Demonstration of an Oscillating Quasi-Optical Slab Power Combiner

F. Poegel†, S. Irrgang†, S. Zeisberg†, A. Schuenemann†, G. P. Monahan†,
H. Hwang†, M. B. Steer†, J. W. Mink†, F. K. Schwering‡, A. Paollela□ and J. Harvey◇

†Electronics Research Laboratory, Department of Electrical and Computer Engineering,
North Carolina State University, Raleigh, North Carolina 27695.

‡CECOM, AMSEO-RD-C3-ST, Ft. Monmouth, NJ 07703.

□Microwave & Lightwave Components Division, AMSRL-EP-MA, US Army Research Laboratory, NJ 07703

◇United States Army Research Office, PO Box 12211, Research Triangle Park, NC 27709

Abstract. Power combining in a hybrid dielectric slab beam waveguide resonator using a MESFET oscillator array is reported for the first time. Four MESFET oscillators lock via quasi-optical modes to produce a signal at 7.4 GHz with a 3 dB linewidth of less than 3 kHz.

1. Introduction

The hybrid dielectric slab beam waveguide system [2, 3] combines the wave-guiding principles of a dielectric surface wave and a confined beam corresponding to Gauss-Hermite beam modes. This two dimensional structure has reduced size and is more amenable to photolithographic reproduction than more conventional open quasi-optical power combining structures (see [4]). In this paper the slab resonator characterized in [3] is used to combine the power of multiple MESFET oscillators.

2. Quasi-optical Slab Power Combiner

The slab resonator power combiner is shown in Figure 1. The resonator consists of a curved and a planar reflector. Energy propagates in a quasi-optical mode in a direction perpendicular to the planar reflector which is at the waist of the resonant modes. The curved reflector is circular approximating the parabolic phase-front of the modes. In this way energy radiating from one oscillator is coupled into a quasi-optical mode, which is reflected by the curved reflector and illuminates all of the other oscillators — thus one-to-many coupling is achieved. The distance between the planar reflector and the center of the curved reflector is 30.48 cm, the radius of the curved reflector is 60.96 cm, and the thickness and width of the dielectric slab are 1.27 cm and 38.10 cm respectively. The dielectric is Rexolite ($\epsilon_r = 2.57$, $\tan\delta = 0.0006$ at X-band). The dimensions of the cavity were chosen for X band operation to facilitate the capture of second and third harmonics in the spectrum of the oscillator signal. The cavity and its characteristics are identical to those reported in [3].

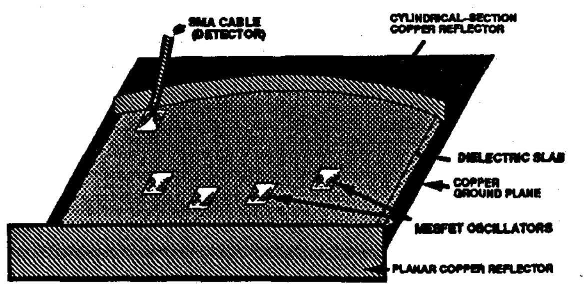

Figure 1: Planar Quasi-optical slab power combining oscillator.

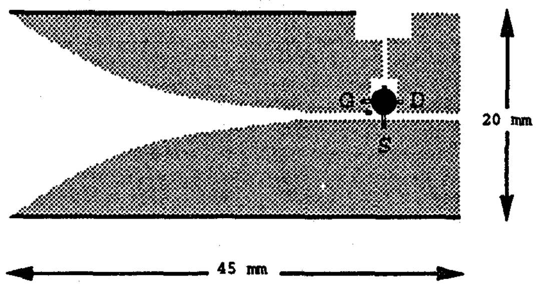

Figure 2: Single oscillator unit constructed on a Rogers RT/Duroid substrate with $\epsilon_r = 2.33$ at 10 GHz.

An oscillator unit is shown in Figure 2. and uses a Hewlett Packard ATF-10235 MESFET. The essential element of the oscillator is the end-fire Vivaldi antenna taper [5, 6] which provides excellent decoupling of forward and backward traveling waves.

In this paper the design of the oscillating elements was optimized so that oscillation in free space did not occur. This involved optimizing the taper and the drain-gate feedback. Furthermore, this oscillator design was not susceptible to surface-of-slab to ground-plane resonance. This was a common problem with earlier antenna designs since the thickness of the slab is close

WE
4B

to a half wavelength. Cavity signals were sensed by a Vivaldi antenna on the periphery of the cavity where the fields are expected to be small. Locking via direct nearest neighbor coupling is avoided by staggering the individual oscillators.

3. Operation

The oscillator spectrum is shown in Figure 3. Locking is achieved via a TE_{00q} HDSBW (hybrid dielectric slab beam waveguide) mode. All possible oscillation modes were found by mounting a single oscillator cell on top of the slab and moving it over the entire surface of the slab and flexing the RT/Duroid substrate. The resultant spectrum with the spectrum analyzer set to maximum hold is shown in Figure 4. Comparing the oscillation frequencies to the unloaded resonator cavity measurements [3], it was determined that the oscillating elements only coupled into the TE hybrid dielectrc slab beam waveguide (HDSBW) modes. TE_{mnq} modes have an electric field parallel to the ground plane and transverse to the cavity axis. The m index refers to field variations through the slab and the n index to variations across the slab. The q is often dropped but refers to the number of standing wave patterns along the axis of the resonator. Oscillation via TE_{00q} mode resonances is preferred as these modes have the lowest loss because the energy is mostly inside the dielectric and is localized along the axis of the resonator.

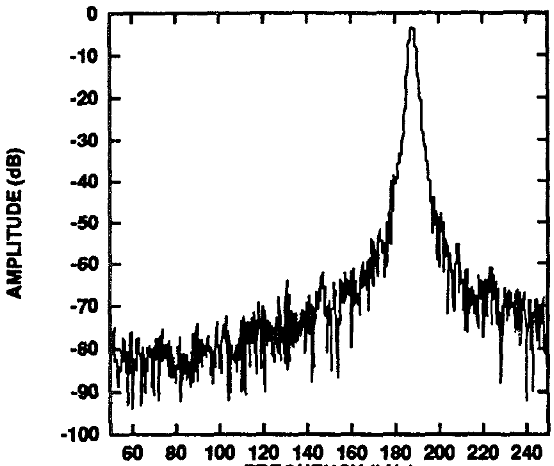

Figure 3: Spectrum with 4 oscillators, frequencies are offset from 7.444 GHz.

Below 7 GHz the oscillator couples into TE_{0nq}, n = 1, 2, 3 modes but above this frequency only TE_{00q} modes are excited as shown in Figure 4. Oscillation frequencies in the range from 7 to 8 GHz are 7.15, 7.44, 7.70 and 7.95 GHz which correspond to TE_{00q} resonances of 7.15, 7.43, 7.72 and 8.00 GHz without the oscillator cell in place [3]. Oscillation above 8 GHz is not observed presumably because of the frequency limitations of the transistor. Furthermore only TE_{00q} modes were excited when the oscillator was near the cavity axis. As such it was a simple matter to select the desired TE_{00q} modes. In this arrangement the oscillators are staggered to avoid nearest neighbor coupling. The desired one-to-many coupling was experimentally verified by selectively suppressing quasi-optical modes by strategically placing pieces of absorbing material at various positions on the slab. Earlier designs were plagued by direct reflections from the curved reflector inducing lock without the establishment of quasi-optical modes. Such oscillations were characterized by broad oscillation line widths.

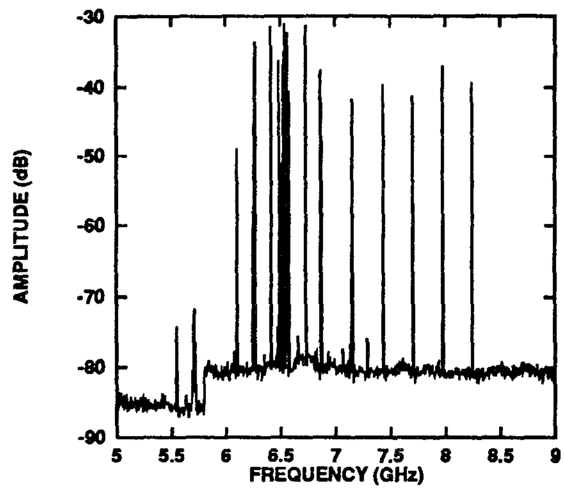

Figure 4: Max hold spectrum with oscillator unit moved over slab. At any one time there is at most only one oscillation frequency.

The procedure for establishing the frequency of oscillation is to establish the dimensions of the cavity (which selects a set of possible TE oscillation modes), apply bias to the on-axis oscillator first (which ensures TE_{00} modes), and tune the length of the drain-gate feedback slit. With this procedure two or three oscillation frequencies are still possible. Which one is selected depends on the distance of the on-axis oscillator from the curved reflector. This has been determined to be due to the establishment of nonquasi-optical interaction between the reflector and the on-axis oscillator. This is undesirable and is an aspect of ongoing engineering efforts. However with appropriate selection of this separation, oscillation at a particular frequency can be accurately and repeatably reproduced when the entire structure is disassembled and reassembled.

4. Results and Discussion

In Figure 5 the oscillation behavior with 1, 2, 3 and then 4 oscillators biased is investigated. The oscillators are arranged on the slab as shown in Figure 1. Note that with just one oscillator (the on-axis one) biased the oscillation is shifted relative to that shown in Figure 4 due to the presence of the other oscillation units on the slab.

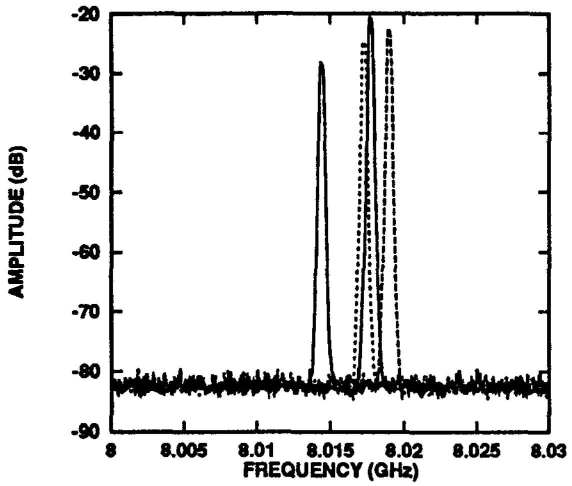

Figure 5: Spectrum with 1, 2, 3 and then 4 oscillator units biased.

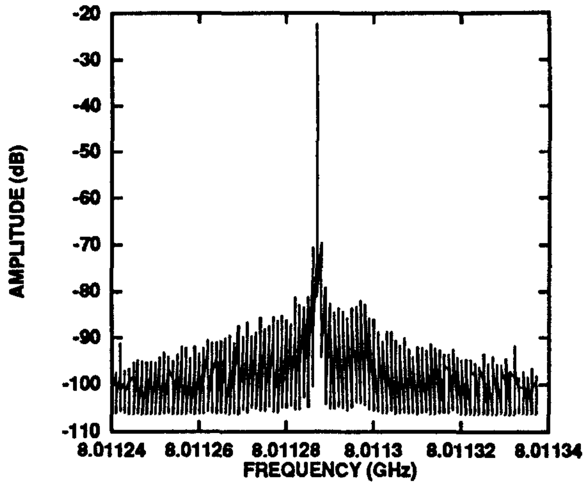

Figure 6: Single shot spectrum with 4 oscillators with injection locking. The resolution bandwidth is 1 kHz.

Subsequently a second, then third and fourth oscillators were biased. With four oscillator units the linewidth is < 6 kHz at 30 dB down (as determined by a single sweep Hewlett Packard HP8566A spectrum analyzer measurement as shown in Figure 3. Over an extended interval (10 s and longer) the center frequency wanders by up to 7 kHz with negligible change in output power level. At all times the narrow linewidth was maintained . The measured DC-to-RF efficiency was 1 %. This is low and is attributed to the low coupling of the sense antenna which is on the edge of the cavity. More realistic on-axis efficiency measurement awaits the development of a fully engineered system with a partially transmitting curved reflector and lenses to propagate and then collect the radiated power.

Injection locking the power combining oscillator with a signal from a Hewlett Packard HP8340B synthesized source 35 dB below the oscillator level reduces the linewidth to < 3 Hz at 30 dB down. Here the resolution bandwidth of the spectrum analyzer was set to the minimum resolution of 1 Hz. Single shot and max hold spectra are shown in Figures 6 and 7. The lock-in bandwidth is 350 kHz and the locking bandwidth is 470 kHz. Increasing the power of the injected signal by 3 dB increases the bandwidth to 590 kHz and 700 kHz respectively. Injection locking by an FM modulated signal at 50 kHz and then 350 kHz is shown in Figures 8 and 9.

5. Conclusion

For the first time a quasi-optical slab power combiner using an oscillator array has been demonstrated. In its present form the HDSBW power combiner is limited to only a few oscillator elements as the presence of the oscillators disturbs the quasi-optical field structure. The next phase of the work will be to move the oscillator elements under the slab so that the field disturbance is minimized.

References

[1] J. W. Mink, "Quasi-optical power combining of solid-state millimeter-wave sources," *IEEE Trans on Microwave Theory and Techniques*, Vol. 34 Feb. 1986, pp. 273-279.

[2] J. W. Mink and F. K. Schwering, "A hybrid dielectric slab-beam waveguide for the sub-millimeter wave region," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 41, Oct. 1993, pp. 1720-1729.

[3] S. Zeisberg, A. Schunemann, G.P. Monahan, P.L. Heron, M.B. Steer, J.W. Mink and F.K. Schwering, "Experimental investigation of a quasi-optical slab resonator," *IEEE Microwave and Guided Wave Letters*, Vol. 3, August 1993, pp. 253-255.

[4] Special issue on quasi-optical techniques, *IEEE Trans. on Microwave Theory and Techniques*, Vol. 41, Oct. 1993

[5] H. Meinel, "A 30-GHz FET-oscillator using fin line circuitry," *Proc. 11th European Microwave Conference Digest*, pp. 297-300, 1981.

[6] W.K. Leverich, X.-D. Wu and K. Chang, "FET active slotline notch antenna for quasi-optical power combining," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 41, pp. 1515-1517, Sept. 1993

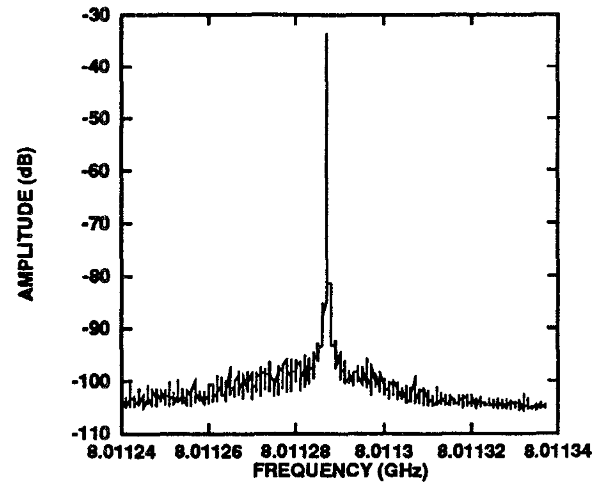

Figure 7: Max hold (10s) spectrum with 4 oscillators and injection locking. The resolution bandwidth is 1 kHz.

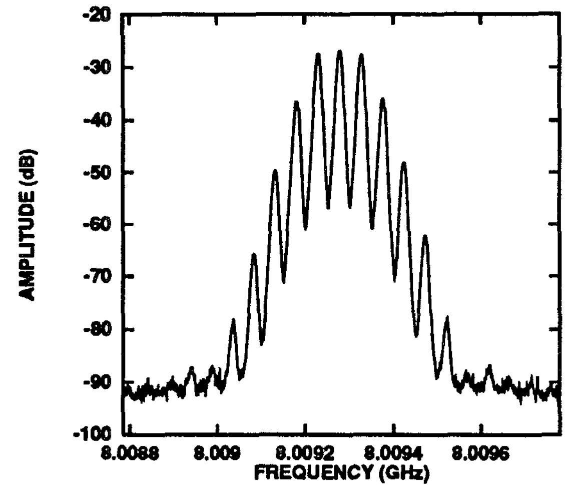

Figure 8: 50 kHz fm modulation.

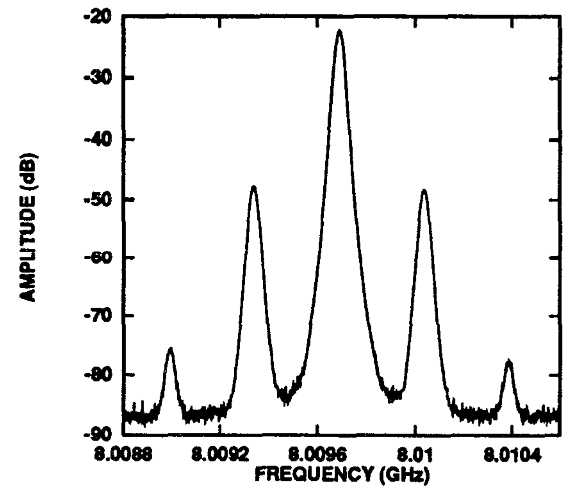

Figure 9: 350 kHz FM modulation.