Optically Generated 60 GHz Millimeter Waves Using AlGaAs/InGaAs HEMT's Integrated with Both Quasi-Optical Antenna Circuits and MMIC's

D. V. Plant, *Member, IEEE,* D. C. Scott, H. R. Fetterman, *Fellow, IEEE,* L. K. Shaw, W. Jones, and K. L. Tan

Abstract—**Continuously tunable 49–67 GHz millimeter wave radiation has been generated using optical mixing in AlGaAs/InGaAs HEMT's integrated with both quasi-optical antenna circuits and multistage MMIC amplifiers. Using these systems, microwatt levels of millimeter wave power has been generated. A quantitative study of the signal strength versus bias, polarization, and light intensity was performed. In addition, the millimeter waves were modulated by applying a RF signal (< 1 GHz) to the FET gate. Using this technique, tunable electrical sidebands were added to the optically generated 60 GHz carrier, thus providing a method of transmitting information.**

Introduction

OPTICAL-MILLIMETER wave interactions have attracted recent attention because of applications which involve the advantages of both lightwave and microwave techniques [1], [2]. It allows the use of optical-fiber technology for interconnection of microwave devices and circuits [3]. Concurrently, high electron mobility transistors (HEMT's) have gained widespread application in low-noise millimeter wave amplifiers due to their superior noise performance compared to MESFET's [4]. In this letter, we report the use of pseudomorphic AlGaAs/InGaAs HEMT's to generate tunable continuous-wave millimeter wave radiation by optical mixing. Three terminal devices offer unique advantages over two terminal devices for generating millimeter waves using optical mixing [5]. In particular, the gate provides a means of applying tunable RF sidebands to a tunable, optically generated carrier for use in communication systems. This technique eliminates the need to directly modulate one of the two heterodyned laser sources. Also, the illuminated HEMT can be optimized as a function of drain and gate bias thus increasing the optical mixing photocurrents.

Previously, we generated 60 GHz millimeter wave radiation using low-frequency, commercially available GaAs MESFET's integrated with quasi-optical antennas [6]. In order to increase the optically generated millimeter wave power, 60 GHz pseudomorphic AlGaAs/InGaAs HEMT's were used in place of GaAs MESFET's [7]. The motivation was to use devices whose optical sensitivity and optical speeds are larger than GaAs MESFET's [8]–[10]. In particular, optically generated electrons are transferred to the high-mobility two-dimensional electron gas (2DEG) which increases the mixing photocurrent and increases the millimeter wave power.

Two different systems were investigated. First, HEMT's were integrated with printed circuit antennas in order to generate freely propagating millimeter wave radiation. Second, HEMT's were integrated into microstrip with 60 GHz multistage MMIC amplifiers to provide gain. Optical fibers were used to deliver light to pump both the optical mixer/antenna circuits and the optical mixer/amplifier circuits. The extension to optical fibers is important with respect to applications of these techniques in systems such as optically controlled phased arrays. [11].

Experimental Setup

The devices used in both experiments were 60 GHz pseudomorphic $Al_{0.25}Ga_{0.75}As/In_{0.28}Ga_{0.72}As$ HEMT's [7]. The HEMT's were illuminated with light from an actively frequency stabilized Kiton red dye laser (600–640 nm) and an actively frequency stabilized He–Ne laser (632.8 nm). The wavelength of each linearly polarized laser was monitored with a wavemeter which had 0.001 nm resolution. The frequency stability of each laser was better than 2 MHz. The beams were combined using a beam splitter and then were coupled into single-mode polarization preserving and nonpolarization preserving optical fibers. The fiber core diameters were 2.75 μm, and the output tips were brought to less than 1 mm from the device active region. In order to prevent feedback into the actively stabilized lasers, the input and output tips of the fibers were polished with 10° wedge angles.

In the optical mixer/antenna circuit experiments, the optically generated millimeter wave radiation was radiated into free space and then coupled into waveguide detectors using

Manuscript received October 1, 1991. The work at UCLA was supported by the Air Force Office of Scientific Research and by the National Center for Integrated Photonics Technology.

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

L. K. Shaw, W. Jones, and K. L. Tan are with TRW Electronics and Technology Division, Redondo Beach, CA 90278.

IEEE Log Number 9105315.

1041-1135/92$03.00

lenses and horns. In the optical mixer/amplifier circuit experiments, the millimeter waves were launched into waveguide via microstrip to coaxial to waveguide transitions. The signals were measured using a heterodyne receiver which employed a tunable (55.5–62 GHz) klystron for a local oscillator. In both experiments, the optically generated millimeter waves and the local oscillator were combined in a directional coupler and fed into a waveguide mixer. The mixer outputs were sent through IF amplifiers and displayed on a computer-controlled spectrum analyzer.

Optical Mixer/Antenna Circuit Results

In the first set of experiments, the HEMT's were integrated on printed circuit RT/Duriod microstrip antennas in a common source mode. Twin dipole antennas designed for optimum gain at 60 GHz were used. In the transmitter configuration, the drain to source was connected across the antenna. The optical mixing produced photocurrents at the desired reradiation frequency. Fig. 1(a) is a recording of a received signal at 61.342 GHz. This figure shows a signal to noise ratio of > 45 dB which is 10 dB larger than our previous results using low frequency GaAs MESFET's [6]. The optimum signals were obtained at pinchoff: $V_{gs} = -0.75$ V at $V_{ds} = 2.5$ V. Based on the transmittivity of the GaAs cap layer (66%), and the differences in the aspect ratios of the fiber output beam and the device active region, we calculated that 3% of the light from each laser is absorbed in the device [12]. Therefore, the maximum absorbed optical power in the device was 2.0 mW and 3.4 μW for the dye laser and the He–Ne laser, respectively. Also, the radiation was measured to be linearly polarized which agreed with the antenna design.

We attribute the larger signals to an increase in the mixing photocurrents. In a HEMT, photoexcited carriers will not suffer from ionized impurity scattering in the channel as is the case for a MESFET. Since the HEMT's were illuminated with visible light which had a photon energy (1.96 eV) greater than the bandgap energy of each of the HEMT materials, photoexcited carriers are generated in each of the layers comprising this structure. Previous studies have shown that the optically controlled characteristics are most efficient at pinchoff [8]–[10]. This is because photogenerated holes in the top GaAs cap layer and the AlGaAs layer flow into the depletion layer under the negatively biased gate resulting in a decrease in the depletion region size and an opening of the 2 DEG channel. Photogenerated electrons in the InGaAs and the underlying GaAs supperlattice experience a vertical field associated with the band bending of the AlGaAs/InGaAs heterojunction, and a lateral field associated with the applied drain voltage. These electrons are collected in the high mobility 2 DEG, and they are the dominant contribution to the optical mixing photocurrent.

As mentioned, three terminal devices can be directly RF modulated. This is demonstrated in Fig. 1(b) where a recording of a received signal at 61.342 GHz with 100 MHz electrical sidebands is shown. With an applied RF signal of 5 dBm, the signal power in the sidebands was large, 15 dB down from the carrier, and the sidebands were tunable over

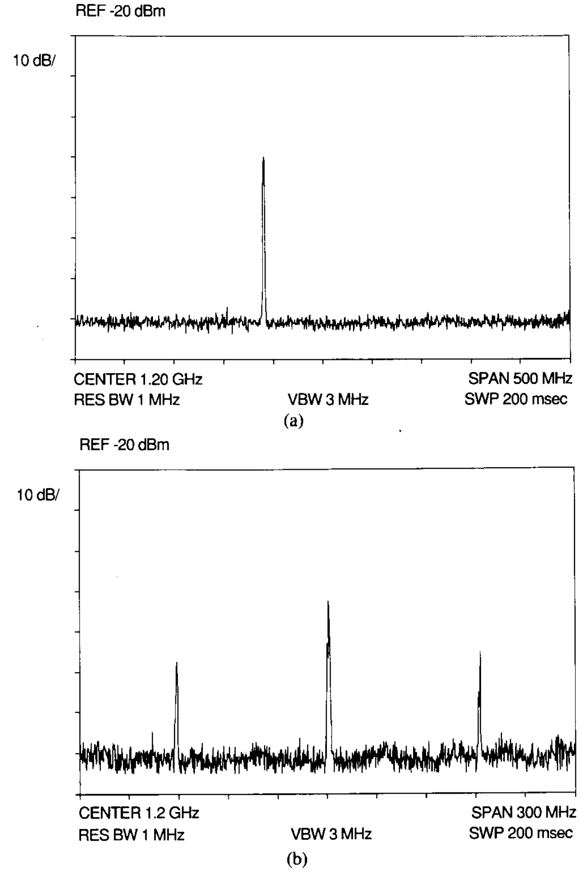

Fig. 1. (a) Recording of received 61.342 GHz radiation from transmitting HEMT/antenna circuit. (b) Recording of signal with 100 MHz RF modulation (5 dBm) applied to transmitter gate.

> 500 MHz of bandwidth. This result demonstrated one of the advantages of using three terminal devices; namely, the ability to apply an information signal without the need to modulate either of the two heterodyned laser sources.

Optical Mixer/Amplifier Circuit Results

In the second set of experiments, the HEMT's were integrated into 50 Ω microstrip with two-stage MMIC amplifiers designed for operation from 57.5 to 65 GHz with > 8 dB of gain [13]. The MMIC active device structures were the same pseudomorphic $Al_{0.25}Ga_{0.75}As/In_{0.28}Ga_{0.72}As$ devices. Fig. 2 is a schematic of the optical mixer/amplifier circuit. The test fixture was equipped with dc to 65 GHz coaxial connectors at both the input and the output. Light from the two lasers was injected into the HEMT using optical fibers. The optical mixing signal from the discrete HEMT device was amplified by the MMIC and launched into waveguide. Fig. 3 is a recording of a received signal at 60.395 GHz. A signal-to-noise ratio of > 55 dB is obtainable. Based on the microstrip to waveguide transition losses and the mixer conversion losses, the optically generated millimeter wave power was estimated to be > 0.3 μW. This represented a 300-fold increase in power from our previous experiments using GaAs

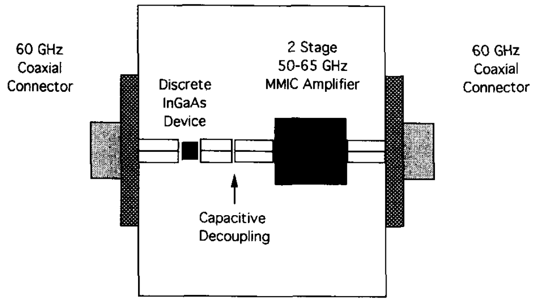

Fig. 2. Diagram of optical mixer/amplifier circuit. The devices were mounted with 50 Ω microstrip and dc to 65 GHz microstrip to coaxial connectors.

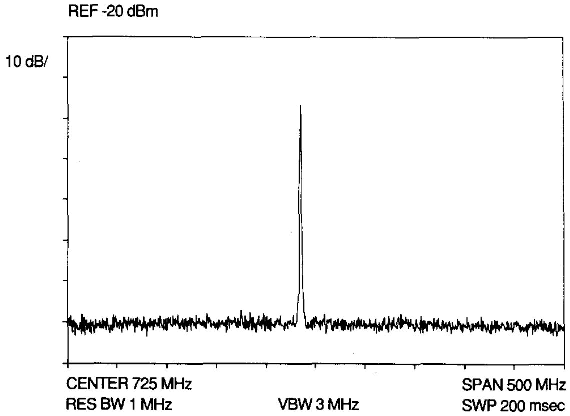

Fig. 3. Recording of measured signal at 60.395 GHz. The optically generated millimeter wave power was estimated to be $> 0.3\ \mu$W and the 3 dB linewidth of the signal was 3 MHz.

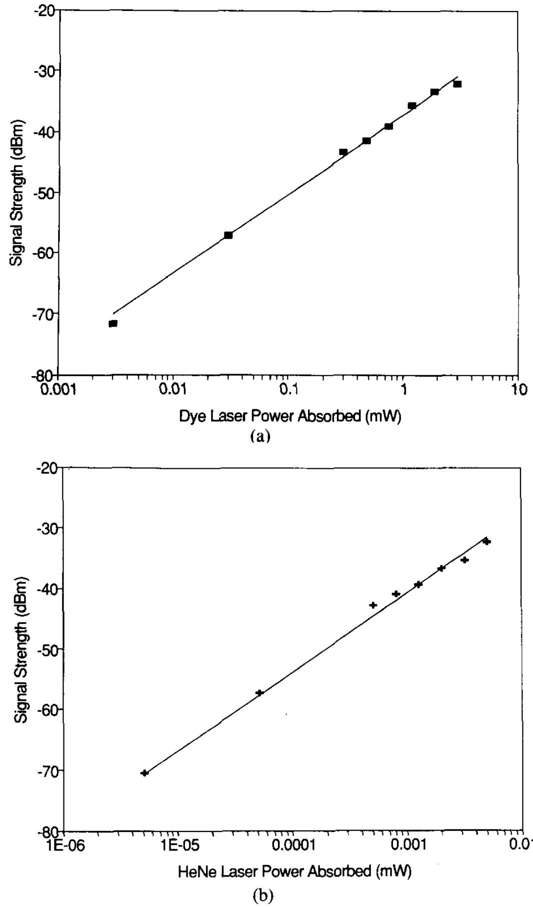

Fig. 4. (a) Signal strength versus dye laser power (He-Ne laser power fixed at 3.4 μW absorbed). (b) Signal strength versus He-Ne laser power (dye laser power fixed at 2.0 mW absorbed). The slopes of the lines fitted to the data were the same indicating that the optical illumination levels for both lasers was in the small signal regime.

MESFET's. It is worth noting that in these experiments the optically generated millimeter waves could have been launched from a horn for use in free space propagation experiments. The electrical performance of the circuit was measured from 50 to 65 GHz. The circuit had gain from 56 to 61 GHz with a peak gain of 7.75 db at 58.5 GHz. The bandwidth of the optically generated millimeter waves was also measured and we found that it extended from 49 to 67 GHz. The optimum signals, signal-to-noise ratios greater than 40 dB, were measured from 57.5 to 62 GHz which correlated well with the electrical measurements.

Using this circuit, quantitative measurements of the optical mixing efficiency versus polarization orientation were made. The data were taken using a lens to focus the light onto the device. As is expected from optical heterodyne theory [14], the signal strength was optimized when the beams were collinearly polarized. The decrease in signal strength for orthogonal beams was 25 dB. Based on these measurements, using polarization preserving fibers is preferred, although not essential to excite the optical mixer/amplifier. Using nonpolarization preserving fibers in which the polarization states were allowed to mix, we obtained a signal to noise ratio of 45 dB.

Next, the mixing efficiency versus intensity of the two lasers was examined. Fig. 4(a) and (b) are log/log plots of the signal strength versus dye laser and He-Ne laser power, respectively, coupled into the device while the second laser power was held constant. The slopes of the lines which were fit to the data are the same. This is expected from optical heterodyne theory, which predicts that the optical mixing output power is linearly proportional to the input signal power. Because the date do not show any saturation behavior, we concluded that the optical illumination levels for both lasers was in the small signal regime. These results also indicated that improved optical coupling efficiency could provide larger millimeter wave powers.

Conclusions

In summary, we have generated useful amounts of millimeter wave power using HEMT's in conjunction with quasi-optical antennas and MMIC's. Direct modulation of the gate produced RF sidebands on the optically generated carrier. The characteristics of the optical mixing were studied and the results agree well with what is expected from optical heterodyne theory. Based on the optical mixing power versus optical input power measurements, similar experiments can be done using low-power, frequency stabilized laser diodes which have temperature tunability over millimeter wave frequencies.

References

[1] P. R. Herczfeld, Guest Ed., "Special issue on applications of lightwave technology to microwave devices," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, 1990.

[2] R. Simons, *Optical Control of Microwave Devices.* Boston and London, Artech House, 1990.

[3] A. J. Seeds and A. A. A. de Salles, "Optical control of microwave semiconductor devices," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, pp. 577-585, 1990.

[4] P. C. Chao, *et al.*, "DC and microwave characteristics of sub-0.1-μm gate-length planar doped pseudomorphic HEMT's," *IEEE Trans. Electron Devices*, vol. 36, pp. 461-471, 1989.

[5] G. J. Simonis and K. G. Purchase, "Optical generation, distribution, and control of microwaves using laser heterodyne," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, pp. 667-669, 1990.

[6] D. V. Plant, D. C. Scott, D. C. Ni, and H. R. Fetterman, "Generation of millimeter-wave radiation by optical mixing in FET's integrated with printed circuit antennas," *IEEE Microwave Guided Wave Lett.*, vol. 1, pp. 132-134, 1991.

[7] K. L. Tan, R. M. Dia, D. C. Streit, L. K. Shaw, A. C. Han, M. D. Sholley, P. H. Liu, T. Q. Trinh, T. Lin, and H. C. Yen, "60-GHz pseudomorphic AlGaAs/InGaAs low-noise HEMT's," *IEEE Electron Device Lett.*, vol. 12, pp. 23-25, 1991.

[8] R. N. Simons and K. B. Bhasin, "Analysis of optically controlled microwave/millimeter wave device structures," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 1349-1355, 1986; R. N. Simons, "Microwave performance of an optically controlled AlGaAs/GaAs high electron mobility transistor and GaAs MESFET," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 1444-1445, 1987.

[9] C. Y. Chen, A. Y. Cho, C. G. Bethea, P. A. Garbinski, and B. F. Levine, "Ultrahigh speed modulation-doped heterostructure field-effect photodetectors," *Appl. Phys. Lett.*, vol. 42, pp. 1040-1042, 1983; C. Y. Chen, Y. M. Pang, A. Y. Cho, and P. A. Garbinski, "New minority hole sinked photoconductive detector," *Appl. Phys. Lett.*, vol. 43, pp. 1115-1117, 1983.

[10] T. Umeda, Y. Cho, and A. Shibatomi, "Picosecond HEMT photodetector," *Japan. J. Appl. Phys.*, vol. 25, pp. L801-L803, 1986.

[11] P. R. Herczfeld and A. S. Daryoush, "Recent developments related to an optically controlled microwave phased array antenna," *Proc. SPIE*, vol. 996, pp. 108-115, 1988.

[12] R. B. Darling and J. P. Uyemura, "Optical gain and large-signal characteristics of illuminated GaAs MESFET's," *IEEE J. Quantum Electron.*, vol. QE-23, pp. 1160-1171, 1987.

[13] L. K. Shaw, D. Brunone, T. Best, B. Nelson, W. Jones, D. Streit, and P. Liu, "A monolithic 60 GHz multistage InGaAs HEMT low noise amplifier," in *Tech. Dig. 15th Internat. Conf. Infrared Millimeter Waves*, 1991, pp. 523-525.

[14] M. C. Teich, "Infrared heterodyne detection," *Proc. IEEE.*, vol. 56, pp. 37-46, 1968.

Simultaneous Thickness and Group Index Measurement Using Optical Low-Coherence Reflectometry

W. V. Sorin and D. F. Gray

Abstract—**Using high-resolution optical reflectometry, group index and physical thickness can both be determined by precisely measuring optical time delays through a sample. Optical low-coherence reflectometry offers both the high-spatial resolution and large dynamic range required to perform accurate measurements using this technique.**

Introduction

Optical low-coherence reflectometry (OLCR), which is also referred to as white-light interferometry or optical coherence domain reflectometry, has recently become a popular technique for characterizing closely spaced reflections in optical components [1]-[4]. Optical low-coherence reflectometry can resolve surfaces spaced by less than 10 μm [2] and can detect optical power reflectivities as low as -136 dB [5]. In this letter we show how the combination of high-spatial resolution and large dynamic range provides a means for simultaneous measurement of both the physical thickness and group index of reasonably transparent objects. This technique has the potential to provide thickness measurements with accuracies of less than 0.1 μm [6] and group index measurements with accuracies on the order of 10^{-5} to 10^{-6} [7] depending on sample size. Possible applications include testing for quality control in production environments and characterization of materials through group index measurements. This technique also provides a quick and simple measurement method for research and development applications.

Theory

Two optical path length measurements are required to determine both the physical distance and group index (i.e.,

Manuscript received September 23, 1991; revised October 17, 1991.
The authors are with Hewlett-Packard Laboratories, Palo Alto, CA 94303.
IEEE Log Number 9105202.

1041-1135/92$03.00