PHOTOMIXING IN LOW-TEMPERATURE-GROWN GaAs

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ABSTRACT

Photomixing occurs in epitaxial low-temperature-grown GaAs between two voltage-biased metal electrodes on which two laser beams are focused and are detuned to a desired difference frequency. Compared with pulsed THz-radiation emitters such as time-domain photoconductive switches, the photomixer is useful when a constant wave source is needed with high spectral brightness and narrow linewidth. Also, a general technique has been demonstrated at microwave frequencies for photoconductive sampling in the frequency domain using two photomixers driven by a single pair of diode lasers. A terahertz implementation would compare favorably to time-domain sampling for narrow-linewidth spectroscopy.

Heterodyne measurements in the region 30−1000 μm can reveal the spectroscopic signatures of molecules that are important for atmospheric sensing and for astrophysical measurements. Recent advances in superconducting THz receivers [1, 2] have created a compelling need for a tunable single-frequency local oscillator with output power $> 1\,\mu$W from roughly 1 to 3 THz.

The photomixer generates a THz difference frequency by photoconductive mixing of two tunable single-frequency lasers in low-temperature-grown (LTG) GaAs [3, 4]. In one design, the combined laser beams are focused on an 8×6-μm area with interdigitated 0.2-μm-wide electrodes that are separated by a 1.8-μm gap and are voltage biased at approximately 30 V. The electrodes are at the drive point of either a log-spiral or a dipole antenna [5] that radiates through the GaAs substrate that is mounted on a Si hyperhemisphere lens. Compared to other fast photoconductors, high-quality LTG GaAs is well suited to this application because of its short carrier lifetime (< 0.25 ps), high electrical breakdown field ($> 5 \times 10^5\,\mathrm{V/cm}$), and its relatively high mobility ($> 100\,\mathrm{cm^2/Vs}$).

Our recent efforts have focused on increasing the maximum THz power available from the photomixer. The available THz power is approximately proportional to P_i^2, where P_i is the total optical power incident on the photomixer. Our room-temperature photomixers

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can withstand a total optical power of $P_i \approx 60\,\text{mW}$ $(9 \times 10^4\,\text{W/cm}^2)$ when biased at 30 V. Above that power, a combination of optical and ohmic heating causes catastrophic failure of the device. Cryogenic operation at 77 K was shown to increase the optical power handling to $\sim 90\,\text{mW}$ which increased the emitted THz power by approximately $\times 2$—because of the increased thermal conductance of the GaAs substrate [6]. Recently, LTG-GaAs layers with carrier lifetime less than $\sim 300\,\text{fs}$ were grown by molecular-beam epitaxy on a high-resistivity silicon substrate. Photomixers that were fabricated from this wafer sustained incident optical power of 120 mW without failing. Also, the output THz power increased commensurately with the optical pump power and THz absorption losses in the silicon substrate degrade the signal at 1.1 THz by only $\sim 20\%$. At present, photomixers with log-spiral antennas are being used for comparison of the THz output power with photomixers on GaAs substrates over a wide range of operating frequencies. Photomixers with resonant antennas have also been fabricated on the silicon substrate. An example of a 1.5-THz full-wave dipole is shown in Fig. 1. The scanning electron micrograph shows the metal electrode pattern that defines the photomixer. The Smith chart shows design calculations that were obtained with a commercial planar-structure solver [7]. Preliminary measurements show a peak output power at 1.4 THz with a 3-dB bandwidth of approximately 15%. By comparing the output power from this antenna with a spiral-antenna from the same wafer, the measured radiation resistance of the dipole will be estimated.

Photomixers show promise for use as local oscillators [4] and for high-resolution gas spectroscopy when coupled to a cryogenic detector such as a bolometer [8]. A recent development is the demonstration of photoconductive sampling in the frequency domain using a pair of photomixers. This technique is analogous to time-domain photoconductive sampling where two photoconductive switches are illuminated by a mode-locked laser. Such a technique, in principle, would use the second photomixer as the receiver rather than a helium-cooled bolometer. For spectroscopy applications that require narrow-resolution linewidth ($< 1\,\text{MHz}$), this technique can offer significant improvement over time-domain sampling in spectral brightness ($\sim 10^6$ times higher). Furthermore, the system is coherent, widely tunable, and can be compact—using inexpensive diode lasers that are fiber coupled to photomixer-transmitter and receiver chips.

Figure 2a shows a block diagram of how narrow-linewidth spectroscopy could be performed coherently and at room temperature using antenna-coupled photomixers as the transmitter and receiver. Figure 2b shows the experimental setup that was used to test the concept at microwave frequencies. The combined light from a pair of distributed-Bragg-reflector laser diodes is split in half and fiber coupled to each photomixer. Each LTG-GaAs photomixer consists of a 20×20-μm active region with 0.2-μm wide interdigitated electrodes spaced by

0.6 μm for the transmitter and by 0.4 μm for the receiver. The transmitter is dc biased through a broadband bias tee and therefore develops an ac current across the electrodes when the photoconductance is modulated at the difference (beat) frequency of the two laser beams. Some of the resulting microwave power is launched onto a coplanar waveguide which transitions into a 50-Ω coaxial line that is connected in similar fashion to the receiver. At the receiver end, the optical beating periodically raises the photoconductance such that a small amount of unipolar current flows into the dc current amplifier. This action is equivalent to homodyne detection of the rf electric field.

Two experiments have been performed to verify that homodyne detection is occurring. First, the transfer characteristic of a narrow bandpass filter has been measured and agrees with that measured using a microwave spectrum analyzer. Second, as shown in Fig. 3, the homodyne signal scales linearly with the dc-bias voltage (or incident electric field) while the transmitted power measured with a spectrum analyzer scales quadratically. The magnitude of the receiver photocurrent is in good agreement with predictions from a theoretical model that accounts for the impedance mismatch between the photomixers and the transmission line.

In summary, photomixers fabricated from low-temperature-grown GaAs deposited on a silicon substrate show improved optical power handling and increased THz output power. Resonant antennas are being evaluated that should further increase the output power. Compared to time-domain sampling, the most important advantages of frequency-domain photoconductive sampling are spectral brightness and the use of compact inexpensive lasers. The disadvantages including longer acquisition times for measuring very broad spectra and standing waves introduced by the high level of coherence. This work was supported by the National Aeronautics and Space Administration, Office of Space Access and Technology, through the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology.

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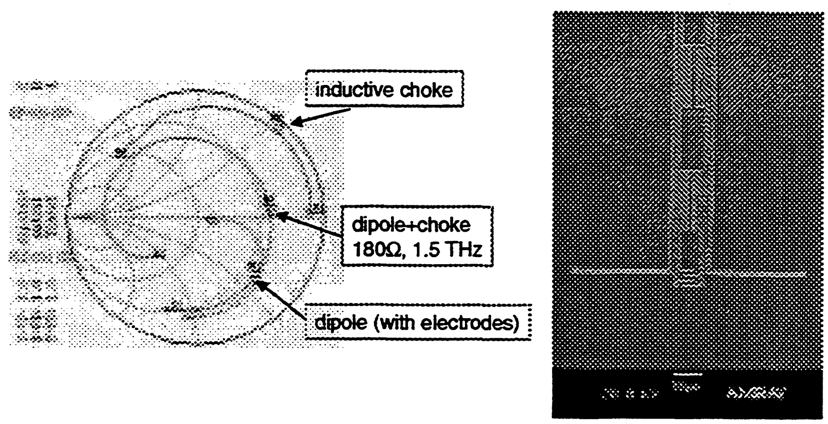

Figure 1: Calculated drive-point impedance for a 1.5-THz full-wave dipole with inductive tuning built into the choke. Also shown: scanning electron micrograph of such an antenna fabricated on LTG-GaAs on a GaAs substrate.

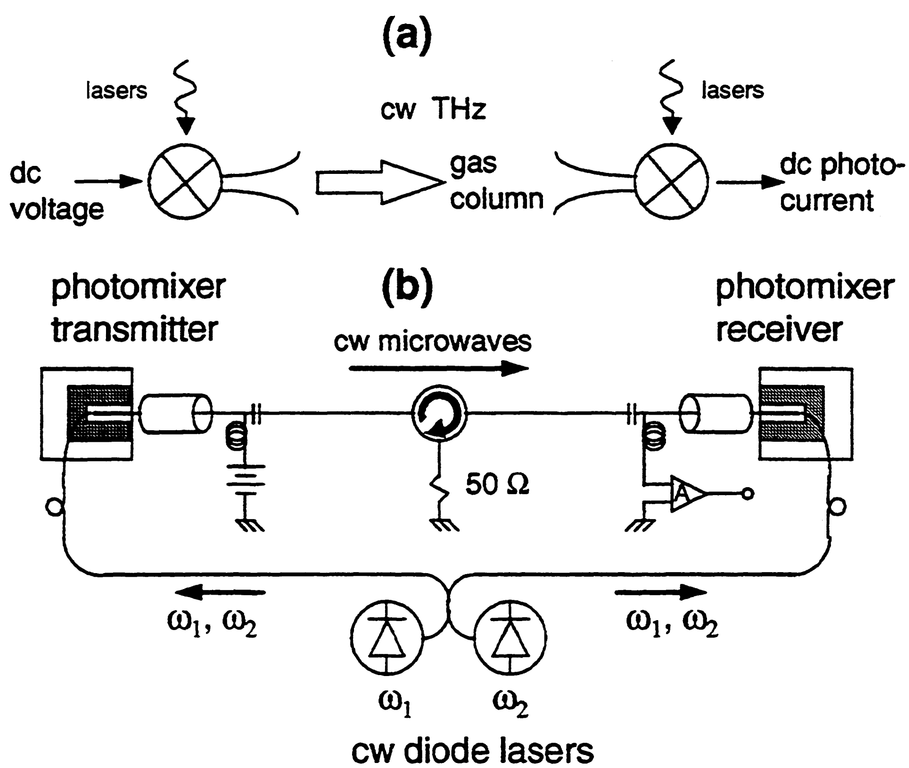

Figure 2: (a) Block diagram for frequency-domain photoconductive sampling. (b) LTG-GaAs photomixers used as transmitter and receiver in proof-of-concept measurements at microwave frequencies (0.05–26.5 GHz).

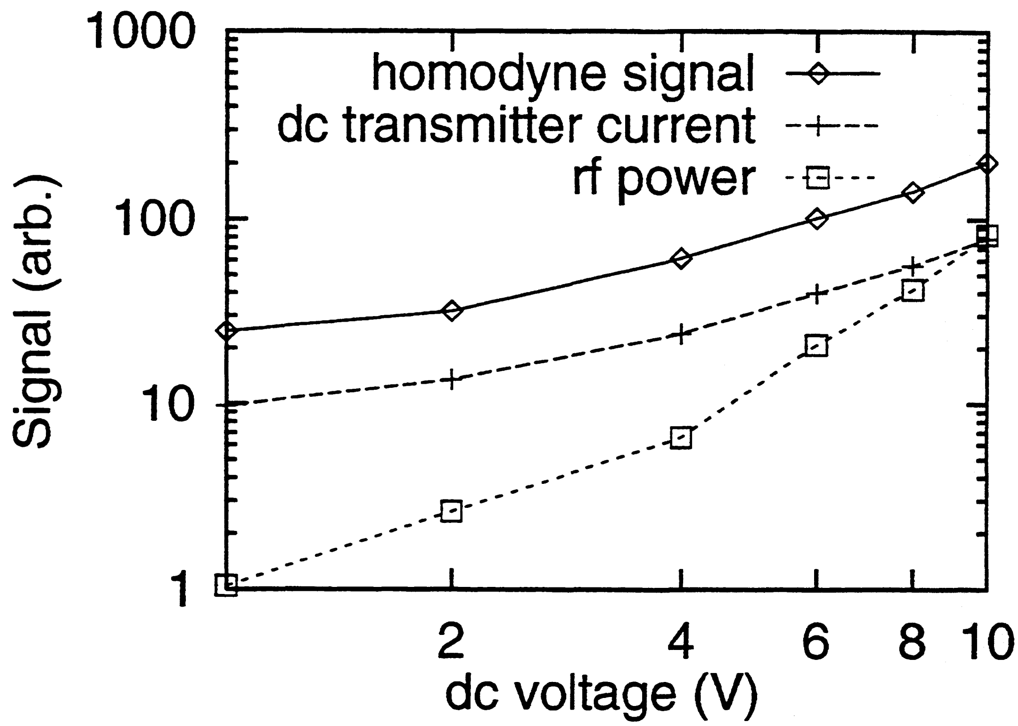

Figure 3: 4.5-GHz homodyne signal detected by the receiver as a function of voltage bias on the transmitter. The coherent signal scales linearly with voltage while the power scales quadratically with voltage. The dc photocurrent in the transmitter is also shown (300 μA at 10V).