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Response of Metal-Insulator-Metal Point Contact Diodes to Visible Laser Light

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Abstract. Video response and mixing behaviour of metal-insulator-metal point contact diodes have been investigated for visible laser light. Thermally enhanced tunneling is shown to dominate the dc detection behavior of those diodes, while mixing of frequencies being more than several MHz apart is a more complex phenomenon involving thermal, field- and photo-assisted tunneling. In further experiments the potential of point contact diodes for optical heterodyne spectroscopy was examined. Two green laser lines of 122 GHz frequency difference were mixed with the second harmonic of an appropriate microwave frequency, generated simultaneously on the diode. The modest S/N ratio achieved has to be assigned to the different behaviour of metal-insulator-metal diodes in the visible and rf range.

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Metal-Insulator-Metal (MIM) diodes in point contact configuration, which consist of a fine tungsten whisker tip in contact with a polished metal platelet, have been successfully employed for absolute measurements of laser frequencies in the infrared and far-infrared range for approximately ten years (see, e.g., the review article of Jimenez [1]). However, the extension of the wavelength range into the visible, equally important for metrological and spectroscopical applications, failed [2]. Though video detection of visible laser radiation was observed [3–5], no beat signals between visible lines and sums or harmonics of infrared frequencies could be obtained [2]. The reasons for this behaviour of the MIM diode are all but certain. While after years of considerable speculation the main detection mechanism for wavelengths up to the 10µm region was established as the tunneling of free electrons through the several Å thick intermediate layer of the MIM junction [6–8], various mechanisms seem to contribute, to video detection in the visible. Faris et al. [4] interpreted their bias voltage versus detected voltage measurements as a tunneling process according to the infrared diode action, neglecting all thermal and field effects. These effects are taken into account by the thermally enhanced field emission (TFE) theory as proposed for infrared wavelengths [9, 10]. This approach includes even tunneling currents induced by geometrical asymmetries of the junction [11]. Finally, there is photoemission of conduction electrons across the tunnel barrier as was shown by Elchinger et al. [12]. Twu and Schwarz [13], who found a completely different detection behaviour for infrared and visible wavelengths, assigned this to a change from electron tunneling to a superposition of several effects.

In the first part of the present work we report some measurements of the bias voltage versus detected current as well as bias voltage versus beat signal characteristics of the point contact diode. Performed with green laser light these experiments provide new insight into the above-mentioned superposition of effects. In the second part of this paper the first mixing of two visible laser lines with microwave frequencies is reported. Even with the comparably low detectivity of the diode and the high conversion loss in the visible

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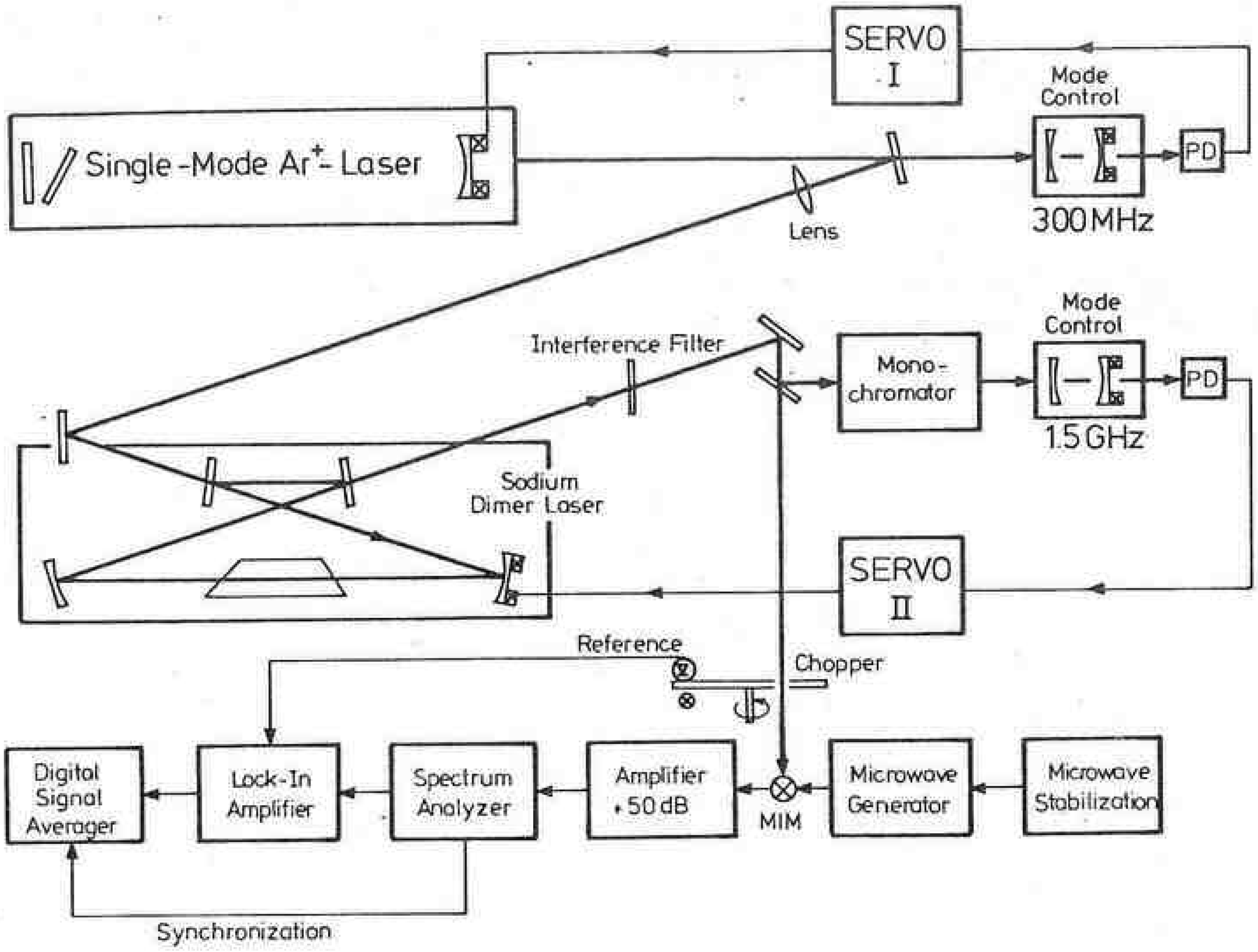

Fig. 1. Scheme of the experimental set-up

[1] this investigation is justified by the potential application of MIM diodes in high precision optical heterodyne spectroscopy.

1. Experimental Set-up

A diagram of the experimental set-up is given in Fig. 1; it essentially consists of four parts: the diode, the laser, the microwave apparatus, and the signal processing unit.

1.1. The Diode

A 25 μm thick tungsten wire was electrolytically etched a 2n KOH solution. Examination by an electron microscope showed reproducible tip radii in the 500–800 Å range. As base electrode a cobalt platelet was chosen. Polished with diamond paste to better than 0.25 μm this material seemed to be of slightly superior stability compared to a nickel or gold base. Natural cobalt oxide as well as surface-attached molecules are supposed to serve as an intermediate layer in this open structure diode.

1.2. The Lasers

During the initial stage of the experiments (frequency differences of less than 1.5 GHz) the sodium dimer laser (Fig. 1) was omitted and an unstabilized argon ion laser (Spectra Physics 171–28) was used in multimode operation at 514.6 nm. For measuring frequency differences of several GHz and more a cw sodium dimer ring-laser (see, e.g. the review article by Wellegehausen [14]) was set up to provide stable dual line/single-mode operation on various wavelengths in the green. This is achieved by narrow-band optical pumping of sodium vapor contained in an intracavity heat pipe oven at approximately 800 K and 5–8 mbar. The Ar ion laser with intracavity etalon served as 2 W single-mode pump source at 488 nm, providing an all line ring laser output of more than 200 mW. The stimulated lines all lie between 520 and 550 nm. Unidirectional laser operation is achieved without special precautions [14]. Two neighbouring lines of approximately 50 mW were selected by means of an interference filter; then the beam of the two intrinsically collinear lines was expanded and focused onto the diode contact by a microscope objective. Polarization orientation was parallel to the diode whisker. Both pump and ring laser had to be frequency stabilized by servos to separate Invar spaced Fabry-Perot cavities, in order to achieve the frequency stability required for signal averaging.

1.3. The Microwave Set-Up (Fig. 2)

To meet the experimental demands for accuracy and stability of microwave frequencies coupled into the diode a 3-stage stabilization system was built up. Starting from a crystal-stabilized 5 MHz reference combined with a frequency synthesizer Ailtech

PM 3601, 1–1800 MHz, frequency variance 10^{-10}/month) the apparatus consisted of frequency-locked wobble-generators [Marconi Model 6600 A with backward wave oszillators (BWO) 6642 and 6643 for 7–12.4 GHz and 12.4–18 GHz, respectively, and Model 6600/1 with a separate Siemens BWO 6655 unit]. Peak output powers were 50 mW in the H-, X-, and E-bands and 100 mW in the P-band.

To rule out long term instabilities a frequency counter (Hewlett-Packard 5340 A, 10 Hz – 22 GHz) fed the actual intermediate frequency ν_1 into a IEEE-488 controller (Commodore PET 2001), see Fig. 2. The latter set the frequency synthesizer in such a way that the output frequency ν_μ was kept within ±1 kHz of its programmed value. The accuracy reached was 10^9 with an overall stability of 10^8 per day. For optimum coupling of microwave power into the diode, the whisker stood in a small groove at the end of a piece of waveguide with the polarization orientation parallel to the shank. A little gold reflector at an appropriate distance from the diode helped to form a cavity-like field distribution.

1.4. Signal Processing

Following sufficient broadband amplification (Avantek AMT 2006 M, 0.1–2 GHz. 49.5 dB gain, 4 dB noise figure) intermode beats of the 514.6 nm Ar^+ line detected by the diode could be measured readily by a microwave spectrum analyzer (Hewlett-Packard 8558 B).

Detection of higher order beat notes between two laser lines and microwave harmonics, however, required averaging. Due to mechanical chopping of the laser beam the video output of each spectrum analyzer scan could be phase-sensitively detected by a lock-in amplifier (Ortec Ortholoc Sc 9505) and, finally, stored in the 512 channels of a synchronously swept signal averager (Tracor Northern NS 575 with correlator NS 588). Measurements of the detection sensitivity obtained in this way showed that signals of −145 dBm power could still be detected at a 300 kHz intermediate frequency bandwidth.

2. Results and Discussion

2.1. Diode Mechanism

Insight into the diode response to visible light can be obtained from measurements of the bias dependence of the detection characteristics. Figure 3 shows an example for the "optical" currents induced in the diode by 50 mW of multimode argon ion laser power at 514.6 nm. All four curves were obtained from the same diode adjusting the diode resistance by controlled

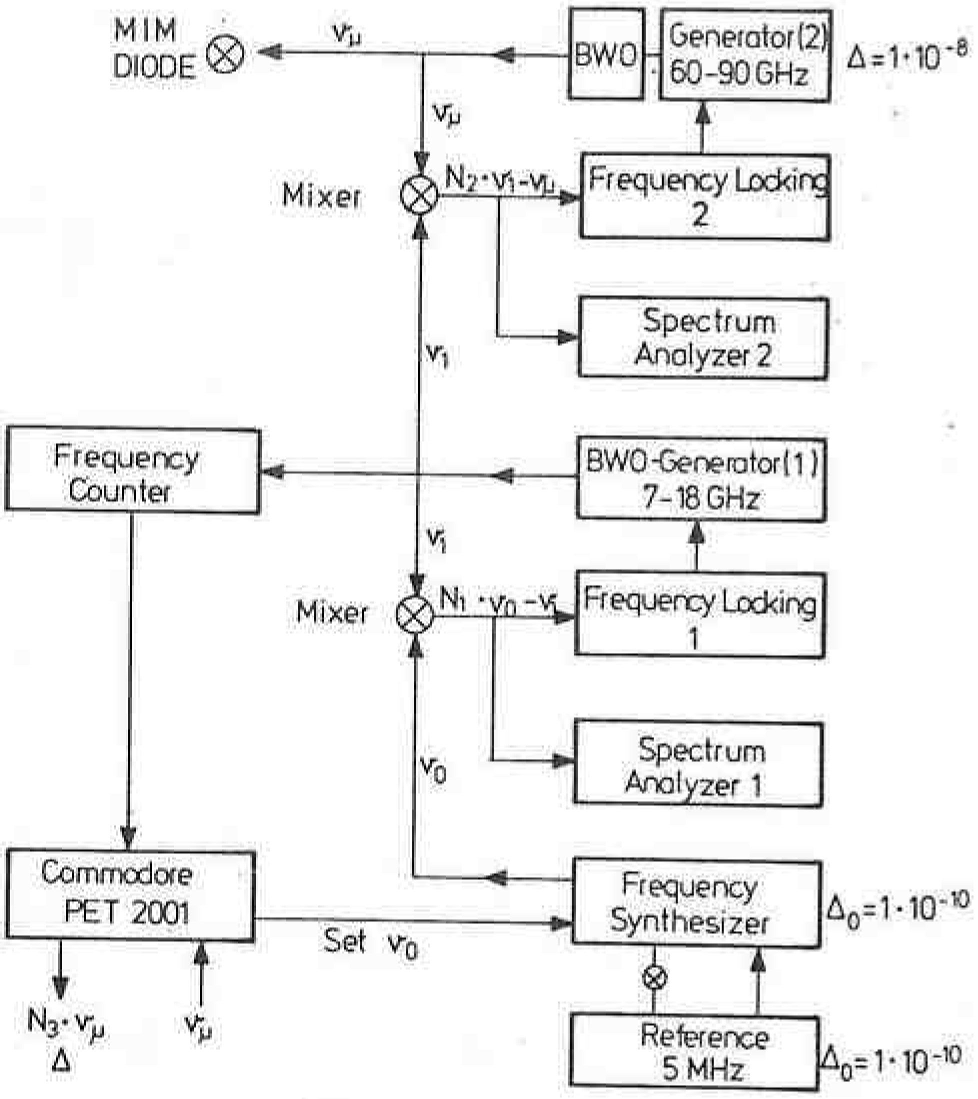

Fig. 2. Scheme of the 3-stage microwave stabilization system. (Δ: standard deviation calculated by the PET. Δ_0: frequency resettability)

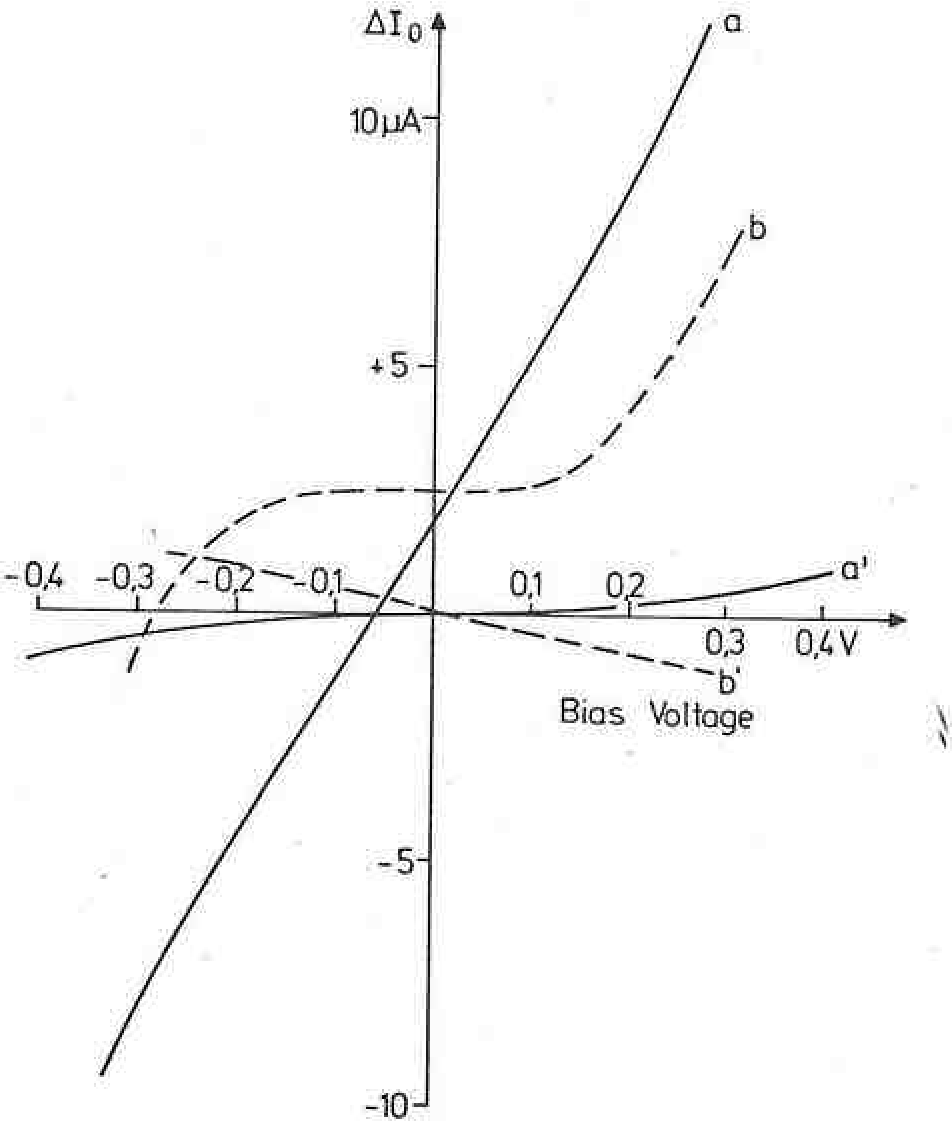

Fig. 3. Laser-induced diode current increase versus dc bias voltage. Curves *a* and *b* show the dc signals detected with 50 and 100 Ω diode resistance, respectively (chopping frequency 2 kHz); curves *a'*, *b'* are simultaneously measured with *a*, *b*; they show the currents induced by longitudinal laser modes with a 167 MHz frequency difference

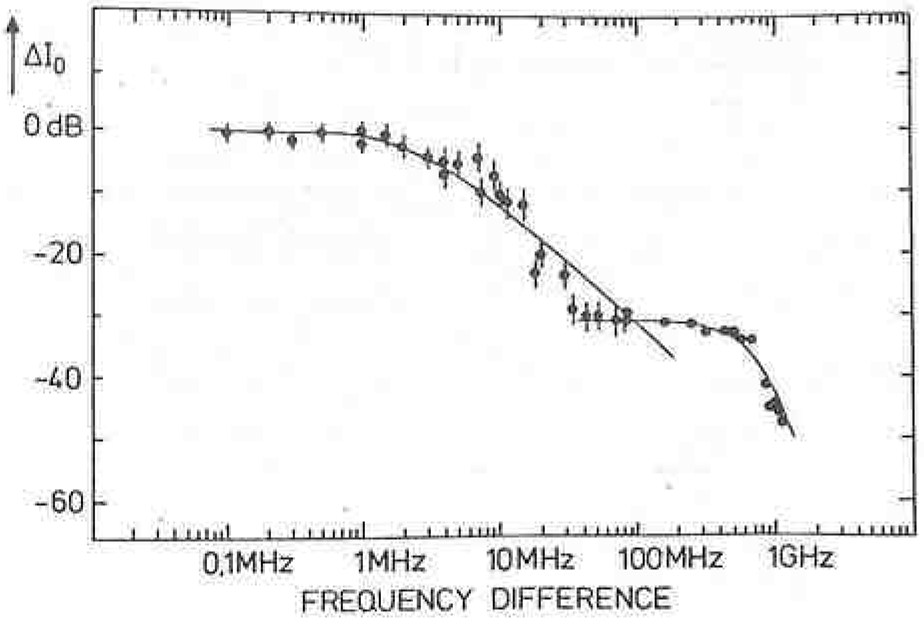

Fig. 4. Laser-induced diode current increase versus modulation frequency of the laser intensity (diode resistance 50 Ω)

change of contact pressure. Curves *a*, *b* (Fig. 3) show the *dc* response at a mechanical chopper frequency of 2 kHz for 50 and 100 Ω diode resistance, respectively; the simultaneously measured intermode beat signals (at 167 MHz) are shown as curves *a*′, *b*′ (the current direction had to be determined by a simultaneous phase measurement). While the dc signals *a*, *b* closely resemble the low bias part of the results reported by Faris et al. [4], the differences in the diode current amplitudes of *a*, *a*′ and *b*, *b*′ as well as in the polarity of *b* and *b*′ can certainly not be explained by laser field driven electron tunneling alone.

As was shown before [4, 12] and was confirmed in the experiments reported here, the diode acts as a square-law-detector in the visible for laser powers below 150 mW; therefore, there should be no significant difference between near dc and beat note detection provided that the frequencies are collinearly coupled into the diode. In order to clarify this contradiction to our experimental findings, the dependence of the diode response on the laser modulation frequency $\Delta\nu_L$ was investigated. Between 50 kHz and 80 MHz $\Delta\nu_L$ was varied by means of an acousto-optical modulator, higher frequencies being measured via intermode beats. The results are given in Fig. 4; with the familiar high frequency roll-off being due to diode mismatch the 30 dB roll-off between 1 and 40 MHz reveals a more interesting phenomenon. The full line drawn between 50 kHz and 200 MHz in Fig. 4 displays the theoretical tunneling current driven by thermal modulations of a whisker tip with a 1.7 MHz thermal cut-off frequency. The calculation follows an estimation given by Lucas and Cutler [9]. It compares favourably with the measured value of approximately 3 MHz in Fig. 4, strongly suggesting thermally excited tunneling currents to dominate the video detection of visible light in MIM diodes. An estimation using the tunneling theory of Stratton [15] and given elsewhere [16] shows that a temperature rise of 200 K leads to a 10 % increase of the tunneling current. Furthermore, it can be shown that the laser field driven diode current is two orders of magnitude smaller than the dc bias current, as was also found experimentally.

More evidence for the importance of thermal influences is gained by measuring the noise temperature increase of the diode when irradiated by laser light. For 100 and 250 mW laser power focused into a 10 μm spot an increase of 200–300 K and 700 K, respectively, was observed, in good accordance with recent findings of Lee et al. [17]. From their data, collected by laser heating of tungsten whisker tips, temperature rises of 370 and 940 K can be derived for the power levels applied by us. Furthermore they report strong emission of photoassisted TFE currents.

Support for the proposed change of detection mechanisms is also given by the resistance-dependent polarity change in curves *b*, *b*′ of Fig. 3. Even with thermal relaxation being too slow the laser-driven part of the TFE diode current should have the same direction for all modulation frequencies.

Despite that we generally found that the high frequency modulated diode signal *b*′ is opposite to the video signal for diode resistances exceeding about 75 Ω, indicating still another current contribution. Whether this has to be assigned to photoemission as was found in TFE experiments [17] or to the onset of backcurrents from surface roughness as is claimed by TFE theory [10], cannot be decided by our experiments. A direct demonstration of photoexcitation of diode currents as was performed by Elchinger et al. [12] failed because of the very low barrier height (approximately 0.5 eV, determined from I–V characteristics).

2.2. *Mixing Experiments*

While the mixing behaviour of point contact structures has been studied at microwave and submillimeter wavelengths [3, 18], a first measurement of the frequency difference between two visible laser lines is reported in this paper. Because of the square-law action of the diode and the inherent "fastness" of field- and photoassisted tunneling there is no reason for assuming different diode action when irradiated by a laser beam containing two longitudinal-mode frequencies or two collinear but independent lines. This led us to study the diode mixer response by superposing two argon ion laser modes with a rf signal. A result is shown in Fig. 5. Here a 1.2523 GHz signal from a frequency synthesizer is mixed with two higher-order intermode beat frequencies at 1.16885 and 1.3358 GHz, respectively, resulting in beat signals with 16 and 10 dB

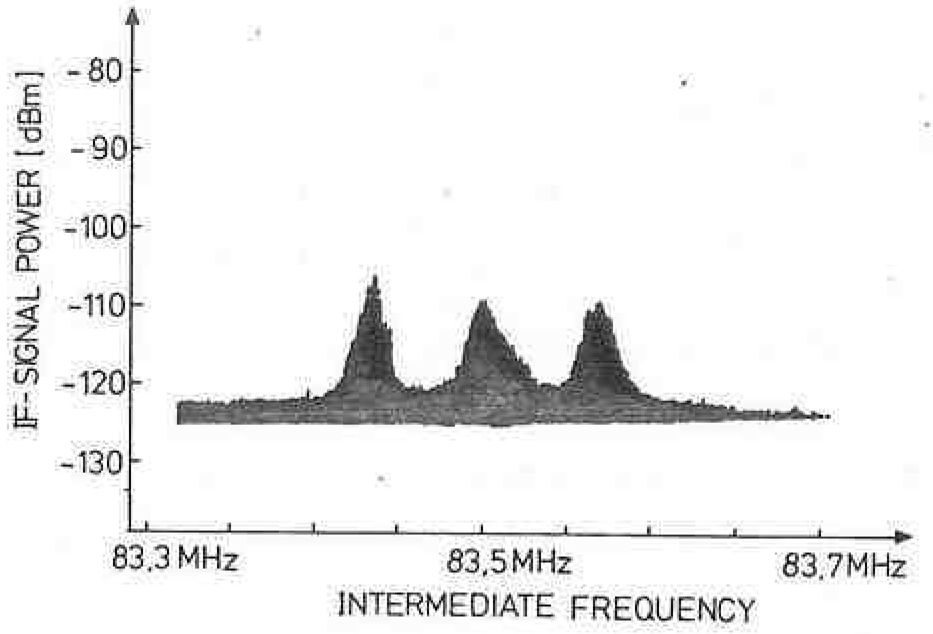

Fig. 5. Superposition of two intermode beats with a 1.2523 GHz signal. The central peak indicates the longitudinal mode spacing of the Ar^+-laser (83.49 MHz); the peak to the left (right) results from beating the rf signal with a higher-order intermode beat at 1.16885 (1.3358) GHz. – Photograph taken from screen of spectrum analyzer (bandwidth 30 kHz, scan time 10 ms/MHz) for a 50 Ω diode

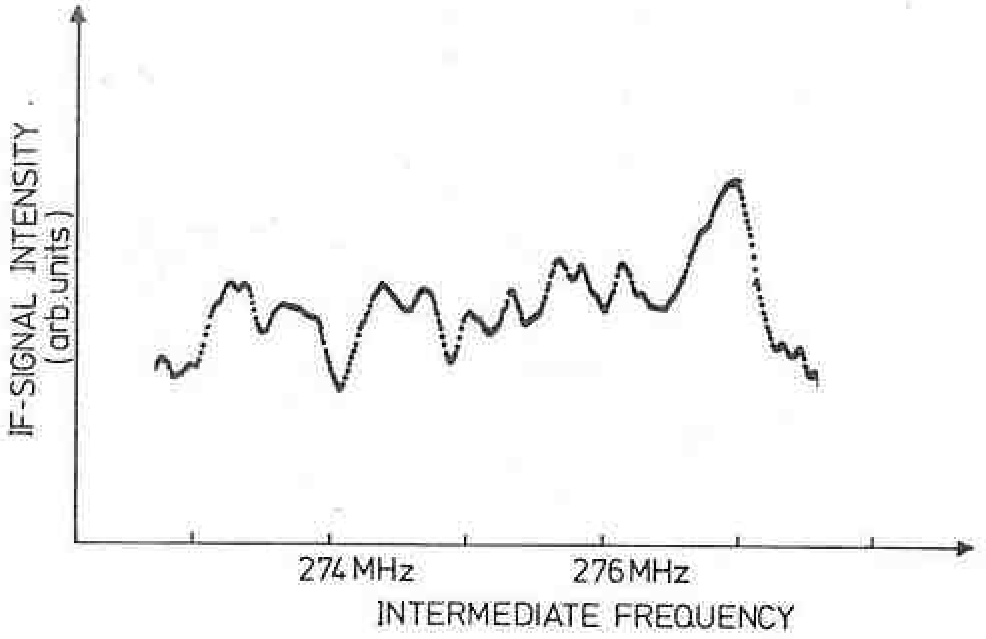

Fig. 6. Beat signal between two Na_2 laser lines (frequency difference 122.269 GHz) with the second harmonic of a microwave frequency (61.273 GHz). – Photograph taken from digital signal averager (1070 runs); spectrum analyzer bandwidth 300 kHz, scan time 10 ms/MHz; diode resistance 50 Ω. The beat signal appears at the intermediate frequency 277 MHz

above noise (analyzer bandwidth 30 kHz, scan time 10 ms/MHz, diode resistance 50 Ω). If only half the rf frequency is coupled into the diode in order to mix with its second harmonic, then the S/N ratio is reproducibly lowered about 40 dB compared to direct mixing.

This loss was much higher than the loss observed when investigating harmonic generation of rf signals alone. It is caused by the fact that we were not able to find simultaneous optimum diode conditions for laser and microwave frequencies probably due to the different diode mechanisms; while the latter is detected and multiplied best at diode resistances of several 100 Ω, laser detection works well only with resistances of the order of 10 Ω. Therefore a compromise has to be chosen with the consequence of serious power loss in microwave harmonics, which is particularly awkward since the mixing of laser lines with microwave harmonics would be of major practical interest in spectroscopy. Because of the low burn-out tresholds of point contact diodes this difficulty cannot be circumvented by a strong local oscillator.

In order to extend the frequency differences measurable by means of the MIM diode, several pairs of Na_2 ring-laser lines were investigated. During the experiments it turned out that no pair was suitable for mixing with a first harmonic microwave frequency so that higher-order mixing had to be employed. The highest frequency measured up to now in our experiments is 122.27 GHz. The beat signal (Fig. 6) was obtained by superposition of two Na_2 laser lines at 532.45 and 532.57 nm with the second harmonic of a 61.273 GHz microwave frequency and employing a time averaging technique. The modest S/N ratio is caused, 1) by the above-mentioned diode losses, and, 2) by the limitation of averaging time by frequency instabilities brought about by the dual-line laser operation.

3. Summary

It has been shown that the video detection behaviour of metal-insulator-metal point contact structures is determined by thermal contributions to the tunneling currents. Laser light of a modulation period short compared with the thermal time-constant of the whisker tip is detected via some different mechanisms, probably field- and photoassisted tunneling. This is in contrast to the diode response to rf and infrared frequencies, where free electron tunneling has been shown as the dominating mechanism.

Mixing has been achieved between two laser lines in the visible with a frequency difference of 122 GHz; for this purpose the second harmonic of a microwave frequency of 61 GHz was simultaneously generated in the diode and superposed on the laser beat frequency. The laser-microwave beat note was detectable only with averaging techniques, because different detection mechanisms in the different frequency regions lead to overall conversion losses of 60 to 80 dB. This prevents the point contact structure from being a practical tool for frequency measurements in the visible. An important improvement in S/N ratios can be expected, however, by prior generation of microwave harmonics in an external Schottky mixer. Continuation of the experiments in this direction is expected to result in much better laser-microwave beat signals.

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