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Terahertz photonic mixers as local oscillators for hot electron bolometer and superconductor-insulator-superconductor astronomical receivers

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A pump experiment of two astronomical heterodyne receivers, a superconductor-insulator-superconductor (SIS) receiver at 450 GHz and a hot-electron-bolometer (HEB) receiver at 750 GHz, is reported. A low-temperature-grown GaAs metal-semiconductor-metal photonic local oscillator (LO) was illuminated by two near infrared semiconductor lasers, generating a beat frequency in the submillimeter range. *I-V* junction characteristics for different LO pump power levels demonstrate that the power delivered by the photomixer is sufficient to pump a SIS and a HEB mixer. SIS receiver noise temperatures were compared using a conventional solid-state LO and a photonic LO. In both cases, the best receiver noise temperature was identical (T_{sys}=170 K).
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I. INTRODUCTION

Photomixing has been used for several years as a technique for signal generation in the millimeter and submillimeter ranges.[1] The huge bandwidth offered by a single photomixing device (from dc to several terahertz) has tremendous potential for various applications such as radio astronomy, terahertz imaging, high-resolution spectroscopy, medicine, security, and defense. The progress made in the fabrication of low-temperature-grown GaAs (LT-GaAs) has lead to carrier trapping times below 1 ps at moderate bias voltages, which is essential for fabrication of photomixers in the terahertz range.

In this paper we report on photomixing as a local oscillator (LO) source for heterodyne detection in radio astronomy. The development is aimed at the integration of a photonic LO in the German Receiver for Astronomy at Terahertz Frequencies (GREAT), which will be a first-generation dual-channel heterodyne instrument for high-resolution spectroscopy aboard Stratospheric Observatory For Infrared Astronomy (SOFIA), and in the high-frequency heterodyne receivers at the Atacama Pathfinder Experiment (APEX), currently in final commissioning.

II. PHOTONIC GENERATION OF TERAHERTZ RADIATION

The scheme for optical heterodyning (Fig. 1) consisted of two slightly detuned near infrared (NIR) ~780 nm continuous-wave (cw) monomode lasers in Littman configuration (New Focus, model Velocity 6312), where at least one laser was tunable to make frequency selection possible. The output power of the lasers, ~6 mW, was insufficient for satisfactory rf power generation in the photomixer. With a set of mirrors and beam splitters, the laser beams were made col-

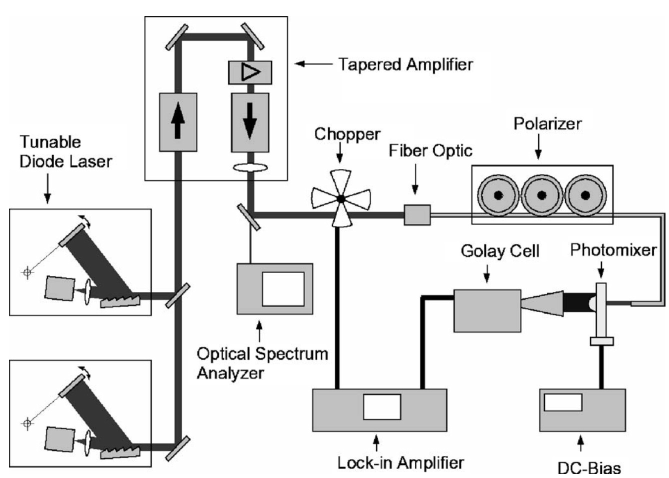

FIG. 1. Schematic diagram of the measurement setup.

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linear and drove a tapered laser amplifier (Toptica TA100). This configuration provided up to 0.5 W of combined power.

The beam was then coupled into a single-mode optical fiber (95%) and to an optical spectrum analyzer (with 5%) to monitor frequency difference and to guarantee equal power distribution between the two colors. To avoid optical feedback to the lasers and amplifier, we included in the setup optical isolators and fiber optics with angled polished connectors (APC), providing >60 dB reflection losses. A fiber polarizer converted the laser polarization of the optical fiber input to a polarization orthogonal to the finger direction of the photomixer. This procedure is mandatory to minimize reflection from the photomixer, since the finger structure has dimensions comparable to the laser wavelength.

To achieve optimal photomixer illumination, the optical fiber was positioned with a piezoelectric actuator. This device allowed a fine (~100 nm) position control in three axes. The air gap between the optical fiber and photomixer substrate acts as a Fabry-Pérot etalon, so we used an optical adhesive[2,3] with a similar refraction index as the optical fiber core to pigtail the fiber optic to the photomixer. This process also inhibited the negative effects of mechanical vibrations, which potentially could lead to mispositioning of the fiber optic over time thus limiting the reproducibility of our experiments.

Once the two lasers interfere on the LT-GaAs photoactive area, electron-hole pairs are generated. The bias voltage applied to the electrodes builds an electric field that separates the photocarriers, creating a photocurrent proportional to the optical intensity. The ultrashort electron lifetimes of LT-GaAs allow the photocurrent to “follow” the envelope of the optical instantaneous power. Details of the underlying physical phenomena can be found elsewhere.[4–6]

The photoactive area was patterned at the feed point of a resonant or broadband antenna, so that the beat signal was radiated to free space. The high dielectric constant of the GaAs photomixer substrate ($\varepsilon_r = 12.8$) prevented the signal from being radiated backwards to the fiber optic. The hyperhemispherical form of the substrate suppressed surface modes and provided acceptable beam directivity.[7,8]

III. MIXING EXPERIMENT WITH A SIS RECEIVER AT 450 GHZ

The power performance and noise temperature of our photomixers were verified first with a superconductor-insulator-superconductor (SIS) mixer. Similar pump[9–11] and noise temperature[11] experiments have already been reported.

It is well known that photomixers have a high internal resistance,[12] and thus impedance matching is difficult. For this reason, high radiation resistance antennas are needed. Full-wave dipole antennas show a higher resistance (~210 Ω on a GaAs substrate) than broadband logarithmic spiral antennas (~73 Ω on a GaAs substrate). The polarization of a dipole is linear, having the same orientation as the dipole itself, whereas the polarization of a spiral is circular (supposing a photomixer area with dimensions much smaller than the wavelength of the terahertz signal). Furthermore, the Gaussicity of a dipole is better than that of a spiral antenna.

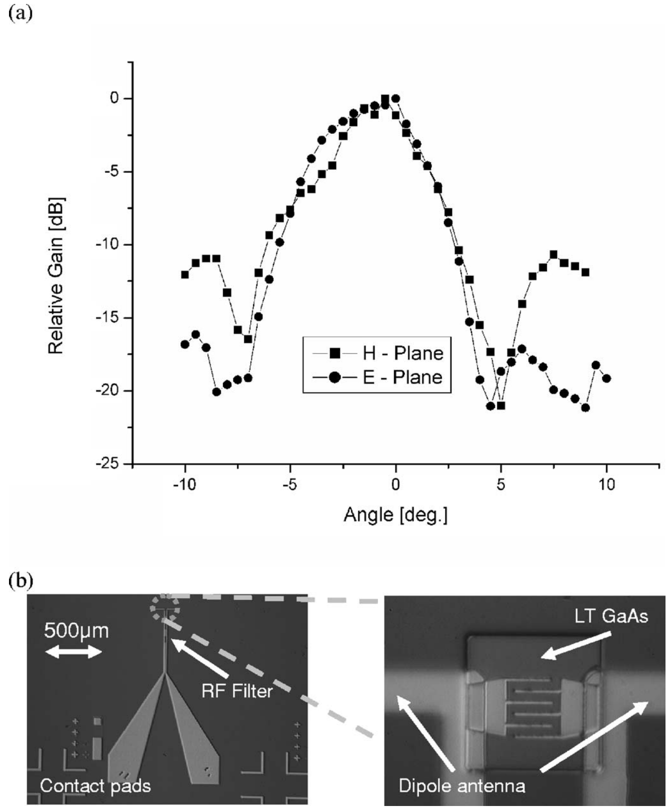

FIG. 2. (a) *E*-plane and *H*-plane power patterns measured for a full-wave dipole in resonance at 450 GHz. The high-resistivity Si substrate has a hyperhemispherical form to reduce the divergence of the beam. (b) Microphotograph of the dipole antenna and finger structure of the photoactive area.

Our SIS mixer was sensitive only to linearly polarized signals, further favoring the use of a dipole antenna.

In our first experiment, a SIS mixer was pumped with a dipole antenna photomixer. Amplitude measurements across the *E* and *H* planes showed good Gaussicity and low sidelobes (Fig. 2).

The SIS junction *I*-*V* characteristic of an astronomical heterodyne receiver at 450 GHz is shown in Fig. 3 for two different LO power pump levels. With a photocurrent of 0.6 mA and a NIR optical power of 70 mW, the rf power generated was 0.8 μW, which is a factor of three below the device burnout at room temperature, so that an acceptable safety margin is available to operate the photonic LO.

To investigate whether the photonic LO adds significant internal noise to the mixer, we compared receiver noise temperatures derived from hot and cold measurements using a conventional solid-state LO and the photonic LO. A Martin-Puplett (MP) diplexer was used to inject the LO signal into the signal path. The divergent beam from the MP diplexer output was transformed to a convergent beam with a plane-convex Teflon lens.

The double sideband (DSB) noise temperatures of the astronomical receiver pumped by the photomixer and by the solid-state LO (both measured at an intermediate frequency band of 2–4 GHz) were identical ($T_{\mathrm{receiver}} = 170$ K). In contrast to cascading multipliers, the noise contribution of a photonic LO is not expected to increase with frequency be-

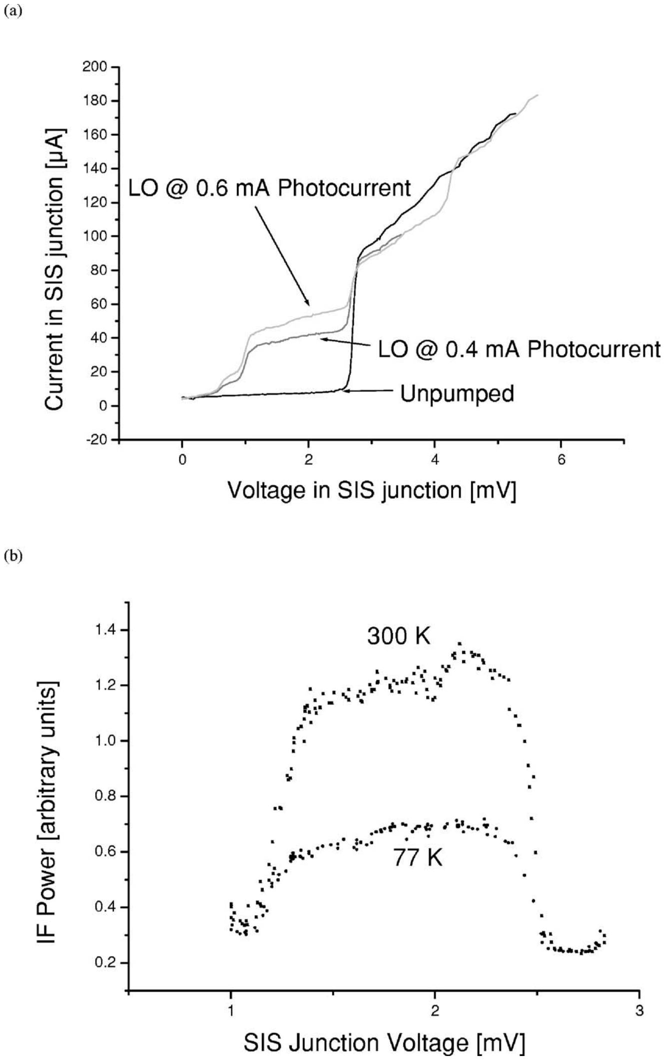

FIG. 3. (a) The I/V curve of the SIS mixer in the absence of LO signal and pumped by a photonic LO signal at 450 GHz for two different LO power levels. (b) Corresponding IF power performance for hot and cold blackbodies.

cause the terahertz signal is directly generated by optical mixing of two laser signals, a process which is frequency independent.

IV. MIXING EXPERIMENT WITH A HEB AT 750 GHZ

The hot electron bolometer (HEB) consisted of a NbTiN bridge on a Si_3N_4 membrane with dimensions approximately $4 \times 0.4 \times 0.004$ μm^3. The design frequency was 750 GHz. At this frequency no resonant antenna photomixer device was available, so a photomixer with an integrated logarithmic spiral antenna was used.

The membrane waveguide HEB mixer used for the experiment was sensitive to vertical polarization. The beam waist position was located at the Dewar window. To optimize the design of the quasioptical coupling, the beam parameters of the photomixer beam were determined previously. For this purpose, a power detector (Golay Cell) was installed on a computer-controlled motorized translation stage. The terahertz beam was scanned bidimensionally, varying the position of the Golay Cell over a matrix of 30×30 pixels. This

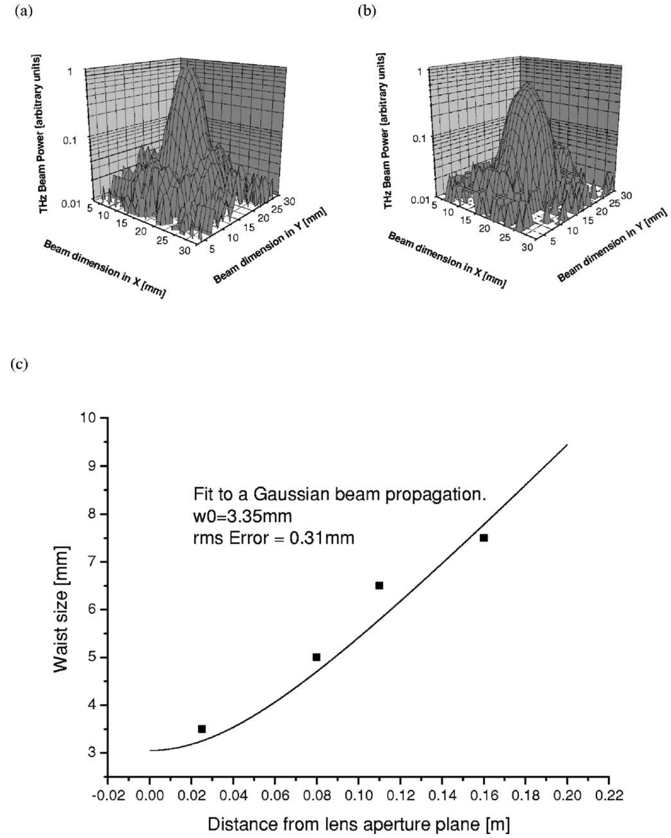

FIG. 4. [(a) and (b)] Beam characterization at 50 and 110 mm from the lens aperture plane. (c) The waist size of the propagating LO beam was measured at different distances from the photomixer lens aperture plane. The data points were fitted to a Gaussian-beam propagation curve. From the fit, the minimum waist (beam waist) w_0 was extracted. The dimensions of the photomixer substrate lens were calculated to synthesize an ellipse. The position of the beam waist coincides with the lens-to-air interface.

process was repeated at different positions to obtain the beam diameter dependence on distance. By fitting the experimental beam diameters to a theoretical Gaussian-beam propagation, the beam waist w_0 was determined to be 3.3 mm (see Fig. 4). The beam waist of the HEB mixer was similar to the photomixer beam waist, avoiding the need of a Gaussian-beam telescope for matching the HEB and photomixer beam waists.

The immediate problem associated with the use of a spiral antenna is the need of transforming its circular polarization to vertical to match the polarization of the HEB mixer. For this purpose, two MP diplexers were used in the quasioptical setup (Fig. 5). The first transformed the polarization from circular to linear. The second MP diplexer was used to inject the hot and cold loads for noise temperature measurements. An off-axis paraboloidal mirror with a focal length of 250 mm was positioned at the center of the quasioptical setup to image the photomixer beam waist into the HEB beam waist. The calculated object and image distances were 485 mm.

To assure that beam truncation in the MP diplexers did not play a major role, the ratio between the beam and aperture diameters at the output and input of the MP diplexers was computed and found to be in the worst case 1/3, which represents[13] negligible spillover losses.

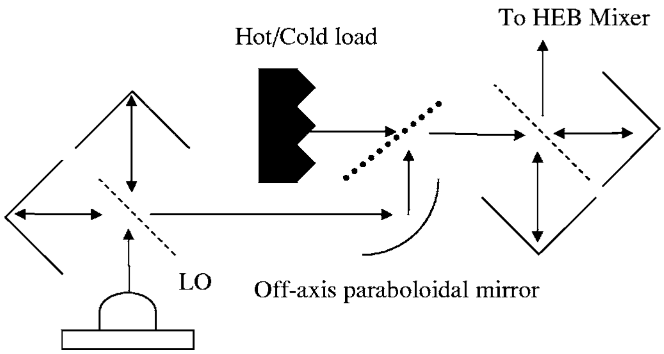

FIG. 5. Schematic of the quasioptical setup. A first MP diplexer transforms the circular polarization from the log-spiral antenna photomixer to vertical. The paraboloidal mirror makes the diverging LO beam convergent. The second MP diplexer injects the hot and cold load signals.

Figure 6 represents the *I-V* characteristic of the HEB mixer with and without photonic LO power. The noise temperature measurements were not reproducible due to the standing waves and microphony. Usually HEBs are much more sensitive than SIS mixers to these effects.

The photomixer was illuminated by 70 mW of NIR power and the photocurrent was 1.7 mA, generating 450 nW of rf power at 750 GHz, which is near the photomixer burnout point at room temperature. At the output of the quasioptical system, the rf power was 375 nW, which implies 20% quasioptical and water absorption losses.

The absorbed rf power in the HEB was calculated using the isothermal method to be 300 nW, which is consistent with the measured power at the input of the HEB Dewar. The same HEB mixer was used in a different experiment pumped with a conventional (frequency-multiplied Gunn oscillator) local oscillator source and showed good heterodyne response ($T_{receiver}$ as low as 500 K at 750 GHz). The direct detection effects (e.g., by thermal broadband emission) in this relatively large ($4 \times 0.4 \times 0.004\ \mu m^3$) device embedded in a waveguide are negligibly small compared to the effect seen by the photomixer pumping. The blackbody radiation power of a 300 K source in a 200 GHz bandwidth (which is roughly the rf bandwidth of the mixer) would only be 0.8 nW. This has to be compared to the 300 nW seen as the absorbed rf power of the photomixer in the device.

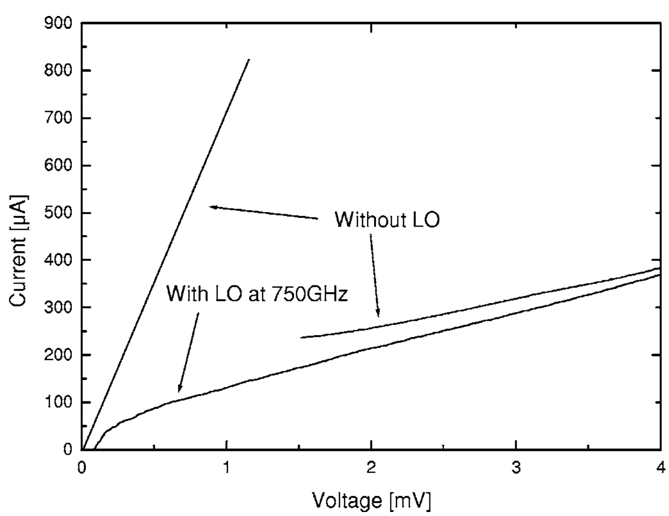

FIG. 6. The *I*/*V* curve of the HEB without LO power and pumped by the photomixer at 750 GHz. The pumped curve has been averaged to eliminate the scatter which resulted from standing waves and microphony. Due to the hysteretic HEB *I*/*V* characteristic in the unpumped case, the superconducting branch and the normal conducting branch of the *I*/*V* curve are separated. The resistance in the superconducting branch (straight line at left) comes from a series resistance in the bias circuit. When irradiated by the local oscillator power, the HEB *I*/*V* becomes nonhysteretic as shown in the lower curve. The difference in current at a given bias voltage between the two curves is proportional to the absorbed local oscillator power.

There is room for rf power improvement by using a full-wave dipole antenna photomixer. In that case, the expected output power would be higher by a factor of 3, due to its higher radiation resistance. Also its better Gaussicity and linear polarization would simplify considerably the quasioptical setup.

V. CONCLUSIONS AND FUTURE WORK

This is an experiment in which a photonic local oscillator has pumped a HEB and is the highest frequency (750 GHz) at which a photonic LO has pumped an astronomical receiver. Noise temperature measurements performed with a SIS receiver at 450 GHz showed a best system noise temperature of 170 K for both photonic LO and a solid-state LO pumping.

Next, we will push our experiments to even higher frequencies using SIS and HEB mixers operated at 1.0 and 1.4 THz, respectively. For this purpose, dipole antenna based photomixers will be processed with inductive canceling of the finger capacity. A further rf power increase is expected through cryogenic operation,[14] which will push up the photomixer breakdown conditions and allows photomixer illumination at higher laser power and bias voltages (rf power scales quadratically with laser power and bias voltage).

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