2.5-THz frequency difference measurements in the visible using metal-insulator-metal diodes

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Using point-contact metal-insulator-metal diodes, we have demonstrated heterodyne detection of visible laser radiation at frequency differences up to 2.5 THz (generated by a 119-μm laser). The signal to noise on the observed rf beat falls off at 2.3 dB/octave of laser frequency difference and would seem to indicate that 30-THz difference beats will be obervable with improved laser stability or signal averaging. While the diode detector "bandwidth" per se has not been evaluated, these measurements demonstrate an increase in the frequency difference which can be measured in the visible by more than an order of magnitude over that previously reported.

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Point-contact metal-insulator-metal (MIM) diodes have been developed, studied, and used over the last ten years as detectors, harmonic generators, and mixers in the frequency range from a few megahertz to 50 THz.[1] Their use has extended frequency measurement technology to the near IR regions of the spectrum.

Although the response mechanisms of these devices are not yet understood in every detail, there is a general consensus that a long wire antenna couples to a tunnel junction.[2] This model is able to explain most of the observed responses of the diodes to μ wave and far-infrared radiation. It also suggests explanations[3,4] for the observed decrease in the diodes ability to generate harmonics above about 30 THz and its apparent inability to synthesize frequencies above about 200 THz.[5] In spite of these limitations the diode is known to respond to visible radiation[6] and recently Daniel *et al.*[7] investigated the potential use of the diodes as broadband heterodyne detectors of visible radiation. In those experiments, light from two visible lasers was focused collinearly onto a MIM diode along with the microwave difference frequency. The mixing of all three radiations produced the rf difference frequency in the diode current. Detector sensitivity to at least 170 GHz was demonstrated. In this letter, we extend those results to 2.5 THz with the use of optically pumped lasers, and show evidence that indicates a 30-THZ difference should be attainable.

The experimental arrangement is shown in Fig. 1. The diodes used in these experiments were of conventional design.[7,8] A 25-μm-thick tungsten wire was electrolytically etched in a KOH(2N) solution producing a long tapered point with a tip radius of about 50 nm. This point was then lightly contacted to a mechanically polished cobalt or nickel post. The post material was not subjected to any overt oxidization process and so the normal air oxidized surface layer formed the insulating barrier. The whisker contacting force was adjusted to give a junction resistance of approximately 300 Ω. No significant differences were observed between the W-Co or W-Ni diodes.

The cw ring dye lasers were servostabilized to Fabry–Perot cavities and had linewidths of about 300 kHz. The "λ meter" was a simplified Hall and Lee[9] design and was used to set the dye lasers to the desired difference frequency to an accuracy of 100 MHz. The visible laser beams were expanded to beam diameters of 5–7 mm, adjusted to have flat wave fronts, combined on a dielectric beam splitter, attenuated to a total power of ~20 mW, and focused onto the diode through a high quality long-working-distance microscope objective. The light was directed in at 45° to the cat whisker with its polarization parallel to the whisker (P polarization). The focused spot diameter was about 5 μ.The far-infrared (FIR) lasers have been described elsewhere.[10] In these experiments, we measured different frequencies corresponding to the CH_3OH laser lines at 571 μm (0.525 THz), 171 μm (1.757 THz), and 119 μm (2.522 THz). A 2-m FIR metal-dielectric waveguide laser produced 5–10 mW of FIR power. The far-infrared radiation was focused through a polyethylene lens into the primary lobe of the diode antenna pattern[11] with P polarization. During a measurement, the

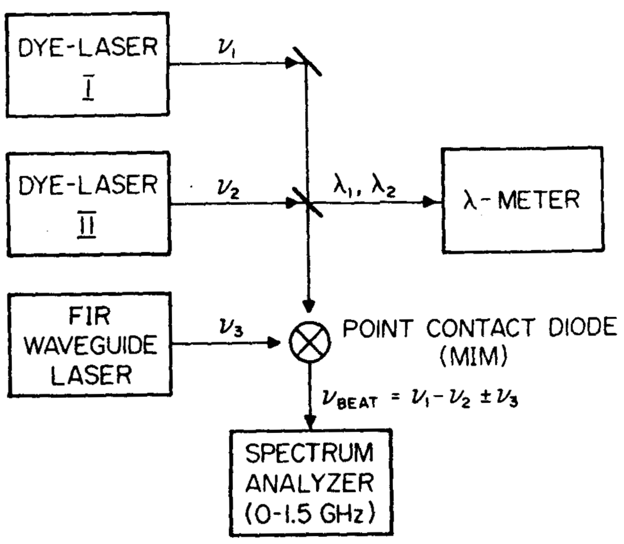

FIG. 1. Schematic diagram of the experiment.

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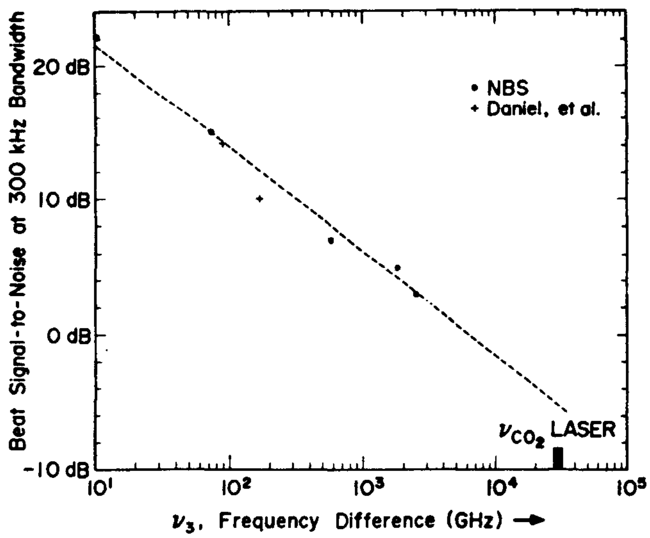

FIG. 2. Signal-to-noise ratios for the observed beat signals as a function of visible laser difference frequency.

various frequencies applied to the diode mix to produce a beat in the rf region which is detected and analyzed:

$$\nu_{\text{rf beat}} = (\nu_1 - \nu_2) \pm \nu_3,$$

where ν_1 and ν_2 are the dye laser frequencies and ν_3 is the frequency of the klystron or far-infrared laser. In these experiments $(\nu_1 - \nu_2)$ was always adjusted such that $\nu_{\text{rf beat}}$ would be in the 400–800-MHz range. This signal was observed on a spectrum analyzer without signal averaging. The results quoted are for the following spectrum analyzer settings: a resolution of 300 kHz, sweep width of 100 MHz, and sweep period of 50 ms.

Figure 2 shows a plot of the signal-to-nose ratio of the observed beat signal as a function of the difference frequency. Also shown in this plot are two points (88 and 170 GHz) from the work of Daniel *et al.*[7] Only the best signal-to-noise ratios have been plotted; they varied about 10 dB at each difference frequency, possibly depending on the sharpness of the whisker. Electron micrographs were not taken of the diodes used in these experiments, but previous micrographs show tip radii from less than 100–600 Å.

The signal-to-noise ratio falls off at 2.3 dB/octave. The reason for this falloff is not known. The capacitive shunting of the diode is expected to be -6 dB/octave, but is not expected to begin until about 10 THz for a 400-Å tip and 30 THz for a 100-Å tip. Previous measurements have shown that the far-infrared sensitivity is constant over the frequency range employed. To compensate for a possible change in coupling efficiency at higher frequencies, the far-infrared laser is chopped during alignment and the alignment and power adjusted to give the same magnitude diode response in all cases.

The response line on Fig. 2 has been extended to 30 THz ($10\,\mu$m). It shows that for the conditions of these experiments a signal-to-noise ratio of -5 dB would be expected. However, more narrowband lasers or signal averaging should allow one to do heterodyne detection in the visible with a bandwidth of at least 30 THz. This corresponds to a wavelength step of 300 Å so only a few such transfers would be necessary to relate one centrally located reference frequency to markers throughout the visible.

We have recently narrowed the dye lasers to less than 3 kHz and feel the 30-THz beat will be achieved soon in a carefully controlled set of experiments. The use of this diode for direct frequency difference measurements in the visible should provide a relatively easy method of performing high accuracy spectroscopic measurements in this portion of the electromagnetic spectrum.

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