA, June 1995, pp. 1300–1303.
[6] P. Preventza, M. Matloubian, and D. B. Rutledge, "A 43-GHz AlInAs/GaIn/As/InP HEMT grid oscillator," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Denver, CO, June 1997, pp. 1057–1060.
[7] D. B. Rutledge, D. P. Neikirk, and D. P. Kasilingam, "Integrated-Circuit Antennas," in *Infrared and Millimeter Waves*, K. J. Button, Ed. New York: Academic, 1983, vol. 10, ch. 1, pp. 1–90.
[8] P. Preventza, "Analysis and design for quasi-optical structures," Ph.D. dissertation, Dept. Elect. Eng., California Inst. Technol., Pasadena, CA, 1999.
[9] D. M. Pozar, "Considerations for millimeter-wave printed antennas," *IEEE Trans. Antennas Propagat.*, vol. AP-31, pp. 740–747, Sept. 1983.
[10] ——, "Analysis of finite phased arrays of printed dipoles," *IEEE Trans. Antennas Propagat.*, vol. AP-33, pp. 1045–1053, Oct. 1985.

[11] H. Kogelnik, "Theory of dielectric waveguides," in *Integrated Optics*, T. Tamir, Ed. Berlin, Germany: Springer-Verlag, 1975, ch. 2, pp. 12–81.

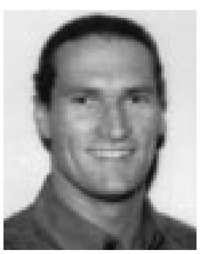
[12] Microwave Products Div., Rogers Corporation, Chandler, AZ, data sheet, Oct. 1998.



Ayman Al-Zayed (S'00) was born in Alfeha, Kuwait, on November 15, 1972. He received the B.Eng. (with honors) degree in communication and electronic engineering from the University of Northumbria, Newcastle, U.K., in 1995, the M.S. degree in electrical engineering from the University of Hawaii at Manoa, in 2000, and is currently working toward the Ph.D. degree in electrical engineering at North Carolina State University, Raleigh.

Robert R. Swisher (S'96) was born in Honolulu, HI, on February 11, 1970. He received the B.S. degree in physics and the M.S. degree in electrical engineering from the University of Hawaii at Manoa, in 1997 and 1999, respectively.

He is currently with the RF Sensors Division, Naval Air Warfare Center, Barking Sands Pacific Missile Range Facility, Kauai, HI. His research interests include high-power circuit design, microwave and millimeter-wave power combining, and quasi-optical devices.



Frédéric Lécuyer (S'96) was born in Grenoble, France, on September 8, 1973. He received the B.S. degree in physics and the M.S. degree in electrical engineering from the University of Hawaii at Manoa, in 1996 and 2000, respectively.

Since January, 2000, he has been an Antenna Design Engineer with Radio Frequency Systems Inc., Meriden, CT. His research interests include microwave and millimeter-wave antennas, microwave and millimeter-wave power combining, and quasi-optical systems.

Andrew C. Guyette (S'00) was born in Grand Forks, ND, on January 23, 1976. He received the B.S. degree in electrical engineering from the University of Hawaii at Manoa, in 1999, and is currently working toward the M.S. degree in electrical engineering at the University of Hawaii at Manoa.

Mr. Guyette is a member of Eta Kappa Nu.

Qi Sun (S'97–M'98) received the B.S. degree in electronic physics from Nanjin University, Nanjin, China, in 1983, and the M.S. degree in electrical engineering from the University of Hawaii at Manoa, in 1998.

From 1983 to 1994, she was an Electrical Engineer at the Nanjin Research Institute of Electronic Technology, Nanjin, China, where she developed microwave active circuits and receiver systems. From 1988 to 2000, she was a Senior Staff Engineer at Hughes Space and Communications, El Segundo, CA, where she was involved with payload subsystems. She is currently a Senior Engineering Specialist at Space System/Loral, Palo Alto, CA, where she is involved with communication satellite systems. Her research interests are microwave circuits and system design, measurements, and quasi-optical arrays.

Michael P. De Lisio (S'90–A'95–M'96) was born in Southfield, MI, on July 29, 1968. He received the B.S.E. degree in electrical engineering from The University of Michigan at Ann Arbor, in 1990, and the M.S. and Ph.D. degrees in electrical engineering from the California Institute of Technology, Pasadena, in 1991 and 1996, respectively.

In January 1996, he joined the Department of Electrical Engineering, University of Hawaii at Manoa, where he is currently an Associate Professor. His research interests include microwave and millimeter-wave power combining, quasi-optical devices, and high-frequency devices, circuits, and antennas.

Prof. De Lisio is a member of Tau Beta Pi, Eta Kappa Nu, and the American Society for Engineering Education. In 1999, he was the secretary of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) Administrative Committee (AdCom). He is currently an AdCom member.