MILLIMETER WAVE RADIATION GENERATED BY OPTICAL MIXING IN FETs INTEGRATED WITH PRINTED CIRCUIT ANTENNAS

by

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ABSTRACT

Millimeter wave radiation has been generated from FETs and HEMTs, integrated with printed circuit antennas, and illuminated with both pulsed and CW laser radiation. In the pulsed laser experiments, the repetitive picosecond (2.0 psec) excitation produced a millimeter wave radiation comb. 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. Using CW lasers, tunable millimeter wave radiation was generated by coherent mixing of the optical radiation in GaAs FETs integrated with printed circuit antennas. Employing a CW Kiton Red dye laser (600nm-640nm) and a frequency stabilized HeNe laser, this arrangement produced continuously tunable millimeter wave radiation optimized at 60 GHz. Planar twin dipole microstrip antennas with integrated FETs were used both to transmit and to receive the radiation. In a demonstration experiment, the millimeter wave radiation was propagated through narrow band quasi-optical Fabry-Perot filters and detected using heterodyne techniques.

I INTRODUCTION

Optical control of microwave and millimeter wave devices has attracted recent attention because of potential applications which 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 paper, we report the generation and propagation of pulsed and continuous wave millimeter wave radiation using optical mixing in integrated GaAs FET printed circuit structures. In both cases, the optically generated and transmitted millimeter wave radiation was detected in real time with a highly sensitive FET antenna circuit using heterodyne detection techniques.

Previously, we demonstrated coherent mixing of optical radiation in FETs, HEMTs, 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 frequency 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 free space propagation of millimeter wave radiation using 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).

II PULSED LASER EXCITATION

Initial experiments aimed at generating millimeter wave radiation were performed via pulsed laser excitation. A schematic representation of the experimental arrangement is illustrated in Figure 1. FETs (NEC/NE7100) and HEMTs (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. However, 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(8).

In the pulsed excitation experiments, the active region of the transmitting device was illuminated by 2.5 picosecond, 578nm optical pulses obtained from a synchronously pumped mode-locked Rhodamine 6G dye laser. The dye laser pump source was an actively mode-locked frequency doubled Nd:YAG laser operating at 76 MHz. The active region of the device was excited by 50 to 150 milliwatts of average power focused to 10 μm in diameter with a 5X lens. Using a sweep oscillator, a RF electrical modulation was applied to the transmitter gate. A reflex klystron, tunable from 55.5 GHz 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 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 (.75 - 2 GHz with a gain of 25 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 Figure 2, where a spectrum analyzer trace of the detected radiation for a local oscillator frequency of 61.4 GHz is shown. This data was taken using the .75 - 2 GHz IF amplifier and the devices biased as follows: the transmitting FET with $V_{ds} = 2.0V$ and $V_{gs} = -3.0V$, and the receiving FET with $V_{ds} = 2.0V$ and $V_{gs} = -0.6V$. 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 Figure 2, the larger amplitude signals are in the upper sideband (61.52 GHz - 63.02 GHz) and the lower amplitude signals are in the lower sideband (59.78 GHz- 61.28 GHz). Using the various IF amplifiers, we measured the bandwidth of the radiation comb and found it extended from 45 GHz 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 nanowatts.

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. Figure 3a 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 Figure 2) and filters the signals in the upper sideband that are out of the passband of the filter. Figure 3b is a spectrum analyzer trace of the filter after applying a swept electrical modulation to the transmitting FET 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.

III CONTINUOUS WAVE LASER EXCITAION

A schematic representation of the continuous wave excitation experimental arrangement is illustrated in Figure 4. The transmitting FET was illuminated with light from a Kiton Red dye laser (600nm to 640nm, 400mW) and a frequency stabilized HeNe laser (632.8nm, 0.6 mW). The penetration depth of these lasers is about 0.3mm, 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 which had 0.001 nm resolution (<1.0 GHz), and an optical spectrum analyzer which 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 $10\mu m$ in diameter. The klystron was used as a local oscillator for heterodyne detection of the radiation. The detected signal output from the receiving FET antenna circuit was sent through the .75 - 2 GHz IF amplifier and displayed on a spectrum analyzer. Again, 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 which 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 Figure 5. 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 $V_{ds} = 2.0V$ and $V_{gs} = -2.0V$, and the receiving FET was biased with $V_{ds} = 2.0V$ and $V_{gs} = -0.6V$. 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 radiating laser difference frequency. For these FETs, previous studies show that the frequency response of the photoconduction mechanism is faster than that of the photovoltaic mechanism(9). The typical achievable signal to noise ratio for experimental conditions similar to those of Figure 5 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 13dB was achievable 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 lasers 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. Using single mode, polarization preserving fiber in place of the lens, we successfully generated millimeter wave radiation using this light delivery system. Laser polarization orientation was controlled by placing a half wave plate in front of the fiber input tip. The output tip was brought to < 1 mm from the device active region and illuminated the device directly. Figure 7 is a typical recording of a received signal using fiber optic light delivery to pump the transmitting device/antenna circuit.

As a demonstration that we have tunable, narrow band millimeter wave radiation, we measured the response of the same tunable Fabry-Perot interferometer. The filter response was measured by tuning the dye laser and therefore, tuning the millimeter wave radiation through the pass band 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. Figure 6 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.

IV CONCLUSIONS

Because the bandwidth of the radiation is limited primarily by the high gain antenna, future improvements to these techniques will include the use of broadband, high frequency antennas integrated with high speed three terminal devices. Devices with F_t's greater than 100 GHz are currently being investigated in this application. 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 paper 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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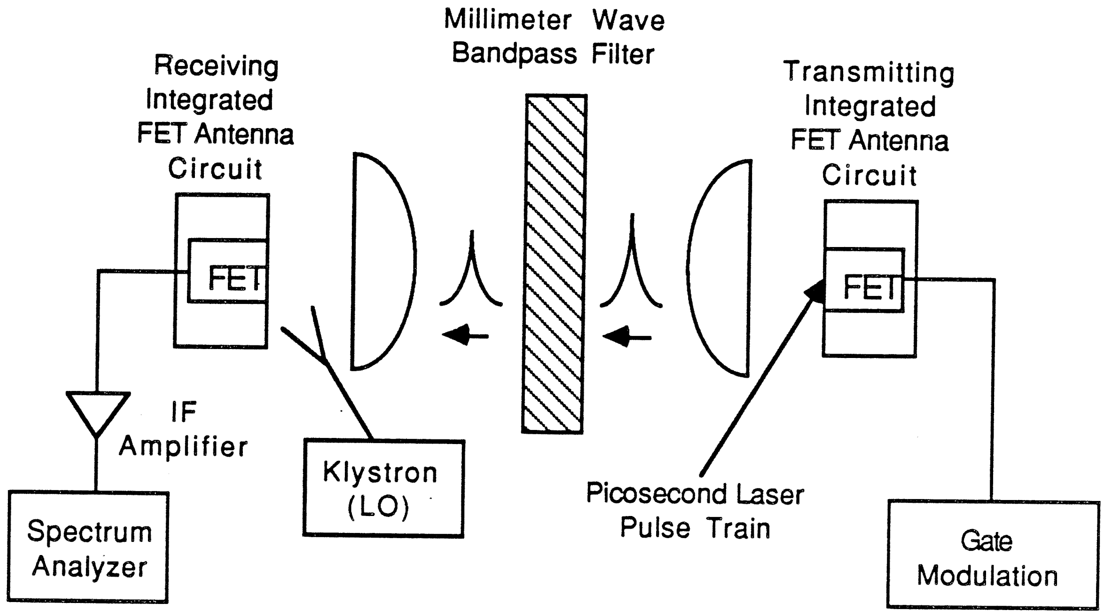

Figure 1: Schematic of the pulsed laser excitation experimental set-up.

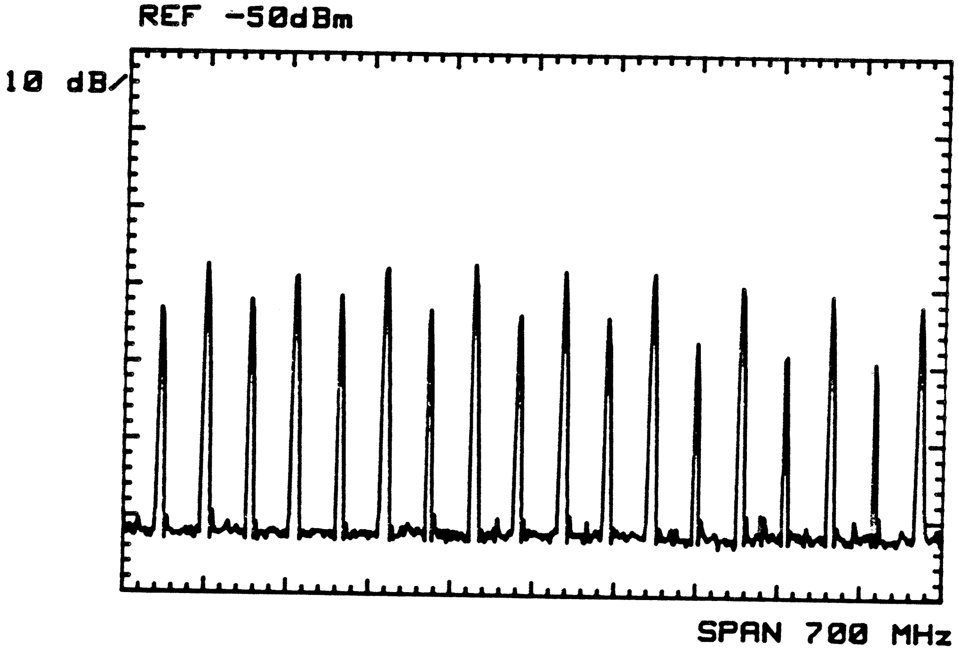

Figure 2: Millimeter wave radiation comb produced by optical excitation for a local oscillator frequency of 61.4 GHz. Signals located in the upper sideband are the larger amplitude signals, and signals located in the lower sideband are the lower amplitude signals.

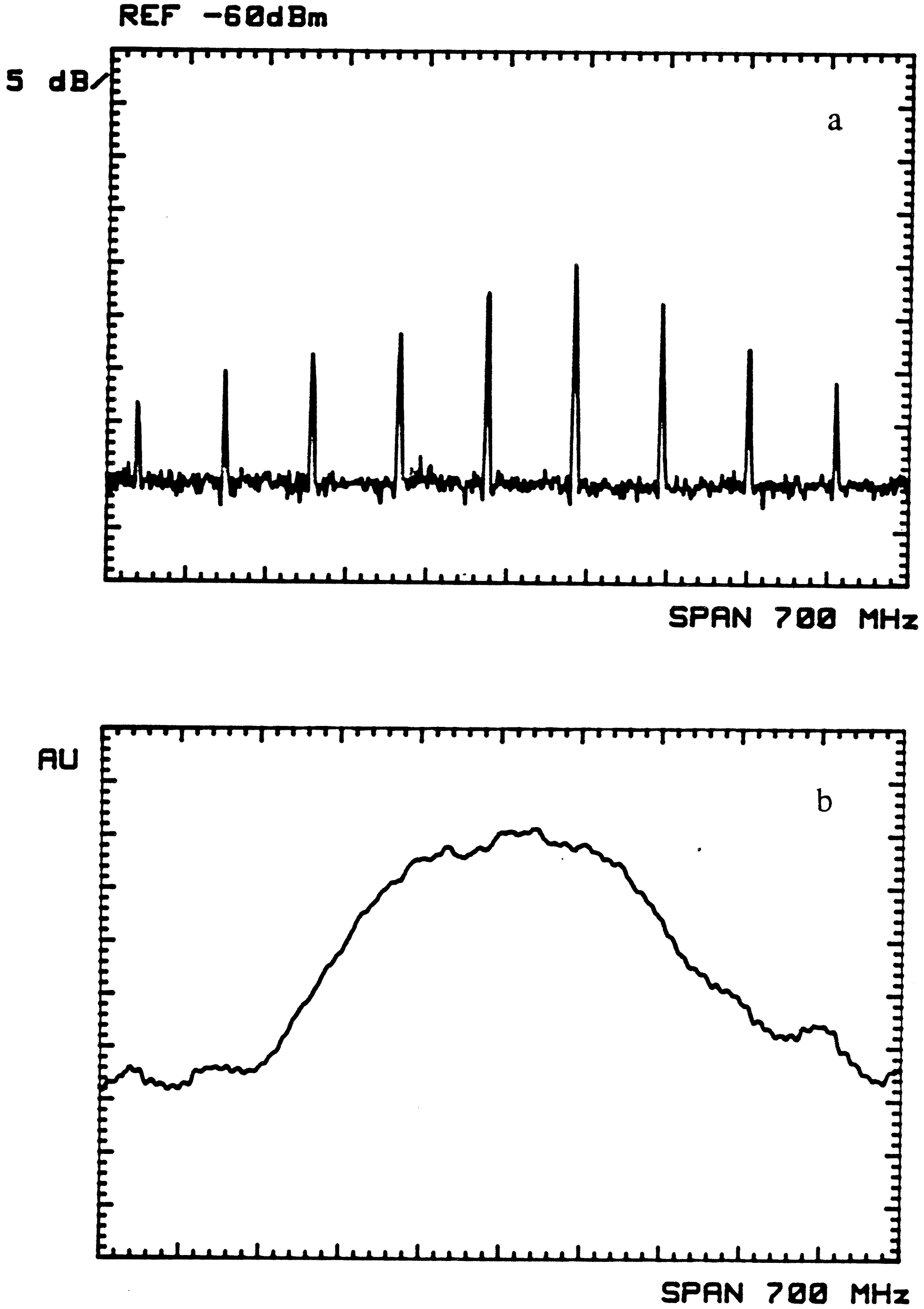

Figure 3: (a)Transmission response of a metal mesh Fabry-Perot interferometer without transmitter gate modulation. Tuned to 62.27 GHz, the filter rejects signals in the lower sideband and filters signals in the upper sideband (b)Transmission response of the same filter with a swept 0 dBm electrical modulation applied to the transmitting FET antenna circuit.

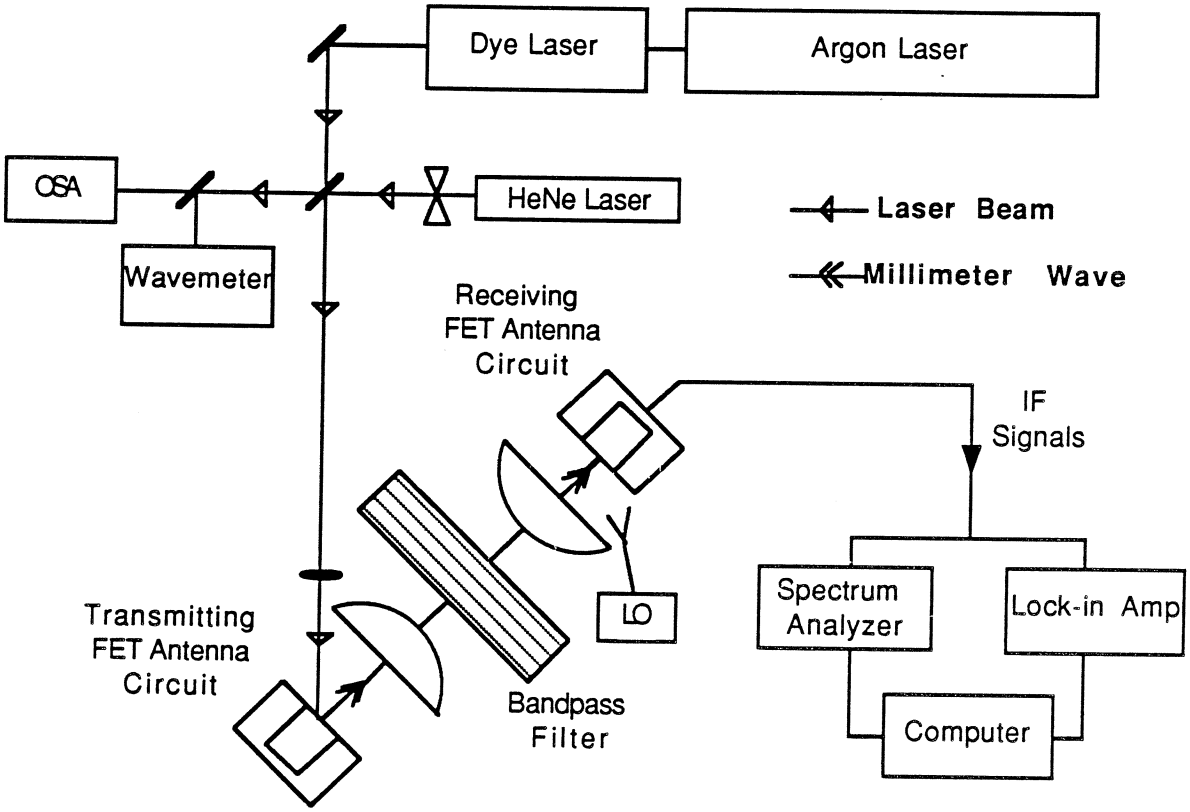

Figure 4: Schematic of the continuous wave excitation experimental set-up.

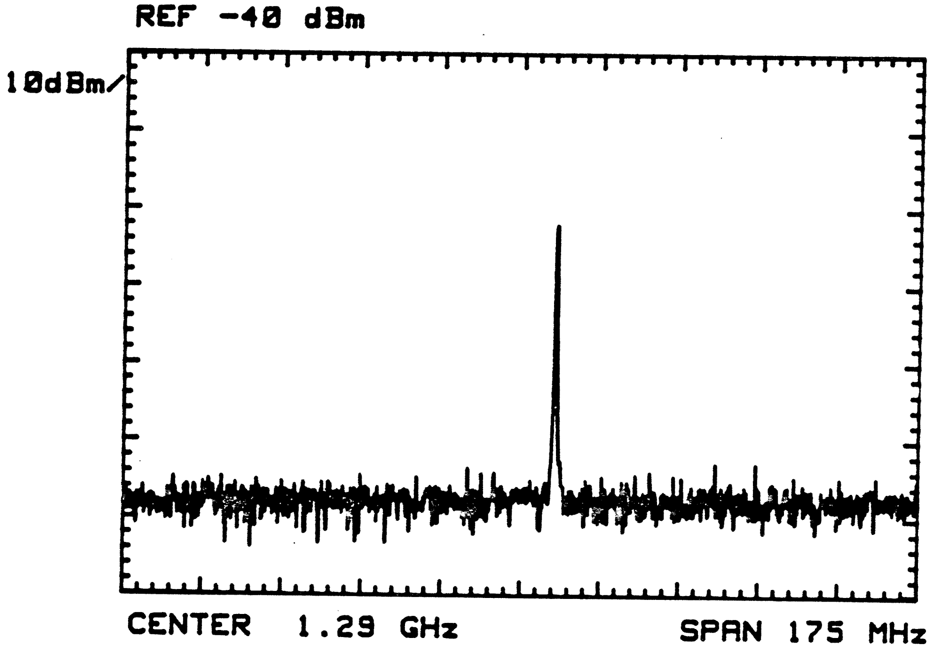

Figure 5: Recording of the received millimeter wave radiation at 60.25 GHz.

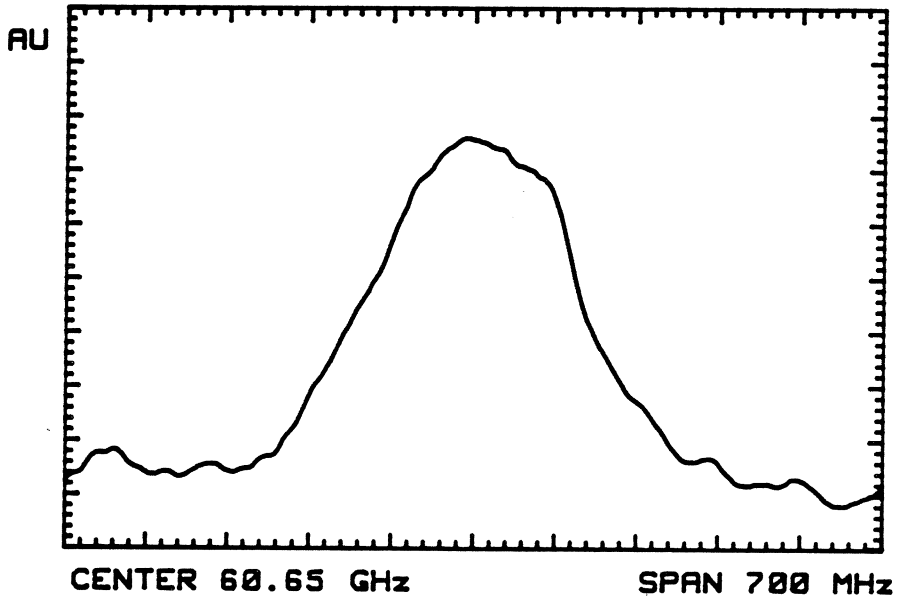

Figure 6: Transmission response of a metal mesh Fabry-Perot interferometer tuned to resonance at 60.65 GHz. Data was taken with a lock-in time constant of 1.0 second.

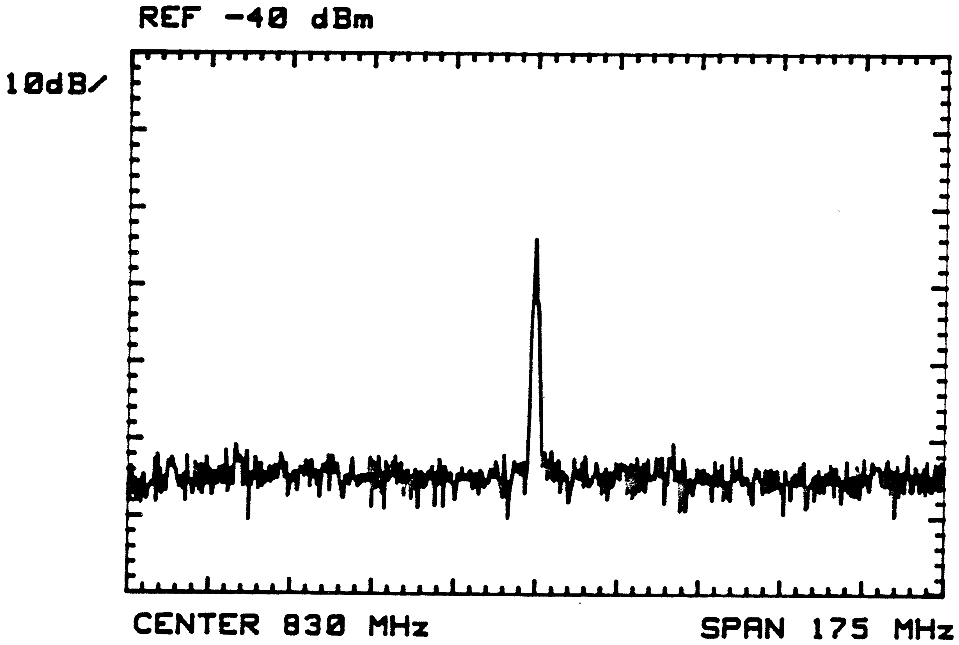

Figure 7: Recording of received millimeter wave radiation at 60.5 Ghz using fiber optic light delivery to pump device/antenna circuit.