20-GHz Power Combining Slot-Oscillator Array

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***Abstract*— A four-element power-combining array of quasi-optical slot oscillators has been constructed at 20 GHz. The array is placed on a dielectric substrate lens to increase the directivity and the effective isotropic radiated power (EIRP). The array delivers a total power output of 68 mW with an effective isotropic radiated power of 4.4 W. The DC to RF efficiency of the array is 12%. The substrate lens approach provides a planar design that eliminates substrate mode problems and, therefore, is easily scaled to millimeter-wave frequencies.**

I. Introduction

CPW-FED quasi-optical slot oscillators were first proposed by Kormanyos *et al.* [1], [2] as an alternative element for power-combining arrays. This area has seen significant advances in past years, and many groups are actively involved in the development of power-combining arrays using both strongly and weakly coupled approaches [3]–[6]. The CPW-fed slot oscillator results in a uniplanar circuit that is compatible with the integration of high-speed transistors. No via holes are required and air bridges are used for ground plane equalization. In this design, the oscillators are placed on a dielectric substrate lens for proper operation. The substrate lens simulates an infinite dielectric medium and eliminates power loss to substrate modes. It also results in a unidirectional pattern with more than 90% of the power radiated to the front side when high dielectric constant materials such as GaAs, silicon or alumina are used [7]. The substrate lens considerably increases the directivity of the radiation pattern from the oscillator array and an elliptical, hyperhemispherical or extended type may be used [8]. Thus, with this design it is possible to achieve a large EIRP with a small number of radiating elements, especially at millimeter-wave frequencies. The high-frequency capability of the CPW-fed slot oscillator has been proven with the construction of transistor oscillators at 155 and 215 GHz [9]. These represent the highest frequency oscillators in the world to use three-terminal devices.

II. Design

The oscillator element design follows the reflection amplifier approach presented in [10]. CPW transmission lines are placed on the gate and source terminals of the device and the slot antenna is connected to the drain through another length of CPW line. The antenna impedance is used as a parameter in the design, resulting in a reduction in circuit size and overall simplification. The antenna impedance on the dielectric lens is accurately calculated using the space domain integral equation technique [11], a full-wave method of moments approach. The individual oscillating elements are designed with consideration of the slot antenna self impedance only and mutual coupling in the array is ignored. The transistors used are commercially available microwave power devices (Fujitsu FLR016XV). The hybrid transistors are mounted in the CPW oscillator circuits. Electrical connection to the transistors and the air bridges for ground plane equalization are made with wire bonds. Small slits in the ground plane isolate the gate and drain terminals of the individual transistors in the array so that the DC bias may be applied. The slits in the ground plane are thin (30 μm) and capacitively overlaid to provide an uninterrupted ground plane for the RF circuit.

The array design follows the approach given for weakly coupled oscillators [6]. The elements are placed as close as possible to each other on an elliptical substrate lens with a movable metal reflector at the back side of the lens. The arrangement of the elements can be extended in two dimensions, thus increasing the total number of oscillators (Fig. 1). The movable reflector enables the phase of the mutual coupling between the elements to be adjusted creating a free parameter in the locking mechanism. The circuit is fabricated using 1.5 μm of evaporated gold on an alumina substrate with ϵ_r of 9.80. An elliptical alumina substrate lens with a diameter of 5.1 cm ($3.4\lambda_{\text{air}}$ at 20 GHz) is used for the array. No antireflection layer or matching cap is used with the lens.

III. Measurements

The DC bias condition for all of the devices in the array is the same ($V_{\text{gs}} = -1$ V, $V_{\text{ds}} = 6.6$ V, and $I_d = 22$ mA per element). With proper alignment of the elliptical substrate lens and reflector, the four oscillators lock to each other and demonstrate single frequency operation at 20.454 GHz. The oscillator array is centered at the back of the substrate lens and the reflector is placed 1.5 mm (about $0.1\lambda_{\text{air}}$) behind the active circuit. The array is linearly polarized due to the orientation of the slot antennas, but a cross-pol peak of −12 dB does appear due to the lens shape and radiation from the CPW lines. The measured co-pol radiation patterns for the array are shown in Fig. 2. An indication that the elements are operating in phase is given by the measured patterns for a single oscillator in the array (Fig. 3). In this case, the pattern peaks at an angle away from boresight due to the placement of the element away from the lens center. When all four elements

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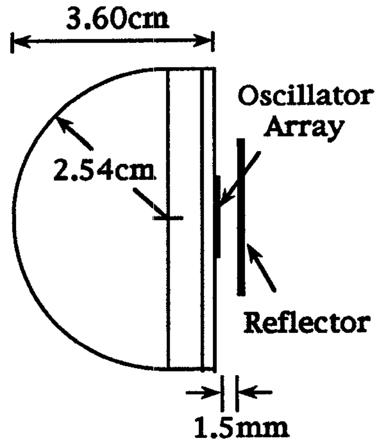
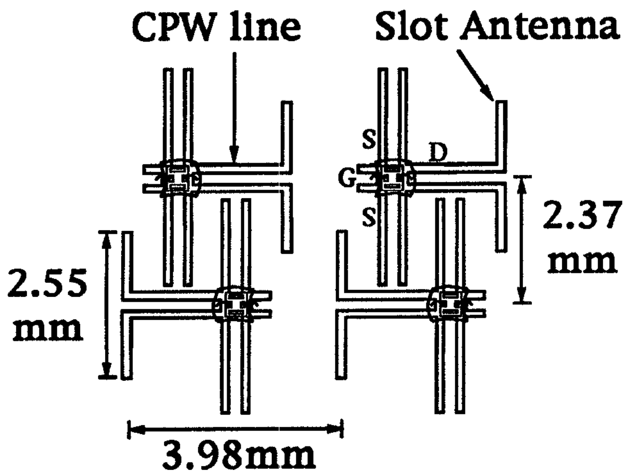


(a)



(b)

Fig. 1. (a) Elliptical substrate lens with adjustable back side reflector. (b) Extendable arrangement of oscillators in the four-element power-combining array.

are activated and locked together, the measured pattern peaks at boresight, indicating that there is no constant phase shift across the array.

The output power for the array is calculated from the absolute power received by a standard gain horn at the pattern peak, the Friis transmission equation, and the directivity. The directivity is calculated from measured patterns, and the value of the front-side directivity is reduced by the measured power radiated to the back side (6%) and lost to cross-polarized components (11%). The resulting front-side directivity for the array is 18.1 ± 0.2 dB. The total output power for the array is 68 ± 3.4 mW. The corresponding EIRP is 4.4 ± 0.2 W. The measured DC to RF efficiency is about 12%. The measured power for a single oscillator of this type is about 17 ± 1 mW [2], indicating that the power-combining efficiency of the array is near 100%. The theoretical maximum oscillator power for this device is estimated to be about 45–50 mW using the relationships given by Johnson [12]. The theoretical maximum DC to RF efficiency [13] is about 30%. This indicates that

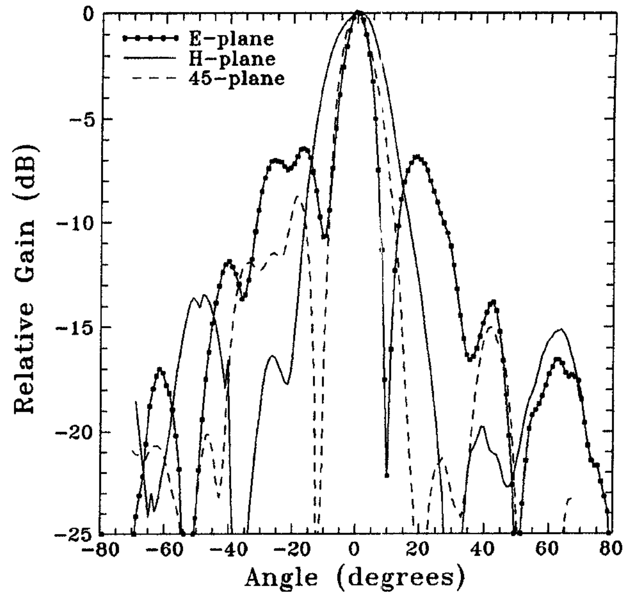


Fig. 2. Measured front-side co-pol patterns for the four-element power-combining array.

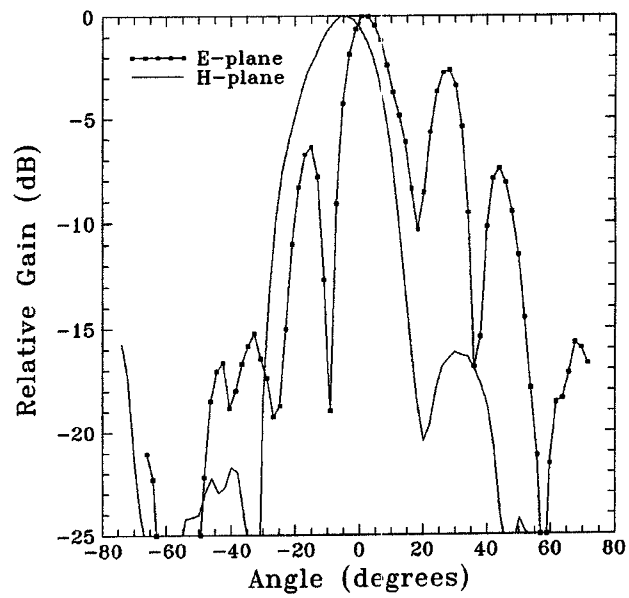


Fig. 3. Measured radiation patterns for a single element in the array.

it is possible to increase the output power and efficiency by adjusting the effective feedback in the circuit design.

The measured phase noise of the signal at 100 KHz from the carrier is about −77 dBc/Hz. The array can be injection locked by introducing a signal quasi-optically into the pattern main beam or by replacing the back-side reflector with the flange of an open-ended waveguide through which the locking signal can be introduced. With injection locking, the phase noise has been reduced to −85 dBc/Hz at 100 KHz from the carrier. The locking bandwidth for the array is 3.2 MHz with an injected power level of 0.028 mW, indicating that the external Q factor is about 130. The free-running spectrum and the spectrum under injection locking are shown in Fig. 4.

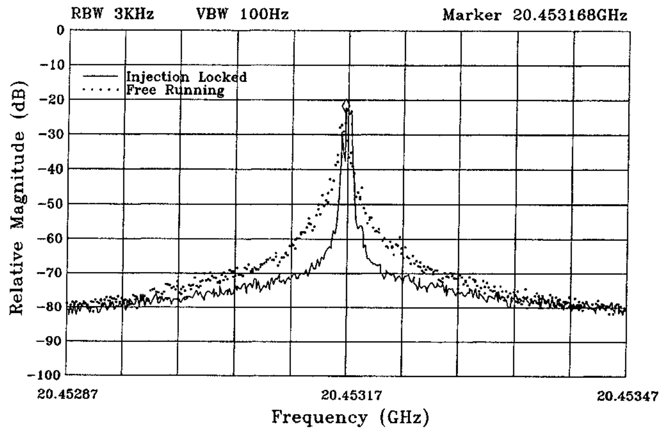


Fig. 4. Free-running spectrum and injection-locked spectrum for the four-element power-combining array.

The array can be operated on hyperhemispherical or extended lenses rather than the elliptical lens. When this is done, the rear reflector position must be adjusted and the frequency of operation generally shifts a bit. This indicates that there are weak multiple reflections within the lens that influence the mutual coupling between the elements.

IV. Conclusion

A four-element power-combining array at 20 GHz has been developed using slot oscillators backed by a substrate lens. The uniplanar CPW circuit design is suitable for medium-sized arrays operating at millimeter-wave frequencies.

References

[1] B. K. Kormanyos and G. M. Rebeiz, "Quasi-optical CPW-fed slot-antenna oscillators," in *Proc. Third Int. Conf. on Space Terahertz Technology*, Mar. 24–26, 1992, Ann Arbor, Michigan, pp. 32–36.

[2] B. K. Kormanyos, W. Harokopus, Jr., L. P. B. Katehi, and G. M. Rebeiz, "CPW-Fed active slot-antennas," *IEEE Trans. Microwave Theory, Tech.* vol. MTT-42, pp. 541–545,, Apr. 1994.

[3] *IEEE Trans. Microwave Theory Tech., Special Issue on Quasi-Optical Techniques*, vol. 41, no. 10, pp. 1762–1856, Oct. 1993.

[4] A. Mortazowi and B. C. De loach, Jr., "Multiple element oscillators utilizing a new power combining technique," *IEEE Trans. Microwave Theory, Tech.*, vol. 40, no. 12, pp. 2397–2402, Dec. 1992.

[5] H. P. Moyer and R. A. York, "Active cavity backed slot antenna using MESFET's," *IEEE Microwave and Guided Wave Lett.*, vol. 3, no. 4, Apr. 1993.

[6] R. A. York and R. C. Compton, "Quasi-Optical Power Combining Using Mutually Synchronized Oscillator Arrays," *IEEE Trans. Microwave Theory, Tech.*, vol. 39, no. 6, pp. 1000–1009, June 1991.

[7] G. M. Rebeiz, "Millimeter-wave and terahertz integrated circuit antennas," *Proc. IEEE*, vol. 80, no. 11, pp. 1748–1770, Nov. 1992.

[8] D. F. Filipovic, S. S. Gearhart, and G. M. Rebeiz, "Double-slot antennas on extended hemispherical and elliptical silicon dielectric lenses," *IEEE Trans. Microwave Theory, Tech.*, vol. 41, no. 10, pp. 1738–1749, Oct. 1993.

[9] B. K. Kormanyos, S. E. Rosenbaum, L. P. B. Katehi, and G. M. Rebeiz, "Monolithic 155 GHz and 215 GHz Quasi-optical slot oscillators," *IEEE MTT-S Int. Microwave Symp.*, May 23–27, 1994, San Diego, CA, pp. 835–838.

[10] G. R. Basawapatna and R. B. Stancliff, "A unified approach to the design of wide-band microwave solid-state oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, no. 5, May 1979.

[11] N. I. Dib and P. B. Katehi, "Modeling of shielded CPW discontinuities using the space domain integral equation method (SDIE)," *J. Electromagnetic Waves and Appl.*, vol. 5, no. 4/5, pp. 503–523, 1991.

[12] K. M. Johnson, "Large Signal GaAs MESFET Oscillator Design," *IEEE Trans. Microwave Theory, Tech.*, vol. MTT-27, no. 3, pp. 217–227, Mar. 1979.

[13] D. H. Evans, "High-efficiency Ka- and Ku-band MESFET Oscillators," *Electronics Lett.*, vol. 21, no. 6, pp. 254–255, 1985.