Active Quasi-Optical Components and Subsystems

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Abstract

Quasi-optical components have recently gained attention in the area of large-scale solid-state power combining. In this paper, the work done at the University of Colorado is overviewed, and results from demonstrated quasi-optical oscillators, amplifiers and other components at C, X, Ka and V-band are presented.

Introduction

What are quasi-optical devices? Usually, the term *quasi-optics* is used for microwave and millimeter-wave systems which use some traditional optical components. Examples of such components are gratings, lenses, Gaussian-beam systems, mirrors and open resonators. In the last decade, it has been suggested that the powers of a very large number of low-power solid-state devices can be combined in free-space using quasi-optical techniques. Usually, such an active device consists of a printed array loaded with diodes or transistors. the active devices feed radiating elements in the array, and the powers of the individual elements are combined coherently in free space. Therefore, these components are also often called *active antennas*. A variety of active quasi-optical components have been demonstrated to date, mostly at microwave frequencies: oscillators [1], [2], [3], [4], [5], [6], [7], [8], amplifiers [9], [10], [11], [12], [13], mixers [14], phase shifters [15], [16], multipliers [17], and switches [18]. Here, first a number of components are described, and then subsystems consisting of several active quasi-optical components are presented.

Quasi-optical Oscillators and Amplifiers

Reliable, compact, solid-state oscillators are needed for signal generation and as LOs. In the first planar grid oscillator to demonstrate large-scale power combining [1], the powers of 100 MESFET oscillators were spatially combined to produce an effective radiated power of 21 W at 5 GHz with a conversion efficiency of 21%. This grid is shown in Fig. 1a.

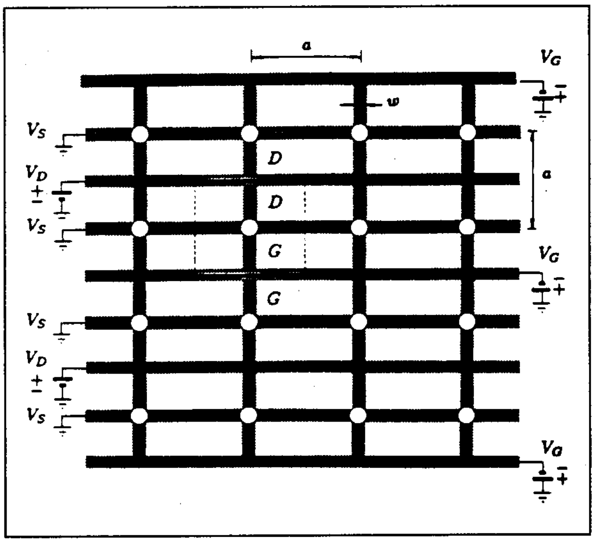

Fig. 1. (a) A 100-MESFET 5 GHz grid oscillator

The gates and drains of the transistors are connected to the vertical lines, and the sources to the horizontal ones. The bias lines are horizontal and do not affect the vertically-polarized radiated field. All the devices are biased in parallel. the grid period is much smaller than a free-space wavelength and the devices are tightly coupled, which causes the grid to act as a uniform active sheet, as opposed to a standard antenna array. A mirror is placed in parallel with the grid and the two surfaces form an instable Fabry-Perot cavity. This allows for self-locking and unidirectional radiation, confirmed experimentally by the measured radiation pattern shown in Fig.1b.

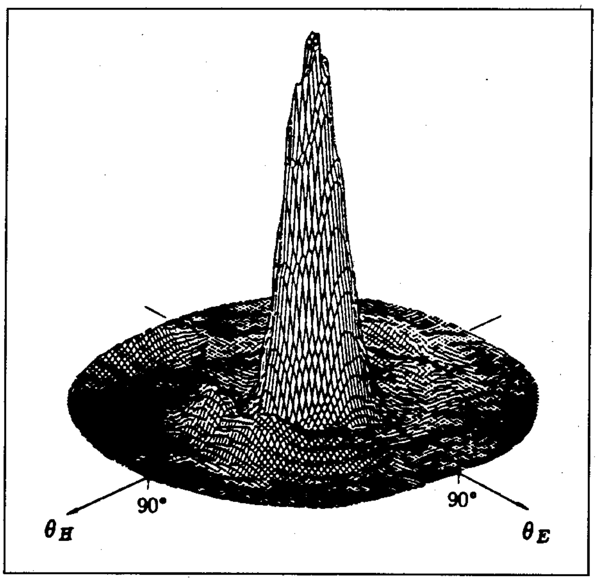

Fig. 1. (b) Radiation pattern of a 100-MESFET 5 GHz grid oscillator

In [7], full-wave theory for analyzing grid oscillators consisting of arbitrarily shaped metal gratings printed on one or both sides of an arbitrary dielectric was presented. several successful grid oscillators have been designed with this analysis tool, including C-band [7], X-band [12], and Ka-band oscillators. For example, Fig.2a shows a grid oscillator designed to operate at 10.25 GHz as a feed of a narrowband free-space lens amplifier. This grid has a rectangular unit cell and an asymmetric metal geometry. It was built with 28 PHEMTs and oscillated exactly at the design frequency. Another example is a millimeter-wave grid oscillator, fabricated and tested in collaboration with TLC Precision Wafer Technology Inc. and Honeywell (Minneapolis). The simulated frequency of oscillation using small-signal device parameters is 31.25 GHz, while the 100-PHEMT monolithic grid fabricated on GaAs locked at 31.1 GHz, Fig.2b.

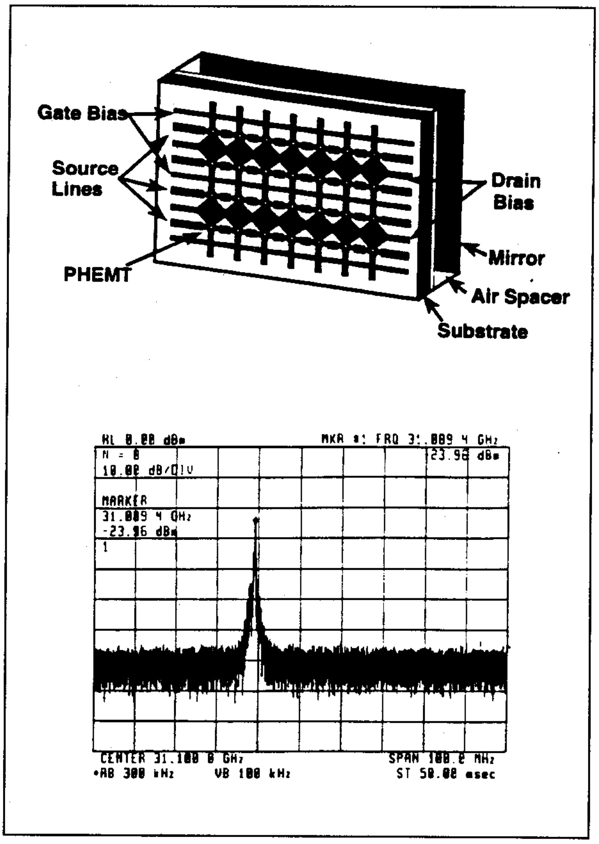

Fig.2. (a) A 10.25 GHz grid oscillator (designed with our full-wave analysis program) operates exactly at the design frequency and is used as a focal-point feed for a lens amplifier combiner. **(b)** Measured spectrum of a Ka-band grid oscillator fabricated by Honeywell (Minneapolis) and in collaboration with TLC prcission Wafer Technology, Inc., and decigned by the University of Colorado. The predicted oscillation frequency using small-signal measured transistor parameters and our full-wave analysis program, gave an oscillation frequency of 31.25 GHz (a 1% difference)

A three-dimensional grid oscillator has been demonstrated in [6]. It consists of a stack of grid oscillators, shown in Fig.3a, which all lock at the same frequency and in phase. The measured power from 1, 2 and 4 identical 25-element low-power PHEMT grids is shown in Fig.3b. The advantage of this approach is that the output power is distributed over several surfaces, which facilitates heat sinking and overcomes limitations on the power-handling capability of the individual device, as the power is distributed between several grids.

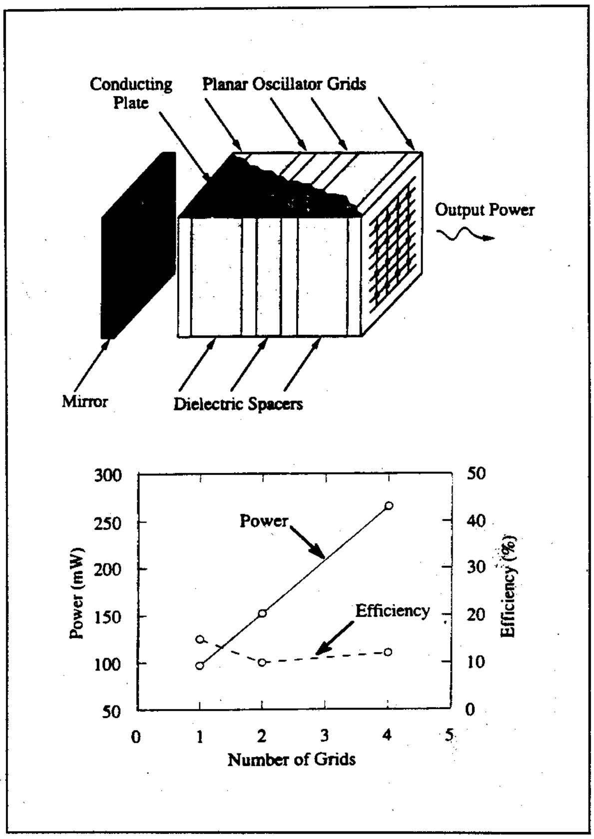

Fig. 3. (a) A 4-grid three-dimensional oscillator power combiner. **(b)** Measured power levels from 1, 2 and 4 grids at the same locked frequency of 5 GHz

High gain, low noise and power amplifiers are necessary parts of every transceiver. The first quasi-optical transmission wave amplifiers, e.g. [9] and [10] were fed from the far field, resulting in large diffraction loss and negative system power gain, even though the amplifiers themselves did exhibit real gain. This problem was overcome by either placing bulky lenses in the system, or building a lens into the array itself. A lens amplifier array using patch antennas is shown in Fig.4a. On the input side, shown in black, the variable delay lines from the receiving antennas to the gates of the transistors make it possible to feed the amplifier from a focal point in the near field, thereby reducing feed loss due to diffraction. This amplifier demonstrated 8 dB of absolute power gain with 20 dB isolation (on/off ratio) in a 3-% bandwidth at 9.7 GHz, Fig.4b. This scheme enables simple transmitter design with the added capability of beam-steering and beam-forming, discussed in the next section.

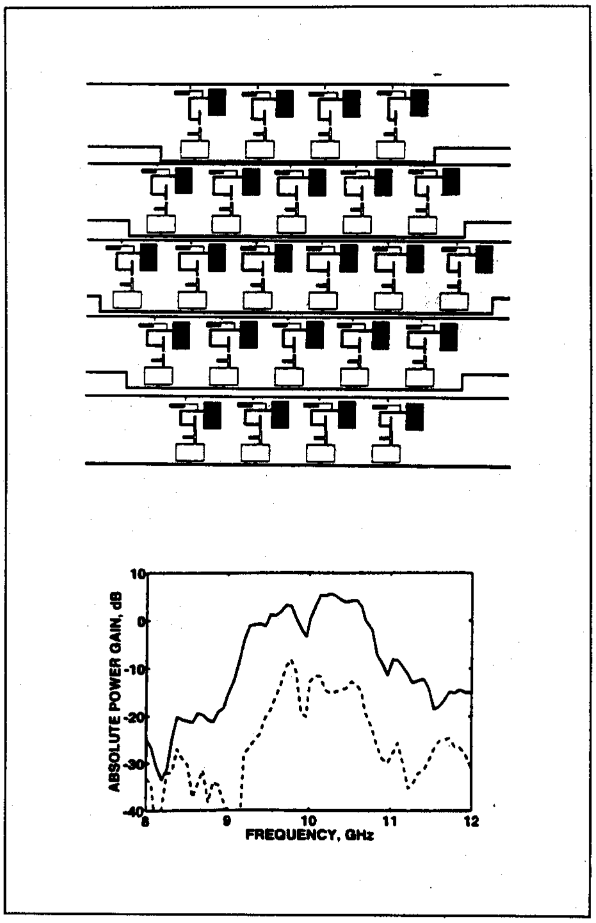

Fig. 4. (a) A quasi-optical planar lens amplifier and its measured absolute power gain **(b)**.

High-efficiency power amplifiers increase battery lifetime, and reduce overall size and weight due to lower heat-sinking requirements. By increasing the efficiency from 50% to 90%, the dissipated heat power is reduced by a factor of nine for the same output amplifier power. For two-dimensional amplifier antenna arrays, low heat dissipation is especially crucial, since the heat flow is lateral. a high-efficiency power amplifier array using antiresonant slot antennas, shown in Fig.5b, exhibits 10 dB gain, 2.5 W of power with 65% power added efficiency at 5 GHz from only 4 MESFETs.

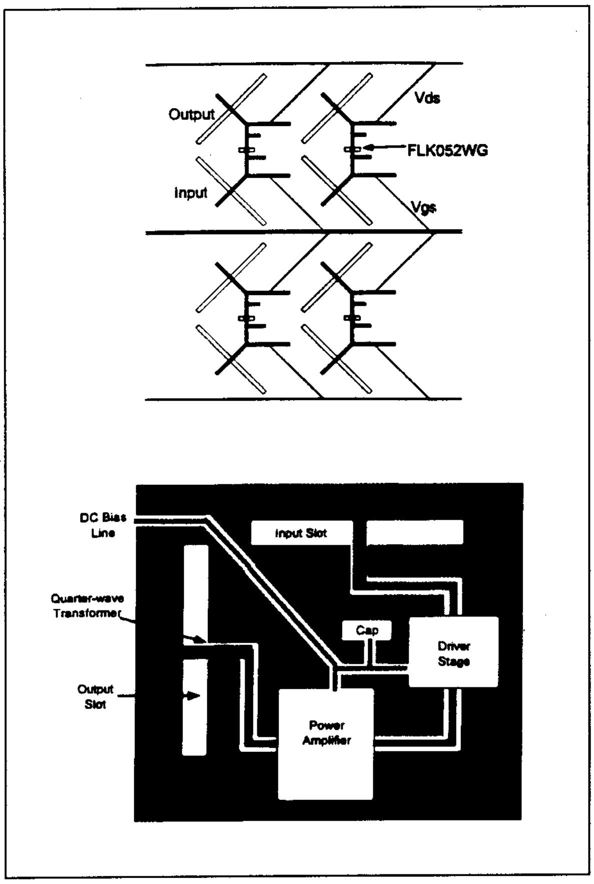

Fig. 5. **(a)** Layout of a plane-wave fed slot antenna power amplifier. **(b)** Layout of a unit cell of a Ka-band amplifier using MMIC chips.

This concept can be extended to millimeter-wave frequencies, as was demonstrated in [19] in a Ka-band amplifier, which produced 1 W at 29 GHz and a small-signal power gain of 6 dB. This was the first demonstration of a millimeter-wave quasi-optical amplifier with real power gain. The amplifier was designed by the group at the University of Colorado and fabricated and tested at the Lockheed/Martin facility in Orlando, Florida. The unit element of this array is sketched in Fig.5b. It uses anti-resonant slots and two-stage MMIC amplifiers mounted on the passive GaAs substrate.

Quasi-Optical Subsystems

More recently, a theory for analyzing cascaded systems of multi-function grids, including fixed-frequency and tuneable filters, and mode-selective grid oscillators was developed [20]. A voltage-controlled frequency-selective surface (FSS) was designed using the theory presented in [20].It consists of a printed grid loaded with varactor diodes, Fig.6a.

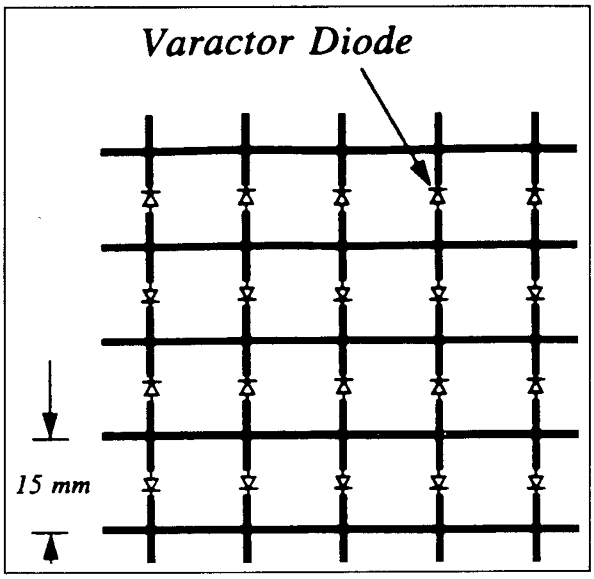

Fig. 6. **(a)** An electronically-variable FSS grid loaded with varactor diodes.

The resonance of this filter tunes in a 30% bandwidth when the bias across the diodes is changed, Fig.6b. This FSS was placed in front of a 25-PHEMT grid oscillator. the grid oscillator alone locks around 6 GHz. When the diodes are biased to provide a reflection coefficient of 85% at 4 GHz and only 42% at 6 GHz, the oscillator radiates the same amount of power as before, but at 4 GHz. the radiation patterns and cross-polarization levels for both frequencies are the same. The ability to selectively choose the carrier frequency for dual-frequency systems.

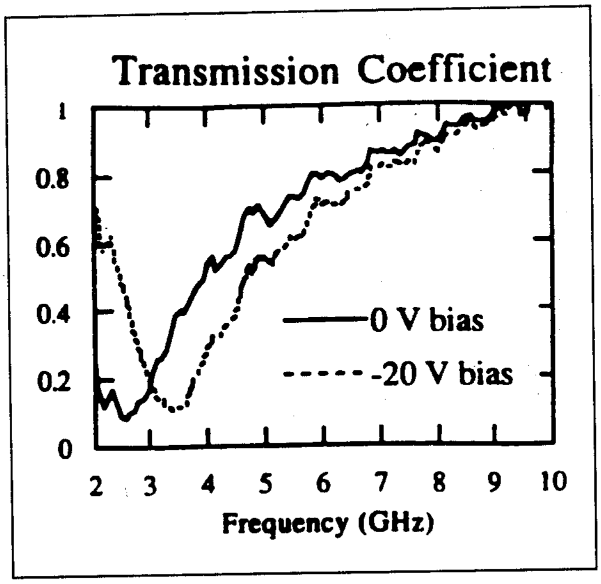

Fig. 6. (b) The measured electrical tuning of the resonance of the FSS shows a 30% bandwidth with very little change in resonance amplitude

Beam-steering and beam-forming have been demonstrated with quasi-optical lens amplifiers [12]. The lens amplifier from Fig.4a is fed by the grid oscillator from Fig.2a in a two-level power-combining subsystem. Beam-steering is obtained when the grid oscillator source is moved along a focal arc.

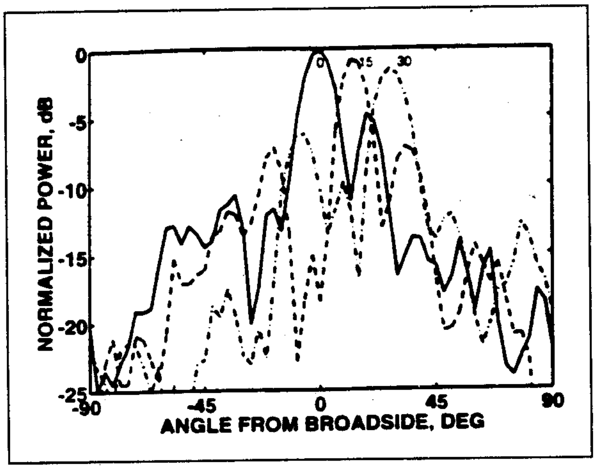

Fig. 7. (a) Beam-steering measured when a grid oscillator source is moved along a focal arc of the lens amplifier

Measured beam-steering patterns are shown in Fig.7a. ±40° of steering in both planes with less than 2 dB of power variation in the main beam were demonstrated.

The lens amplifier can also be fed by two identical grid oscillator sources positioned along a focal arc. When the two sources are turned on simultaneously, the fields are linearly superimposed at the amplifier output to produce a pattern with two distinct beams due to the two respective sources (Fig.7b). However, the two sources can also be switched on and off one at a time to produce a fixed number of discrete switchable beams for a steering system. We have measured a 5-kHz speed, limited by the settling time of the oscillator feeds.

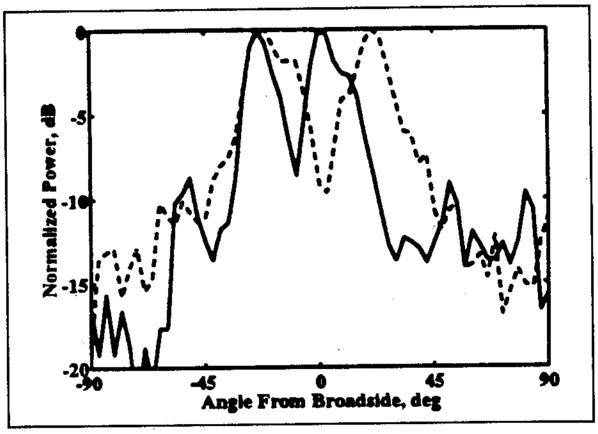

Fig. 7. (b) Beam forming patterns measured when two grid oscillator sources were positioned at different points on the local surface in the E (solid line) and H planes (dashed line)

Discussion

The measured properties of basic components which make up a quasi-optical transceiver is shown in Fig.8. It consists of a solid-state power-combining source that generates the carrier frequency for the transmitter and also serves as the local oscillator and self-oscillating mixer for the receiver. A planar array of transmit/receive (T/R) active antennas performs the power amplification for the transmit and the low-noise-amplification for the receive. Both the input and output waves are focused. Locating the source/mixer at the focal point of the amplifier reduces diffraction loss and thus increases system efficiency. The close proximity of the oscillator and amplifier also implies compact transceiver design. Reliability is improved since the degradation is graceful. This approach is modular, since individual grids or arrays, serving different functions can be cascaded into systems.

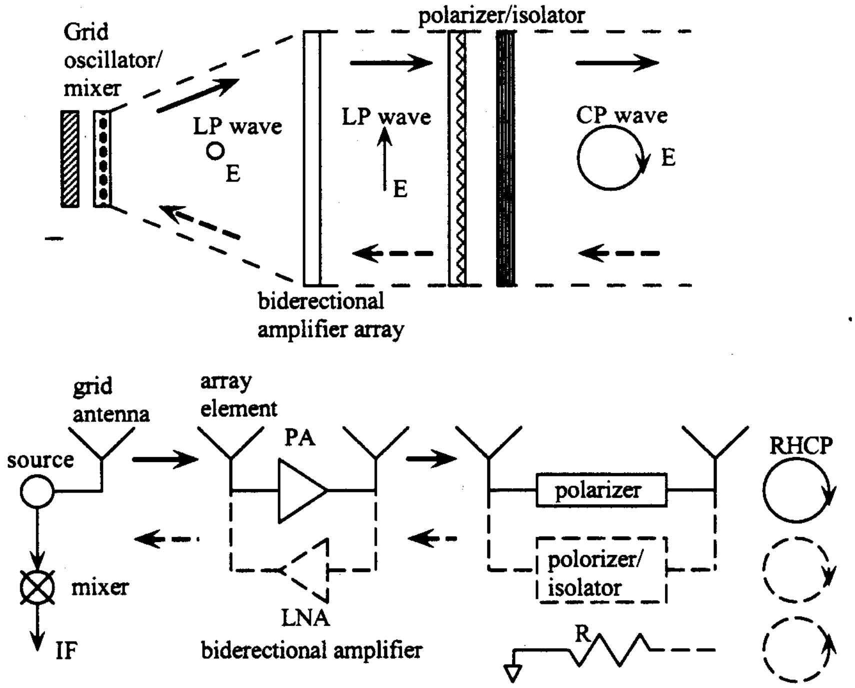

Fig. 8. Block diagram of a quasi-optical transceiver. The transmitted signal is shown in solid-line arrows and the receiving signal path in dashed-line.

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] R. A. York and R. C. Compton, "Quasi-optical power-combining using mutually synchronized oscillator arrays", *IEEE Trans. Microwave Theory Tech., vol. 39,* pp. 1000-1009, June 1991.

[3] J. Birkeland and T. Itoh, "A 16-element quasi-optical FET oscillator power-combining array with external injection locking", *IEEE Trans. Microwave Theory Tech., vol. 40,* pp. 475-481, Mar. 1992.

[4] T. B. Mader, S. C. Bundy, and Z. B. Popović, "Quasi-optical VCOs", *IEEE Trans. Microwave Theory Tech., vol. 41,* pp. 1775-1781, Oct. 1993.

[5] J. B. Hacker, *et al.*, "A 10-Watt X-band grid oscillator", *1994 IEEE MTT-S Int. Microwave Symp. Dig. (San Diego, CA),* pp. 823-826.

[6] W. A. Shiroma, B. L. Shaw, and Z. B. Popović, "A 100-transistor quadruple grid oscillator", *IEEE Microwave and Guided Wave Lett., vol. 4,* pp. 350-351, Oct. 1994.

[7] S. C. Bundy and Z. B. Popović, "A generalized analysis for grid oscillator design", *IEEE Trans. Microwave Theory Tech., vol. 42,* pp. 2486-2491, Dec. 1994.

[8] P. Liao and R. A. York, "A new phase-shiftless beam-scanning technique using arrays of coupled oscillators", *IEEE Trans. Microwave Theory Tech., vol. 41,* pp. 1810-1815, Oct. 1993.

[9] M. Kim, E. A. Sovero, J. B. Hacker, M. P. De Lisio, J.-C. Chiao, S.-J. Li, D. R. Gagnon, J. J. Rosenberg, and D. B. Rutledge, "A 100-element HBT grid amplifier", *IEEE Trans. Microwave Theory Tech., vol. 41,* pp. 1762-1771, Oct. 1993.

[10] T. Mader, J. Schoenberg, L. Harmon, and Z. B. Popović, "Planar MESFET transmission wave amplifier", *Electronics Lett., vol. 28,* no. 19, pp. 1699-1701, Sep. 1993.

[11] N. Sheth, T. Ivanov, A. Balasudramaniyan, A. Mortazawi, "A 9-HEMT spatial amplifier", *1994 IEEE MTT-S Int. Symp. Dig. (San Diego, CA),* pp. 1239-1242, May 1994.

[12] J. S. H. Schoenberg, S. C. Bundy, and Z. B. Popović, "Two-level power combining using a lens amplifier", *IEEE Trans. Microwave Theory Tech., vol. 42,* pp. 2480-2486, Dec. 1994.

[13] J. S. H. Schoenberg, T. Mader, B. Shaw, and Z. B. Popović, "Quasi-optical antenna array amplifiers", *1995 IEEE MTT-S Int. Symp. Dig. (Orlando, FL),* paper WE3B-6.

[14] J. B. Hacker, R. M. Weikle II, M. Kim, M. P. De Lisio, and D. B. Rutledge, "A 100-element planar Schottky diode grid mixer", *IEEE Trans. Microwave Theory Tech., vol. 40,* pp. 557-562, Mar. 1992.

[15] W. W. Lam, C. F. Jou, H. Z. Chen, K. S. Stolt, N. C. Luhmann Jr., and D. B. Rutledge, "Millimeter-wave diode-grid phase shifters", *IEEE Trans. Microwave Theory Tech., vol. 36,* pp. 902-907, May 1988.

[16] L. B. Sjorgen, H.-X. Liu, X. Qin, C. W. Domier, and N. C. Luhmann Jr., "Phased-array operation of a diode grid impedance surface", *IEEE Trans. Microwave Theory Tech., vol. 42,* pp. 565-572, Apr. 1994.

[17] C. G. Jou, W. W. Lam, H. Z. Chen, K. S. Stolt, N. C. Luhmann Jr., and D. B. Rutledge, "Millimeter-wave diode-grid frequency doubler", *IEEE Trans. Microwave Theory Tech., vol. 36,* pp. 1507-1514, Nov. 1988.

[18] K. D. Stephan and P. F. Goldsmith, "W-band quasioptical integrated PIN diode switch", *1992 IEEE MTT-S Int. Symp. Dig. (Albuquerque, NM),* pp. 591-594.

[19] J. Hubert, J. Schoenberg, and Z. B. Popović, "A Ka-band quasi-optical amplifier", *1995 IEEE MTT-S Int. Symp. Dig., WEB3, (Orlando, FL),* May 1995.

[20] J. Hubert, J. Shiroma, Z. Popović, "Analysis of Cascaded Quasi-Optical Grids", *1995 IEEE MTT-S Int. Symp. Dig., WEB3, (Orlando, FL),* May 1995.

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