Generation of Millimeter-Wave Radiation by Optical Mixing in FET's Integrated with Printed Circuit Antennas

D. V. Plant, D. C. Scott, D. C. Ni, and H. R. Fetterman

Abstract—**Using optical mixing, we have demonstrated the generation of continuous wave 60-GHz millimeter wave radiation from FET's integrated with planar antennas. The radiation was propagated through narrow band quasi-optical Fabry–Perot filters and heterodyne detected in a second FET antenna structure. In addition to spectroscopic applications, this transmitter/receiver system demonstrates the feasibility of having optically fed arrays of millimeter wave sources.**

OPTICAL control of microwave and millimeter-wave devices has attracted recent attention because of potential applications that involve both the advantages of optical interconnections and microwave propagation. Various control functions including gain control of amplifiers, oscillation tuning, locking and frequency modulation, switching, optical mixing, and optically induced negative photoconductivity have already been demonstrated [1]–[6]. In this letter, we report the first generation and propagation of 60-GHz tunable, continuous wave millimeter-wave radiation using optical mixing in integrated GaAs FET printed circuit structures. The optically generated and transmitted millimeter-wave radiation was detected with a highly sensitive FET antenna circuit using heterodyne detection techniques.

Previously, we demonstrated coherent mixing of optical radiation in FET's, HEMT's, and related three terminal devices [3]. This technique was then extended to 64 GHz using a GaAs FET integrated with a printed circuit antenna, which was designed to couple to millimeter wave frequencies [5]. This configuration permitted direct injection of a fundamental local oscillator and the optical radiation simultaneously to the device active region and demonstrated the mixing capability of these devices at high frequencies. In the series of experiments reported here, the active region of a GaAs FET antenna circuit is illuminated simultaneously by optical radiation from a CW dye laser and a stabilized HeNe laser. The difference frequency between these optical signals radiates from the antenna and propagates in free space. It is then detected in a similar planar FET structure. This is the first report of the generation and detection of millimeter wave radiation by optical mixing in these three terminal devices integrated with printed circuit antennas. The use of two FET antenna circuits further demonstrates the capabilities of these circuits in an optically controlled transmitter and receiver system. Based on recent studies of optically controlled phased array antennas, this technique is well suited for applications in such systems [7], [8].

A schematic representation of the experimental arrangement is illustrated in Fig. 1. Commercially available FET's (NEC/NE71000) having gate lengths of 0.3 μm and drain to sources distances of 2 μm were integrated on printed circuit RT/Duroid microstrip antennas. Identical twin dipole antennas with integrated FET's were used not only to transmit, but also to receive the radiation. However, in the case of the transmitter, the drain and source of the FET were connected to the antenna, while in the case of the receiver, the gate and source were connected to the antenna. The full characterization of the 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 [9].

The transmitting FET was illuminated with light from a Kiton Red dye laser (600 nm to 640 nm, 400 mW) and a frequency stabilized HeNe laser (632.8 nm, 0.6 mW). The penetration depth of these lasers is about 0.3 μm, which is of the same order as the thickness of the active region of the FET, and therefore sufficient to excite the GaAs active layer. The wavelength of the dye laser was locked to an external temperature stabilized Fabry–Perot reference cavity. The wavelength of the laser was monitored with both an optical wavemeter that had 0.001 nm resolution (< 1.0 GHz), and an optical spectrum analyzer that had a 30-GHz free spectral range. The linewidth and stability of both lasers was typically less than 2 MHz. The beams were combined using a variable beam splitter which permitted changing the ratio of dye laser power to the HeNe laser power. In these experiments, the transmitting FET active region was excited by 20 to 80 milliwatts (25–100 kW/cm^2) from the dye laser and 0.15 to 0.36 milliwatts (200–450 W/cm^2) from the HeNe laser. Using a lens, the beams were focused to a spot size of 10 μm in diameter. A reflex klystron, tunable from 55.5 to 62 GHz was used as a local oscillator for heterodyne detection of the radiation. The detected signal output from the receiving FET

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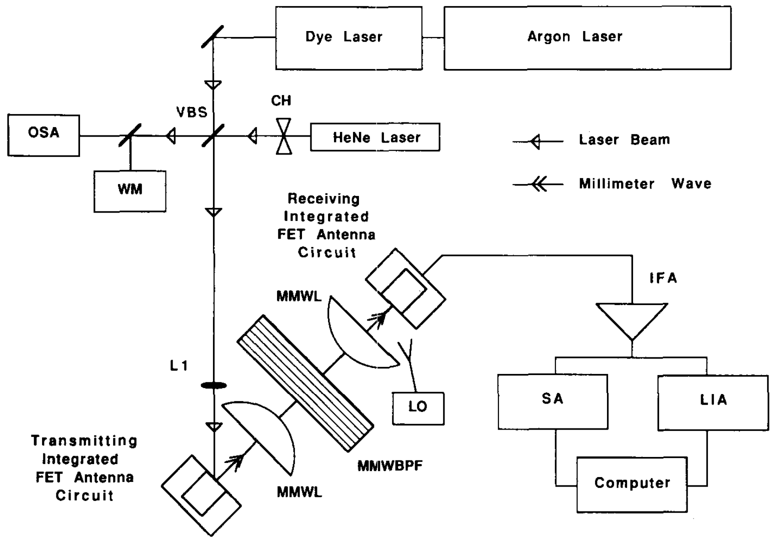

Fig. 1. Schematic of the experimental set-up. VBS, variable beam splitter; OSA, optical spectrum analyzer (30 GHz FSR); WM, wavemeter; L1, 25-mm focal length lens; MMWL, millimeter wave lens; MMWBPF, millimeter wave bandpass filter; IFA, 0.75-2.0 GHz 25-dB gain amplifier; LO, 55.5-62.0 GHz reflex klystron local oscillator; SA, spectrum analyzer; LIA, lock-in amplifier. Optical beam was injected into the device at an angle of 45 degrees with respect to the plane of the transmitting antenna. Teflon lenses were separated by 10 cm.

antenna circuit was sent through an IF amplifier (0.75-2.0 GHz with a gain of 25 db) and displayed on a spectrum analyzer. Two teflon lenses with 25.4 mm focal lengths were placed between the transmitter and the receiver to create a 10-cm long collimated beam into which millimeter wave filters were inserted. A Hewlett Packard 9836 computer was used for data acquisition and processing.

The optical excitation produces continuous wave, tunable, millimeter wave radiation that is optimized at 60 GHz due to the performance of the high gain antenna. A recording of a received signal at 60.25 GHz is shown in Fig. 2. Here, the transmitting FET was illuminated by 80 mW from the dye laser and 0.15 mW from the HeNe laser. The local oscillator is tuned to 61.54 GHz and is irradiating the receiving FET antenna circuit with approximately 25 mW of power. For this data, the devices are biased as follows: The transmitting FET was biased with $V_{ds} = 2.0$ V and $V_{gs} = -2.0$ V and the receiving FET was biased with $V_{ds} = 2.0$ V and $V_{gs} = -0.6$ V. In the case of the transmitter the device is biased below pinchoff (pinchoff voltage for this device at $V_{ds} = 2.0$ V is $V_{gs} = -1.1$ V), therefore photoexcited carriers via photoconduction mechanisms are responsible for generating the radiated laser difference frequency. For these FET's, previous studies show that the frequency response of the photoconduction mechanism is faster than that of the photovoltaic mechanism [10]-[12]. The typical achievable signal to noise ratio for experimental conditions similar to those of Fig. 2 was 30-35 db. Based on the receiver conversion losses and the millimeter-wave collecting optics, the power in the millimeter-wave beam was estimated to be 1 nW. The polarization of the radiation was measured and found to be linearly polarized as was expected from antenna design considerations.

In an effort to determine the lower limits at which the millimeter-wave radiation could be generated, the ratio of the laser powers was varied. Although a complete study of the performance of the transmitting FET antenna circuit under various conditions of bias and illumination is necessary, preliminary results indicate that the mixing and re-radiation mechanisms require only modest levels of optical power. A S/N of 13 dB was achieveable with 20 mW of dye laser power and 0.38 mW of HeNe laser power. Conversely, saturation of the radiating signal strength was observed for dye laser powers in excess of 60 mW indicating a saturation of carriers in the active region of the transmitting device. Also, measurements of the radiating signal strength versus the orientation of the two laser's polarization showed that the optical mixing mechanism is optimized when the two beams are colinearly polarized. This result is critical with respect to the use of a fiber optic light delivery system, and experiments are currently under way using single-mode polarization-preserving fibers. This delivery system will be particularly useful in optically controlled phased array applications that are not limited by fiber-optic losses.

As a demonstration that we have tunable, narrow-band millimeter-wave radiation, we measured the response of a tunable Fabry-Perot interferometer. The filter consisted of two 50-lines/inch metal meshes mounted on optically flat retaining rings. The filter response was measured by tuning the dye laser and therefore, tuning the millimeter-wave radia-

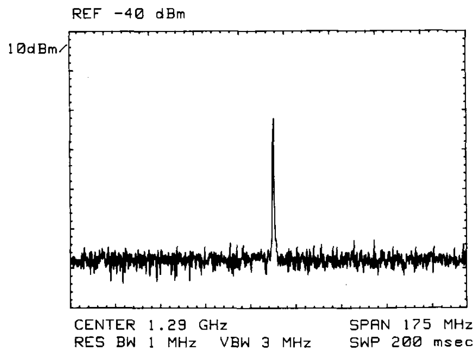

Fig. 2. Spectrum analyzer trace of the received millimeter-wave radiation at 60.25 GHz. Local oscillator is at 61.54 GHz. Transmitting FET was illuminated by 80 mW of dye laser power and 0.15 mW of HeNe laser power.

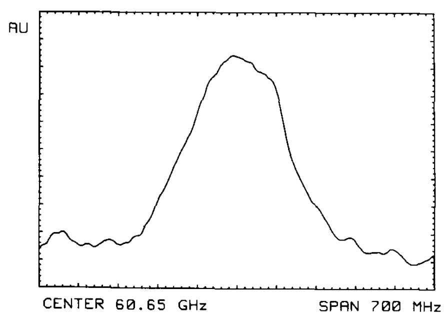

Fig. 3. Transmission response of a metal mesh Fabry-Perot interferometer tuned to resonance at 60.65 GHz. The response is measured by tuning the dye laser and therefore, tuning the millimeter-wave radiation frequency through the passband of the filter. Data were taken with a lock-in time constant of 1.0 second.

tion through the passband of the filter. The signal from the receiving FET was measured using a lock-in amplifier. The lock-in reference channel was locked to the chopped HeNe laser. Fig. 3 shows a recording of the response of the filter. The filter center frequency is at 60.65 GHz, and the full width at half maximum of the filter is 220 MHz. This is in good agreement with the calculated value.

Because the bandwidth of the radiation is limited primarily by the high gain antenna, future improvements to this technique will include the use of broadband, high frequency antennas integrated with high-speed three-terminal devices. Cascading devices will provide optical mixing signal amplification prior to driving the antenna. Based on the preliminary study of the performance of the transmitting FET antenna circuit under varying conditions of illumination, our results indicate that low power, frequency stabilized, infrared semiconductor lasers could be used to replace the CW dye and HeNe lasers thus providing alternative compact light sources. Finally, this letter demonstrates the potential of converting millimeter-wave signals on light directly into propagating millimeter wave radiation using planar FET structures. It should now be possible to make arrays of distributed sources using this technology.

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