60 GHz sources using optically driven heterojunction bipolar transistors

D. C. Scott, D. V. Plant, and H. R. Fetterman
Department of Electrical Engineering, University of California at Los Angeles, Los Angeles, California 90024

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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 gains and quantum efficiencies of the heterojunction bipolar transistor photodetectors were determined.

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 heterojunction bipolar transistors (HBTs) 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.

The devices used in these experiments were abrupt emitter-base junction $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ heterojunction bipolar transistors with dc common-emitter current gains of 15. These transistors can have cutoff frequencies (f_T) and maximum oscillation frequencies ($f_{\max}$) of 90 and 70 GHz, respectively.[6] However, in order to allow optical access to the device active region, an 8×8 μm emitter window was included, which significantly reduced the frequency performance of the device. The device layer structure is shown in Fig. 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.

In the first set of experiments, the HBTs were illuminated with light from a frequency stabilized Kiton Red dye laser (600–640 nm, 0.6 mW) and a frequency stabilized HeNe laser (632.8 nm, 0.6 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 $5\times$ lens objective. The total electric field vector, E_t, impinging on the HBT can be written as

$$E_t=E_h\exp(j\omega_h t)+E_d\exp(j\omega_d t), \tag{1}$$

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

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

The first two terms in Eq. (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]

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			

FIG. 1. HBT device layer structure.

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

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 $P_h=P_d=0.6$ 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 $Ga_{0.47}In_{0.53}As$ layer is 30%,[10] thus reducing the incident optical power to $P_i=0.84$ 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 Eq. (3) yields a dc photocurrent gain (M) of 3.5. The quantum efficiency can be determined using the relation[11]

$$\eta=\frac{M}{\beta+1}, \tag{4}$$

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 Eq. (4) yields a dc quantum efficiency of 22%.

Looking back at Eq. (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 this 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 $2\sqrt{P_hP_d}$, where P_h,P_d are the HeNe and dye laser powers, respectively. Since $P_h=P_d=0.6$ mW, the magnitude of the input optical signal as given by $2\sqrt{P_hP_d}$ is 1.2 mW. 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 0.84 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. Part of the losses in the conversion from the incident optical power to the output millimeter wave power result from the parasitics associated with the 8×8 μm emitter window. Grading the base of the HBT and impedance matching the device to the antenna will significantly improve the performance of the system. We estimate that the output millimeter wave power can become comparable to the incident light power.

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 Fig. 3). This configuration produced sidebands spaced 118 MHz away from the 59.4 GHz carrier. This result demonstrates that one can encode an IF information signal onto an optically generated millimeter wave signal.

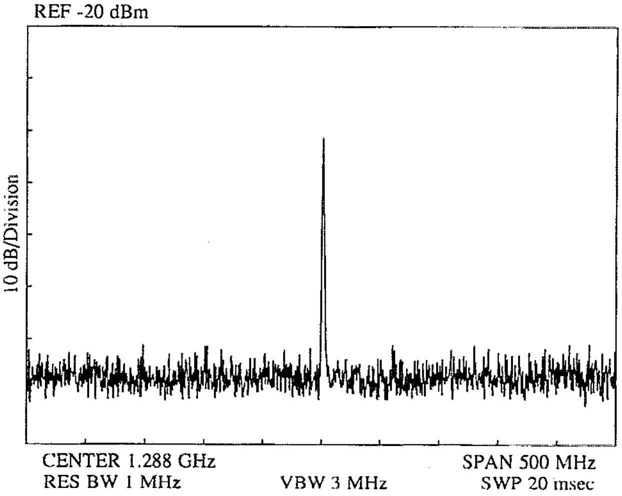

FIG. 2. Spectrum analyzer trace of the received millimeter wave radiation at 59.5 GHz. Transmitting HBT was illuminated by 0.6 mW of dye laser power and 0.6 mW of HeNe laser power.

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 Fig. 4.[4] 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 pulses <2.5 ps 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. At 830 nm, the absorption coefficient of the $Ga_{0.47}In_{0.53}As$ is $\approx 1.5\times10^4$ cm^{-1} (Ref. 3) and the $Al_{0.48}In_{0.52}As$ layers are transparent.[12] Therefore, it is reasonable to assume that all of the light is absorbed in the base and collector regions and contributes to the photocurrent. Given that the reflectivity of the top

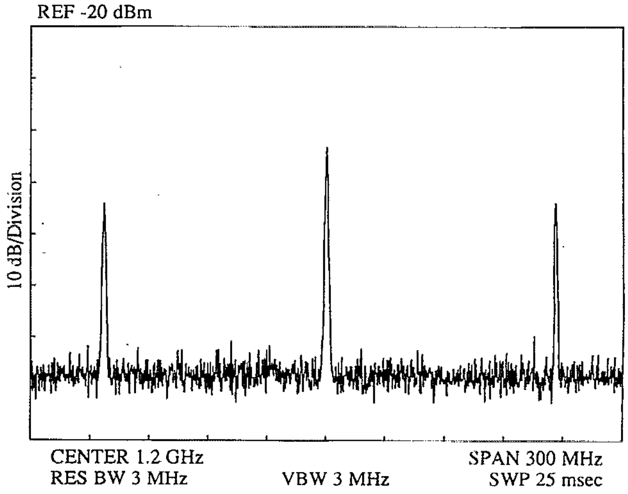

FIG. 3. Received millimeter wave signal with 118 MHz (-9 dBm) IF modulation electrically applied to the base of the HBT.

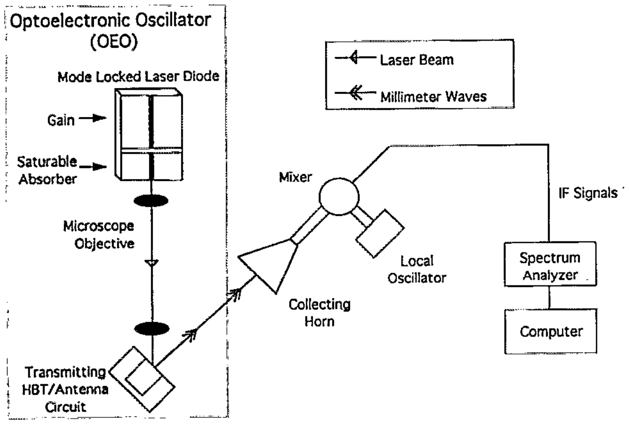

FIG. 4. Experimental setup of the millimeter wave Optoelectronic Oscillator (OEO).

$Ga_{0.47}In_{0.53}As$ contact layer is 30%, we calculate that the amount of light absorbed in the HBTs active region is $P_i = 1.12$ mW. The measured collector current is $I_c = 7.6$ mA and the dark current is the same as before. Substituting these values into Eq. (3) gives a dc optical gain of $M = 10$. From Eq. (4), this leads to a dc quantum efficiency of $\eta = 50\%$. 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 Fig. 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 phase array radar.

The previous experiments showed that the experiments performed at 830 nm were more efficient than those at 633 nm. This can be explained by discussing the dynamics of the carriers generated by the absorption of light in the various regions of the HBT. The major component of the photocurrent is due to electron-hole pairs generated in the base, in the base-collector depletion region, and within a diffusion length of the depletion edge in the bulk collector. The electrons that are generated in these regions are collected by the field of the reverse biased base-collector junction leading to a current flow in the external circuit. The holes that are generated in these regions are swept into the base thereby increasing the base potential. This increases the forward bias at the base-emitter junction causing a large number of electrons to be injected from the emitter into the base, which results in a large electron current flow from the emitter to the collector. This is the mechanism for photocurrent gain. If light is absorbed in the emitter, than the emitter injection efficiency will be reduced and this will reduce the photocurrent gain of the device. Based on the band gap of the AlInAs emitter, we find that at 830 nm the emitter is transparent and at 633 nm light is being absorbed.[12] This explains the reduced photocurrent current gain that was observed at 633 nm. From the above observations, it is clear that these heterojunction phototransistors are most efficient in the long wavelength range of 0.830–1.3 μm.

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. Future efforts to increase this millimeter wave power include incorporating faster HBTs with larger gains, optimizing the optical absorption interaction region using new materials and new structures, and coupling to specially designed matched broadband antenna systems. 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

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