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Mixing of 28 THz (10.7 μm) CO_2-laser radiation by nanometer thin-film Ni–NiO–Ni diodes with difference frequencies up to 176 GHz

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Abstract

Difference frequencies up to 176 GHz between CO_2-laser transitions at 28 THz (10.7 μm) are generated by thin-film nanometer-scale Ni–NiO–Ni diodes (MOM, MIM) with integrated bow-tie antennas and rhodium waveguides. A signal-to-noise (S/N) ratio of 47 dB was measured for a 58.7 GHz difference frequency and a 100 kHz bandwidth, while a S/N ratio of 14 dB was observed for a 176.2 GHz difference frequency and a 300 kHz bandwidth. The frequencies reported are considerably higher than those reported previously for thin-film diodes. The comparison of the mixing signals for the antenna parallel and perpendicular to the E-polarization of the infrared radiation yields a ratio of over 34 dB. These results imply the extension of millimeter-wave techniques to the infrared. © 1997 Elsevier Science B.V.

Point-contact Metal–Oxide–Metal diodes were first used for mixing two adjacent CO_2-laser transitions by Hocker et al. in 1968 [1]. Since then these devices are used in absolute frequency measurements and high-resolution spectroscopy [2] at microwave, infrared and optical frequencies. In the early seventies, Javan and co-workers [3] reported the first fabrication of thin-film diodes which permitted the mixing of 964.6 GHz (311 μm) and 890.2 GHz (337 μm) HCN laser radiation with a difference frequency of 74.4 GHz. The fast response of MIM or MOM diodes, which is needed for high-frequency mixing, demands a thin oxide layer for nonlinear electron tunneling and an extremely small contact area that implies a sufficiently short RC time constant. Our development of thin-film Ni–NiO–Ni diodes with integrated dipole, bow-tie and spiral antennas and their application to the detection of 10 μm CO_2-laser radiation is described elsewhere [4–7]. First experiments on mixing of CO_2-laser radiation with our thin-film Ni–NiO–Ni diodes were performed at LENS (Florence, Italy). On this occasion we have succeeded to measure difference frequencies up to 85 MHz [8]. Here, we report on the first successful mixing of two 28 THz (10.7 μm) CO_2-laser transitions in the 10P branch with difference frequencies up to 176.2 GHz. For this purpose we used our thin-film Ni–NiO–Ni diodes with inte-

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Fig. 1. Electron microscope image of our thin-film Ni–NiO–Ni diode with integrated bow-tie antenna taken at 45° incidence.

grated bow-tie antennas and new integrated rhodium waveguides.

The manufacture of the nanometer-scale Ni–NiO–Ni diodes is described in [6]. For our previous mixing experiments, the contact area was already reduced to approximately 110 nm × 110 nm [8] by making use of electron-beam lithography at the IBM Research Laboratory (Rüschlikon, Switzerland).

Fig. 1 shows an electron micrograph of our diode and an integrated bow-tie antenna with a resonant half-length of 2.3 μm. This diode is based on a high-resistivity (> 3 kΩcm) silicon substrate, whereas our previous diodes [5–8] were supported by 3–5 Ωcm silicon wafers. This minimizes the

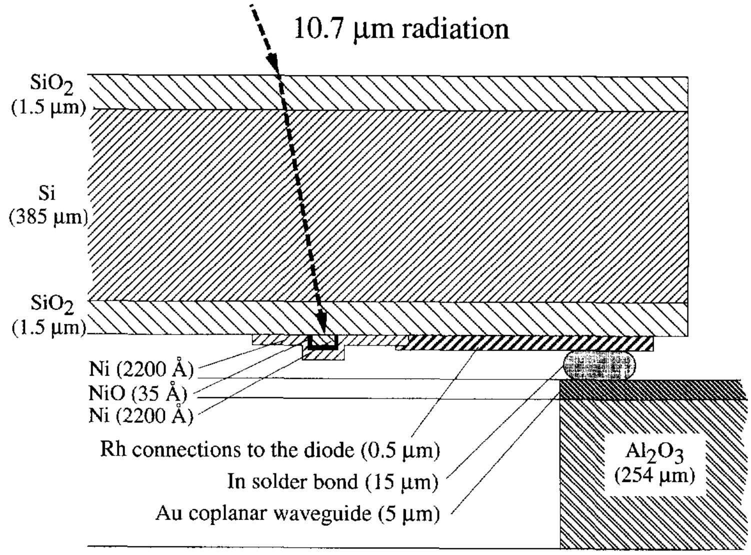

Fig. 2. Schematic cross section of Ni–NiO–Ni diode and its connections (not to scale).

Table 1
Frequencies and wavelengths of the vibrational–rotational CO_2-laser transitions [11] used in our mixing experiments

CO_2-laser emission	Frequency (THz)	Wavelength (μm)
10P(30)	28.0274319	10.7640602
10P(32)	27.9694499	10.7411219
10P(34)	27.9107213	10.7185683
10P(36)	27.8512433	10.6963942

substrate losses in the microwave region [9] and, in addition, decreases the attenuation of the antenna currents at infrared frequencies. The previous connections to the diode with bond-wires [8] have now been replaced by coplanar rhodium waveguides and indium solder flip-chip connections as illustrated in Fig. 2. They constitute excellent high-frequency connections from the diode to the coplanar gold waveguide on a ceramic substrate and permit the illumination of the antenna from the back side of the substrate. The high transmission of about 80% of the SiO_2/Si substrate at wavelengths of about 10.7 μm permits us to take advantage of the higher sensitivity of an antenna to the radiation incident from the substrate side [10].

The radiation of two CO_2-lasers tuned to two of the transitions listed in Table 1 [11] was focused on the diode. The total infrared power on the diode was approximately 400 mW. The two lasers constitute part of the permanent frequency-measurement chain of the PTB (Braunschweig, Germany) [12]. Part of the mixing performed is shown in Table 2. In the second-order mixing experiment, the difference-frequency signal of two adjacent laser lines at 58.7 GHz was transmitted by HF coaxial cables (Wiltron-V) to an external high-sensitivity microwave receiver developed at Swiss Post Office Research Laboratory (PTT, Bern, Switzerland), which was connected to a spectrum analyzer. The higher-order mixing processes measured required the microwave radiation produced by a Gunn oscillator working at the frequencies 58.8 GHz ± 50 MHz and with a power of 100 mW. The diode was irradiated with the microwaves emitted from the open end of a hollow waveguide. The measured mixing signals listed in Table 2 show significant S/N ratios, especially in the third-order mixing with 47 dB for a bandwidth of 100 kHz. The highest difference frequency of 176.19 GHz was generated by mixing the 10P(30) and 10P(36) emissions with the third harmonic of the Gunn oscillator in a fifth-order mixing process (Fig. 3).

We have also measured the mixing signals for the antenna parallel and perpendicular to the E-polarization of the 10.7 μm CO_2-laser radiation. The ratios of the corresponding signals in the 58 to 176 GHz range are over 34 dB. This demonstrates that our bow-tie antennas show almost perfect polarization as predicted by the antenna theory of microwave techniques [13]. This can be explained by the fact that in our range of difference frequencies, the polarization-independent thermal effects are too slow to influence the mixing signal.

Our experiments represent the first mixing of 10 μm CO_2-laser radiation with thin-film MOM diodes with difference frequencies in the 50 to 200 GHz range. The S/N ratio of 14 to 47 dB can be improved by narrower focusing of the infrared radiation, a more efficient coupling of the microwave radiation to the diode and an optimization of the bias voltage based on a better knowledge of the $I(V)$ characteristics of the diode. The difference frequencies of the mixing of 28 THz radiation with our thin-film diodes can be increased by using higher-order mixing processes or microwave sources with higher frequencies, e.g. 200 GHz klystrons. Finally, our experiments have revealed that a further reduction of the present contact area (110 nm × 110 nm)

Table 2
Mixing with our thin-film Ni–NiO–Ni diodes

Combination of two CO_2-laser transitions	Difference frequency $\Delta\nu$	Microwave frequency	Mixing order	S/N ratio	Bandwidth
10P(32)-10P(34)	58.7286 GHz	—	2	22 dB	100 kHz
10P(32)-10P(34)	58.7286 GHz	58.8 GHz	3	47 dB	100 kHz
10P(30)-10P(34)	116.7106 GHz	2 × 58.8 GHz	4	19 dB	100 kHz
10P(30)-10P(36)	176.1886 GHz	3 × 58.8 GHz	5	14 dB	300 kHz

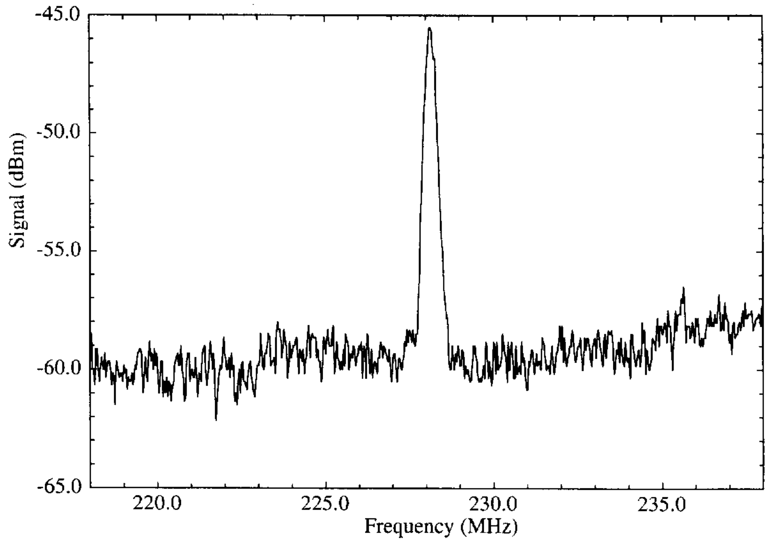

Fig. 3. Fifth-order mixing signal between the two CO_2-laser emissions 10P(30) and 10P(36) and the third harmonic of a Gunn oscillator working at 58.8 GHz. The two CO_2-laser emissions, each with a power of ≈ 200 mW, are polarized parallel to the antenna axis. Both are focused on our thin-film Ni–NiO–Ni diode with a lens of 63.5 mm focal length. The bandwidth of the spectrum analyzer is 300 kHz.

does probably not improve noticeably the performance of the diodes in experiments with 10 μm CO_2-laser radiation.

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