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Room Temperature, Quantum-Limited THz Heterodyne Detection? Not Yet

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In their article, Wang et al. [1] report a new scheme for THz heterodyne detection using a laser-driven LTG-GaAs photomixer [2, 3] and make the impressive claim of achieving near quantum-limited sensitivity at room temperature. Unfortunately, their experimental methodology is incorrect, and furthermore the paper provides no information on the mixer conversion loss, an important quantity that could readily have been measured and reported as a consistency check. The paper thus offers no reliable experimental evidence that substantiates the claimed sensitivities. To the contrary, the very high value reported for their photomixer impedance strongly suggests that the conversion loss is quite poor and that the actual sensitivity is far worse than claimed.

THz heterodyne detection has been used in astronomy for over three decades [4] and is primarily of interest for high-resolution spectroscopy [5]. An illustrative application is the measurement of rotational transitions of isotopologues of water vapor to estimate the D/H ratio in comets – indeed, recent data from the SOFIA airborne observatory have reactivated the debate on whether the water in the Earth's oceans was delivered by comets [6]. To date, the best detection sensitivities have been achieved using cryocooled superconducting devices [5] such as the superconductor-insulator-superconductor (SIS) receivers that enable ALMA [7] or the hot-electron bolometers (HEB) used in the HIFI instrument on the Herschel

Space Observatory [8]. However, other THz space instruments [9] have generally not used cryocooled detectors due to power, mass, and cost constraints, thereby incurring a sensitivity penalty of 10× or more. If the sensitivities reported by Wang *et al.* were correct, this severe penalty for ambient-temperature operation would be erased and numerous applications would be enabled.

The sensitivity of a heterodyne receiver is usually reported as a double sideband (DSB) receiver noise temperature $T_{\rm rec}$. By definition, $T_{\rm rec}$ is the Rayleigh-Jeans temperature of a perfect blackbody source that, when illuminating the receiver's THz-frequency input, would contribute the same noise power at the output of the final IF amplifier (typically in the GHz range) as contributed by all of the different components of the THz receiver. The sensitivity of a heterodyne receiver is subject to the quantum limit [10] arising from the Heisenberg uncertainty principle, corresponding to $T_{\rm rec} \geq h\nu/2k$ for the DSB noise temperature. As shown in their Figure 3c, the sensitivity claimed by Wang *et al.* for their room-temperature receiver lies impressively close to this limit, matching or exceeding the performance of cryocooled SIS or HEB receivers.

Unfortunately, the experimental procedure used by Wang *et al.* to measure sensitivity is fatally flawed. The standard technique for determining the noise temperature is the "Y-factor" method where the IF noise power $P_{\rm IF}$ is measured using two blackbodies with different Rayleigh-Jeans temperatures, $T_{\rm hot}$ and $T_{\rm cold}$. The Y-factor is the ratio of these two measurements,

$$Y = \frac{P_{\rm IF,hot}}{P_{\rm IF,cold}}$$

from which the receiver sensitivity is calculated according to

$$T_{\rm rec} = \frac{T_{\rm hot} - T_{\rm cold}}{Y - 1} - T_{\rm cold} \ .$$

In their Methods section, Wang *et al.* claim to measure sensitivities "using the standard Y-factor method", but this is not the case. In that section, we learn that:

> "...the output IF signal at ~ 1 GHz is detected by a power meter (Mini-Circuits ZX47-60LN) using a lock-in amplifier with the 100 kHz modulation reference frequency...".

The output of the ZX47-60LN power detector [11] is a voltage that responds logarithmically to the IF power $P_{\rm IF}$; one could presumably use the measured DC voltage along with a calibration curve to obtain $P_{\rm IF}$, as needed for calculation of the Y-factor. However, a lock-in amplifier does not measure the DC voltage; rather, it measures *changes* in the voltage that occur at a 100 kHz rate in response to a modulation. Their Methods section states

> "...the optical pump beam from the dual DFB laser system is modulated using an acousto-optic modulator ... at a 100 kHz rate"

meaning that the laser source that drives the photomixer is being turned on and off at the 100 kHz lock-in frequency. Thus, the lock-in reports a quantity that is related to the change in the IF power that occurs in response to turning the laser on and off, $\Delta P_{\mathrm{IF}} = P_{\mathrm{IF,on}} - P_{\mathrm{IF,off}}$. Given their statement regarding use of the Y-factor method, Wang *et al.* presumably take the ratio of such lock-in readings for hot and cold loads. Although not explicitly stated in their paper, they apparently make the assumption that the response of their logarithmic ZX47-60LN detector is linear for small perturbations, in which case taking the ratio yields

$$Y' = \frac{P_{\mathrm{IF,hot,on}} - P_{\mathrm{IF,hot,off}}}{P_{\mathrm{IF,cold,on}} - P_{\mathrm{IF,cold,off}}} \ .$$

This quantity is very different than the standard Y factor. In particular, Y' remains invariant if a constant is added to all power levels, e.g., as a result of a uniform increase of the IF amplifier noise contribution, whereas Y is definitely not invariant. Furthermore, the paper makes no mention of measurements of $P_{\mathrm{IF,hot,off}}$ or $P_{\mathrm{IF,cold,off}}$, and because this information is missing, it is not possible to convert the reported values of Y' into corrected values for Y. Noise temperatures calculated using Y' are meaningless, and can be radically different from the true noise temperatures calculated using Y. Thus, one cannot place any confidence in the sensitivities reported by Wang *et al.* in their Figure 3c.

What would a properly executed Y-factor measurement reveal about the performance of their device? Judging from the large photomixer impedance reported by Wang *et al.*, the sensitivity is likely $\sim 100\times$ worse than claimed. Our argument involves the mixer conversion loss L, which has a direct impact on receiver sensitivity T_{rec} according to

$$T_{\mathrm{rec}} = T_{\mathrm{mixer}} + L T_{\mathrm{IF\,system}} \ .$$

The mixer noise temperature T_{mixer} cannot be negative, and the noise temperature of the first-stage low-noise amplifier T_{LNA} sets a lower bound for the noise of the IF system, $T_{\mathrm{IF\,system}}$. Thus, $T_{\mathrm{rec}} \geq L T_{\mathrm{LNA}}$ must hold. Unfortunately, Wang *et al.* do not report any values for the conversion loss L, apparently missing several opportunities for measuring L while collecting data for their figures 2 and 3. Wang *et al.* also do not report measurements for $T_{\mathrm{IF\,system}}$ or T_{LNA}, although according to the manufacturer's data sheet for their Mini Circuits ZRL-1150 first-stage amplifier [11], we may take $T_{\mathrm{LNA}} \geq 70$ K as a reasonable value including cable losses. Thus, the ~ 150 K noise temperatures reported by Wang *et al.* at frequencies up to 1 THz require a conversion loss no higher than $L \approx 2$, or 3 dB. This is an extremely low value, comparable to the conversion loss of a well-optimized SIS mixer; if their 300 K mixer contributes any noise at all, the conversion loss would need to be even lower.

The actual conversion loss is likely $\sim$ 20 dB worse, as indicated by the photomixer impedance reported by Wang *et al.* on page 8 of the supplemental information:

> "...R_P is the average electrical resistance of the photomixer at a 30 mW pump power. The estimated R_P value from the numerical simulations is in agreement with the experimentally measured photomixer resistance of $25\,\mathrm{k\Omega}$."

This large impedance is in line with data on other LTG-GaAs photomixers including those previously studied by this group [3]. Thus, there is a severe impedance mismatch between the $25\,\mathrm{k}\Omega$ photomixer and the $50\,\Omega$ IF amplifier, corresponding to a coupling loss of 21 dB. For the overall conversion loss to be no worse than 3 dB, as required by the reported sensivity, the photomixer would need to have an internal conversion gain of at least 18 dB! Internal conversion gain in this device seems implausible, especially such a large value, given the lack of any measurements of conversion loss and the absence of a clear physical mechanism for gain.

Indeed, the theory of operation presented by Wang *et al.* makes no mention of conversion gain. According to equation (6) of their supplemental information, they assume a linear, local relationship between the current density $\vec{J}$ and THz electric field $\vec{E}$ at frequency f_{THz}. For $f_{\mathrm{THz}} < 1/2\pi\tau \approx 500$ GHz where $\tau = 0.3\,\mathrm{ps}$ is the stated carrier lifetime, the response is essentially instantaneous and their equation (6) is equivalent to Ohm's law $\vec{J}(\vec{r},t) = \sigma(\vec{r},t)\vec{E}(\vec{r},t)$. Here $\sigma(\vec{r},t)$ is the (real) conductivity that varies with time t and position $\vec{r}$ due to the photogeneration of carriers by the two lasers with beat frequency f_{beat}. The equation $\vec{J} = \sigma\vec{E}$ simply describes current flow in an ordinary resistor, and leads to the circuit version of Ohm's law $I = V/R$, or $I(t) = V(t)/R(t)$ when the conductivity is time dependent. Here $I(t)$ and $V(t)$ are the current and voltage across the terminals of the THz spiral antenna, and the $R(t)$ is the time-dependent photomixer resistance as seen from the antenna terminals. Thus, the theory offered by Wang *et al.* places the device into a well-known class of "resistive mixers" that includes diode mixers [12] and FET mixers [13], which are not capable of conversion gain and in fact are subject to a theoretical minimum conversion loss of 3 dB [14, 15]. Their theory is therefore incompatible with their claimed sensitivity, which requires a large internal conversion gain to overcome the severe IF impedance mismatch as discussed above. While the resistive mixer argument strictly holds only for $f_{\mathrm{THz}} < 500$ GHz, one expects photomixer performance to deteriorate at higher frequencies [2], as Wang *et al.* themselves state when discussing the utility of the short lifetime $\tau = 0.3$ ps to "recombine the slow photocarriers that degrade the terahertz-to-RF conversion efficiency".

We close by offering recommendations the authors could adopt to address our concerns and to build confidence in their results:

- Eliminate the lock-in and use the standard Y-factor method to determine T_{rec}. It may be helpful to add IF gain to boost the detector output and to use a square-law IF detector rather than a logarithmic detector.
- Measure and report the mixer conversion loss, an urgently needed consistency check. This could be measured during the hot/cold load procedure if the IF system is calibrated.
- Measure the noise temperature of the IF system, and estimate the IF contribution to the receiver noise using the measured conversion loss.

- Experimentally demonstrate that the receiver response is truly heterodyne, e.g., by using infrared-blocking filters, THz passband filters, and ideally gas-cell measurements of molecular absorption lines.

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