Oscillator and Amplifier Grids

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Abstract

In this paper we present the largest recorded output power for a quasi-optical power-combining array and a new planar HBT grid amplifier design. A 16-element MESFET grid oscillator has been fabricated that generates an effective radiated power (ERP) of 28 W at 9.21 GHz. The total radiated power is estimated to be 2.0 W giving a dc to rf efficiency of 28%. A new planar grid amplifier is also presented that is suitable for monolithic fabrication. The planar amplifier grid is a hybrid design using HBT transistors monolithically fabricated in a differential pair configuration and wire bonded to a Duroid substrate. The grid amplifier has a measured gain of 11 dB at 9.9 GHz.

Introduction

Power combining schemes involving solid-state devices quasi-optically coupled in free space have attracted attention as an efficient means of combining power at microwave and millimeter-wave frequencies. A variety of quasi-optical configurations have been explored including oscillators [1,2,3], amplifiers [4], and mixers [5]. Because the power is combined in free space, quasi-optical devices eliminate losses associated with waveguide walls and feed networks. A typical quasi-optical oscillator or amplifier consists of a two-dimensional array of active devices producing a planar sheet with a reflection or transmission coefficient greater than unity. A resonator can be used to provide feedback to couple the devices together to form a high-power oscillator, or the active sheet can be placed between polarizers to form a grid amplifier. By integrating large numbers of devices into the grid, very large powers can be achieved The planar configuration of the grids is suitable for monolithic integration and provides an attractive means of obtaining high power from solid-state devices that is easily scalable to millimeter-wave frequencies.

High-Power Oscillator Grid

Recent work on grid oscillators [1,2,3] has convincingly demonstrated proof of concept. However, these grids have all used relatively low power devices, and have not delivered the promised large powers. To date, the highest published total radiated power for a grid oscillator is 550 mW at 5 GHz from a 100 element grid [2] and 335 mW at 11.6 GHz from a 16 element grid [3]. In order to demonstrate Watt level powers from a quasi-optical grid oscillator, we have developed an X-band grid using Fujitsu FLK052XP power MESFET transistors with a saturated power of 0.5 Watts per device.

A diagram of the MESFET grid oscillator is shown in Figure 1. The MESFET lies in the center of a unit cell which is defined by the grid symmetry. The drain and source leads lie vertically while the gate lead runs horizontally across the grid and is orthogonal to the radiated field. If the devices in the grid are assumed to be identical, then for a grid infinite in extent, each transistor lies in an equivalent waveguide unit cell with electric walls on the top and bottom and magnetic walls on each side. Since the unit cell is small compared to a wavelength, the induced EMF method can be used to analyze the impedances presented to the MESFET terminals. Such an analysis leads to the transmission-line model shown in Figure 2. Free space is modelled by a 377 Ω resistor, and a mirror placed behind the grid is modelled as a shunt short-circuited stub with reactance jB. Currents in the vertical leads couple to the radiated field through a center tapped transformer. The coupling of the currents to evanescent TM and TE modes is approximated with reactive elements.

In order to obtain maximum output power from the transistors, it is necessary to present the appropriate load impedance across the transistor drain and source leads. A very simple linear theory is used to compute the optimal load impedance to present to the transistor for maximum power [6]. The optimal load impedance (R_{opt}) is defined as

X

the impedance that allows the transistor output terminals to swing between the maximum allowable voltage and current limits and is given approximately by

$$R_{opt} = \frac{2V_{DSS}}{I_{DSS}} \qquad (1)$$

where V_{DSS} is the dc bias voltage and I_{DSS} is the maximum drain-source current at saturation. For the Fujitsu FLK052XP transistor biased at 10 V and 120 mA, the optimal load impedance is 83 Ω. If a load impedance less than R_{opt} is presented to the device, the circuit will be current limited and the voltage across the transistor output leads will be less than the maximum allowed. Similarly, if the load impedance is greater than R_{opt}, the circuit will be voltage limited, and the current through the transistor output terminals will be less than the maximum allowed. Either case will result in less power being delivered to the load. At microwave frequencies, the effects of parasitic elements, especially the output capacitance, must be de-embedded as part of the external load before this simple theory is applied. Using this technique, it is possible to come reasonably close to the optimal impedance for maximum output power.

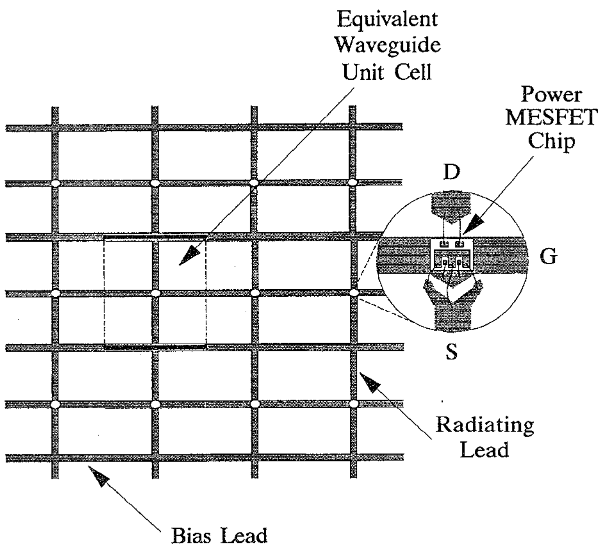


Figure 1. Schematic of the grid oscillator. For analysis, grid symmetry reduces the grid to an equivalent waveguide with electric walls top and bottom and magnetic walls on the sides. The adjacent rows share horizontal bias lines.

The grid was designed to oscillate near 10 GHz with an optimal load impedance presented to the transistor output terminals. The grid pattern was fabricated on a Duroid substrate with a dielectric constant of 2.2. The substrate is 2.54 mm thick and is placed in front of a planar mirror. The unit cell is 8.6 mm × 8.6 mm and the bias lines are 0.5 mm wide. Figure 3 shows the load impedance the grid presents to the transistor as a function of mirror position at the oscillation frequency. The design was optimized to present 83 Ω to the transistor after de-embedding the transistor parasitics. A double slug tuner consisting of two Duroid slabs with dielectric constants of 10.2 and electrical lengths of 90° at the oscillation frequency were placed in front of the grid to help transform the free space impedance to the optimal load impedance for the transistor.

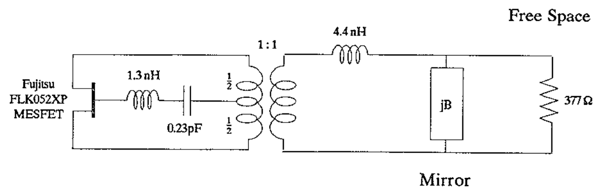


Figure 2. Transmission-line model for the grid oscillator. The values given are calculated from an EMF analysis on the equivalent waveguide unit cell.

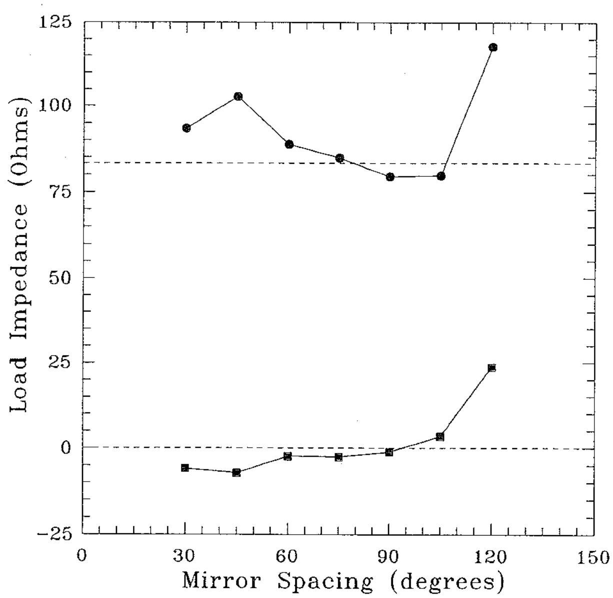


Figure 3. Theoretical load impedance presented to the transistor as a function of mirror spacing at the frequency of oscillation. The load impedance is split into real (•) and imaginary (▪) plots. The dashed line represents the desired value for maximum output power.

Based on preliminary measurements, a 16-element grid has generated an effective radiated power of 28 W at 9.21 GHz. Assuming an effective area equal to the physical area of the grid, the total radiated power is estimated to be 2.0 W with a dc to rf efficiency of 28%. Figure 4 shows the output spectrum of the grid oscillator. The potential problem of dissipating the large amount of heat generated by a grid of power transistors was solved by developing a simple and reliable forced air cooling system.

Based on the success of this 16-element grid, we are fabricating a 100-element grid that will use the same unit cell design. This 100-element grid has a projected total radiated power of 12.5 W and an effective radiated power of 1.1 kW. These power levels are sufficient to present a serious challenge to the tube sources that dominate in this region and will conclusively demonstrate the ability of quasi-optical power combining to generate Watt level power at microwave frequencies.

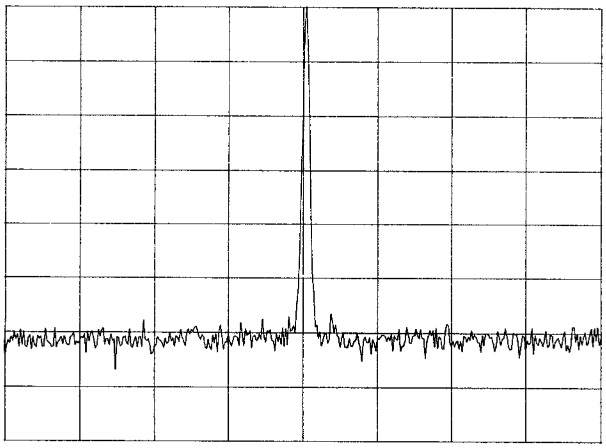


Figure 4. Measured spectrum of the grid oscillator showing an oscillation at 9.21 GHz. The horizontal scale is 5 MHz per division and the vertical scale is 10 dB per division. The resolution bandwidth is 100 kHz. An effective radiated power (ERP) of 28 W was measured.

Grid Amplifier

Previously, the quasi-optical power combining technique was employed in the design of an amplifier grid for C band [4]. This amplifier grid demonstrated a gain of 11 dB at 3.3 GHz with a 3 dB bandwidth of 90 MHz. However, this grid contains VIA holes which are difficult to fabricate monolithically. Recently, planar structures that are more suitable for monolithic integration have been studied. We have developed a planar amplifier grid that uses a chip containing a pair of differentially connected heterojunction bipolar transistors fabricated by the Rockwell International.

Figure 5 illustrates a typical setup for an amplifier grid. The grid is designed to receive an incident beam from one side, and radiates the amplified beam to the opposite side. The output beam is cross-polarized from the input beam to minimize coupling and to diminish the chance of unwanted oscillations. Furthermore, the cross-polarization allows independent tuning of the input and output with polarizers.

The coupling between input and output should come mainly from the active devices embedded in the grid. A four-port device formed by attaching two three-terminal devices in a differential configuration is well suited for this

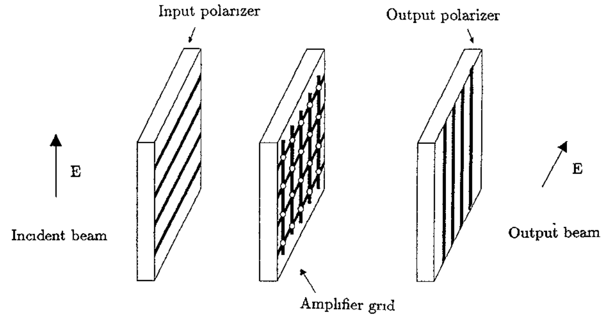


Figure 5. A grid amplifier with polarizers.

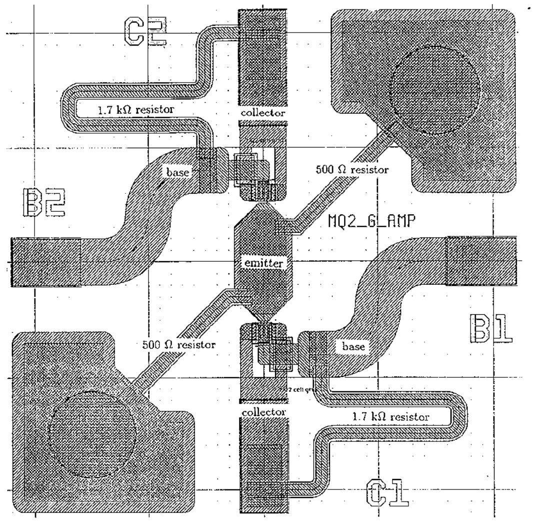
type of operation. Rockwell International and Caltech have designed a differential-pair HBT chip which is shown in Figure 6(a). These HBT transistors show gain up to 40 GHz. The chip consists of two HBT's with their emitters tied together that are then connected to a 250 Ω resistor needed for biasing the transistors. This resistor also reduces the gain of the HBT's in common mode operation. A feedback resistor of 1.7 $k\Omega$ is connected between base and collector to allow the base to be self-biased. A typical dc bias for the collector-emitter junction is 3 V with a collector current of 10 mA.

The metal structures on the grid consist of two parts: one for input and output coupling, the other for biasing the active devices. Unlike the first amplifier grid which had bias lines and radiating/receiving leads on separate planes [4], the new grid has both structures on the same plane (Figure 6(b)). The new grid uses inductive strips as coupling antennae for both the input and output. The thin bias lines present a large inductive reactance to the incident beam, and have a minimal effect on the input coupling between the incident beam and the base lead.

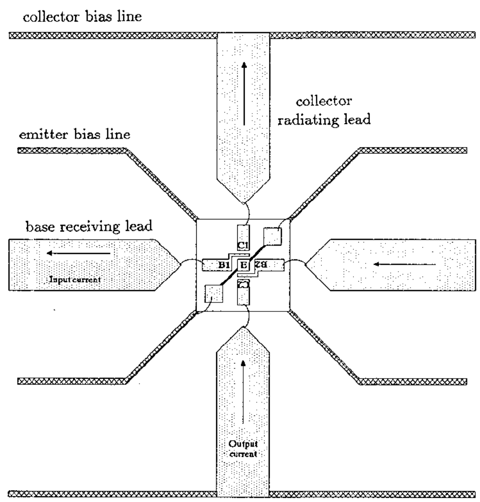
An 16-element amplifier grid with polarizers has been fabricated on a 3.175 mm thick Duroid substrate with a dielectric constant of 2.2. The unit cell size is chosen to be 8 mm, while the width of the coupling leads is 0.8 mm. The whole grid is biased at 5 V and 135 mA including the voltage across the resistors. Figure 7 shows the measured gain as a function of frequency. The peak gain is 11 dB at 9.9 GHz. The 3 dB bandwidth extends from 9.5 GHz to 10.2 GHz. The peak gain and the bandwidth are very sensitive to the position of the polarizers which indicates that the amplifier grid is well coupled to the free space.

Conclusion

In this paper we have demonstrated a high-power grid oscillator producing 120 mW per device at a frequency of 9.21 GHz with an estimated efficiency of 28%. A simple linear theory was used to compute the optimal load impedance to present to the transistors for maximum output power. We have also demonstrated a planar grid amplifier utilizing HBT transistors connected in a differential pair configuration with integrated source resistors. The grid amplifier shows up to 11 dB gain at 9.9 GHz. The planar arrangement of these grids makes them suitable for monolithic integration and with appropriate scaling it should be possible to produce grids with significant powers at millimeter-wave frequencies.



(a)



(b)

Figure 6. (a) The chip layout produced by Rockwell International. Emitters of the two HBT transistors are tied together to form a differential-pair. (b) A sketch of the grid amplifier unit cell. Arrows indicate the direction of the rf currents on the coupling leads when the grid is operating in a differential mode.

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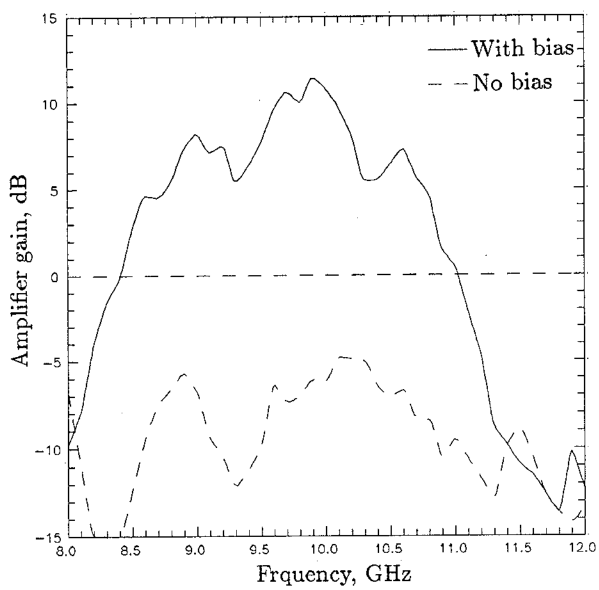

Figure 7. The measured gain of the 16-element amplifier grid. The peak gain is 11 dB at 9.9 GHz. The dashed line shows the gain when the bias is turned off.

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