60 GHz Sources Using Optically Driven HBTs

D.C. Scott, D.V. Plant, *Member, IEEE*, and H.R. Fetterman, *Fellow, IEEE*

Electrical Engineering Department
University of California at Los Angeles
Los Angeles, California

ABSTRACT

Millimeter wave sources at 60 GHz have been demonstrated using optically driven heterojunction bipolar transistors configured as photodetectors. Two techniques were used to optically generate the millimeter waves; the mixing of two cw lasers and the mode locking of a semiconductor laser. The millimeter wave power generated from these two configurations was radiated into free-space using integrated planar twin dipole antennas and heterodyne detected with signal to noise ratios > 40 dB. As part of these experiments, the DC optical gain and quantum efficiency of the HBT photodetectors was determined.

I. INTRODUCTION

There has been a growing interest in the use of optical wavelengths both in the transmission and generation of millimeter wave signals. The development of large bandwidth millimeter wave systems requiring a low-loss, lightweight, and interference free transmission medium has stimulated recent research in the area of optically controlled millimeter wave devices [1,2]. In addition, there has been considerable interest in the development of HBT phototransistors as an alternative to p-i-n detectors because HBTs can provide large photocurrent gains without high bias voltages and excess avalanche noise characteristics [3]. In the series of experiments presented here, high frequency heterojunction bipolar transistors are used as photodetectors integrated with planar twin-dipole antenna structures to generate 60 GHz radiation. Our initial efforts employed two cw lasers in a mixing configuration to demonstrate proof of principle. In subsequent experiments, a mode locked semiconductor laser was substituted for the mixing system to produce a compact and highly stable radiation source [4,5]. This combination of an optical transit time device (mode locked laser) and a high speed phototransistor (HBT) defines a new type of optoelectronic millimeter wave source which can be distributed to form novel coherent arrays.

II. EXPERIMENTAL SETUP

The devices used in these experiments were abrupt emitter-base junction $Al_{.48}In_{.52}As/Ga_{.47}In_{.53}As$ heterojunction bipolar phototransistors with DC common-emitter current gains of 15. These transistors can have cutoff frequencies (f_T) and maximum oscillation frequencies (f_{max}) of 90 GHz and 70 GHz, respectively [6]. However, in order to allow optical access to the device active region, an 8x8 μm emitter window was included which significantly reduced the frequency performance of the device. The device layer structure is shown in figure 1. The HBTs were mounted onto twin dipole printed circuit antennas that were designed to have optimum gain at 60 GHz [7]. The optically generated millimeter waves were then radiated into free-space and collected into waveguide using a large aperture horn. Using a Gunn diode as a local oscillator, the millimeter wave signals were heterodyne detected via a waveguide mixer.

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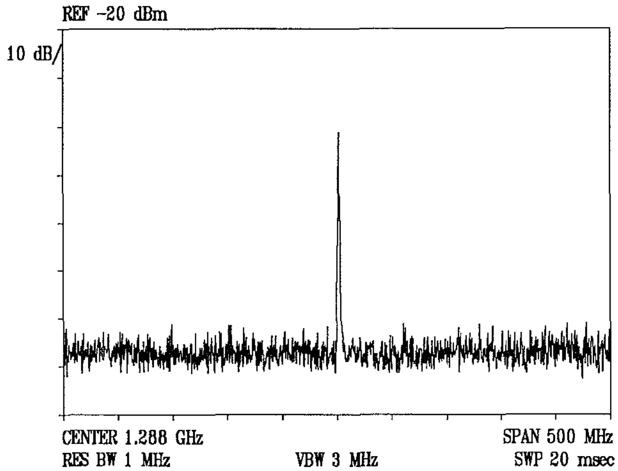

Figure 2: Spectrum analyzer trace of the received millimeter wave radiation at 59.5 GHz. Transmitting HBT was illuminated by .6 mW of dye laser and .6 mW of HeNe laser.

In order to illustrate how the above experiment could be useful for applications in phased array antenna systems, we electrically injected a -9 dBm, 118 MHz IF signal into the base of the antenna mounted HBT while simultaneously optically mixing at 59.4 GHz (see figure 3). This configuration produced sidebands spaced at integer multiples of 118 MHz away from the 59.4 GHz carrier. This result demonstrates that one can encode an IF information signal onto an optically generated carrier.

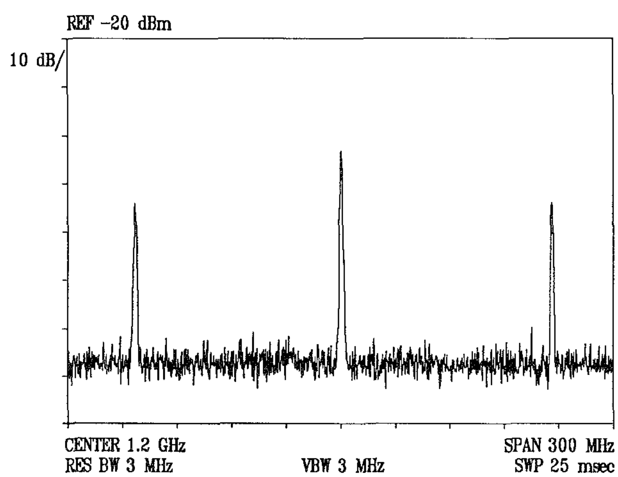

Figure 3: Received millimeter wave signal with 118 MHz (-9 dBm) IF modulation electrically applied to the base of the HBT.

IV. EXPERIMENT 2

In a second set of experiments, a mode locked GaAs/AlGaAs multiple quantum well semiconductor laser was used to drive the HBT/antenna circuit as is shown in figure 4 [4,13]. The diode lasers used were two section lasers which were mode locked using one section as a saturable absorber. In these devices, the saturable absorber region is biased to adjust the steady state absorption to the point where small round trip oscillations become unstable and mode locking occurs. The laser produces < 2.5 psec pulses at 830 nm with an average power of 1.6 mW. The mode locked output can be regarded as a highly efficient means of directly modulating an optical carrier at a millimeter wave frequency, and this output can be used to directly drive the HBT/antenna circuit. The diode laser output was imaged onto the HBT active region using a single lens. At 830 nm, the absorption coefficient of the $Ga_{.47}In_{.53}As$ is $\approx$1.5 x 10^4 cm^{-1} [3] and the $Al_{.48}In_{.52}As$ layers are assumed to be transparent [14]. Therefore, it is reasonable to assume that all of the light reaches the base and contributes to the photocurrent. Given that the reflectivity of the top $Ga_{.47}In_{.53}As$ contact layer is 30%, we calculate that the amount of light absorbed in the HBT's active region is P_1 = 1.12 mW. The measured collector current is I_c = 7.6 mA and the dark current is the same as before. Substituting these values into equation (3) gives a DC optical gain of M = 10. From equation (4), this leads to a DC quantum efficiency of η = 50%. The millimeter wave output had a signal to noise ratio of 40 dB and a 3 dB linewidth of ≤500 KHz. The center frequency was 65.12 GHz which corresponds to the laser mode locking frequency. The output millimeter wave power was measured to be 10^{-4} mW. As shown in figure 4, the combination of the laser diode and the HBT results in a fixed frequency, narrow linewidth source and defines a new type of semiconductor based optoelectronic millimeter wave oscillator. This compact millimeter wave source lends itself well to monolithic integration and an array of on-wafer sources can be assembled for use in phased array radar.

GaInAs	CONTACT	$n^+ = 1 \times 10^{19}$	100 nm
AlInAs	EMITTER CONTACT	$n^+ = 1 \times 10^{19}$	80 nm
AlInAs	EMITTER	$n = 8 \times 10^{17}$	180 nm
GaInAs	BASE	$p^+ = 1 \times 10^{20}$	80 nm
GaInAs	COLLECTOR	$n = 4 \times 10^{16}$	270 nm
GaInAs	SUBCOLLECTOR	$n^+ = 1 \times 10^{19}$	800 nm
GaInAs	BUFFER	UNDOPED	10 nm
	InP SEMI-INSULATING SUBSTRATE		

Figure 1: HBT device layer structure.

III. EXPERIMENT 1

In the first set of experiments, the HBTs were illuminated with light from a Kiton Red dye laser (600 nm - 640 nm, .6 mW) and a frequency stabilized HeNe laser (632.8 nm, .6 mW). The wavelength of each linearly polarized laser was monitored with a wavemeter that had 0.001 nm resolution. Using a beam splitter, the two output beams of the lasers were made collinear and then were focused onto the HBT using a 5x lens objective. The total electric field vector, E_t, impinging on the HBT can be written as

$$E_t = E_h \exp(j\omega_h t) + E_d \exp(j\omega_d t) \qquad (1)$$

where E_h, E_d are the field amplitudes and ω_h, ω_d are the optical frequencies of the HeNe and dye lasers, respectively. It can be shown that the optically induced output current of the HBT is proportional to the square of the electric field [8]:

$$i \propto |E_t|^2 = E_h^2 + E_d^2 + 2E_hE_d \cos(\omega_h - \omega_d)t\,. \qquad (2)$$

The first two terms in equation (2) correspond to the DC component of the optically generated output current of the HBT. Rewriting this component in terms of the incident optical power shows that the DC component of the optically generated output current is proportional to $P_h + P_d$. The DC photocurrent gain (M), which relates the number of electrons (or holes) in the collector current to the number of incident photons is given by [3,9]

$$M = \frac{h\nu}{qP_i}(I_c - I_D)\,, \qquad (3)$$

where I_c is the collector current measured with a floating base, I_D is the dark current, ν is the frequency of the incident photon, h is Planck's constant, q is the electronic charge, and P_i is the incident optical power. Given that $P_h = P_d = .6$ mW, the total incident optical power as given by $P_h + P_d$ is $P_i = 1.2$ mW. At 633 nm, the reflectivity of the top $Ga_{.47}In_{.53}As$ layer is 30% [10] thus reducing the incident optical power to $P_i = .84$ mW. The measured collector current, I_c, is 1.5 mA and the measured dark current, I_D, is 130 nA. Substituting these values into equation (3) yields a DC photocurrent gain (M) of 3.5. The quantum efficiency can be determined using the relation [11]

$$\eta = \frac{M}{\beta + 1}\,, \qquad (4)$$

where M is the DC photocurrent gain and β is the DC common-emitter current gain which was measured to be 15. Substituting these values into equation (4) yields a DC quantum efficiency of 22%.

Looking back at equation (2), we see that the last term oscillates at the difference frequency $|\omega_h - \omega_d|$ with magnitude proportional to $2E_hE_d$. We tune the frequency of the dye laser such that the difference frequency, $|\omega_h - \omega_d|$, is at 60 GHz and the millimeter wave signal is efficiently radiated into free-space by the twin dipole antenna. Converting to optical powers, the magnitude of the input optical signal that is responsible for this millimeter wave signal can be shown to be $2\sqrt{P_hP_d}$ [12], where P_h, P_d are the HeNe and dye laser powers, respectively. Since $P_h = P_d = .6$ mW, the magnitude of the input optical signal as given by $2\sqrt{P_hP_d}$ is 1.2 mW. Notice that the magnitudes of the DC optical power and millimeter wave optical power are the same. This is a direct consequence of mixing two cw lasers at the same power and is the most efficient means of producing millimeter wave optical intensity modulation via optical mixing. Taking into account the reflectivity of the top layer of the device in the same manner as before reduces the incident millimeter wave optical power to .84 mW. Figure 2 is a radiated signal with a center frequency of 59.5 GHz, a signal to noise ratio of 45 dB, and a 3 dB linewidth of 2.5 MHz. Based on the receiver conversion losses, the power in the millimeter wave signal was estimated to be 10^{-5} mW. Future efforts to increase this millimeter wave power include incorporating faster HBTs with larger internal gains, increasing the optical absorption interaction region, and carefully impedance matching the devices to the radiating antenna circuit.

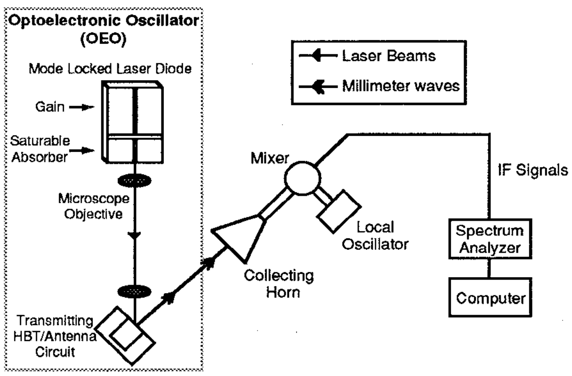

Figure 4: Experimental setup of the millimeter wave Optoelectronic Oscillator (OEO).

V. CONCLUSIONS

In summary, we have demonstrated the generation of usable amounts of coherent millimeter wave power using both optical mixing techniques and modulation techniques with mode locked laser diodes. High frequency heterojunction phototransistors and optical waveguides can be used to form simple versatile systems with applications in communications and phased array radars. Because of the intrinsic gain of the high frequency HBTs and the ease in which amplifying MMIC circuits can be incorporated, substantial radiated powers can be obtained with this approach. Current efforts are underway to make integrated configurations with multiple planar optical waveguide feeds.

The authors would like to thank the Microwave Devices and Circuits Department at Hughes Research Laboratories in Malibu, California for providing the HBTs and Ortel Corporation in Alhambra, California for providing the mode locked laser diodes used in these experiments. This work was supported by the Air Force Office of Scientific Research under the direction of H.R. Schlossberg and by the National Center for Integrated Photonics Technology.

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