FIBER-COUPLED PHOTOMIXERS OPERATING AT CRYOGENIC TEMPERATURES

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ABSTRACT

Optical heterodyne conversion, or photomixing, occurs in epitaxial low-temperature-grown GaAs between two voltage-biased metal electrodes on which two laser beams are focused with their frequencies offset by a desired difference frequency. Compared with optoelectronic THz 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.

The spectral region 30 – 1000 μm lies beyond the capabilities of both solid-state optical sources on the short wavelength side and of electronic sources on the long wavelength side. Heterodyne measurements in this region 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 2.5 THz.

The photomixer generates a THz difference frequency by photoconductive mixing of two tunable single-frequency lasers in low-temperature-grown (LTG) GaAs [3]–[5]. Both Ti:sapphire and diode-laser pairs have been used with no measurable difference observed in the photomixer performance. In one of our designs, the combined laser beams are focused on an 8×8-μm area with interdigitated 0.2-μm-wide electrodes that are separated by a 1.8-μm gap and voltage biased at approximately 30 V. The electrodes are at the drive point of either a spiral or a dipole [4] antenna 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 ($> 5 \times 10^5$ 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 can

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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 expected to increase the maximum withstandable optical power because the base temperature is reduced by 223 K and because the thermal conductivity of the GaAs substrate increases by a factor of 6 at 77 K relative to 300 K [6]. In principle, this would allow operation with increased pump power and would result in much higher emission of THz power. In this paper, we report on the increase in emitted THz power that was realized experimentally upon cooling to 77 K.

The cooled photomixer was operated in a liquid-nitrogen cryostat with fiber-optic coupling used to route the optical beams. Figure 1 shows the fiber-optic coupling scheme. Combined light from two continuous-wave Ti:sapphire lasers operating between $813-819$ nm was coupled into a 4-m length of polarization-maintaining optical fiber [7]. The fiber entered the cryostat through a 1-cm-long length of stainless steel tubing that was filled with low vapor-pressure epoxy. The cleaved end of the fiber was positioned over the photomixer active area and was cemented to a position roughly $50\,\mu\text{m}$ away from the photomixer chip. At this distance, the mode field of the light in the fiber expands to approximately fill the $8 \times 8\,\mu\text{m}$ active area. The result is a robust package that allows independent alignment of the THz and optical beams and is immune to thermal motion in the cryostat. For comparison, measurements were also performed using free-space coupling to the photomixer through an optical window.

Figure 2 shows a comparison of the THz output power for photomixers operating at 300 and 77 K. The THz power was measured with a calibrated 4.2-K bolometer. Curve (a) is a bandwidth curve for a fiber-coupled photomixer operating at 300 K with $P_i = 20\,\text{mW}$ and a bias voltage of $V = 30\,\text{V}$. Curve (b) was measured for a free-space-coupled photomixer operating at 300 K, with $P_i = 30\,\text{mW}$, and $V = 20\,\text{V}$. The bandwidth of the fiber-coupled device is in agreement with the free-space-coupled device. The output power is proportional to P_i^2 and to V^2. Therefore, curves (a) and (b) were expected to agree in amplitude, as well. Curve (c) was measured from the free-space-coupled photomixer used in (b) after it was cooled to 77 K. The shapes of the curves (b) and (c) are similar and the 3-dB bandwidth of ~ 0.9 THz was preserved as the device was cooled to 77 K. This suggests that the ultrafast trapping of carriers by the midgap defect states is not very temperature dependent. Curves (d) and (e) are measured from a fiber-coupled device at 77 K with optical pump powers of 40 and 60 mW respectively. The amplitude of the measured output power scales roughly as the square of the optical pump power. The point on curve 2(f) is from a free-space coupled photomixer operating at 77 K with $P_i = 90\,\text{mW}$. This point is our highest measured output power $(0.2\,\mu\text{W})$ at 2.5 THz to date. The line shows the expected scaling of the THz output to lower frequencies. The

0.2-μW point was limited by the available power from the cw Ti:sapphire lasers. Damage-threshold measurements made with a single, more powerful Ti:sapphire laser suggest that the photomixer can withstand approximately $P_i = 96\,\text{mW}$ before failure. A detailed understanding of the failure mechanism is being explored [8].

In summary, cooled photomixers can withstand increased power from the pump lasers and consequently have been shown to emit unprecedented levels of power. A fiber coupling scheme allowed for more robust alignment and packaging compared to free-space coupling. There was no observed reduction in bandwidth when the photomixer was cooled to 77 K. This work was supported in part 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 and by the Air Force under Contract F19628-95-C-0002.

References

[1] D. E. Prober, *Appl. Phys. Lett.*, **62**, 2119 (1993); A. Skalare, W. R. McGrath, B. Bumble, H. G. LeDuc, P. J. Burke, A. A. Verheijen, and D. E. Prober, *IEEE Trans. Appl. Supercond.* **5**, 2236 (1995).

[2] G. N. Gol'tsman, B. S. Karasik, O. V. Okunev, A. L. Dzardanov, E. M. Gershenzon, H. Ekstroem, S. Jacobsson, and E. Kollberg, *IEEE Trans. Appl. Supercond.* **5**, 3065 (1995).

[3] K. A. McIntosh, E. R. Brown, K. B. Nichols, O. B. McMahon, W. F. Dinatale, and T. M. Lyszczarz, *Appl. Phys. Lett.* **67**, 3844 (1995).

[4] K. A. McIntosh, E. R. Brown, K. B. Nichols, O. B. McMahon, W. F. Dinatale, and T. M. Lyszczarz, *Appl. Phys. Lett.* **69**, 3632 (1996).

[5] S. Verghese, K. A. McIntosh, and E. R. Brown, to appear in *IEEE Trans. Microwave Theory Tech.*, August 1997.

[6] J. S. Blakemore, *J. Appl. Phys.* **53**, R123 (1982).

[7] Single-mode, polarization-maintaining optical fiber, 850-nm center wavelength. Model FS-4625-PM, 3M Specialty Optical Fibers, West Haven, CT.

[8] S. Verghese, K. A. McIntosh, and E. R. Brown, submitted to *Appl. Phys. Lett.* on 30 April, 1997.

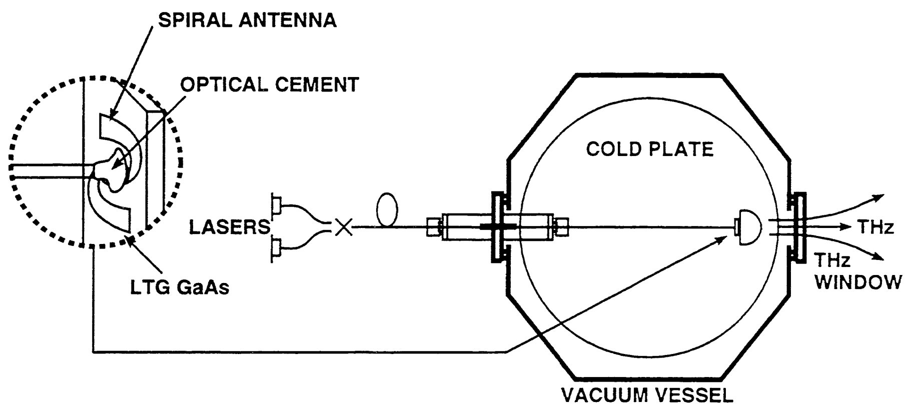

Figure 1: Schematic diagram of the cryogenic LTG-GaAs photomixer coupled to two lasers via optical fiber. Both diode lasers and Ti:sapphire lasers have been used.

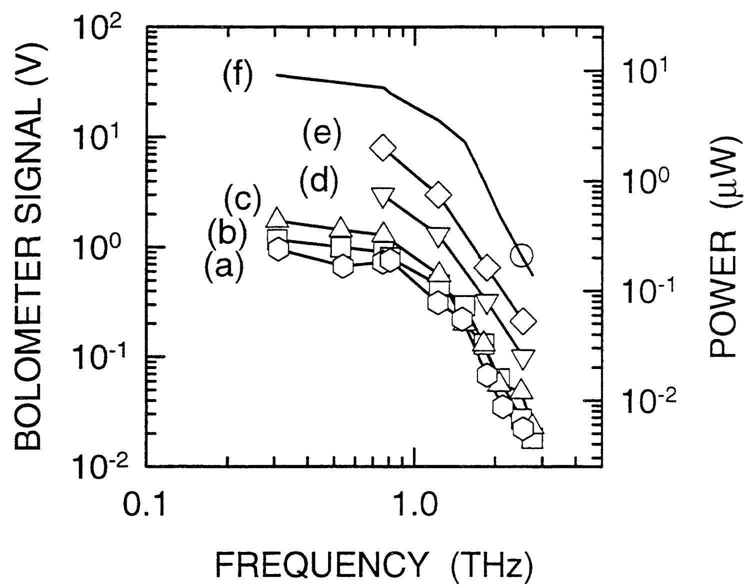

Figure 2: Measured bandwidth curves for photomixers operating at room temperature and at liquid nitrogen temperature. (a) 300-K operation of a fiber-optic coupled photomixer with 30-V bias and $P_i \approx 20\,\mathrm{mW}$. (b) 300-K operation of a free-space coupled photomixer with 20-V bias and $P_i = 30\,\mathrm{mW}$. (c) 77-K free-space coupled photomixer under same conditions as curve (b). (d) 77-K fiber-coupled photomixer with 30-V bias and $P_i \approx 40\,\mathrm{mW}$. (e) 77-K fiber-coupled photomixer with 30-V bias and $P_i \approx 60\,\mathrm{mW}$. (f) 77-K free-space coupled photomixer with 30-V bias and $P_i \approx 90\,\mathrm{mW}$.