A 60-GHz IMPATT Oscillator Array with Pulsed Operation

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Abstract— **This paper describes the design and operation of a 60-GHz quasi-optical power combining array employing IMPATT diodes in a weakly coupled, hybrid, two by four arrangement. Frequency-locked operation of all eight elements has been achieved for CW operation with a total radiated power in excess of 2 W. Approximately 61 W of DC power was required to drive the array. Pulsed operation was investigated as a means of preventing overheating. In particular, the locking behavior of these pulsed arrays was characterized. The array was pulsed with a 2-μs rise time, low duty cycle, 4-kHz bias. Under these conditions, single frequency operation was observed throughout the duration of the pulse, including the turn-on period.**

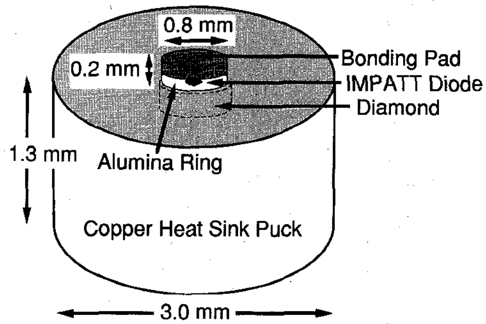

Fig. 1. Detail of diode mounting and package.

I. Introduction

IN RECENT years the problem of generating practical millimeter-wave powers from solid state devices has been addressed with planar arrays of oscillators coupled together by various means to produce frequency locking and hence spatial power combining. Coupling between elements in the array has been achieved by methods such as placing the arrays in Fabry–Perot cavities, using conducting grids which serve as both bias leads and radiating elements, relying on inter-element coupling resulting from close proximity, and using FET oscillators which have injection ports for external locking [1]–[15]. Much of this experimental work has been performed with scale models below 20 GHz. A review article [16] summarizes numerous results, ranging from a 100-GHz Gunn diode array [13] to a 9 GHz, 16-element, 2.0 W grid array [15]. In this paper, results from a 60 GHz high power hybrid array are presented. IMPATT diodes were chosen for their high output capabilities (1 W per device in a tuned waveguide system). The array may be used as a source to illuminate a multiplier grid such as that described in reference [17]. High power 60 GHz systems are also of interest for secure satellite to satellite communications because of the absorption peak in the atmosphere at this frequency.

Spatial power combining is a method well suited to monolithic implementation at millimeter wave frequencies. However, adequate heat sinking is crucial to achieving useful output powers. As the frequency increases, array elements become more closely spaced and heat dissipation becomes more difficult. Monolithic construction can be exploited to overcome this problem to some extent. By using large numbers of devices over a larger area with a lower power output per device, the array directivity can be improved, decreasing the total power required while distributing the power dissipation. An additional way to reduce thermal problems is to pulse the array. Pulsed operation is also required in radar systems. The time required to achieve frequency locking in arrays of weakly coupled oscillators is examined experimentally in the latter portion of this paper.

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II. Single Element Design and Performance

The array was built by first constructing and optimizing the performance of a single element. A collection of these elements were then placed with prescribed separations [6] so that mutual coupling causes the elements to lock in phase at a single frequency. If the coupling is weak, the individual oscillators are only slightly perturbed from their individual state [1], [9]. The devices used were GaAs IMPATT diodes, type IDV-100 fabricated by the Raytheon Company. The diodes have demonstrated DC-to-RF conversion efficiencies of 13% at 60 GHz when mounted in optimized waveguide based circuits. The diodes are mounted in a package designed for heat dissipation, the details of which are shown in Fig. 1.

Bias current to each diode was controlled independently. Op-amp regulated current sources were used to prevent low frequency oscillations. The high bias conditions of 0.5 A at 20 V necessitate good heat sinking. Although the individual diodes can be comfortably biased at 0.5 A, the bias level used for the array was 0.425 A to avoid overheating. Bias was supplied through a 0.002″ gold ribbon bonded to the package. Preliminary designs achieved isolation with a quarter wave bias line connected to a microstrip short circuit. However the performance was not changed significantly by using only a long ribbon to achieve bias isolation; this approach was used in the final construction.

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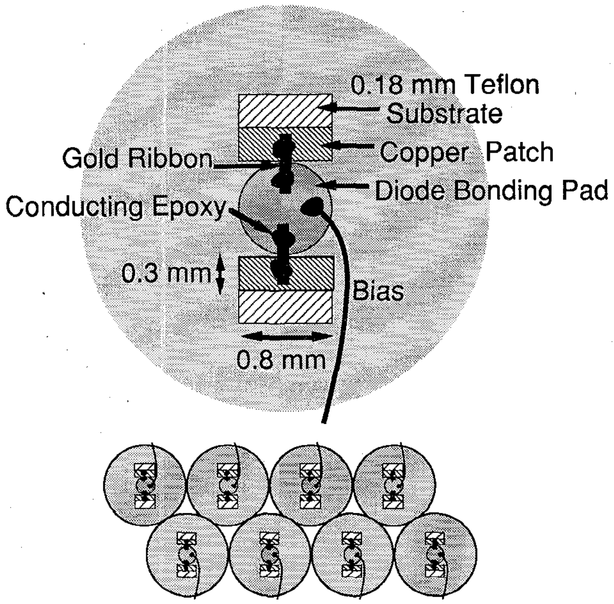

Fig. 2. Detail of single 60-GHz antenna and array configuration. The substrate is larger than the copper patch to provide greater structural support. Note that the diode bonding pad is a significant fraction of the radiating structure.

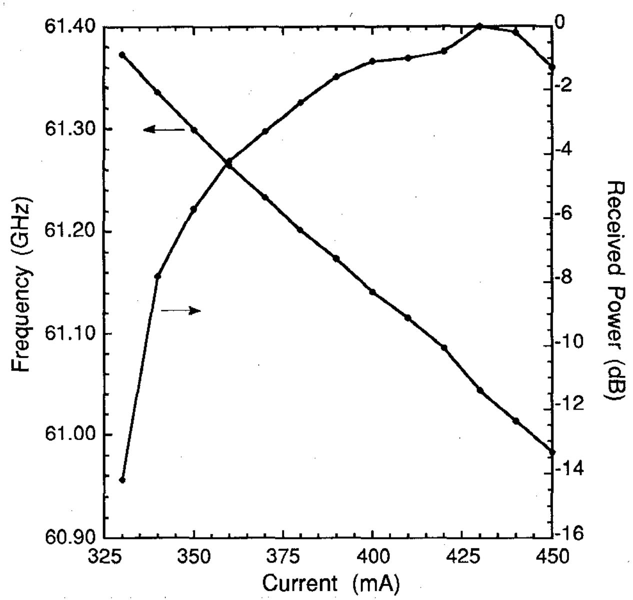

Fig. 3. Tuning characteristics for one of the eight array elements showing a 400 MHz tuning range. Other elements had tuning ranges between 200 and 600 MHz.

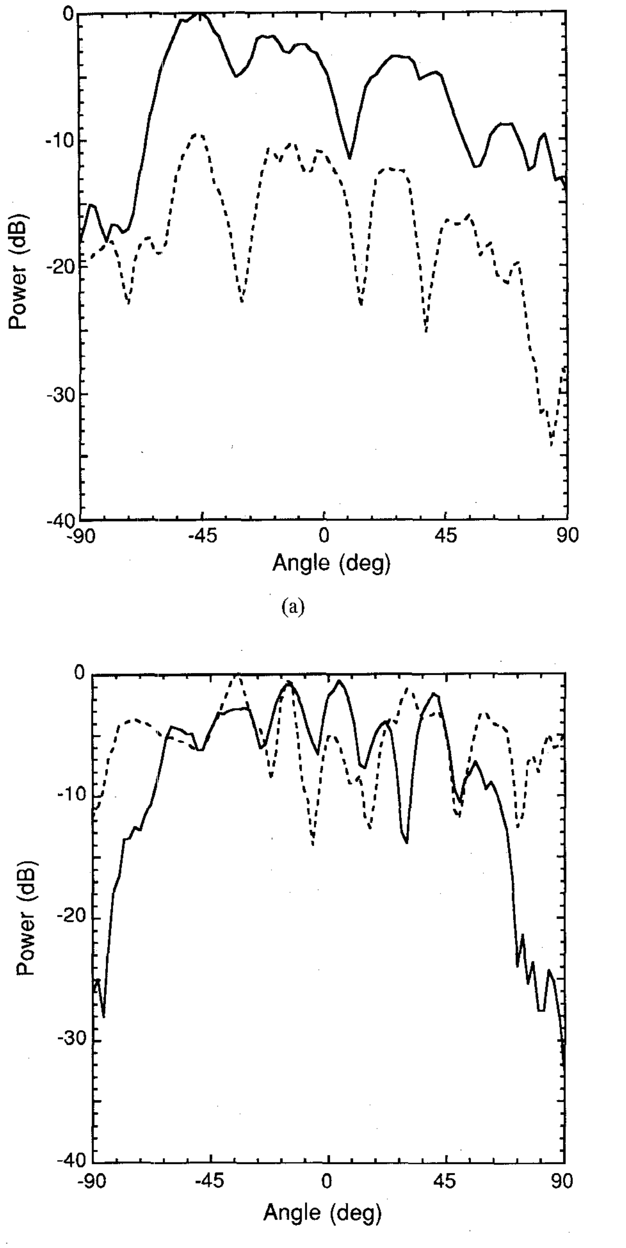

Fig. 4. Example single element (a) E-plane and (b) H-plane antenna patterns. Solid line is co-polarization, dotted is cross-polarization. Among the eight elements some variation existed in antenna patterns due to imprecise hybrid construction.

In initial designs the diode fed a microstrip patch antenna via a 50-Ω microstrip transmission line. This approach produced oscillations at 67 GHz. Despite attempts at tuning to 60 GHz by decreasing the patch size, the frequency remained relatively invariant, changing only by hundreds of MHz. The 67 GHz oscillation persisted after the removal of all circuitry except the bias line. Various bias circuits were tried with little effect, leading to the conclusion that the resonance was associated with the package. Control over the oscillation frequency was finally achieved by tuning the package resonance. Microstrip patches were connected directly to the bonding pad of the diode as seen in Fig. 2. In this manner the patches and package together become the resonant structure. Frequency tuning was accomplished by altering the length of the copper patch; no attempt was made to simultaneously optimize the output power.

Fig. 3 shows a tuning curve and the associated power for a single element. For this diode there is a 400 MHz tuning range. The tuning ranges for other diodes varied from 200 MHz to 600 MHz.

Examples of typical single element antenna patterns are seen in Fig. 4. These provide a general picture of the performance of the individual radiators; the individual patterns of the eight antennas varied somewhat due to the difficulties of hybrid

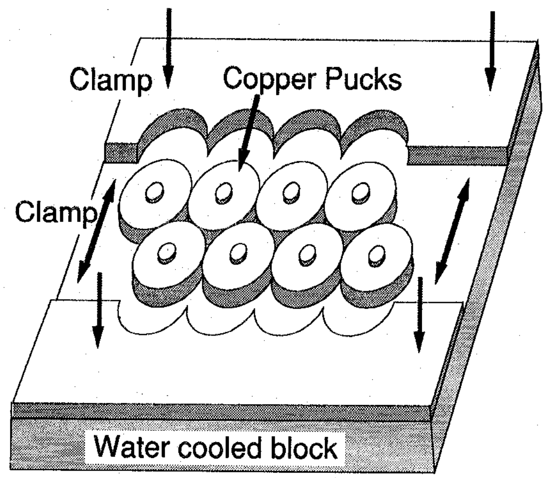

Fig. 5. Construction of IMPATT array for heat dissipation. The pucks were first clamped into position between the two "jaws", and the resulting assembly then bolted to the water cooled block. A low temperature solder was used between the pucks and the water cooled block to ensure good thermal contact. Antenna and bias components were then added.

circuit construction at 60 GHz (copper patch size $\approx$ 0.3 mm). One explanation for the strong cross-polarization lies in the geometry of the top surface formed by the diode bonding pad and the two copper patches, with connections made by the relatively narrow ribbons. Since currents may not travel purely longitudinally as on a conventional microstrip patch, this might enhance the cross-polarization component. To investigate this, an element was constructed with three ribbons (instead of one) distributed across the width of the patches. This did not reduce the cross-polarization. To verify that the bias ribbon was not influencing the polarization, patches were rotated 90 degrees relative to the bias ribbon. Again polarization was not improved. By a process of elimination, orthogonal package resonance appears to be the main contributor to the cross-polarization component.

III. Array Operation and Performance

Heat dissipation was a major issue in the array design. Toward this end, the diodes were positioned as shown in Fig. 5 so that heat could flow through both the sides and bases of the copper pucks. Frequency-locked operation of all eight elements was accomplished by individually tuning each of the eight oscillators as described above, until all of their free-running frequencies were within a few hundred MHz of one another at 0.425 A. It was empirically determined that if all of the frequencies lay within roughly a 400 MHz window then the array would frequency lock.

The antenna patterns for locked operation are seen in Fig. 6. The peaked nature of the H-plane pattern demonstrates a uniform coupling phase between elements as desired [6]. The position of the peak is slightly off center indicating that the value of the coupling phase is not an integral wavelength as would be preferred. The E-plane is less peaked, as expected, since the array is only two elements wide in this direction. The total radiated power (TRP) and effective isotropic radiated power (EIRP), calculated as in [1], were 1.4 W and 17 W, respectively, for the co-polarization and 0.8 W and 23 W for the cross-polarization. The TRP values were determined by linearly interpolating between measured data points and integrating over the solid angle (2π steradians) above the array. Specifically, the azimuthal dependence was assumed linear between the measurements made in the E- and H-planes. Thus, the TRP values obtained are approximate. The EIRP values were calculated from the maximum measured powers. With each diode operating at 0.425 A the total power consumed was 61 W, leading to a DC to RF efficiency of 3.6%, roughly 4 times less than waveguide based systems. The sum of the TRP's for the individual free-running oscillators equals 2 W indicating efficient power combining. It is believed the efficiency is low because the oscillators were

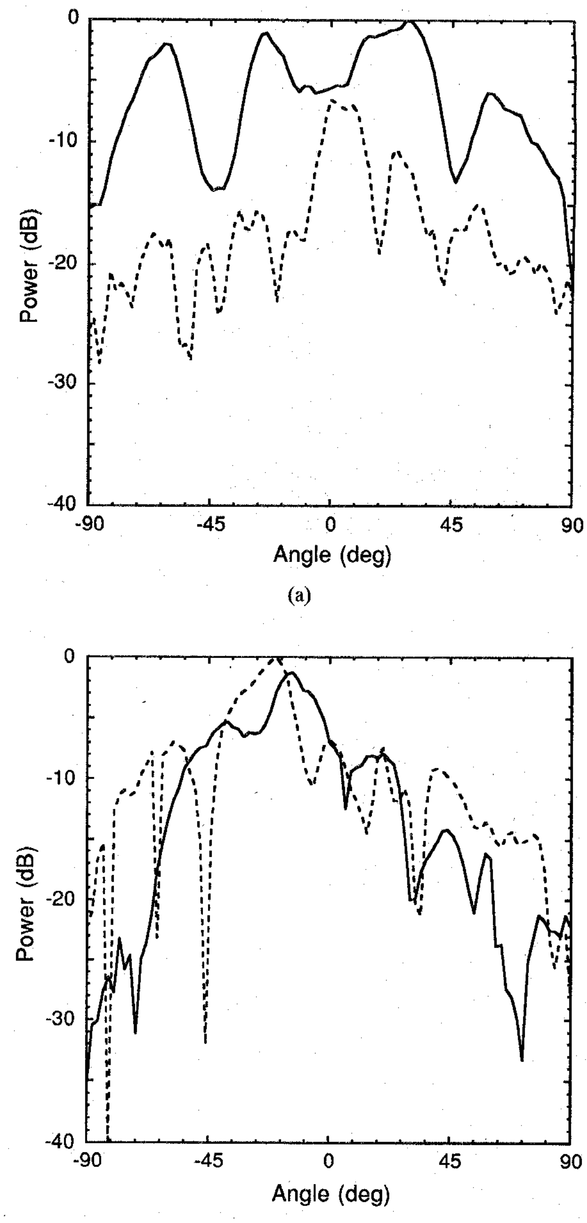

Fig. 6. Normalized array (a) E-plane and (b) H-plane antenna patterns. Solid line is co-polarization, dotted is cross-polarization. It is suspected that the lack of linear polarization in the H-plane is caused by the diode packages.

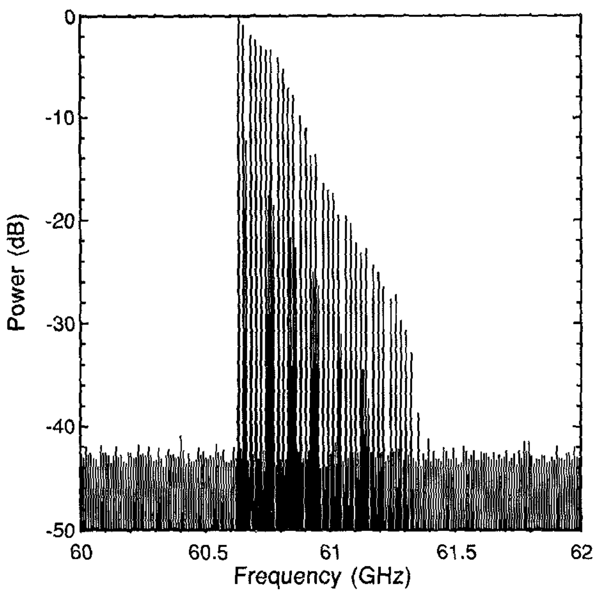

Fig. 7. Spectrum of a pulsed four-element array measured non-synchronously using min/max acquisition mode. The broad spectrum is due primarily to the turn-on and turn-off of the supply.

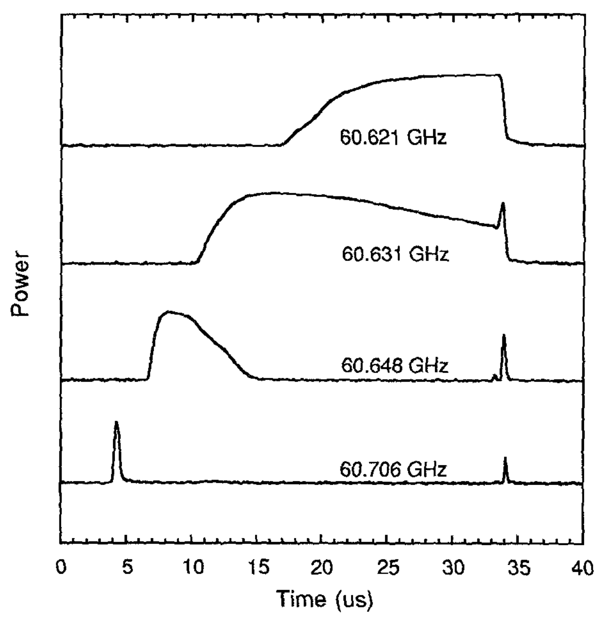

Fig. 8. Power in a 10 MHz bandwidth versus time for four locked oscillators. The frequency of the top trace corresponds to the left edge of the spectrum in Fig. 7.

tuned for frequency and not power. Simultaneously tuning the frequency and power output is difficult because the real and imaginary load impedances are not independent variables of the patch dimensions. Determining the optimal design to achieve the desired frequency and maximum output power at these high frequencies would be best suited to monolithic fabrication techniques since many design variations could be simultaneously constructed for evaluation. Monolithic designs may also reduce the high cross-polarized component due to the package.

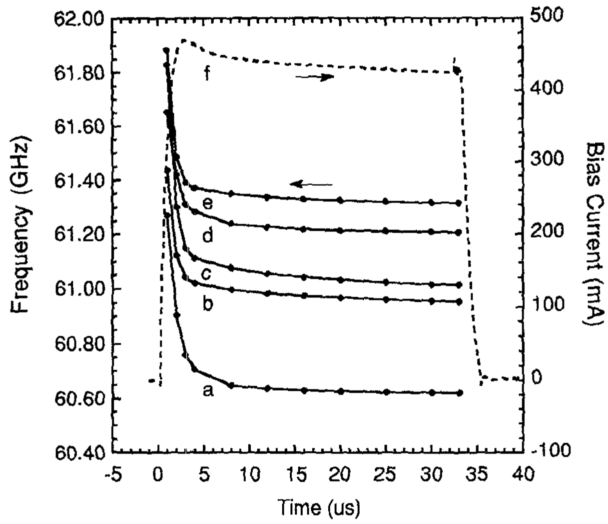

Fig. 9. Frequency vs time during the pulse for four locked oscillators (a) and for each of the free-running oscillators (b)–(e). Also shown is the current for one of the diodes (f). The frequency versus time curves were constructed from the locations of peaks in curves such as those in Fig. 8.

IV. Pulsed Operation

To study the behavior of pulsed weakly coupled oscillator arrays, a two-by-two grouping from the eight element array was operated with a 34-μs wide pulse at a 4-kHz repetition rate and a 2-μs risetime. The pulsing was achieved by biasing each diode with an independent voltage supply and placing a single transistor in the common return groundpath. The transistor was switched with a square wave supplied by a function generator. As the diodes are cycled their temperatures fluctuate. Hence the resulting pulse will be slightly "chirped"—the frequency will have a slight time dependence. Based on tuning curves such as in Fig. 3 one also expects a time dependence of the frequency as the current ramps up.

To determine the time required for frequency locking to take place one needs the spectrum as a function of time. This is not easily accomplished due to the finite sweep times of spectrum analyzers. But since only a small number of frequencies are present at any given time, these can be tracked versus time as described below

A Tektronix 2782 spectrum analyzer was used in min/max mode to look at the output spectrum (Fig. 7). This spectrum shows the range of frequencies occurring during the pulse, including the turn-on and turn-off periods. Next, the spectrum analyzer was set to zero span (at a frequency within the spectrum of Fig. 7) with a 10 MHz resolution bandwidth, and the vertical real-time output was displayed on a Tektronix CSA803 digitizing oscilloscope. The oscilloscope was synchronized to the diode pulse, thus displaying the power within a 10 MHz bandwidth versus time. Variation of the spectrum analyzer measurement frequency resulted in a collection of traces such as those seen in Fig. 8, from which a new plot was made of frequency versus time. This is shown in trace (a) of Fig. 9 for the four locked oscillators. Also shown are similar plots for each of the free-running oscillators, as well as the shape of the current pulse through one of the diodes. Note that trace (a) in Fig. 9 is single valued for all

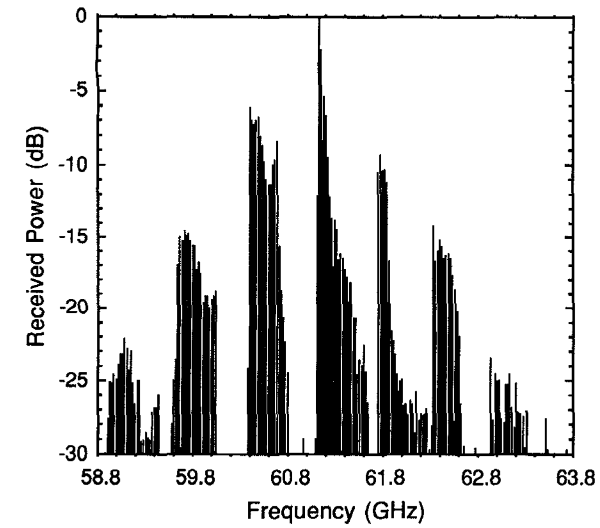

Fig. 10. Spectrum for two unlocked diodes in pulse mode.

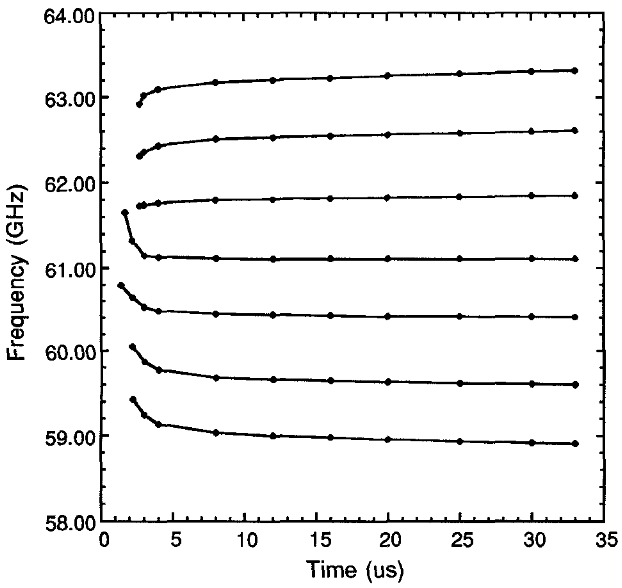

Fig. 11. Frequency versus time for a pair of unlocked oscillators. All frequencies occur simultaneously.

time, showing that the diodes are locked even during the turn-on period. They have been turned on slowly enough such that the locking mechanism has kept pace with the change in bias. Thus we may conclude that the locking-time for the diodes is less than 2 μs. To study shorter risetimes, a more sophisticated pulsed power supply is required. In contrast to the locked case, similar measurements were made for a pair of diodes which were not frequency-locked. The resulting spectrum is shown in Figs. 10 and 11.

V. Conclusions

Successful proof-of-concept of operation of a 60 GHz, eight element power combining hybrid array has been achieved using IMPATT diode oscillators. Total power output of 2.2 W and EIRP's of 17 W and 23 W in the co- and cross-polarizations were achieved. Monolithic fabrication of such arrays would greatly enhance both the design task and the final performance. An upper bound of 2 μs was measured for the time to achieve frequency locking, demonstrating the viability of power combining arrays for use with pulsed systems operating in the low kilohertz range.

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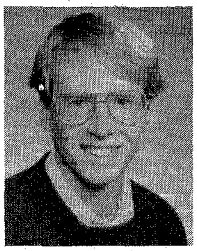
References

[1] R. A. York, "Millimeter-wave power combining with radiating oscillator arrays," Ph.D. dissertation, Cornell University, 1991.
[2] J. Birkeland and T. Itoh, "Two port FET oscillators with applications to active arrays," *IEEE Microwave Guided Wave Lett.,* vol. 1, pp. 112–113, May, 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, Mar. 1992.
[4] Z. B. Popovic, R. M. Weikle, M. Kim, K. A. Potter, and D. B. Rutledge, "Bar grid oscillators," *IEEE Trans. Microwave Theory Tech.,* vol. 38, pp. 225–230, Mar. 1990.
[5] Z. B. Popovic, R. M. Weikle, M. Kim, and D. B. Rutledge, "A 100-MESFET Planar grid oscillator," *IEEE Trans. Microwave Theory Tech.,* vol. 39, pp. 193–200, Feb. 1991.
[6] 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.
[7] D. B. Rutledge, Z. B. Popovic, R. M. Weikle, M. Kim, K. A. Potter, R. A. York, and R. C. Compton, "Quasi-optical power combining arrays," in *1990 IEEE MTT-S Int. Microwave Symp. Dig.,* Dallas, May 1990.
[8] K. Chang and C. Sun, "Millimeter-wave power-combining techniques," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-31, pp. 91–107, Feb. 1983.
[9] K. Chang, K. A. Hummer, and J. L. Klein, "Experiments on injection-locking of active antenna elements for active phased arrays and spatial power combiners," *IEEE Trans. Microwave Theory Tech.,* vol. 37, pp. 1078–1084, July 1989.
[10] K. D. Stephan, "Inter-injection-locked oscillators for power combining and phased arrays," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-34, pp. 1017–1025, Oct. 1986.
[11] K. D. Stephan and S. L. Young, "Mode stability of radiation-coupled interinjection-locked oscillators for integrated phased arrays," *IEEE Trans. Microwave Theory Tech.,* vol. 36, pp. 921–924, May 1988.
[12] S. L. Young and K. D. Stephan, "Radiation coupling of inter-injection-locked oscillators," *Millimeter Wave Technology IV and Radio Frequency Power Sources, Proc. SPIE 791,* pp. 69–76, 1987.
[13] C. Xue, Q. Wang, H. Li, and F. Wu, "Optimized design of quasi-optical source-array of solid state source power combiner at frequency of 100 GHz," *Int. J. Infrared and Millimeter Waves,* vol. 11, pp. 1269–1283, Nov. 1990.
[14] N. Nakayama, M. Hieda, T. Tanaka, H. Kondo, K. Osakabe and K. Mizuno, "Millimeter and submillimeter quasi-optical oscillator with multi-elements," *Proc. of the Second Int. Symp. on Space Terahertz Technology,* Feb. 1991, pp. 187–190.
[15] D. Rutledge, J. B. Hacker, M. Kim, R. M. Weikle, R. P. Smith, and E. Sovero, "Oscillator and amplifier grids," *IEEE MTT-S Int. Microwave Symp. Dig.,* pp. 815–818, 1992.
[16] J. C. Wiltse and J. W. Mink, "Quasi-optical power combining of solid state sources," *Microwave J.,* pp. 144–156, Feb. 1992.
[17] H. Liu, X. Qin, L. Sjogren, E. Chung, C. Domier and N. Luhmann, "Monolithic high power millimeter wave quasi-optical frequency multiplier arrays using quantum barrier devices," *IEEE Device Research Conf. Dig.,* paper VB-2, June 1992.



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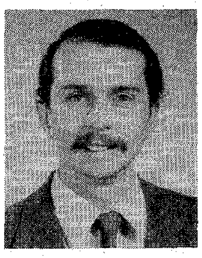

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