MM Wave Mixing in a Quantum Well IR Photo Detector

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Abstract— **We report on the experimental investigation of combining MM wave mixing with optical heterodyne detection in a quantum well infrared photo detector. The effects of two different non-linear conductances were observed and attributed to the dark conductance and the photo conductance. The bias dependence was found to be similar for each of the conductances.**

I. Introduction

Quantum well infrared photo detectors (QWIP) have been developed for sensing applications and are candidates for ultra fast detector applications in free space optical communication. In past work response up to 82 GHz was demonstrated using a QWIP as both an optical detector and a microwave mixer. There are two advantages in using the QWIP as a microwave mixer. First it allows us to make measurements at frequencies above the range of our spectrum analyzer by making use of the QWIP as a down converter. Second is that we can use an up conversion to calibrate the attenuation in our package. This attenuation can be considerable as these are still research devices and do not have optimal microwave design. We have not developed a theory of microwave mixing that is specific to QWIPs, but, have assumed the the inherent non-linearity of the current versus voltage (IV) characteristic was the cause. Since the IV changes smoothly and rather slowly with voltage we have assumed that the mixing was not very efficient, but, has been useful for characterizing our devices. The motivation for the work reported in this paper is the need to characterize a new family of QWIPs which we have developed and which we expect to be even faster than our earlier detectors. The new family of devices are 100 period, heavily doped, GaAs/AlGaAs quantum wells that are described in detail in reference [1]. To test the high speed response of these devices we expect to make use of their inherent mixing ability in combination with an optical heterodyne system to measure their photo-response up to frequencies above 100 GHz. In initial tests we observed both optical heterodyne behavior as well as microwave mixing, but the optimum bias conditions for optical mixing seemed to be different from the optimum conditions for microwave mixing. Hence, we decided to examine each mixing behavior independently. The result is the subject of this paper. We begin with a brief review of optical mixing in a photo-conductor.

II. Optical Heterodyne Theory

When two laser beams are superimposed on the voltage biased QWIP, a photo-current results in response to the optical power [2].

$$I = I_0 + A(E_1 \cos(\omega_0 t) + E_2 \cos((\omega_0 + \omega_h)t))^2 \quad (1)$$

I_0 is the dark current, A is the photo-conductance, E_1 and E_2 are the magnitude of the electric fields of each laser beam, ω_0 and $\omega_0+\omega_h$ are the laser frequencies. The equation is written in this particular form to show that optical interference occurs as a result of the summation of the fields in the laser electro magnetic waves while the QWIP responds to the power in the optical wave which is proportional to the field squared. Through a few algebraic steps and trigonometric identities we can write equation 1 as follows.

$$I = I_0 + I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\omega_h t) \quad (2)$$

Where I_1 and I_2 are photo-current contributions due to lasers 1 and 2 respectively, ω_h is the difference frequency and terms at 2 times the laser frequency have been dropped. A useful result of equation 2 is the fact that the amplitude of the heterodyne signal should be related to the DC photo-response by $I_{RMS} = \sqrt{2 I_1 I_2}$. The DC photo-response can be easily measured.

Both of the current terms are dependent on the bias voltage applied to the QWIP. When a microwave signal is superimposed on the bias voltage, it modulates the small signal conductance of the QWIP, leading to a further mixing between the microwave signal and the heterodyne signal. First, the small signal conductance is the derivative of the current with respect to voltage

$$g = g_0 + 2g_p + 2g_p \cos(w_h t) \quad (3)$$

where g_0 is the small signal conductance of the dark current and g_p is the small signal photo-conductance. Here, the assumption has been made that $I_1 \approx I_2$ which allows using a single g_p. In this conductance, there are two constant terms plus a time dependant term. When we multiply equation 3 by a microwave voltage of amplitude V_m and frequency ω_m we get 3 terms, of which the product of the time dependant conductance and the microwave voltage is the desired down conversion signal.

$$i = 2V_m g_p \cos(\omega_h t)\cos(\omega_m t) \qquad (4)$$

In an ideal photo conductor the first two terms are linear and produce no mixing products. However, we know that $\frac{dg_0}{dV}$ is not zero and we expect that g_0 and g_p to have similar voltage dependence [3]. Thus we must also consider the non-linear factors. When the conductance is a function of voltage and two small AC signals of amplitudes V_1 and V_2 at frequencies ω_1 and ω_2 are applied, the resulting current is given by

$$i = V_1 \cos(\omega_1 t)\left(\left(\frac{dg_0}{dV} + \frac{dg_p}{dV}\right) V_2 \cos(\omega_2 t)\right) \qquad (5)$$

In the case of self mixing or rectification $V_1 = V_2 = V_\mu$ and the DC component of equation 5 reduces to

$$i = \frac{1}{2}\frac{dg_0}{dV} V_\mu^2 \qquad (6)$$

By noting that the first derivative of conductance is the second derivative of current, it can be seen that this is the form used in reference [3] to investigate QWIP lifetimes. In our investigation we use the general form in equation 5 as a demodulator to measure $\frac{dg_0}{dV}$.

III. Experimental Procedure

The beams from two CO_2 lasers are combined in a beam splitter to generate the optical heterodyne signal. An Anritsu V255 bias T was used to separate the DC bias from the microwave signals. The RF port of the bias T was connected to a circulator which permitted injection of the local oscillator signal and extraction of the difference frequency which was connected to an HP 70909A spectrum analyzer.

Our objective is to validate qualitative elements of equation 3. We want to confirm that there are two distinct conductance components g_0 and g_p and we want to find the general nature of these components. The experimental plan is to start by examining the ideal photo mixer condition. This we do by measuring the heterodyne photo current at a frequency within the frequency range of our spectrum analyzer. Using an external mixer, we chose 39.228 GHz which is the difference between CO_2 laser lines 10R(20) and 10R(18). By sweeping the bias voltage we can determine the heterodyne signal amplitude as a function of voltage. Then, we can superimpose a 19.604 GHz microwave signal on the bias line using circulator. The reflected signal plus the down converted heterodyne signal at 19.618 GHz is collected from the third port of the circulator and taken to an HP 70000 spectrum analyzer. Again the bias voltage will be swept to determine the voltage dependence. The third experiment is to measure the non ideal mixing due to the voltage dependence of the two conductances g_0, g_p. This is done by injecting an amplitude modulated 1 GHz signal and measuring the demodulated result while bias voltage is again swept. We also inject a single laser beam and step to power to separate g_0 and g_p.

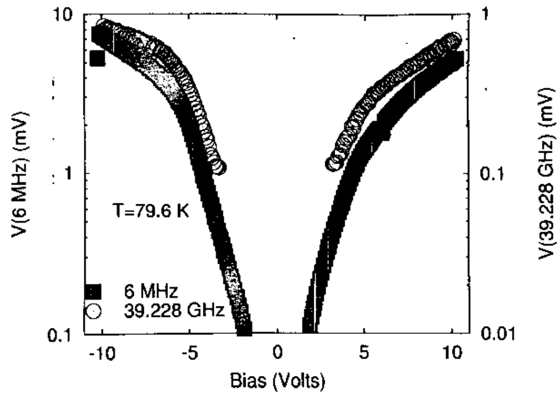

Fig. 1. Heterodyne photo-current for $\omega_h = 6\ MHz$ and $\omega_h = 39.228\ GHz$ Note that the higher frequency result is plotted using the right hand scale. It is 1/10 the amplitude of the low frequency signal due to attenuation in the package.

IV. Results

A. Heterodyne photo-current

Graphs of the heterodyne photo-current versus bias voltage for a zero beat and for 39.228 GHz beat frequency are shown in Fig. 1. The laser frequencies were 29.257658 THz and 29.218430 THz to produce the 39.228 GHz beat. Both lasers were set to 29.257658 THz for the zero beat with one being offset from the gain peak by 6 MHz to produce a signal within the response range of the spectrum analyzer. The need to use 6 MHz arose because of the lower cutoff frequency of the spectrum analyzer. The 39.228 GHz signal was measured directly by using an HP 11970Q external mixer with the spectrum analyzer. To measure the 6 MHz signal, the bias T was replaced by a 475.5Ω resistor and a 1μF capacitor to allow the low frequency signal to be coupled to the spectrum analyzer. Qualitatively, the curves are almost the same shape while in amplitude the 39.228GHz signal is only 1/10 that of the 6 MHz signal. The small amplitude is caused by the passive network, in particular, the need to use wire bonds. Since a negative bias produced a larger signal than positive bias, subsequent work focused more on negative bias.

The amplitude of the 6 MHz photo-current was compared with the DC photo-currents while the QWIP was biased at $-10.5V$, $T = 79.6K$. The photo-current due to laser 1 was 176μA while that from laser 2 was 78μA.

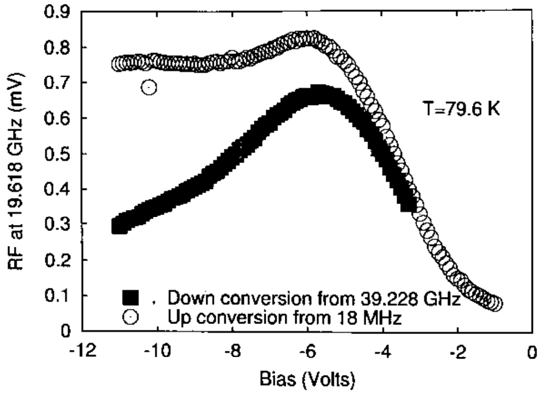

Fig. 2. Amplitude of mixed signal as a function of bias voltage. The fact that the amplitudes are very similar indicates that the 39.228 GHz amplitude is only slightly less than the 18 MHz amplitude.

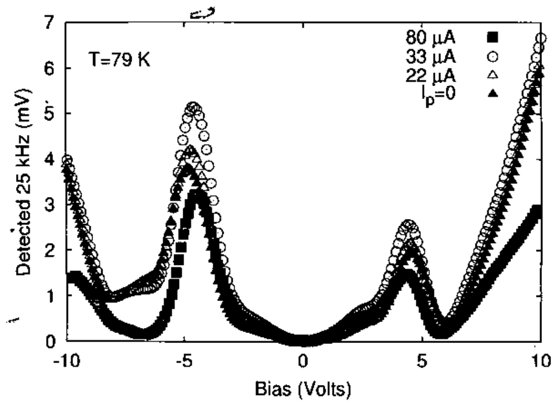

Fig. 3. Amplitude of detected 25kHz modulation due to the total conductance non-linearity. Optical power was varied as a parameter.

Equation 2 gives an RF voltage of $7.5mV$ while we actually measured $6.6mV$. The discrepancy indicates that our measurements have an uncertainty of about 20 %.

B. Optical plus microwave mixing

Using the heterodyne signals as one source, a microwave local oscillator signal was injected using the circulator and bias T. The local oscillator frequency of 19.604 GHz was selected to be slightly less than 1/2 of the heterodyne frequency. It was then possible to convert low frequency heterodyne signals, the zero beat frequency, up to 19.618 GHz and the 39.228 GHz down to 19.618 GHz. The effect of the passive network should be the same for both signals. For this experiment, the zero beat frequency was adjusted to 18 MHz because of the bias T roll-off at lower frequencies. The results plotted as a function of voltage for negative bias are shown in Fig. 2.

While the direct measurements showed that the heterodyne signals increase exponentially with bias voltage, the mixed signals peak at about $-6V$ bias and then decrease. The second major difference is that the amplitudes are very similar; the amplitude of the down converted 39.228 GHz signal is about 0.8 that of the up-converted signal at $-6V$.

C. Non linearity of the photo conductance

The voltage dependant properties of g_0 and g_p are demonstrated in Fig. 3. Zero optical power gave a dark current of $17.5\mu A$ at $-5V$ and a mixing characteristic shown in solid triangles. There are strong peaks at $\pm 5V$ and at $\pm 10V$. Optical power was then applied to produce photo currents of $22\mu A$, $33\mu A$ and $80\mu A$ as shown in Fig. 3. The result was qualitatively similar to that of the dark current. The first two steps of optical power produced an increasing signal while the highest power produced the lowest signal. It is clear that the rectified signal is strongly dependant on bias voltage.

V. Discussion

The heterodyne measurement demonstrates that at low frequencies the QWIP operates about as well as a photo mixer can. For both positive and negative bias, the optical heterodyne signal increases in amplitude exponentially with bias voltage magnitude. When plotted on a log scale in Fig. 1, there is an almost linear increase in signal amplitude, a break at about 5 V followed by a lower slope but still rapidly increasing signal at higher voltages. This behavior is consistent with the responsivity reported in reference [1]. The small amplitude at 39.228 GHz we believe to be a consequence of our passive wiring.

The microwave plus heterodyne measurement plotted in Fig. 2 shows a qualitatively different behavior. As bias voltage increases from a low voltage the mixed voltage increases, but, reaches a peak and then drops. The peak seems to be at about $6V$, a similar value to that where a slope change is observed in Fig. 1. It was desirable that the term $\frac{dg_p}{dV}$ of equation 5 be measured. Since this is also the second derivative of the current versus voltage (IV) curve several attempts were made to measure the DC IV and take the second derivative. However, temperature fluctuations in the dewar as well as laser power fluctuations dominated the derivatives. We found it much easier to experimentally measure the second derivative by using the demodulation method. This measurement is shown in Fig. 3. The result is surprisingly peaked at about $5V$. The rapid drop in $\frac{dg_0}{dV}$ as bias is increased above $5V$ can explain the drop seen in Fig. 2. The curves should not be compared directly because in Fig. 3 the AC voltage was constant while in

Fig. 2 one of the AC voltages, the optical heterodyne signal, was a strong function of bias voltage. This is strong evidence for remarkably different behavior in the microwave mixing and optical mixing in the QWIP.

Before drawing the conclusion that the peaks observed in the rectified signal coincide with the peak in the conversion gain, we attempted to normalize the amplitude of the optical heterodyne signal. Fig. 4 shows two curves calculated by dividing the amplitude of the converted optical heterodyne signal by measured photo current signal amplitudes. The left scale of Fig. 4 is for the ratio of the signal converted down from 39.228 GHz and the heterodyne photo signal. It is plotted in solid squares. The right scale is for the ratio of the up converted signal amplitude and the measured low frequency photo current. We label the scales as arbitrary because they are related by the attenuation of the passive network that we are not at present equipped to measure. While the two curves are some what different, they both show a steady drop with increasing bias voltage. There is no broad peak as observed in Fig. 2 or the some what sharper peak observed in Fig. 3. The most appropriate explanation for the peak in Fig. 2 is that Fig. 4 represents $\frac{dg_p}{dV}$. As bias voltage increases, $\frac{dg_p}{dV}$ decreases steadily, but, the total photo current increases rapidly. The resulting product gives the broad peak observed in Fig. 2.

The relationship between the microwave rectified signal and the microwave mixing of the heterodyne photo signal is not obvious. The peaked behavior observed in Fig. 3 near $-5V$ suggests it could contribute to mixing. However, we do not observe the increase in mixing products near $-10V$ that Fig. 3 also suggests. Hence, we conclude that there are two voltage dependant conductances as shown in equation 3, but that their voltage dependence is quite different.

Finally, we note that the behavior demonstrated in Fig. 3 is qualitatively similar to that observed in point contact diodes and Schottky barrier diodes [4]. The QWIP has multiple peaks while Schottky diodes have a single peak. Also, the width of the peak in the QWIP is about 1 order of magnitude wider in voltage than that of a Schottky diode. Additional work is needed to identify the correct physical model for this behavior.

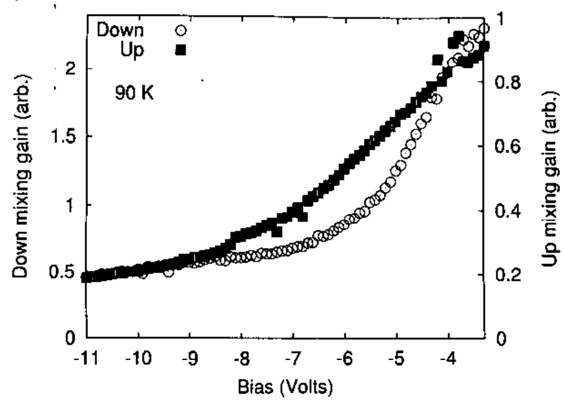

Fig. 4. Mixer gain normalized by dividing the graphs of Fig. 2 by the heterodyne photo signal measured under similar conditions. The scales are labeled (arb.) because the actual levels depend on the unknown passive network attenuation.

VI. Conclusions

Both optical heterodyne and electrical heterodyne measurements were performed on a QWIP.

1 The optical mixing behavior is well described by photo conductive mixing theory as given by equations 1 and 2 above. As bias voltage is increased, the optical heterodyne signal increases in the same fashion as the responsivity.

2 The electrical mixing of either a heterodyne optical signal or two injected electrical signals has a qualitatively different dependence on bias voltage than the optical heterodyne case. A simple extension of the theory of optical mixing by an applied AC voltage appears to be a good model for the electrical plus optical mixing.

3 The case of electrical mixing with other electrical signals reveals additional peaks in the dark current conductance. There are several sharp peaks, separated by about 5 volts.

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