QUASI-OPTICAL POWER COMBINING OF SOLID STATE SOURCES IN K_a-BAND

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ABSTRACT

Planar arrays of HEMTs (high electron mobility transistors) have been fabricated and tested at 37 GHz. The square arrays, consisting of 9 or 16 devices, have been mounted in a Fabry-Perot interferometer, which provides frequency locking. Measured power output and frequency spectra will be given, and will be compared with analytical predictions. Output power is in the milliwatt range, and line width of a typical array is about 50 kHz.

INTRODUCTION

Various power combining techniques have been investigated in recent years[1]. Significant investigations have been carried out at microwave frequencies to develop planar arrays of solid-state oscillators or amplifiers in order to produce spatial combining. Some of these structures have used quasi-optical resonators for coupling the sources to provide feedback for frequency locking. Sources utilized have included Gunn or IMPATT diodes and FETs. Three-terminal devices are preferred because they offer higher efficiency, better control, and monolithic capability. This presentation will summarize the progress and describe recent results using FETs and HEMTs at 37 GHz.

Our investigation has centered on using a semi-confocal Fabry-Perot resonator, with the array of sources placed on the planar reflector of the resonator. The curved reflector is partially reflecting to couple power out of the quasi-optical cavity. The array grid was based on extending the theory of Weikle, et al, who developed FET arrays at lower frequencies [2,3]. Source selection, quasi-optical cavity design and characteristics, and calculation of the circuit parameters for the oscillator interconnection grid are discussed below.

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SOURCE SELECTION

Two-terminal devices, such as IMPATT diodes, are available and provide significant power at 35 GHz. Three-terminal devices typically do not provide as much output power at these frequencies; however, they offer additional freedom with respect to control and provide higher dc to RF power conversion efficiencies. Additionally, these devices are undergoing continual improvement and offer potential for monolithic fabrication.

Table 1 lists the output power and power added efficiency of HEMT devices which have been designed for millimeter wave frequencies.[4] These data reflect state-of-the-art research devices and demonstrate the power potential of HEMTs. As a result of the demonstrated performance of HEMT devices and the potential to combine devices on-wafer for 94 GHz applications, we selected a commercially available pseudomorphic HEMT for proof-of-concept at 35 GHz. Raw power output was not the critical focus of this study, so an economical, low power device was selected.

The Mitsubishi MGFC-4414 pseudomorphic HEMT has a gate length of 0.3 microns and a gate width of 150 microns. Total power dissipation for this chip is 355 mW and the maximum drain to source current is 50 mA. Typical transconductance is 55 mS which corresponds to a normalized transconductance of 366 mS/mm of gate width. Figure 1 is a lumped-element equivalent circuit model which includes transistor and grid parameters.

Frequency (GHz)	Output Power (mW)	Power Density (W/mm)	Power Added Efficiency (%)	Power Gain
35	32	0.65	51	9.0
	42	0.83	37	8.5
	95	0.63	50	8.0
	137	0.91	40	7.6
	658	0.73	24	3.2

Table 1. Millimeter Wave HEMTs [4].

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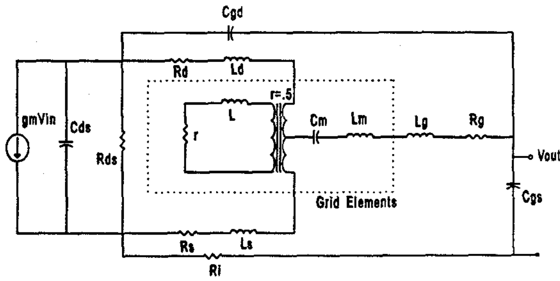

Figure 1. Lumped-Element Equivalent Circuit for the Oscillator which includes Transistor and Grid Parameters.

GRID DESIGN

Based on grid parameter calculations, a cell spacing of 2 mm was selected for initial power combining experiments near 35 GHz. Interconnect widths of 0.2 mm were used. Figure 2a is a layout of the initial grid which was designed to permit gate feedback and accommodate the HEMT chip.

RF sputtering was used to deposit chrome-gold metallizations on the substrates. Quartz substrates were electroplated with gold to provide a thickness of greater than four skin depths at 35 GHz. Standard photolithographic procedures were used to pattern the metallization. Thermosonic wire bonding, using 0.7 mil gold wire, was used to electrically connect the chips to the grid.

Early designs allowed extra space on the die attach pad to permit the gate wire bonds to be made easily. This enlargement of the die attach pad made it impossible to provide normal drain and source leads on the quartz substrate. As a result, the reflection characteristics of the grid deviated significantly from the ideal case. We have gained appreciable experience in wire bonding these HEMT devices and are now able to reduce the free bonding area on the die attach pad. This allows us to fabricate a more regular grid pattern as shown in Figure 2b. The new design includes reduced die attach pads, on-substrate connection to the large pads for external connection and reduced gaps between the gate die attach pad and the drain and source leads. Figure 3 shows a HEMT mounted on a grid.

QUASI-OPTICAL POWER COMBINING CAVITY DESIGN

The design of the quasi-optical power combining cavity is based on that treated in the paper by Mink.[5] The source array is mounted on a quartz substrate with a nominal thickness of 1 mm, although thicknesses of 1.5 and 2 mm were also used. This substrate is in turn mounted on the metal mirror which serves as the plane reflector of the semiconfocal interferometer. This mirror is movable so that the cavity may be tuned for optimum array output. The partially-reflecting spherical mirror is placed at a distance of 25 cm. This mirror is formed by machining a spherical shell from Rexolite^{R} and stretching a gold-flashed electroformed square nickel mesh tightly over it by means of an aluminum ring bolted to its periphery. The period of this mesh is 0.565 mm and the width of the wires is 0.035 mm. The reflectivity of this mesh was calculated to be 85 percent based on a method used by Simpson.[6] Meshes of 50 and 95 percent reflectivity were used in some experiments. This thickness of the Rexolite^{R} substrate was chosen to be three half-waves in the material so that it serves as a resonant Fabry-Perot interferometer. In this way the reflectivity of the mirror is determined by the mesh and not by the Fresnel reflectivity of the dielectric substrate.

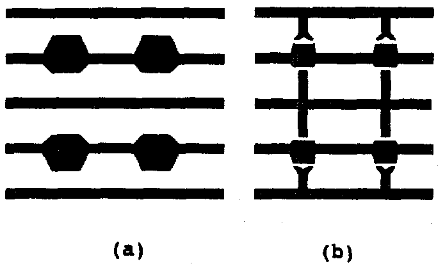

Figure 2. (a) Initial Grid Design (b) Improved Design.

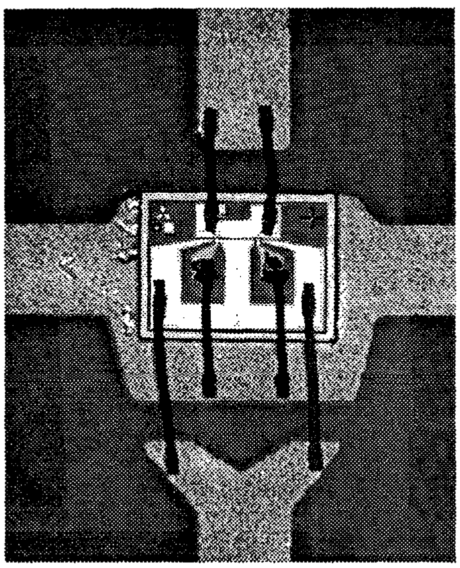

Figure 3. Photograph of HEMT Mounted on a Grid Showing Bond Wires.

The cavity was tested by introducing a 35 GHz signal from a klyston oscillator into it by means of a dielectric beam splitter. The mirror spacing was changed and resonances were observed every one-half wavelength. The unloaded Q of this cavity was measured to be 3100, while loading with an unpowered array reduced the Q to 600. This corresponds to a resonance line width of about 62 MHz. Early unloaded measurements showed the presence of some off-axis modes which were essentially eliminated by placing a ring of microwave absorber with an inside diameter of 7.5 cm on the plane mirror.

RESULTS

The experimental arrangement shown in Figure 4 was used to test the combiner. This figure also illustrates the design of the combining cavity. The quartz substrate supporting the array is mounted to the movable plane metal mirror as shown. The partially reflecting spherical mirror is located nominally 25 cm from the array, and the whole structure is supported by stainless steel rods. Radiation from the array is collected by a lens-horn combination, whose output passes directly through a directional coupler to a power meter. The 37 GHz coupled output is mixed with the fourth harmonic of a 9.2 GHz microwave synthesizer to generate an intermediate frequency of 200 MHz. This output is observed on a spectrum analyzer and high-frequency oscilloscope.

The best results in this experiment were obtained with a 2X3 array of HEMT sources, although both 1X3 and 3X3 arrays were also tested, as was a 3X3 array of FETs. Assuming that the output of the cavity is a gaussian beam with its 2 x 1/e power level coinciding with the edge of the partial reflector, and considering the diameter of the collecting lens and its distance from the reflector, it was estimated that the horn collects one-half of the radiation from the combiner. Losses in the horn and waveguide are estimated to be 2 dB each, so that the total collection system loss is taken to be 7 dB. Thus a 200 microwatt reading on the power meter, obtained with the 2X3 array, translates into a estimated unoptimized array power output of 1 mW. Using the coupled port of the directional coupler, it was possible to measure the spectrum of the array, which is shown in Figure 5. The line width of this spectrum is about 50 KHz.

Experiments were also performed with output coupler reflectivities of 50 and 95 percent. The 50 percent reflector gave the best power output of 5 mW, but the spectrum was degraded significantly from that shown in Figure 5. One would expect the lower reflectivity mirror to give higher output if the combiner is regarded as a laser. Laser theory shows that a higher gain material will give higher output with a lower reflectivity output coupler. Since the HEMTs have a high gain of perhaps 6 dB at 37 GHz, they would be expected to give more output with a lower reflectivity mirror. The best output obtained with the 95 percent reflector was a few hundred microwatts.

The electronic tuning range was measured by varying the HEMT gate voltage which changes the frequency as well as the drain-source current. The electronic tuning range between 3 dB points was determined to be 22 MHz and the gate voltage tuning coefficient is 1.47 MHz/mV. This large tuning coefficient is an indication that the array will not be difficult to phase lock, so that it should be possible to improve the spectral output by this method. Although the mechanical tuning range was difficult to measure because of the erratic performance of the array away from resonance, it was estimated to be about 68 MHz between 3 dB points based on the above measurements.

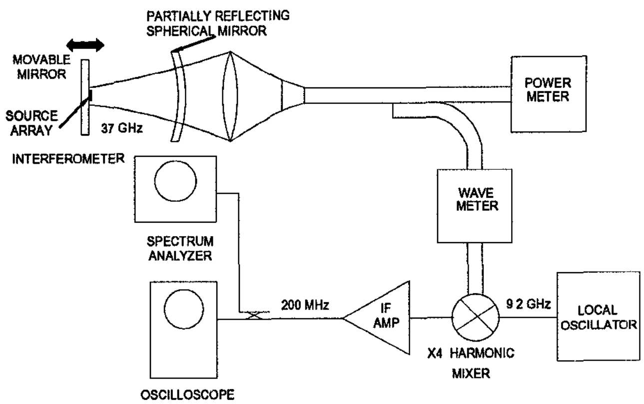

Figure 4. Experimental Arrangement Used for Testing the Grid Oscillator.

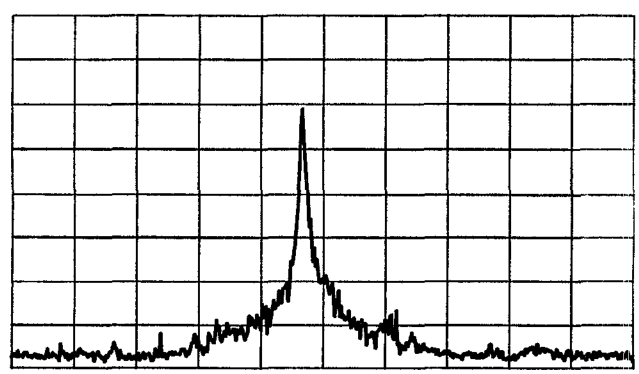

Figure 5. Spectrum of the Grid Array. The Horizontal and Vertical Scales are 1 MHz and 10 dB per Division, Respectively, and the Resolution Bandwidth is 30 kHz.

CALCULATION OF CIRCUIT PARAMETERS FOR THE GRID OSCILLATOR

The transmission line model of the grid using three terminal transistors such as HEMTs has been described by Weikle[1,2] and is shown in Figure 1. This model uses the grid inductance (L), mutual inductance (L_m), and mutual capacitance (C_m), in conjunction with HEMT equivalent circuit parameters. These parameters determine the oscillation frequency of the grid and the cut off frequency above which the fundamental mode will not oscillate.

The grid is a two dimensional periodic structure with HEMT devices at specific lattice sites. It is assumed to be infinite in both directions and uses identical devices. Our grids are finite in size and use devices that are nearly identical. A grid of N^2 devices is composed of N by N unit cells each acting as a equivalent waveguide with a radiating element at the center of the unit cell.

Mutual capacitance (C_m) of the grid has frequency dependence as well as unit cell size dependence. The center-to-center spacings of the grid wires in the horizontal and vertical directions are a and b, respectively, and w and W_s are the widths of the drain/source and gate wires, respectively. The dielectric constant of the substrate is ϵ_r. For a grid of $a = b = 0.2$cm, $w = w_s = 0.02$cm and $\epsilon_r = 3.78$, the fundamental frequency becomes complex near 40 GHz. This cut off frequency is lower than that obtained in evaluation of L_m or L, hence it is taken as the cut off frequency for the grid.

Significant results of these calculations are that for high frequency power combining on a grid we need the following:

1. Substrate material with lowest dielectric constant commensurate with power dissipation requirements.

2. Unit cell size small enough to support fundamental mode propagation as calculated for C_m.

These results also indicate that the width of the grid lines can be used as a variable parameter to adjust L, L_m, and C_m for the grid circuit model.

SUMMARY

Measurement on the 9-element and 16-element arrays are continuing, as are measurements for different grid configurations. A larger array will be fabricated and measured also. These results will be presented at the Symposium.

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