Millimeter-Wave Generation and Characterization of a GaAs FET by Optical Mixing

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Abstract **—Coherent mixing of optical radiation from a tunable CW dye laser and a stabilized He–Ne laser was used to generate millimeter-wave signals in GaAs FET's attached to printed circuit millimeter-wave antennas. The generated signal was further down-converted to a 2 GHz IF by an antenna-coupled millimeter-wave LO at 62 GHz. Detailed characterizations of power and S/N under different bias conditions have been performed. This technique is expected to allow signal generation and frequency-response evaluation of millimeter-wave devices at frequencies as high as 100 GHz.**

I. Introduction

OPTICAL CONTROL of millimeter-wave devices has attracted recent attention because of its potential applications, such as enhancement of device performance, signal switching, signal synchronization, and distributed control of communications and radar systems [1]–[8]. Recently we demonstrated coherent mixing of optical radiation to generate stable broad-band microwave signals beyond *Ka* band in FET's and related three-terminal devices [9]–[10]. In this paper we describe the use of this optical mixing technique to generate a 64 GHz signal in a GaAs FET with an integrated printed-circuit antenna designed for quasi-optical millimeter-wave applications [11]. This configuration permits the direct coupling of a millimeter-wave local oscillator (LO) through the antenna to the illuminated gate terminal of the GaAs FET. We obtain IF (1–2 GHz) beat signals between the optical beat signal and the millimeter-wave LO (klystron, IMPATT diode, or Gunn diode), which can then be characterized for power and gain.

Using intensity-stabilized and optically tunable lasers together with millimeter-wave sources will allow the generation of signals and the characterization of millimeter-wave devices at frequencies as high as 100 GHz relatively free from the limitations imposed by the mounting fixtures and the related parasitics associated with these devices. In addition to testing, this approach has potential for the generation and heterodyne detection of millimeter waves.

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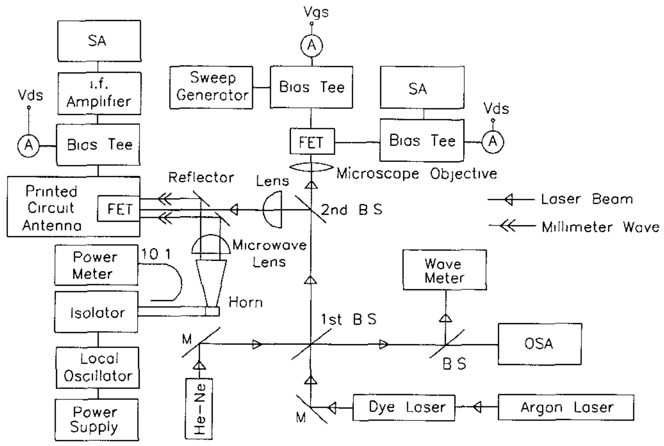

Fig. 1 Experimental setup shows the calibrated FET and the FET in the printed antenna circuit

II. Experiment

The experimental setup is shown in Fig. 1. A stabilized He–Ne laser (model 200/Coherent) and a CW ring dye laser (model 699-21/Coherent) optically pumped by an Ar^+ laser were used to illuminate the GaAs FET's. The penetration depth of these lasers into GaAs is about 0.3 μm, which is the same order as the thickness of the active region of the FET's. The wavelength of the ring dye laser locked to a temperature-stabilized Fabry–Perot was monitored by a Burleigh optical wavemeter which can be continuously tuned to any value within the dye emission spectrum. For the Kiton 620 dye (600–640 nm), the tuning range is more than 40 nm around the He–Ne line. Consequently the beat frequency of the two CW lasers can be easily varied from zero to several hundred GHz while the intensities of the lasers are kept constant.

Generation of optical millimeter-wave beat frequencies requires that the wavelength of the dye laser be very close to the wavelength of the He–Ne laser. A 7.5 GHz optical beat frequency, for example, corresponds to tuning a 0.01 nm wavelength difference between two lasers. Therefore,

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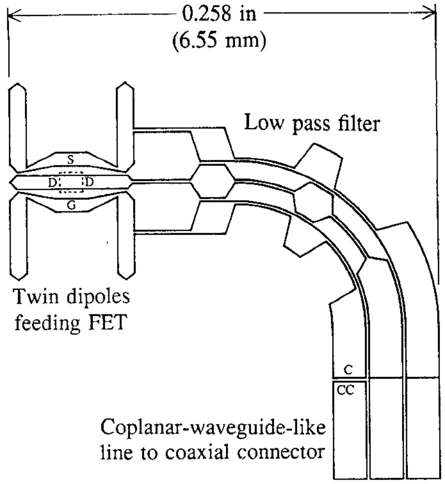

Fig. 2 Pattern of the millimeter-wave antenna FET source, drain, and gate are wire-bonded to points S, D, and G Gate bias chip capacitor is attached at point CC and wire-bonded to point C [11].

an extremely accurate measurement of the frequency difference between the lasers is required to make this technique practical. For final tuning, an optical spectrum analyzer (OSA/Coherent model 240) was used in addition to the optical wavemeter. The laser powers are approximately 0.5 mW for the He–Ne laser and 400 mW for the dye laser. The line width and stability of both lasers were typically less than 1 MHz.

Commercially available FET's (NEC/NE71000), which have gate lengths of about 0.3 μm and drain–source distances of 2 μm, were integrated on a printed-circuit RT/Duroid microstrip antenna (dash-lined area in Fig. 2). This microstrip circuit was designed as a FET gate mixer on a RT/Duroid substrate with permittivity of 2.2 (from Rogers Corporation). The FET also serves to convert from the balanced dipole RF feed (signal and LO) at its input to an unbalanced IF transmission line at the drain terminal of the FET. The IF transmission line is intended to work as coplanar waveguide backed by a lower ground plane. These IF lines, which also carry the dc biases, consist of cascaded quarter-wave (at RF) sections forming low-pass filters which approximately present an effective short circuit for RF at the FET output without disturbing the antenna feed. Effects of the IF at the input are minimized by operating the IF line in the coplanar waveguide mode without exciting the balanced IF mode. A 100 pF capacitor grounds the FET gate line at the IF to prevent oscillations of the circuit [11].

The above configuration prevents the direct application of microwave signals to the FET in the antenna circuit via the IF and bias lines. Therefore we used a second FET of the same type mounted and connected to 50 Ω microstrip lines on the alumina substrate at the gate and the drain for calibration and normalization [9]. This calibration FET, marked "FET" in Fig. 1, was used to evaluate optical conversion loss, loss in the printed-circuit-antenna circuit, and noise figures at IF frequencies.

In order to detect the millimeter waves generated by optical beating, an LO can be introduced to the gate of the FET either by an external generator [9] or by the FET itself, configured with a feedback loop [12]. As a result of the nonlinearity of the GaAs FET's transconductance, the electrical RF signal mixes with the RF signal produced by optical beating, and produces an IF beat signal. In the past, millimeter-wave signals generated in this manner have been measured using harmonic mixing with *Ka*-band sources [9]. However, the power output of the different harmonics has been observed to be highly nonlinear in the FET's. For example, depending on the input power, the output power of the third harmonic can be higher than that of the second harmonic at microwave frequencies [12], [13]. Although these harmonics can be used for frequency measurements, they are generally not sufficient to serve as LO. In order to characterize the device performance more precisely, we used a fundamental millimeter-wave LO from either a reflex klystron (Varian VC-1112 with Harris 819 power supply), a Gunn diode (Hughes 47224H), or an IMPATT solid-state source (Hughes 47174H) quasi-optically coupled to the antenna to generate the IF beat signal.

To couple simultaneously the optical and millimeter-wave signals to the FET, a flat brass reflector with a central hole (1 mm diameter) was used. A 25 dB directivity horn and a polyethylene lens with focal length (f.l.) of 25.4 mm effectively coupled the LO to the antenna. A 50 mm f.l. lens was inserted between the reflector and the beam splitter to focus the laser beam into a spot 4.5 μm in diameter (original beam is 0.75 mm in diameter). A dc current meter was used to monitor indirectly the power of the optical and millimeter-wave signals. Since the power of the stabilized He–Ne laser is about two orders lower than that of the dye laser, the first variable beam splitter was adjusted to transmit less than 10% of the total dye-laser power to the second beam splitter. On the other arm of the second beam splitter, the microstrip-line-mounted FET on the alumina substrate with the gate connected to a sweep generator and the drain connected to a spectrum analyzer directly was illuminated by the focused lasers through a microscope objective (f.l. 16 mm). The optical power densities on the calibration FET were approximately 1 kW/cm^2 for He–Ne laser and 40 kW/cm^2 for the dye laser, respectively.

In our experiment, we first looked into an optical mixing mechanism. Power versus V_{gs}, for both optical mixing signals and electrical signals without illumination, was measured at 2 GHz (Fig. 3). A rather flat frequency response of the optical mixing signals to the applied V_{gs} indicates this mechanism is related to photoconductivity, which will be further discussed later. Secondly we calibrated the RF power gain of the optical input/electrical output against that of an electrical input/output and evaluated the conversion loss with the FET on the alumina substrate at 1–2 GHz. This frequency range is beyond the $1/f$ noise corner and subsequently is selected as IF band. The noise figure of this FET is specified to be 0.6 dB at 1–4 GHz. Instead of S-parameter measurements, the increases of the power and of the S/N between the biased and the unbiased condition, i.e., $V_{ds} = V_{gs} = 0$ V, were

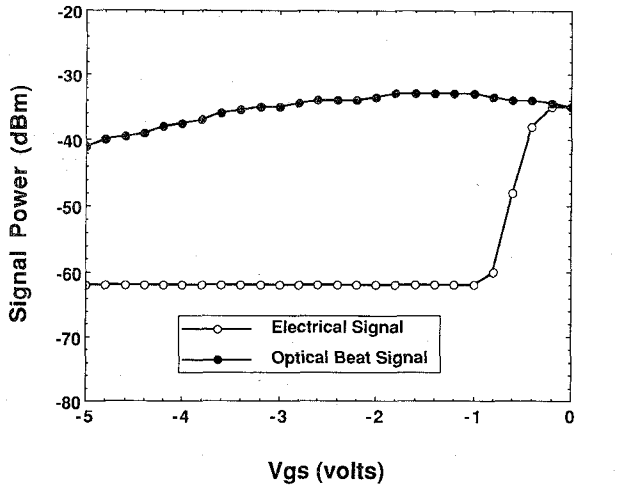

Fig. 3. Output power versus V_{gs} of optical beat signal and electrical signal without illumination at 2 GHz. The output powers are normalized to −35 dBm at $V_{gs} = 0$ V.

measured. In most measurements at IF frequencies, the S/N increases will be presented. Since the noise figures of the FET are almost constant at these frequencies, the S/N increases were approximately equal to the power increases in our measurements. At millimeter-wave frequencies, however, the noise figure of the FET changes; therefore, the power and the S/N are presented together. The adoption of this approach will be discussed later.

The S/N increase of the optical mixing signal between the biased and the unbiased condition was 27 dB. This was within 5% of the S/N increase measured with an electrical signal (−10 dBm) applied to the gate from a sweep generator under the same dc biases (V_{ds} and I_{ds}) and unbiased conditions while the FET was not illuminated. Therefore we consider the S/N increase of the optical input/electrical output as that of the electrical input/output of a matched network. To evaluate the conversion loss at the IF, we applied a 0 dBm electrical signal at 4 GHz from the sweep generator to the gate of the FET on the alumina substrate to mix the optical beat signal (S/N was 37 dB) at 2 GHz. The resulting IF beat signal was found to have an S/N of 30 dB near 2 GHz (Fig. 4(a)). A conversion loss of 7 dB was therefore obtained in down-converting the optical beat signal, which is close to that of a GaAs Schottky diode (about 6 dB). With an adequate LO power, the conversion loss of 64 GHz mixing is expected to be of the same order of magnitude as this measurement since the mixing mechanism is the same. This prediction is based on the similar data for the conversion loss of the GaAs Schottky diodes at these frequencies and is consistent with the known gate parasitics of the FET [14].

Next, looking at the antenna-coupled FET, we found that the power of an optical beat signal of this FET at 2 GHz was substantially lower than that of the FET on the alumina substrate at 2 GHz. This difference is attributed both to the gate configuration, which bypasses a portion of the signals, and the low-permittivity substrate of the antenna circuit, which results in a radiative loss. Because the

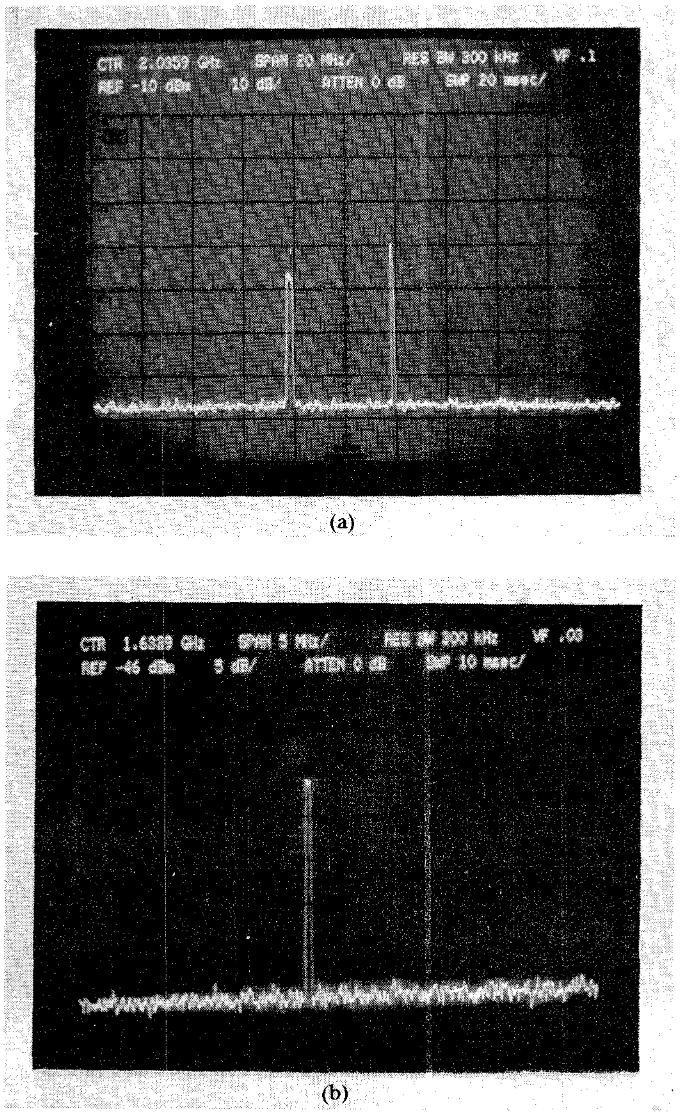

Fig. 4. (a) A −39 dBm optical beat signal with 37 dB S/N at 2.056 GHz and a −45 dBm second beat signal at 2.016 GHz (between electrical and optical beat signal). A 7 dB conversion loss is shown. (b) A S/N 25 dB second-beat IF between klystron signal and optical-beat signal.

detectable power at IF was substantially lower for the antenna circuit, a 1–2 GHz, 37-dB-gain IF amplifier with a noise figure of 1.0 dB was inserted between the FET of the antenna circuit and the spectrum analyzer.

Using this system, the performance of the FET at 64 GHz was evaluated when the optical beat signal was tuned to millimeter-wave frequencies. A 50 mW klystron LO was mixed with the optical beat signal and an IF at 2 GHz with an S/N of 25 dB, and power of −52 dBm was observed (Fig. 4(b)). The conversion loss of the IF beat signal is assumed to be 7 dB as determined previously. Using a Gunn diode as LO at 20 mW, the S/N was about 15 dB and power was at −66 dBm. Using a noisier 50 mW IMPATT diode as LO, the S/N was only 7 dB and power was at −54 dBm. The observed noise levels were therefore attributed to the LO noise components and not to the background signal levels. No sidebands had been observed for the three different LO's. By tuning the wavelength of the dye laser, we performed optical scanning over the

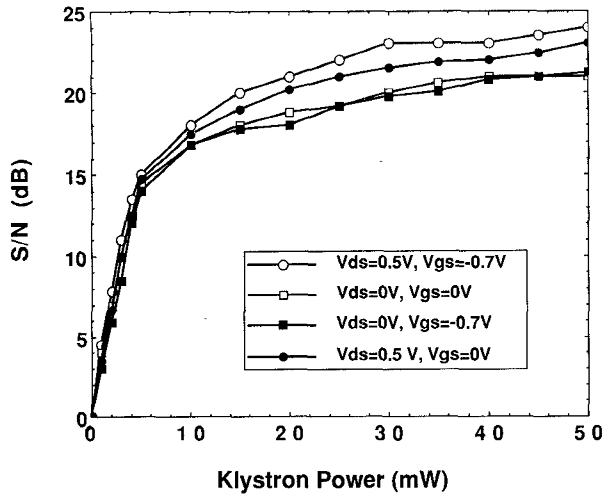

Fig. 5. S/N of the second beat signal versus klystron power at different biases of V_{gs} and V_{ds}.

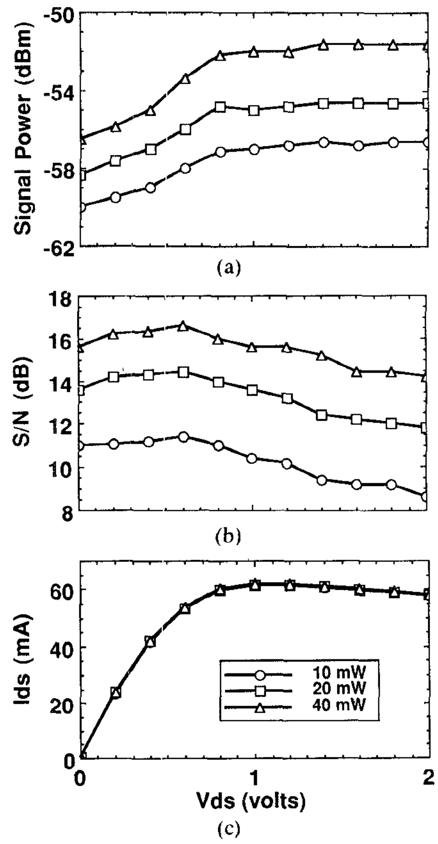

Fig. 6. (a) Signal power, (b) S/N, and (c) I_{ds} of the second beat signal versus V_{ds} at 10 mW, 20 mW, and 40 mW of klystron power V_{gs} is at -0.7 V

bandwidth of the IF amplifier. Although this technique could in principle be used to determine the bandwidth of the antenna structure, we found the frequency response to be limited by the IF amplifier.

Saturation phenomena were observed when the power of the klystron (Fig. 5) or the dye laser was higher than a critical value. This effect indicates a compression of the signal resulting from the nonlinear response to klystron power [13] and the saturation of electron–hole pair generation in the active area of the FET with the dye laser power. The input power of the FET at 1 dB compression point is about 0 dBm, which is estimated from klystron power including the losses (see Fig. 5) and is compatible with the manufacturer's specifications. We attribute this optical saturation of the signal to either density-of-states limitations in the conduction band (effective density of states, N_c, is equal to 4.7×10^{17} cm^{-3} for GaAs) or quadratic recombination at the band edge (intraband relaxation times are of the order of picoseconds and lifetimes of the carriers are in the 10 ns range at doping concentrations of 10^{17} cm^{-3}). Fig. 5 also shows the S/N to be more sensitive to V_{ds} than to V_{gs}. In these experiments, the optical intensities were intentionally adjusted to the saturation region to prevent the influence of small intensity fluctuations of the lasers. The intensity of the dye laser was adjusted such that I_{ds} and the output power of the beat signals remained the same when there was a 10% fluctuation of intensity. Under the above conditions, the power, S/N, and I_{ds} versus V_{ds} curves were obtained, as shown in parts (a), (b), and (c) of Fig. 6.

III. Discussion

One of the current efforts in the optical control of millimeter-wave devices has been focused on the transport mechanism of the photoexcited carriers. For the bulk-type devices of the high-purity semiconducting materials, such as optical switches and delay lines, or diode-type devices, such as p-i-n diodes and avalanche diodes, several authors have discussed the related mechanisms in detail (for example in [3] and [5]). For the FET's, the experimental studies on these devices have indicated that the frequency response of the photoconductivity mechanism is higher than that of the photovoltaic mechanism [15]–[17]. Using high-intensity illumination, we suppressed photovoltaic-related mechanisms such as trap, capacitance, and back-gating effects and obtained a higher frequency response [10].

Fig. 3 shows the output power versus gate bias, V_{gs}, at 2 GHz. The pinch-off voltage of this particular FET is -0.8 V. When the electrical signals are applied to the gate of the FET without illumination, the output signals show no gain when V_{gs} is less than -0.8 V. Under illumination, the output power of the beat signal increases to a maximum value around $V_{gs} = -1.0$ V, then declines slowly far beyond the pinch-off voltage. For the latter case, the change of built-in voltage, ΔV_{bi}, of the Schottky barrier between the gate electrode and the GaAs active area under illumination is given as [4]

$$\Delta V_{bi} = \frac{KT}{q} \ln\left(1 + \frac{p_l}{p_o}\right) \approx \frac{KT}{q} \ln\frac{p_l}{p_o} \qquad \text{when } p_l \gg p_o \tag{1}$$

where p_l and p_o are the photoexcited and dark hole (lifetime about 50 ns) concentrations, respectively. By comparing the photogenerated currents (of the order of 10 mA when V_{gs} is biased at pinch-off voltage) from the CW lasers with the currents of no illumination, we estimate p_l

to be of the order of $10^{17}/\mathrm{cm}^3$ and obtain a ΔV_{bi} of about 1.0 V. This indicates that the space-charge region under the gate electrode was suppressed by the photogenerated carriers. For the steady state under illumination and without biases, the fluctuation of carrier concentration is expected in the limit of dielectric relaxation time (subpicoseconds). Under these circumstances, the FET can be thought of as a photoconductive device since the related input capacitances are either suppressed or not related to the optical mixing signals. Obtaining a peak output power is equivalent to having optimal modulation depth, which occurs when the original carriers are depleted by the applied V_{gs}. The injected holes suppress the space-charge region while the injected electrons are deeply modulated by the beat frequency. Consistent observations of the peak power at both 2 GHz and 64 GHz were obtained with V_{gs} biased around the pinch-off voltages.

The mechanism we observe in these experiments involves millimeter-wave currents generated by square law detection of the optical signal in the GaAs material. Mixing between these signals and electrical LO input results from the measured nonlinear $I-V$ characteristics of the FET itself. Other three-wave-mixing processes are also taking place and efforts are being made to identify them. Optimal coupling between the LO and the antenna was actually achieved by maximizing the dc voltages (in mV), rectified from the RF signals, by the device's nonlinearity, across the source and the drain terminals of the unbiased FET. The evaluation of optical–electrical conversion efficiency and the explanation of an interesting noise-suppressed phenomenon in the following paragraphs are based on this two-step processes.

For power gain analysis the light input can be represented as a signal which perturbs the parameters of the equivalent circuit model of the FET. In some sense, this is equivalent to converting a two-port network into a three-port one by the addition of an optical signal port. In the current case, one port is attached to the LO, another port is a RF isolated IF port, and the third is operating at the optical frequencies. In terms of the signals, these three ports are well isolated and can be treated independently. For the optical signal port, the optical beat signal generated by two CW lasers can be technically considered as eliminating the electrical input and therefore the reflected signal, i.e., $S_{11}=0$. Since power gain can be defined as follows:

$$\text{Power Gain} = \frac{|S_{21}|^2(1-\Gamma_L)}{(1-|S_{11}|^2)+\Gamma_L^2(|S_{22}|^2-D^2)-2\,\mathrm{Re}(\Gamma_L N)} \tag{2}$$

where

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$$

$$D = S_{11}S_{22} - S_{12}S_{21}$$

$$N = S_{22} - DS_{11}^*$$

we assume the impedance is matched for our circuit, i.e., $Z_L = Z_0$. The power gain is then equal to $|S_{21}|^2$ of the FET under illumination. Further, the measured power increase of the IF signals is equivalent to the ratio between $|S_{21}|^2$ and unbiased $|S_{21}|^2$. This is because the unbiased $|S_{21}|^2$, which closes to unity for a matched passive circuit, can be determined rather straightforwardly at 1–2 GHz and treated as a constant in this case. Therefore the power increase after being normalized by the proportional constant can be considered as RF power gain for the optically generated signal. From Fig. 6(b), we observed a power gain of 1 dB at 62 GHz for this particular device. The maximum available gain cannot be obtained since S_{12} could not be measured by the current setup.

The power conversion efficiency from the optical signal to the electrical signal is estimated as follows. If the lens loss is neglected, then the possible losses are the blocking loss due to the metallization pads, especially gate metallization, the coupling loss between the FET and the air, the quantum efficiency of converting photon to electron–hole pairs, the saturation effect, the recombination loss, and the conversion loss. Although the GaAs FET's are passivated by a mixture layer of SiO_2 and Si_3N_4 (with indices of refraction 1.46 and 2.05, respectively) to stabilize the device performance, the thickness of this particular layer is not trimmed to be an antireflecting coating; therefore coupling loss is expected to be significant. The optical mixing efficiency can attain 50% at maximum if a square-law detector is assumed [18]. Based on the above considerations, we estimate the conversion efficiency to be about 2%. Using 20 mW of optical power of the dye laser as input, the maximum power of the optical mixing signals was observed to be -10 dBm, equivalent to 0.5% of conversion efficiency, at the frequencies below 1 GHz for the calibration FET. However, the conversion efficiency is about three orders of magnitude lower at millimeter-wave frequencies for the FET in the antenna circuit. We attribute this to the radiation loss at the IF frequency, the dielectric loss tangent of the FET substrate, and the parasitic loss of the FET in LO coupling.

When the signal from the LO was applied to the FET, the noise floor was raised at IF frequencies. For example, when the noisy IMPATT diode was used as LO, a rise of more than 5 dB of the noise floor was observed. If only one laser illuminated the FET with the LO applied, the noise floor was raised more but in negligible fractions of 1 dB. However, when FET's were illuminated by both lasers, the noise induced by LO's was significantly suppressed. A possible explanation of this phenomenon follows from the similarity of this configuration to that of a 180° hybrid microwave mixer in which the LO noise is suppressed [19]. At 64 GHz, the phase angle of S_{21} of the RF signal from the LO is assumed to be 180°. The optical beat signals, on the other hand, were generated at both gate–source and gate–drain terminals simultaneously with a 0° phase angle. This out-of-phase situation results in noise cancellation. Observation of the LO excess-noise suppression by a similar configuration, in which a double-detector system with a

180° phase shifter was connected to one of the detectors, has also been reported in optical regime [20]. The concept of local oscillator noise suppression can also be explained in terms of well-known DPSK (differential phase shift keying) receiver systems [21].

Under the condition of $V_{gs} = 0$ V and $V_{ds} = 0$ V, which is similar to a Schottky diode without bias, the IF beat signal was still observed (Fig. 6). In Fig. 6(a), a power increase of 3.8 dB was observed when $V_{ds} = 1.0$ V in comparison with the power at $V_{ds} = 0$ V. But the best S/N increase, about 1 dB, was obtained when $V_{ds} = 0.6$ V (Fig. 6(b)). The noise temperature parameters of the GaAs FET's are lower than expected but still reasonable, in agreement with the previous observations (see [22] and references therein). When V_{ds} was greater than 0.8 V, both S/N and I_{ds} declined and power saturated (Fig. 6(a)–(c)). The decreasing S/N and I_{ds} were observed only when both optical signals and the LO signal were applied simultaneously and V_{ds} exceeded the saturation voltage (or electrical field).

For further comparison, the S/N of the IF beat signal versus V_{ds} was measured in the FET on an alumina substrate. This IF beat signal was generated by the same method for evaluating the conversion loss as described previously, i.e., by a 2 GHz optical beat and a 4 GHz electrical signal introduced to the gate from a sweep generator. A similar decline of S/N when V_{ds} exceeded 0.8 V was observed. This degradation of performance of both S/N and I_{ds} can be explained by the electron heating and intervalley scattering effect in the GaAs FET. The increase of the scattering noise degrades the S/N while the lower mobility of electrons in the upper valley degrades I_{ds} [23]. Fig. 6(b) indicates that for obtaining the optimal noise figure, the device should be biased at V_{ds} just below the saturation voltage.

In summary, both optical and millimeter-wave mixing occurred in the FET's without requiring biases. Adjusting both V_{ds} and V_{gs} will improve the beat signals, with V_{ds} having a greater effect. At 64 GHz, adjusting V_{ds} can add a few dB to the S/N. For the GaAs FET under test (NE71000), we observed an equivalent power gain of 1 dB and an S/N of 25 dB at an output power of -45 dBm (external losses were compensated by an amplifier) with the best noise figure when V_{ds} was around 0.6 V and peak power when V_{gs} was biased around the pinch-off voltage. Using this setup, we demonstrated an efficient method to down-convert the millimeter-wave signals to the IF signals, which were further characterized with minimum parasitics associated with the mounting fixture as well as the devices. The optically generated millimeter-wave signals can radiate and be detected by the same setup with the dipole connected across the source and drain of the FET (replacing the millimeter-wave source which serves as LO by a detector).

The performance of related devices, such as high electron mobility transistors (HEMT's), heterostructure bipolar transistors (HBT's), and monolithic HEMT amplifiers, is currently being investigated.

IV. Conclusion

This paper reports the generation and detection of a millimeter-wave signal at 64 GHz in a GaAs FET integrated with a millimeter-wave antenna by optical mixing. An interesting noise-suppression phenomenon is observed in the process of signal generation which suggests potential applications. The demonstrated technique also shows the capability of measuring a three-terminal millimeter-wave device. The performance of the devices (power, gain, noise, bandwidth, etc.) can be obtained.

These advantages come from the optical mixing of the lasers, which supply a stable source to generate millimeter-wave signals in these devices relatively free from the parasitics and the limitations associated with the devices as well as the mounting features. Using minor modifications, the technique is ready to be extended up to 100 GHz. Future work will include improvements in the antenna design and the extension of the bandwidth of the IF amplifier to allow the measurement of the frequency response of the candidate millimeter-wave devices by tuning the optical sources.

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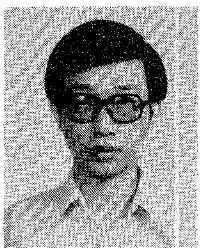

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