Use of Picosecond Optical Pulses and FET's Integrated with Printed Circuit Antennas to Generate Millimeter Wave Radiation

D. C. Ni, D. V. Plant, M. Matloubian, and H. R. Fetterman

Abstract—**Millimeter wave radiation has been generated from FET's and HEMT's, integrated with printed circuit antennas, and illuminated with picosecond optical pulses. Modulation of the millimeter waves was achieved by applying a swept RF signal to the transistor gate. Using this technique, tunable electrical sidebands were added to the optically generated carrier providing a method of transmitting information and doing high resolution spectroscopy. Heterodyne detection demonstrated that the system continuously generated tunable radiation, constrained by the high gain antenna, from 45 to 75 GHz.**

RECENT experiments have shown that optoelectronic switches monolithically integrated with planar antenna structures can be used to generate electromagnetic radiation in the microwave and millimeter wave regions [1]–[3]. In these experiments, an optical pump and probe arrangement is used to coherently generate and sample the microwave and millimeter wave radiation. The bandwidth of these systems, when driven by picosecond optical pulses, is from below 10 GHz to greater than 200 GHz [4], [5]. Femtosecond optical pulses have now been used to extend this frequency coverage to greater than 2.0 THz [6]. Measurements of the transient far-field radiation properties of integrated optoelectronic antennas have provided both the temporal and spatial characteristics of these devices [7]. Spectroscopic applications of these systems include measurements of the frequency dependent loss and dispersion properties of materials in the 10–130 GHz range, with a frequency resolution of 4.94 GHz [5]. In addition, the optical generation and control of millimeter waves has attracted considerable attention because its importance in distributed communications and radar systems [8], [9].

In this letter, we report an alternative approach to the two terminal switch concept for generating millimeter waves which utilizes three terminal devices integrated with printed circuit antennas. This technique employs GaAs FET's and AlGaAs-GaAs HEMT's mounted with printed circuit antennas and illuminated with picosecond optical pulses. Unlike two terminal devices, using three terminal devices provides a way of both optimizing output and incorporating information signals on the carrier signal. Also, using three terminal devices improves the signal power since the devices are driven an order of magnitude lower in impedance by the light than the switches.

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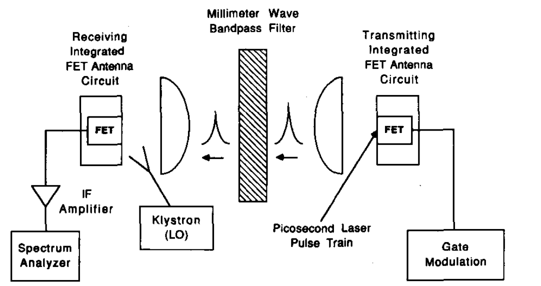

Fig. 1. Schematic of the experimental setup. The optical beam was injected onto the device at an angle of 30° with respect to the plane of the transmitting antenna, and the teflon lenses were separated by 10 cm.

Heterodyne detection rather than photoconductive sampling is used to measure the radiation with the measured signals displayed in real time on a spectrum analyzer. Electrical modulation is applied to the transmitter gate and thus produces a tunable sideband on the optically generated carrier. The technique also provides increased resolution for use in spectroscopic applications. The high resolution capabilities of this technique, on the order of 1 MHz, are demonstrated by measuring the transmission response of a narrow bandpass filter.

A schematic representation of the experimental arrangement is illustrated in Fig. 1. FET's (NEC/NE7100) and HEMT's (Rockwell International Science Center) were integrated on printed circuit RT/Duroid microstrip antennas. Identical twin dipole antennas with integrated devices were used both to transmit and to receive the radiation. In the case of the transmitter, the drain and source of the device were connected to the antenna, and in the case of the receiver, the gate and source were connected to the antenna. The full characterization of an integrated FET antenna circuit as a microwave gate mixer has been described previously, and results show the circuit has a conversion loss of approximately 6 dB when used as a heterodyne detector [10].

In these experiments, the active region of the transmitting device was illuminated by 1.5 ps, 578 nm optical pulses obtained from a synchronously pumped mode-locked Rhodamine 6 G dye laser (Coherent 701-2). The dye laser pump source was an actively mode-locked frequency doubled Nd:YAG laser operating at 76 MHz (Coherent Antaries). The active region of the device was excited by 50 to 150 mW of average power focused to 10 μm in diameter with a 5 × lens. Using a sweep oscillator, a RF electrical modulation was applied to the transmitter gate. A klystron, tunable from 55.5 to 62.0 GHz, was used as a local oscillator for heterodyne detection of the radiation. Two teflon lenses with 25.4 mm focal lengths were placed between the

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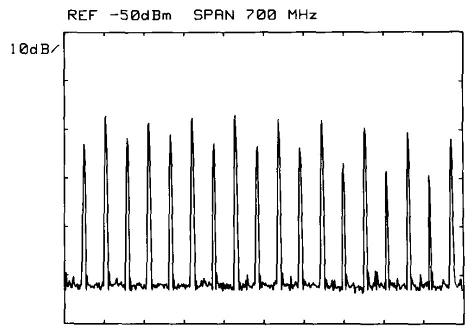
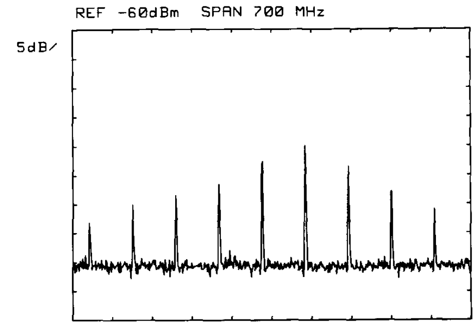


Fig. 2. Millimeter wave radiation comb produced by optical excitation for a local oscillator frequency of 61.4 GHz. Signals located in the upper sideband (61.52 to 63.02 GHz) are the larger amplitude signals, and signals located in the lower sideband (59.78 to 61.28 GHz) are the lower amplitude signals.

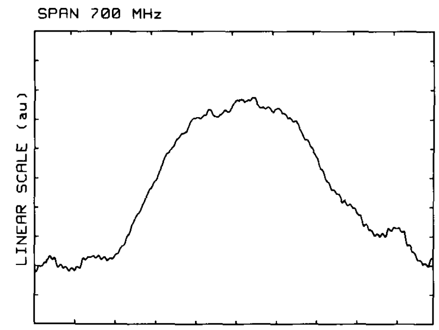
transmitter and the receiver to create a collimated beam into which millimeter wave filters were inserted. The detected output from the receiver was sent through various IF amplifiers (0.75–2 GHz with a gain of 37 dB, and 6–18 GHz with a gain of 25 dB) and displayed in real time on a spectrum analyzer. A Hewlett Packard 9836 computer was used for data acquisition and processing.

The repetitive picosecond excitation produces a millimeter wave radiation comb whose signals are spaced at the laser mode-locking frequency (76 MHz). Because heterodyne detection is used, mixed signals which fall within the bandwidth of the IF amplifier from both the high- and the low-frequency side of the local oscillator will be detected. This is seen in Fig. 2 where a spectrum analyzer trace of the detected radiation for a local oscillator frequency of 61.4 GHz is shown. These data were taken using the 0.75–2 GHz IF amplifier and the devices biased as follows: the transmitting FET with $V_{ds} = 2.0$ V and $V_{gs} = -3.0$ V, and the receiving FET with $V_{ds} = 2.0$ V and $V_{gs} = -0.6$ V. By tuning the local oscillator $+/-$ 5.0 MHz the signals located in the upper sideband could be distinguished from those located in the lower sideband. In Fig. 2, the larger amplitude signals are in the upper sideband (61.52–63.02 GHz) and the lower amplitude signals are in the lower sideband (59.78–61.28 GHz). Using various IF amplifiers, we measured the bandwidth of the radiation comb and found it extended from 45 to 75 GHz. The average power in the millimeter wave beam was also measured using a slow response time liquid helium cooled silicon bolometer, and this measurement yielded an estimated power of > 100 nW.

Next, an electrical modulation was applied to the transmitter gate in addition to the dc bias, and this RF modulation produced tunable sidebands on the millimeter wave radiation. These sidebands could be used to completely fill in the transmission spectrum of a millimeter wave bandpass filter. In order to demonstrate this capability, we placed a Fabry–Perot interferometer with a narrow passband into the millimeter wave beam. The filter consisted of two 50 lines/inch metal meshes mounted on optically flat retaining rings. Fig. 3(a) is a spectrum analyzer trace of the transmission response of this filter without gate modulation. The filter both rejects the signals in the lower sideband (the lower amplitude signals in Fig. 2) and filters the signals in the upper sideband that are out of the passband of the filter. Fig. 3(b) is spectrum analyzer trace of the filter after applying a swept electrical modulation to the transmitting FET



(a)



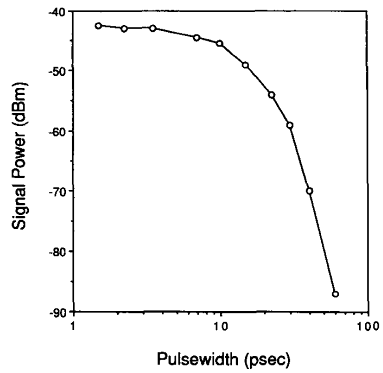
(b)

Fig. 3. (a) Transmission response of a metal mesh Fabry–Perot interferometer without transmitter gate modulation. The filter is tuned to 62.27 GHz, and the local oscillator is tuned to 61.4 GHz. The filter rejects signals in the lower sideband and filters signals in the upper sideband that fall outside the passband. (b) Transmission response of the same filter with a swept 0 dBm electrical modulation applied to the transmitting FET antenna circuit. This result demonstrates the high spectral resolution obtainable with this technique.

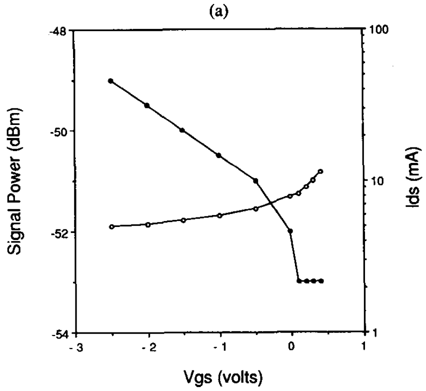
gate. The filter is tuned to approximately 62.27 GHz and has a FWHM of approximately 250 MHz, which is in good agreement with the calculated finesse. This result demonstrates the high spectral resolution obtainable with this technique.

Measuring the radiating millimeter wave signal strength under various conditions of bias and illumination also provides a method of optimizing the transmitting device's frequency response. Studies of the pulsed response of FET's and HEMT's have shown that the intrinsic device speed can be improved by increasing the negative gate bias [11], [12]. The components of the signal power at 60 GHz were measured as a function of both pulse width and gate bias. Fig. 4(a) is plot of signal power versus optical pulse width for an enhancement type HEMT. If a hypersecant shaped optical pulse is assumed, the 3 dB point of the device performance is 7 ps. This value corresponds to a 70 GHz bandwidth, which is in good agreement with the device specifications. The frequency response of the device can be enhanced by appropriate biasing of the gate terminal, as shown in Fig. 4(b) where a plot of signal power and drain current versus gate bias is shown. For a gate bias of -2.5 V, the power of the received signal is increased by 4 dB over a zero bias condition.

In conclusion, we have demonstrated a technique for generating high power millimeter wave radiation utilizing active three terminal devices rather than two terminal switches. In addition, application of an electrical sideband to the optically generated



(a)



(b)

Fig. 4. (a) Signal power at 60 GHz versus optical pulsewidth, and (b) signal power at 60 GHz (dark circles), and transmitter drain current I_{ds} (light circles), versus gate bias (V_{gs}) for an enhancement type HEMT.

carrier provided a method of transmitting information and increasing spectral coverage. Signals were detected in real time thus eliminating the need for photoconductive sampling and Fourier transforming the detected transient radiation. Although fundamental mixing with the local oscillator frequency was used, detecting the millimeter wave radiation could also be accomplished using harmonics of a lower frequency local oscillator. Signals could be applied via a coaxial cable to the receiver gate at subharmonics of the desired local oscillator frequency, thus eliminating the need for a high frequency source.

The bandwidth of the radiation was limited primarily by the high-gain antenna and future improvements to this technique include broad-band, high-frequency antennas integrated with high-speed three terminal devices. Recently, work has been done to characterize some of the optical and electrical properties of FET's, HEMT's, and HBT's, and the results of these investigations indicate such devices have gain at frequencies in excess of 100 GHz [13]. Integrating high-speed three terminal devices with broad-band antennas could potentially lead to complete frequency coverage up to 300 GHz. Tailoring the transmitting device to increase optical absorption will also increase signal strength. In addition, more efficient coupling of the light into the devices's active region can be accomplished using fiber optics. An array of device/antenna circuits, driven by light, and modulated electrically could potentially provide a way of constructing a pulsed, optically controlled millimeter wave transmission system.

Acknowledgment

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