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Characteristics of Tungsten–Nickel Point Contact Diodes Used as Laser Harmonic-Generator Mixers

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***Abstract*—Properties of tungsten–nickel point contact diodes, when used as harmonic-generator mixers, were measured. The measured properties are those which will be useful to workers wishing to use these high-speed devices (faster than 10^{-14} s). Some of the properties measured were: the decrease in signal with mixing order; the detected signal as a function of laser frequency; and the power required to optimize the harmonic beat notes.**

Introduction

RECENTLY, the cesium beam frequency standard and the krypton wavelength standard were linked in a definitive speed of light experiment by measuring both the frequency and wavelength of a 3.39-μm (88-THz) methane-stabilized He–Ne laser [1]–[3]. In extending frequency measurements to this high value, tungsten on nickel (W–Ni) point contact diodes were used as harmonic-generator mixers. These room temperature diodes were first reported in 1966 in a submillimeter wave application [4] and then used at laser frequencies in 1969 [5]. The extension of their use to 88 THz by the generation of 88 THz from the third harmonic of 29 THz in 1972 [6] demonstrated a response to at least 1.1×10^{-14} s. In a more recent experiment, sideband reradiation from the diode has been reported at 30 THz [7].

There are at least four different theories of operation for the point contact diode: 1) tunneling through an oxide layer [8]–[12]; 2) field emission [13]; 3) a quantum mechanical-scattering explanation [14]; and 4) a geometrically induced asymetrical tunneling [15]. We wish to report the measurement of some characteristics of these diodes some of which differ from those recently reported

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[16]. It is hoped that these data will be useful both to those working toward a physical explanation of the operation of the diode as well as to those just wishing to build and use these devices as harmonic-generator mixers.

The diodes have been chiefly used to synthesize (and hence measure) extremely high frequencies (laser frequencies), and we concentrated on measurements to characterize their use as harmonic-generator mixers. The RF beat note signal intensity itself as generated in the diode was measured as a function of mixing order, driving power, and bias voltage. DC impedances, sensitivity as a detector, and the optimum driving power were also observed.

To measure an unknown frequency ν_u, a radio frequency difference (a beat note) between ν_u and a frequency synthesized from harmonics of several sources ($l\nu_l \pm m\nu_m \pm n\nu_n$) is generated by a mixing process in the same diode in which the harmonic generation occurred. That is, the diodes are irradiated with all of the frequencies and the beat note ν_{RF} developed across the diode is given by

$$\nu_{RF} = \nu_u - (l\nu_l \pm m\nu_m \pm n\nu_n)$$

where ν_u is a laser frequency, ν_l and ν_m are lower basis or reference laser frequencies and ν_n is a microwave frequency. The quantity within the parentheses is the synthesized frequency close to the unknown laser frequency ν_u. l, m, and n are harmonic numbers and the mixing order is $(1 + |l| + |m| + |n|)$. For example, $\nu_{H_2O} = 12\,\nu_{HCN} + \nu_n$, where $\nu_{H_2O} = 10.718$ THz, $\nu_{HCN} = 0.891$ THz, $\nu_n = 29$ GHz, $l = 12$, $m = 0$, and $n = 1$.

The Measurements

Open structure diodes were employed which were identical to those used previously [1], [6]. The optically polished end of a 99.5-percent-pure nickel wire 2 mm in diameter served as the base element of the diode. When other samples of nickel with purities from 98 to 99.99 percent were tried, there was no correlation between purity and signal intensity. Beat note strengths from sample to sample varied by as much as 20 dB and the 99.5-percent samples exhibited somewhat smaller variability. A 25-μm-diameter tungsten wire (the type typically used in field emission devices) electrochemically etched to a point less than 2000 Å in radius served as the point element and antenna. The tungsten side of the diode was connected to a 0–100-MHz amplifier with a 3-dB noise figure: its output was connected to a conventional spectrum analyzer.

The diodes were somewhat finicky and delicate and changed during use; however, several different contacts could be made before repointing the tungsten catwhisker. A necessary prerequisite for obtaining a "good" beat note (and the "good" signals varied by many decibels) was to observe a rectified voltage which responded as a square wave at a chopping frequency of 500–1000 Hz. To use the tungsten–nickel point contact diode, the drive signal (the oscillator generating the harmonic near the unknown frequency) should have sufficient power to generate a millivolt or more of rectified voltage on the diode (usually 1–100 mW of power and careful focusing is required). Powers from the unknown oscillator and the other oscillators are adjusted so the rectified voltage on the diode is about 1/4–1/10th of that from the drive oscillator; at these levels, and after trying several diodes, a beat signal is generally detectable.

The largest beat signals were obtained when the tungsten whisker was driven negative by the applied radiation. It should be mentioned that beat notes could be obtained when the rectified signal was of the opposite polarity; however, the signals were much weaker under these circumstances.

To find the response of the diodes as a function of the mixing order, microwaves as well as lasers were used because of a lack of sufficient laser line sources. Three microwave sources were used which supplied 50–100 mW of power. Two were stabilized X- and K-band klystrons which supplied power to irradiate the diodes from open waveguides located about 2–3 cm from the whisker antenna. The third was a variable-frequency unstabilized (1.7–4.1-GHz) commercial microwave oscillator which was coupled capacitively with a 4-cm-long copper wire connected to the end of a coaxial cable and located approximately 1 cm from the whisker. The power coupled to the diode was not measured but we estimate that it was only a few percent of the power available.

To test the operation of the diode at laser frequencies, linearly polarized radiation from HCN (311 and 337 μm), H_2O (28 μm), and CO_2 (9.3 μm) lasers was used. Available maximum powers were 75, 200, and 500 mW, respectively. Coupling of laser radiations to the 2-mm-long tungsten antenna is explained by the application of well-known antenna theory at these wavelengths [6], [17]. S/N ratios of the RF beat notes at various mixing orders were measured with the signal optimized at each one by varying the oscillator power.

As the power was increased, the beat signal and noise level varied such that an optimum S/N ratio could be achieved. In all cases, one could obtain a maximum S/N by adjusting the power of each source independently. Fig. 1 shows the general behavior of the optimized RF beat notes versus total mixing order. These data were taken using many diodes, and each point is an averaged value. The RF beat notes were between 20 and 40 MHz. The third-order point at 73 dB is questionable since it was later discovered that the spectrum analyzer saturated above 70 dB. The results of mixing two microwave frequencies are shown by the circles. Here, $\nu_u \cong l\nu_l$ with $\nu_u = 8.1$ GHz, and $l = 2, 3$, and 4, or with $\nu_u \cong 19.94$ GHz and $l = 5, 6, 7, 8, 9$, and 10. The results of mixing three microwave frequencies is shown by the squares where $\nu_u \cong \nu_l + m\nu_m$, with $\nu_u = 19.94$ GHz, $\nu_l = 9.97$ GHz, and $m = 3, 4, 5, 6$.

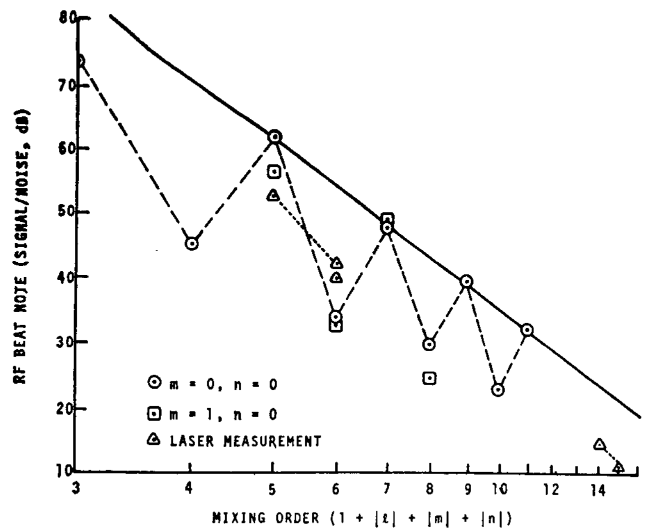

Fig. 1. RF beat note (S/N) versus mixing order for microwave signals at 20 GHz and laser signals at 3–11 THz. No bias voltage was used.

Laser frequency signals are indicated by triangles on Fig. 1. The triangles connected by the dashed line at mixing orders 5 and 6 are from ν_u = 32.1 THz, ν_l = 10.7 THz, l = 3, n = 0, and either ν_m = 20 GHz, m = 1, or ν_m = 10 GHz, m = 2. The lower triangle at the sixth order corresponds to ν_u = 3.8 THz, ν_l = 0.964 THz, l = 4, ν_m = 35 GHz, m = 1, and n = 0. At the fourteenth and fifteenth mixing orders, the following laser signals are plotted: ν_u = 10.7 THz, v_l = 0.891 THz, l = 12, ν_m = 29 GHz, m = 1, and n = 0; and also l = 12, m = 2, ν_m = 14.564, and n = 0.

At microwave frequencies the beat notes for the odd and even mixing orders form two distinct groups of data with the even mixing order signals lying 10–30 dB lower than the odd ones. It is the mixing order which denotes the even or odd character of the synthesized frequency as is shown by the three microwave signal case shown in Fig. 1. There are other differences between the two cases. In the even case, we sometimes observed two beat signal maxima as a function of power of the low frequency oscillator with the high frequency oscillator power kept at a low level. But when the high frequency oscillator power was increased, the low power maximum decreased and the high one increased. The latter is plotted in Fig. 1. In the odd case, the beat notes were more stable than in the even case where the peak value fluctuated several decibels. The largest signals from several different contacts are plotted in Fig. 1.

It has been reported that a dc bias increases the beat signal for the even order mixing [7]. A dc bias was applied after maximizing the beat note by adjusting the different microwave power levels. The dc bias increased the S/N of the even mixing case 15 dB at n = 3 and 7 dB at n = 9. In general, it decreased the signal for the odd mixing case. (We observed a slight increase under some conditions, but it was at most 1–2 dB.)

The S/N ratio for the odd microwave harmonics falls off roughly as the harmonic number to the minus 7.4 power. This rapid decrease precludes the synthesis of signals at high harmonics. A 0-dB signal (with a time constant of 1 ms) would be reached at the harmonic number 30, so that with some signal averaging, and sufficiently stable sources, a usable signal might be obtained at orders as high as 30–40.

At laser frequencies the odd–even difference was not observed; however, lack of sufficient data points makes it difficult to generalize. The laser data lie approximately between the envelope formed by the odd and even cases taken at microwave frequencies and there is very little difference between the odd and even cases. A dc bias increased the S/N for both the odd and even beat notes at the fifth and sixth orders, however, it was only by 2–4 dB (the bias had increased the microwave beat note by some 12 dB). A significant improvement at laser frequencies resulted from the use of a somewhat sharper tungsten wire and a lighter contact pressure. A somewhat higher dc impedance (100–200 Ω compared to 30–60 Ω with the coarser microwave contacts) and a larger rectified voltage were observed. It seems quite likely that the thinner–lighter contact has a significantly smaller capacitance, and consequently operates better at laser frequencies.

To test the diode's operation as a mixer at even higher frequencies, CW lasers, each oscillating on several modes at 1.06, 0.63, and 0.51 μm, radiated the diodes. In all cases the intermode beat signals were observed indicating that the diode was still operable as a mixer clear into the visible.

The responses of the microwave generated beat signals as a function of bias voltages are shown in Figs. 2–4. An even harmonic case (mixing order equal to 6) is shown in Figs. 2 and 3 for two different contacts with quite different impedances; the signal is very close to a minimum at zero bias. In Fig. 3 the zero bias is offset from center, and the oscillatory behavior of the diode is seen. The odd harmonic case with order 7 has its maximum approximately at zero bias, but otherwise possesses a similarly oscillatory behavior. The voltage spacing between minima of the beat signals depends strongly upon the contact pressure and the microwave power level. It becomes less as the microwave power is decreased.

At laser frequencies similar effects were seen; however, the minimum was no longer at zero bias in the even harmonic case, and there was less difference between the even and odd cases. Part of this effect might be due to self-biasing by the laser radiation.

To check the linearity of the beat signal versus the power of the lower basis frequency, the second harmonic of an X-band klystron was beat with a 19.98-GHz klystron with $\nu_{beat} \cong$ 20 MHz. Fig. 5 shows the results. After maximizing the beat signal by varying the power of the higher frequency, we changed the power of the lower frequency with a calibrated X-band attenuator.

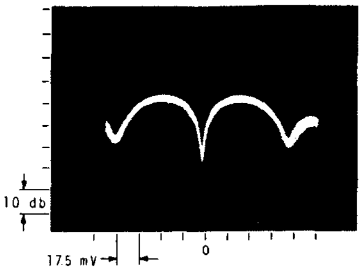

Fig. 2. RF beat note versus dc bias—even mixing case ($n = 5$).

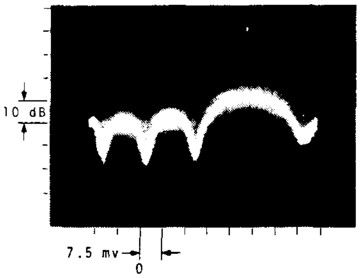

Fig. 3. RF beat note versus dc bias—even mixing case ($n = 5$) 0 bias displaced from center.

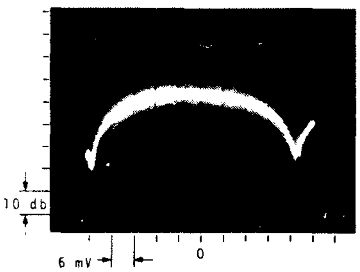

Fig. 4. RF beat note versus dc bias—odd mixing case ($n = 6$).

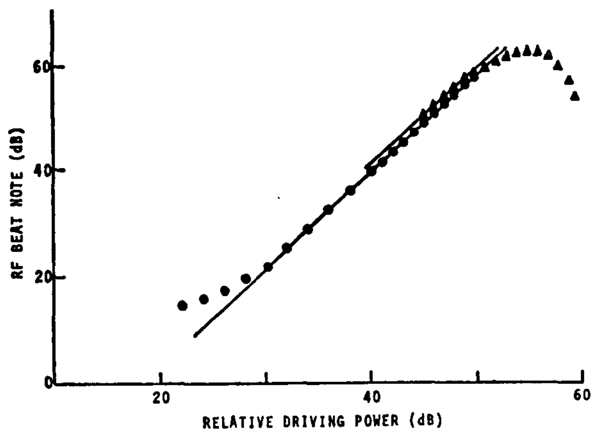

Fig. 5. RF beat signal generated by two microwave oscillators as a function of the lower frequency microwave oscillator power.

The power levels of the klystrons could be optimized independently. Sometimes, at high power, the diode condition changed and the beat intensity decreased many decibels. The erratic behavior of the diode necessitated the measurement first under low power and then under high power. The two sets of data in Fig. 5 show this result. The linear portion of this plot is represented by

$$\text{beat signal} \propto (\text{Drive power})^{+1.84}.$$

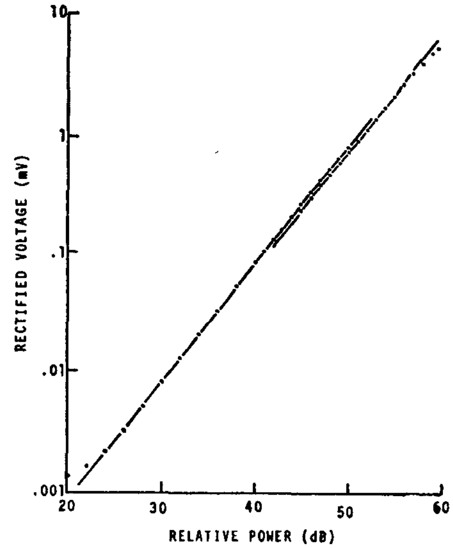

Fig. 6. Response of diode used as detector: rectified dc voltage versus microwave power.

The amount of drive power needed to generate the maximum RF beat note at different harmonics (with the high frequency power fixed) increased by 40 percent as the order was changed between 6 and 10.

The linearity of the rectified voltage from the detector was measured as a function of X-band power and is shown in Fig. 6. The detector is a linear device over three orders of magnitude (that is, the rectified voltage is proportional to the drive power). The voltage was detected with a calibrated phase sensitive detector and the X-band power was "chopped." The linearity of response indicates a small contribution from even terms of fourth order and higher in a power expansion of the voltage across the diode in terms of the applied radiation.

We also measured the dc response of the diode as a function of frequency and found a decrease of about an order of magnitude in going from 0.89 to 88 THz with about equal power from each laser. This decrease is a good deal smaller than the four orders of magnitude recently reported [16].

Conclusion

Several interesting characteristics of the metal–metal point contact diode have been revealed in this study, such as the oscillatory behavior shown in Fig. 3. It is hoped that some of these phenomena will be useful in finding an explanation for the physical processes occurring in the diode and also that they may be a guide to those simply wishing to use this device as a high-speed detector, harmonic generator, or mixer.

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