# Superconductor – Insulator - Superconductor (SIS) and Hot Electron Bolometer (HEB) pumping with LT-GaAs based photonic local oscillators.

I. Cámara Mayorga , P. Muñoz Pradas, M. Mikulics, A. Schmitz, C. Kasemann, P. van der Wal, K. Jacobs and R. Güsten.

**Abstract—Two astronomical heterodyne receivers - SIS at 450 GHz and HEB at 750 GHz – were successfully pumped. A photonic local oscillator fabricated with LT-GaAs was illuminated by two NIR semiconductor lasers, creating a beat frequency in the submm range. SIS junction I-V characteristics for two different LO power pump levels demonstrate that the power delivered by the photomixer is sufficient to pump an SIS mixer with an acceptable safety margin.**

**In order to investigate that the photonic LO does not add significant internal noise to the mixer, we compared SIS-receiver noise temperatures -from hot / cold measurements-using a conventional solid-state LO and a photonic LO. A Martin-Puplett diplexer (MPD) was used to inject the LO signal into the signal path. In both cases, the system noise temperature was identical ($T_{receiver}$=170 K).**

**Additionally, the photomixer was used as an LO in a heterodyne mixing experiment with a phonon-cooled HEB mixer from 650 GHz to 750 GHz. For this purpose, the circularly polarized output signal from a spiral antenna photomixer was transformed to a lineal polarization by a MPD and mixed with a Hot-Cold Load in a second MPD, making the overall losses of the quasioptical design approximately 20 %. The HEB mixer consisted of a NbTiN bridge (approx 4.5 x 0.4 x 0.004µm³) on a $Si_3N_4$ membrane fabricated at KOSMA.**

**Experiments realized under cryogenic conditions show that the power can be still considerably increased as to be sufficient for successful pumping of astronomical mixers in the supra-THz range.**

Keywords: *Index Terms*— **LT GaAs, Photonic local oscillators, Terahertz, SIS, HEB, photomixers**.

Manuscript received May 25 2005. This work was supported by the the "Deutsche Forschungsgemeinschaft" through grant SFB 494

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## I. Introduction

Terahertz generation by photonic techniques like difference-frequency mixing in ultrafast low-temperature grown GaAs (LT GaAs) photodetectors has been studied extensively during the last decade [1]. The huge bandwidth offered by one photomixing device (from DC to several THz) has a tremendous potential for many applications as radioastronomy, THz imaging, high resolution spectroscopy, skin cancer detection, security, defence, etc.

The progress made in fabrication of LT-GaAs photomixers has leaded to carrier lifetimes below 0.5 ps at moderate bias voltages. This is important for operation in the supra-THz range because (together with the RC constant for MSM photomixers) it limits the 3 dB cutoff frequency of the device by $(2\pi\tau)^{-1}$ where $\tau$ is carrier recombination lifetime.

In this paper we report on activities regarding photomixing as a Local Oscillator (LO) source for heterodyne detection in radio astronomy. The aim of these preliminary experiments is to allow the integration of a photonic LO in:

- GREAT (German Receiver for Astronomy at Terahertz Frequencies), which will be a first-generation dual-channel heterodyne instrument for high resolution spectroscopy aboard SOFIA (Stratospheric Observatory For Infrared Astronomy).
- APEX, the Atacama Pathfinder Experiment.

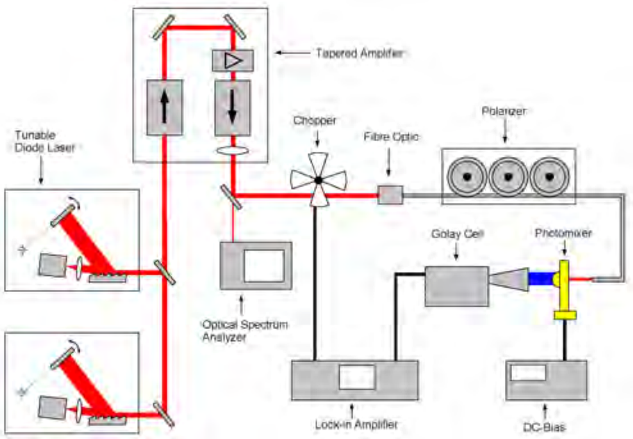


Fig. 1. Schematic diagram of the measurement system

## II. OPTICAL HETERODYNE MIXING

### A. *Photomixer section.*

As shown in figure 1, the scheme for optical heterodyning consisted of two near infrared (NIR) 780nm continuous-wave (CW) single mode lasers in Littman configuration (New Focus, model Velocity 6312), where at least one laser diode was tunable to make frequency selection possible. The output signal of the lasers ~6mW was combined and amplified in a tapered laser amplifier (Toptica TA100), which provided up to 0.5W of combined power.

The beam was then coupled into a single mode optical fiber and to an optical spectrometer to monitor frequency difference and to guarantee an equal power distribution between the two colors. To avoid optical feedback to the lasers and amplifier, optical isolators were included in the setup as well fiber optics with APC connectors (>60dB reflection losses).

(a)

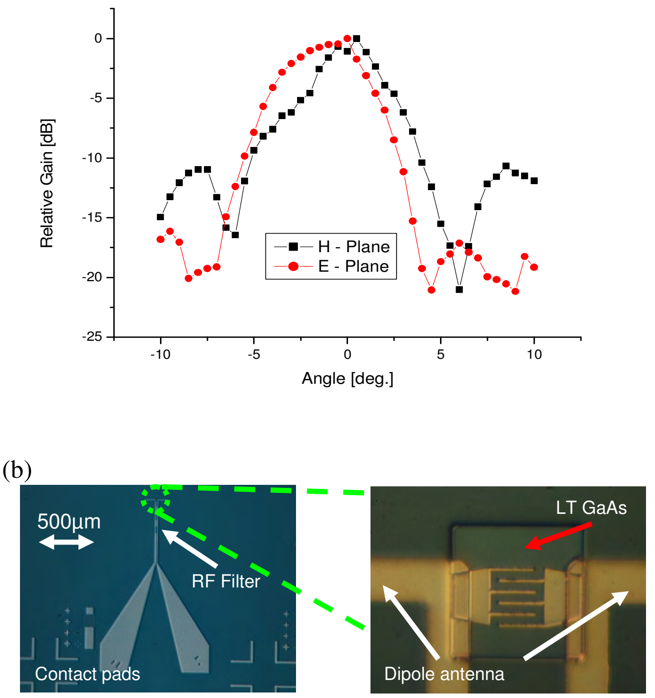


Fig. 2. (a) E-plane and H-plane power patterns measured for a λ dipole in resonance at 450 GHz. The high resistivity Si substrate has a hyperhemispherical form to reduce the divergence of the beam. (b) Microphotograph of the dipole antenna and finger structure of the photoactive area.

The fiber optic was positioned to achieve an optimal photomixer illumination with a piezoelectric actuator. This device allowed a fine (~100nm) position control in three axes. The air gap between fiber optic and photomixer substrate acts as a Fabry-Perot etalon. To cancel out this effect, the air gap was filled with an optical adhesive [2] [3], which has a similar refraction index as the fiber optic, pigtailing the fiber optic to the photomixer. This step also inhibited the negative influence of mechanical vibrations which misaligned the fiber optic at large timescales and restricted the reproducibility of our experiments.

Once the two colors interfere on the photoactive area, electron-hole pairs are generated and immediately separated by the applied bias voltage. Details on the underlying physics phenomena may be found elsewhere [4], [5], [6]. The ultrashort carrier lifetime of LT-GaAs enable the photogenerated carriers to "follow" the envelope of the optical power. Since the photoactive area was patterned in the feed point of a resonant or broadband antenna, the beat signal was radiated to free space. The high dielectric constant of the GaAs photomixer substrate ($\varepsilon_r$=12.8), prevents the signal from being radiated backwards to the fiber optic. Its hyperhemispherical form avoided the formation of surface modes and provided acceptable beam directivity [7], [8].

### B. *Mixing experiment with a SIS at 450 GHz.*

The power performance and noise temperature of our photomixers was tested with a SIS mixer.

It is well known that a photomixers have a high internal resistance [9] and thus impedance matching is difficult. For this reason, high radiation resistance antennas are preferable. A full wave dipole antenna shows a higher radiation resistance (~210 Ω on a GaAs Substrate) than a broadband logarithmic spiral antenna (~73 Ω on a GaAs Substrate). The polarization of a dipole is lineal; having the same orientation as the dipole itself and its gaussicity is higher than in case of spiral antenna. Our SIS mixer was only sensitive to linearly-polarized signals [10], which favored the use of a dipole antenna.

The above mentioned characteristics motivated our group to perform a SIS mixer pumping experiment with a dipole antenna photomixer. Measurements of E and H planes show goog gaussicity and low sidelobes (figure 2).

I-V characteristics at 450 GHz for two different LO power pump levels are shown in Figure 3. With a photocurrent of 0.6 mA and a NIR optical power of 70 mW, the RF power generated was a factor 3 under device burnout, so that an acceptable safety margin was available to operate the photonic LO.

In order to investigate wether the photonic LO does add significant internal noise to the mixer, we compared receiver noise temperatures -from hot/cold measurements- using a con-

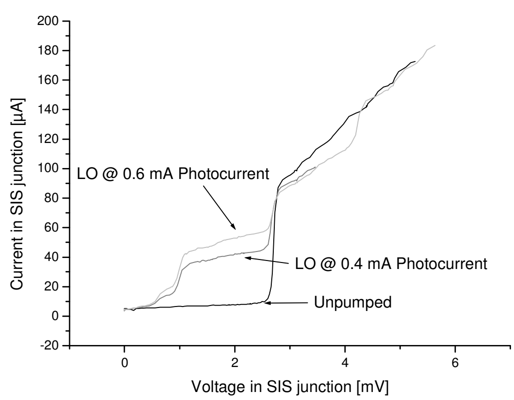


Fig. 3. The I-V curve of the SIS mixer in absence of LO signal and pumped by a photonic LO signal at 450GHz for different powers.

ventional solid-state LO and the photonic LO. A Martin-Puplett diplexer (MPD) was used to inject the LO signal into the signal path. The divergent beam from the MPD output was transformed to a convergent beam with a plane-convex Teflon lens.

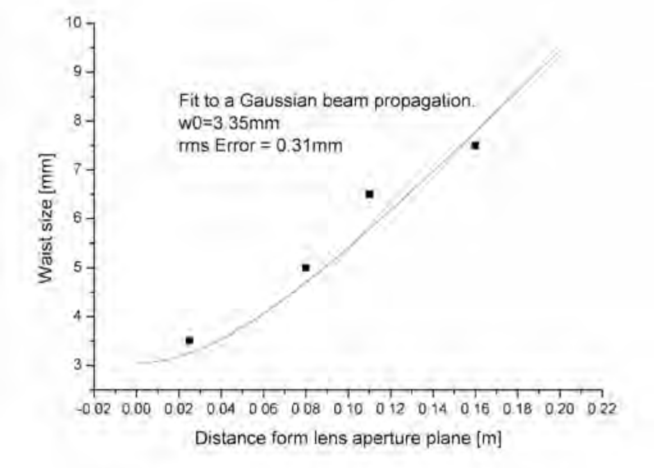


Fig. 4. The waist size was measured at different distances from the photomixer lens aperture plane. The data points were fitted to a Gaussian beam propagation curve. From the fit, the minimum waist (beam waist) w0 was extracted. The dimensions of the photomixer substrate lens were calculated to synthesize an ellipse. The position of the beam waist coincides with the lens-to-air interface.

The double sideband (DSB) noise temperature of the photomixer and solid state LO was measured at an intermediate frequency band of 2 to GHz. The result was identical ($T_{receiver}$ = 170 K). In contrast to cascading multipliers, the noise contribution of a photonic LO is not expected to increase with frequency because the THz is directly generated by optical mixing of two laser signals, a process which is frequency independent.

### *C. Mixing experiment with a HEB at 750 GHz.*

Once having tested the performance of our photonic LO with an SIS mixer, a more challenging experiment with a HEB at 750 GHz was proposed.

At theses frequencies no resonant antenna photomixer device was available so we used a photomixer with integrated logarithmic spiral (broadband) antenna.

The HEB consisted of a NbTiN bridge on a $Si_3N_4$ membrane with dimensions approximately 4x0.4x0.004 µm³. Its design frequency was 750 GHz.

The membrane waveguide HEB mixer used for the experiment was sensitive for vertical polarization. The 3.3mm beam waist position was located at the Dewar window. To make an optimum quasioptical coupling design, the beam parameters of the photomixer beam were previously measured.

A computer controlled motorized translation stage in three axes was designed. Our RF power detector, a Golay cell, was installed with an iris diaphragm that was setup to achieve sufficient spatial resolution while obtaining an acceptable S/N ratio in the power detection. The beam was spatially characterized from measurements at different distances from the photomixer. A fit to a theoretical Gaussian-beam propagation was performed and the beam waist radius was extracted giving as result 3.3 mm (see figure 4). This result was similar to the beam waist of the HEB mixer, simplifying considerably the quasioptical design .

The immediate problem associated with the use of a spiral antenna is the need of transforming its circular polarization to vertical, in order to match the vertical polarization of the HEB mixer.

Two Martin-Puplett diplexers were used. The first transformed the polarization form circular to linear. The other MPD was used to inject Hot/Cold load for noise temperature measurements.

To assure that beam truncation doesn't play a major role, the ratio between beam to aperture diameter at the output of the Martin-Purplett diplexer was computed giving as result 1/3, which corresponded to -77.8dB spillover loss.

The quasioptical design of figure 5, which is symmetrical due to the identical beam waists of photonic LO and HEB mixer, uses an off-axis paraboloidal mirror with a focal length of 250mm.

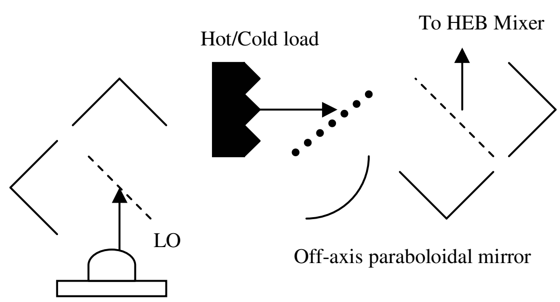


Fig. 5. Schematic of the quasioptical setup. A first MP diplexer transforms the circular polarization from the log-spiral antenna photomixer to vertical. The paraboloidal mirror makes the diverging LO beam convergent. The second MP diplexer injects the hot/cold load signal.

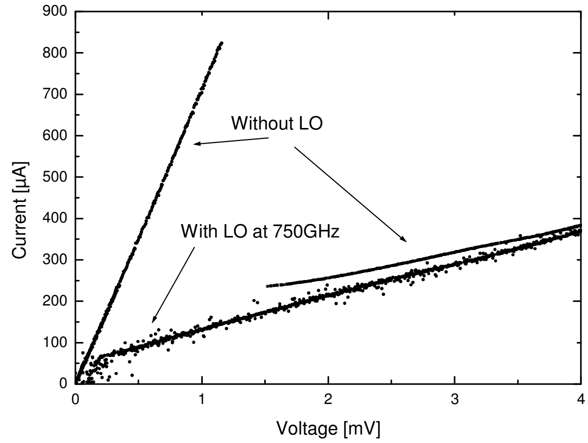


Fig. 6. IV-Characteristics of the HEB without LO power and pumped by the photomixer at 750GHz. The serial resistance originates at the IF-Filter of the HEB.

Figure 6 represents the IV characteristics of the HEB mixer with photonic LO power and without. The scatter results from standing waves and microphony.

The photomixer was illuminated by 70mW NIR power and the photocurrent was 1.7mA, generating 450nW of RF power, which is near the photomixer burnout point. At the output of the quasioptical system, the RF power was 375 nW, which represents 20% quasi-optical and water absorption losses.

The absorbed RF power was calculated by the isothermal method in the HEB to be 300 nW, which is congruent with this measurement.

In case of using a resonant antenna design photomixer, the expected power could be higher by a factor of 3, due to its higher radiation resistance. Also the gaussicity and lineal polarization would simplify the quasioptical setup.

## III. Future work.

Next we will perform pump experiments at higher frequencies with Hot Electron Bolometer mixers operated at 1.4 THz. For these purposes, dipole antenna design photomixers will be processed. Since the frequency roll-off of the photomixer drops 40dB/dec from 1THz, the photomixers will be operated at higher laser power and bias voltages to generate sufficient LO power. To avoid device burnout, our cryogenic setup [10] will be used.

On the other hand, we will work on the reduction of our laser diode linewidth in order to achieve a sub-mm wave linewidth smaller than 100 KHz.

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