Demonstration of a phase-lockable microwave to submillimeter-wave sweeper

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ABSTRACT

The development of low-temperature-grown GaAs photomixers enables the construction of a microwave to submillimeter-wave source capable of large frequency sweeps. By utilizing semiconductor diode lasers to drive the photomixer, this source is all solid-state and compact, and has small power consumption. Frequency stabilization of the semiconductor diode lasers allows this source to be phase-locked to an external microwave reference. Two 805 nm extended-cavity-diode lasers are mixed in a low-temperature-grown GaAs photoconductive photomixer. The difference-frequency mixing product is radiated by a planar spiral antenna and collimated by a Si lens. This output is phase-locked to a microwave reference by downconverting it in a whisker-contacted Schottky-barrier diode harmonic mixer and using the output to offset-phase-lock one laser to the other. The photomixer output power is 300 nW at 200 GHz and 10 nW at 1.6 THz, as measured by a 4 K InSb bolometer calibrated with a methanol laser and a power meter at 526 and 812 GHz.

1. INTRODUCTION

The earliest and possibly the most important application of submillimeter-wave radiation was spectroscopy.[1] As submillimeter-wave sources have become more compact and robust, spectroscopic applications outside the laboratory, such as remote sensing for atmospheric science and astrophysics, have become practical. The most serviceable present submillimeter-wave source is a 50-100 GHz Gunn diode oscillator harmonically multiplied with a whisker-contacted Schottky-diode varactor. However, this source is not yet electrically tunable over even a 10% bandwidth with high power.[2]

Optical heterodyne conversion, or photomixing, was proposed as a method for producing coherent microwave and millimeter-wave radiation over three decades ago.[3] But application of this method was delayed until the development of suitable photomixers. Such photomixers have recently become possible with the advent of low-temperature-grown (LTG) GaAs with photoconductive response, sub-picosecond electron-hole recombination time, and $>10^5$ V•cm^{-1} dc breakdown field properties.[4] Photomixers made from this material have produced as much as about 3 μW of output power with a 3 dB bandwidth of 650 GHz.[5,6]

One advantage of photomixing over other ways of generating millimeter and submillimeter-wave radiation is the ease of tuning the output frequency by tuning one of the pump lasers. Diode lasers with a single-mode frequency sweep range of 1.4 THz at 100 Hz sweep rate have been demonstrated. Since the photomixer conversion efficiency is approximately constant below its corner frequency, multi-octave frequency sweeps with minimal amplitude variation are possible.

A nice demonstration of the spectroscopic capabilities of these photomixers has been made by A. Pine.[7] A spectrometer based on LTG GaAs photomixers was used to study SO_2 self broadening coefficients in the 0.1-1.0 THz

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frequency range. In this instrument, the photomixer was driven by two single-mode dye lasers which were pumped by an argon ion laser. Subsequent work demonstrated operation of LTG GaAs photomixers pumped by semiconductor diode lasers.[6] Semiconductor diode lasers are ideal for driving photomixers because they are compact, efficient, tunable, and relatively inexpensive. They also have sufficient output power and can be spectrally narrow. The extended-cavity tunable diode lasers used in this work occupy 780 cm^3, consume less than 1 W of electrical power, and can be mechanically tuned over at least 14 THz.

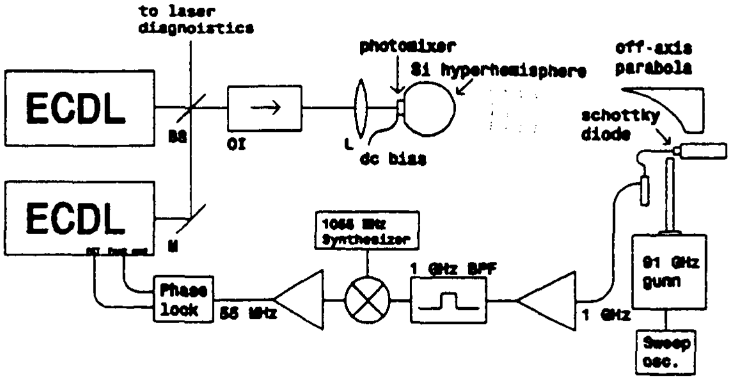

Figure 1. Experimental setup. The extended-cavity diode lasers use commercial 100 mW, 805 nm devices.

The linewidth and stability of the radiation produced by the photomixer is determined by the lasers used to drive it. The lasers in this work have linewidths of approximately 100 kHz and low-frequency jitter of a few megahertz. By coherently detecting the radiation, we can phase-lock the offset between the two lasers to a harmonic of a microwave source. The linewidth, stability, and accuracy of the millimeter and submillimeter radiation are then determined by the phase noise, stability, and accuracy of the microwave source.

2. EXPERIMENT DESCRIPTION

The photomixers used in this work consist of interdigitated electrodes on an epitaxial layer of LTG GaAs. The electrodes are 0.2 μm wide, separated by 1.8 μm wide gaps, and cover a total area of 8x8 μm. The electrodes drive a three-turn self-complementary spiral antenna. The output radiation propagates through the GaAs substrate and is coupled out of the substrate and partially collimated by a hyperhemispherical Si lens mounted in contact with the back of the GaAs chip.

The experimental setup is illustrated in Figure 1. The photomixer is driven by two extended-cavity diode lasers (ECDLs). Each is a commercial 100 mW 805 nm diode laser with an anti-reflection coating on the output facet. The extended cavities are in a Littman configuration,[8] and the output frequency of the laser is adjusted by tilt and translation of the mirror. Adjustment screws on the mirror mount provide coarse tuning with a range of 14 THz, and piezoelectric actuators provide fine tuning. Single mode scans of 19 GHz are possible in the present system by electronically matching the ratio of tilt and translation to synchronize the bandpass frequency determined by the grating with the frequency of an extended-cavity mode. This tuning range is determined by the 9 μm translation range of the piezoelectric actuators used and the cavity dimensions. Special lasers designed for long-scanning range have demonstrated multi-terahertz continuous scans. For phase-locking, electronic feedback to the injection current provides fast frequency control with a 3 dB bandwidth of approximately 2 MHz.

The two laser beams are combined by a beam splitter and then circularized with an anamorphic prism pair. After passing through two Faraday isolators, the combined beam is resized by a telescope and focused on the photomixer by a lens. The beam size and lens focal length were chosen to produce a 7 μm spot size on the photomixer. Typical powers from each of the lasers are 9 mW and 22 mW. The performances of the two lasers differ due to differences in the quality of their anti-reflection coatings.

The dc photocurrent and the millimeter-wave output power both increase with increasing dc bias across the photomixer electrodes. At 30 V bias the responsivity was 14 mA/W. Electrical or thermal burnout of the photomixer becomes likely at higher bias voltages or at total optical power levels above 100 mW.

The output radiation of the photomixer is focused by an off-axis paraboloid onto the long-wire whisker antenna of a point-contact Schottky diode. A 91 GHz local oscillator signal from a Gunn diode is also coupled onto the whisker. The Schottky diode down-converts the millimeter or submillimeter radiation from the photomixer by mixing it with a harmonic of the local oscillator. The down-converted signal near 1 GHz is amplified, filtered, and then sent to a spectrum analyzer and a phase-locking circuit.

3. RESULTS

The power produced by the photomixer was measured by focusing it onto an InSb bolometer with a polyethylene lens; the result of these measurements is shown in Figure 2. The bolometer's response was calibrated at 526 GHz and 812 GHz by using an attenuated methanol laser whose full output power was measured separately with a broadband power meter.[9]

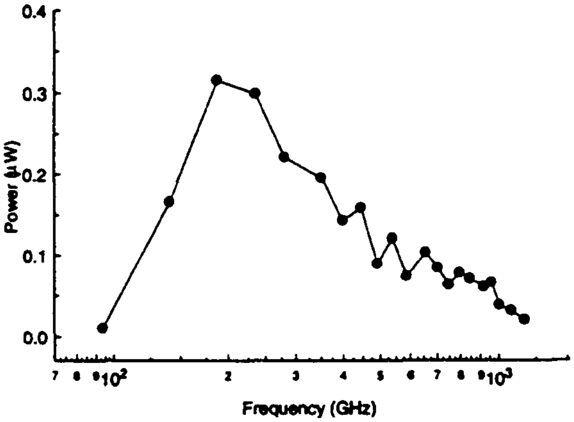

Figure 2. Photomixer output vs. frequency. Power measurements were made with a 4 K InSb bolometer which was calibrated at 526 and 812 GHz with a methanol laser.

Figure 3 shows the signal-to-noise ratio of the down-converted signal as a function of local oscillator harmonic number. The signal-to-noise ratio in the present system is sufficient to maintain an offset phase lock of one of the lasers to the other for harmonic numbers up to 5. Figure 4 shows the down-converted signal with the lasers locked using the fourth harmonic, an offset of 366 GHz. The linewidth of the submillimeter wave signal is limited by the phase noise of the 91 GHz Gunn diode local oscillator. If the Gunn diode had been locked to a low phase-noise synthesis chain, the linewidth could have been as narrow as a few hertz.[10]

One method for sweeping the photomixer's output frequency while maintaining a phase-lock is to mix the down-converted output from the harmonic mixer with a variable frequency before sending it to the phase-locking circuit. This topology was tested for offset-frequency laser phase-locks with frequency differences up to 18 GHz by using a fast photodetector in place of the photomixer. Phase-locked sweeps encompassing the full synthesizer band of 7 GHz worked reliably. When the synthesizer switched bands, the rf output was briefly absent. Unless the phase-locking integrator was carefully nulled, the system failed to automatically relock after the band switch. If it relocked, then it was possible to sweep over the full 19 GHz electronic tuning range of the lasers. However, without a tracking filter or a single-sideband mixer, the signal-to-noise ratio of the signal at the phase detector was degraded by 3 dB by the noise from the unwanted mixing sideband. These minor difficulties could be overcome in a system specifically designed for long-range scans.

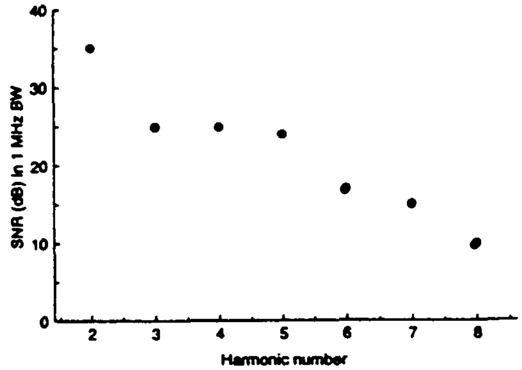

Figure 3. Detected signal-to-noise ratio (SNR) vs. 91 GHz local oscillator harmonic number. Phase-locks are possible for harmonic numbers less than six.

A second method for sweeping the photomixer's output frequency while maintaining a phase lock is to sweep the 91 GHz local oscillator's frequency. This allows a fixed-frequency filter to be used to reject the unwanted mixing sideband. This approach was tested with the photomixer's output phase-locked to the fourth harmonic of the 91 GHz local oscillator. The Gunn diode oscillator used in this experiment had only 1.10 GHz of bias tuning range. Applying a voltage ramp to the Gunn diode bias produced a phase-locked sweep of 4 GHz span centered at 364 GHz.

4. FUTURE PROSPECTS

The present system would allow free-running sweeps with a width over 1 THz with an appropriate laser. For phase-locked sweeps, sweeps broader than 4 GHz should be possible with a local oscillator which has more tuning range. The loss of local oscillator power that comes with a broader tuning range should not be a problem, since the Gunn diode had significantly more power than was necessary for these experiments.

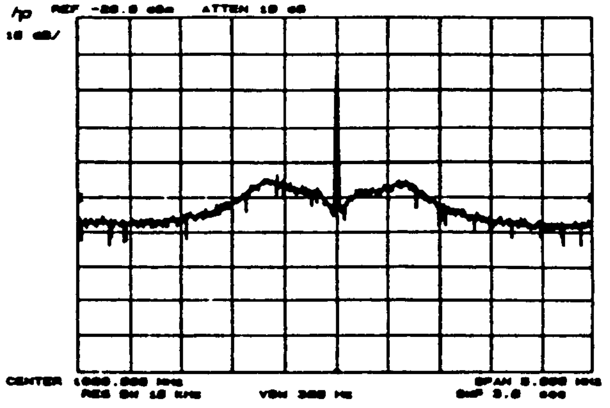

Figure 4. Power spectrum of phase-lock using the fourth harmonic of the 91 GHz local oscillator.

Figure 4 shows that power measurements made by observing the down-converted signal amplitude could have a noise floor of 3 fW/Hz. This is much lower than a cryogenic Si bolometer with a NEP of 0.13 pW/√Hz.[7] Compared to cryogenic bolometers, heterodyne detection also has the practical advantage of room-temperature operation.

As the speed of LTG GaAs material improves, photomixers with greater bandwidth will become possible. Some recent LTG GaAs samples have shown photoconductive lifetimes on the order of 100 fs, raising hopes for photomixers with bandwidths of several terahertz. Improvements in the photomixer design may also increase their burnout threshold, so stronger pumps can be used to increase the output power. When combined with semiconductor diode lasers, these photomixers will make possible a broadly tunable, narrow-linewidth millimeter-wave source which will also be compact and transportable. This in turn would allow new spectroscopic and coherent-detection applications.

7. ACKNOWLEDGMENTS

At NIST this work was supported by the Air Force Office of Scientific Research. At Lincoln Laboratories this work was supported by NASA through the Jet Propulsion Laboratory. The authors thank Lyndon Zink and Ken Evenson for supplying assistance, equipment, and laboratory space.

8. REFERENCES

1. F. C. DeLucia, T. M. Goyette, "Terahertz source requirements for molecular spectroscopy," *Nonlinear Optics for High-Speed Electronics and Optical Frequency Conversion*, pp. 239-247, SPIE, Los Angeles, CA, USA, 1994.
2. M. A. Frerking, "Submillimeter Source Needs for NASA Missions," *Nonlinear Optics for High-Speed Electronics and Optical Frequency Conversion*, pp. 222-229, SPIE, Los Angeles, CA, USA, 1994.
3. R. H. Pantell, J. M. DiDomenico, O. Svelto, J. N. Weaver, "The Theory of Optical Mixing in Semi-conductors," *Proceedings of the 3rd International Conference on Quantum Electronics*, P. Grivet, N. Bloembergen, Eds., pp. 1811-1818, Columbia Univ. Press, 1963.
4. E. R. Brown, F. W. Smith, K. A. McIntosh, *J. Appl. Phys.* **73**, 1480-1484 (1993).
5. E. R. Brown, K. A. McIntosh, K. B. Nichols, C. L. Dennis, *Appl. Phys. Lett.* **66**, 285-287 (1995).
6. K. A. McIntosh, et al., *Appl. Phys. Lett.* **67**, 3844-3846 (1995).
7. A. S. Pine, R. D. Suenram, E. R. Brown, K. A. McIntosh, *Journal of Molecular Spectroscopy* **175**, 37-47 (1996).
8. M. G. Littman, H. J. Metcalf, *Applied Optics* **17**, 2224-2227 (1978).
9. K. M. Evenson, et al., *IEEE Journal of Quantum Electronics* **QE-13**, 442-444 (1977).
10. F. L. Walls, C. M. Felton, "High Spectral Purity X-Band Source," *Fourty-Fourth Annual Symposium on Frequency Control*, pp. 542-547, Baltimore, Maryland, 1990.