National Aeronautics and Space Administration

FY24 Topic Areas Research and Technology Development (TRTD)

Quantum-noise limited Terahertz Amplifier for Astrophysics and Planetary Science

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Strategic Focus Area: Origin, evolution, and structure of the universe

Objectives: We propose to demonstrate a near-quantum noise-limited amplifier operating at THz frequencies utilizing a free-space reflective quantum cascade metasurface. When such a device is optimized as an amplifier for gain and noise, it will enable a significant reduction of the overall input noise temperature, theoretically to a small factor of the quantum noise limit. Considering that the sensitivity of state-of-the-art superconducting THz hot-electron bolometers has largely stagnated in performance since their introduction over 20 years ago, this amplifier concept is the breakthrough required to extend near-quantum-limited coherent detection beyond the frequency range reached by superconducting tunnel junction (SIS) mixers, from ~1.5 THz up to 5 THz using currently available materials technology. In terms of performance, the THz amplifier will improve the sensitivity of the best THz mixers by a factor of ~10x, improving the speed of observations by two orders of magnitude. With sufficient gain, it will be possible to exploit these amplifiers in front of ambient temperature Schottky-barrier diode to significantly sensitivity. This option may be extremely attractive for deep space missions for which sensitivity is a prime requirement, but deep cryogenic cooling is prohibitive.

Background: A mission roadmap for high-spectral resolution astronomy includes short-term opportunities for Pioneer-class suborbital (e.g., ASTHROS+) and Explorer-class (GEMS) concepts, which will be severely cost constrained, to longer-term Flagship-class (SCIFI, HERO) concepts that will demand high return on investment. Two critical technology needs identified are as follows. (1) Improving mixer sensitivity across the 1-5 THz frequency range is a key priority. Sensitivity of superconducting mixers in the THz frequency range has not significantly improved since their introduction about 20 years ago, and there is substantial room for improvement towards the quantum limit. (2) Either a low-cost high-reliability 4 K space cryocooler must be developed, or alternatively, a sensitive front-end that does not require deep cryogenic cooling, and rather can be operated at an elevated temperature, e.g., at >20 K, is needed. Deep cryogenic cooling inevitably brings up cost and complexity comparisons to Spitzer, Herschel and JWST. Although the use of novel material systems such as MgB2 for the mixer material may help to relax thermal requirements, a successful demonstration of the proposed terahertz amplifier will improve the sensitivity and greatly relax the operating temperature when used with either a moderately cold (20K MgB2 mixer) or a warm Schottky mixer.

Approach and Results: Maser amplifiers have a rich history in radio astronomy, particularly at JPL, albeit at much lower frequencies. The approach here is the same, but instead of using an optically pumped solid state material, such as a ruby, we employ an electrically pumped semiconductor gain material (THz quantum cascade structure). The key difference is the need for an antenna structure to couple the free-space THz radiation into and out of the thin quantum cascade gain material, unlike the older masers, which are made out of bulk material. The general approach of a free-space reflective amplifier was demonstrated several years ago [Kao Optica 4 2017] and we have measured viable gain in JPL-developed THz quantum cascade gain material at 2.74 THz. Following this work, we have made several designs for the amplifier metasurface and produced amplifiers at 2.7 THz and 4.7 THz. The work in the last year included USI and JPL evaluating several designs for the optical train that can reliably measure gain of a metasurface, a challenge when the gain is low (Figure 2) . High gain designs (5-10 dB) have been fabricated and measured, but there is a need to understand what causes self-lasing from the metasurface (Figure 1 & 3). For a less aggressive design, a preliminary gain of ~1 dB (1.3x) has been measured in the new measurement scheme that does not take into account path length losses.

Significance/Benefits to JPL and NASA: Current THz receivers are quite far from quantum-noise limited, and much the effort in recent years has gone into forming arrays with N pixels as a way to increase the overall mapping speed. However, because the mapping speed scales as $N/Tsys^2$, there is an incentive to reduce overall system noise if it is possible to do so. The quantum cascade amplifier design operates at modest bath temperature and is used in practical QCL devices today. A quantum-noise limited receiver will revolutionize the study of ISM tracers such as C+, N+, OI, and HD.

Figure 1

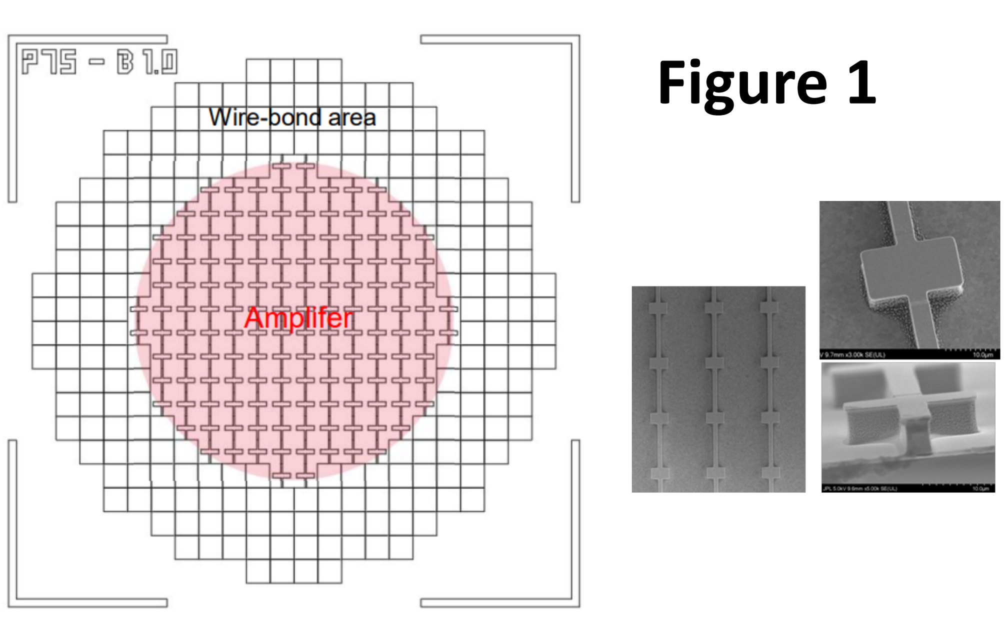


Figure 2

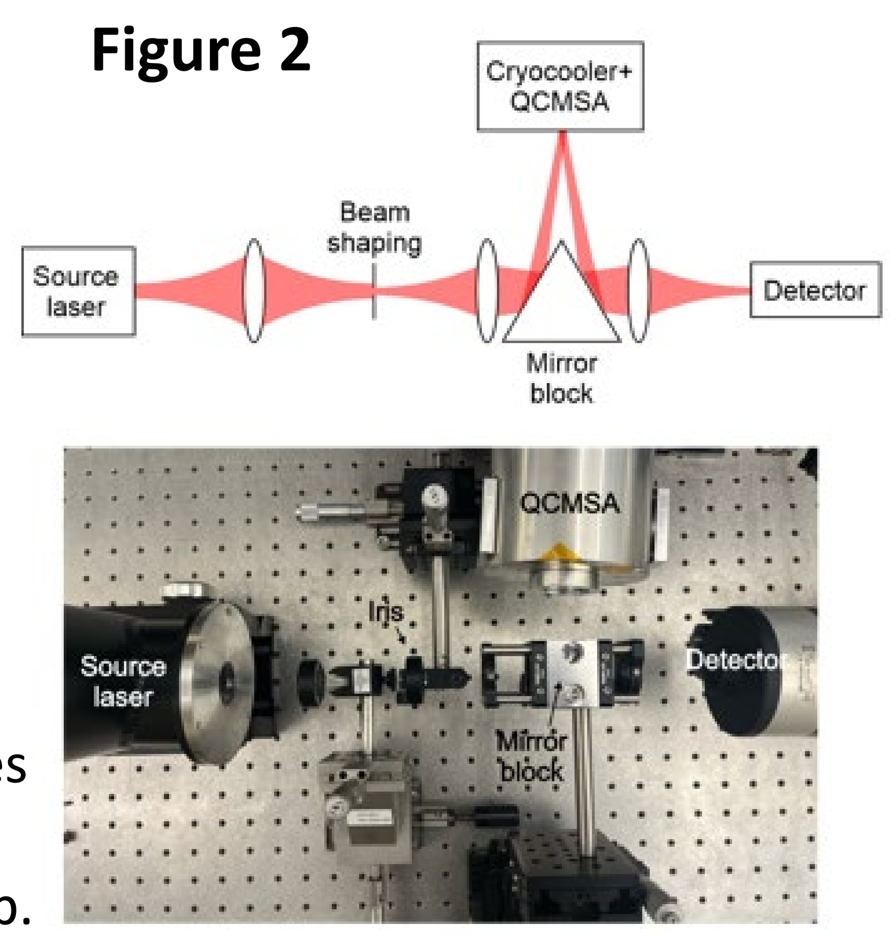
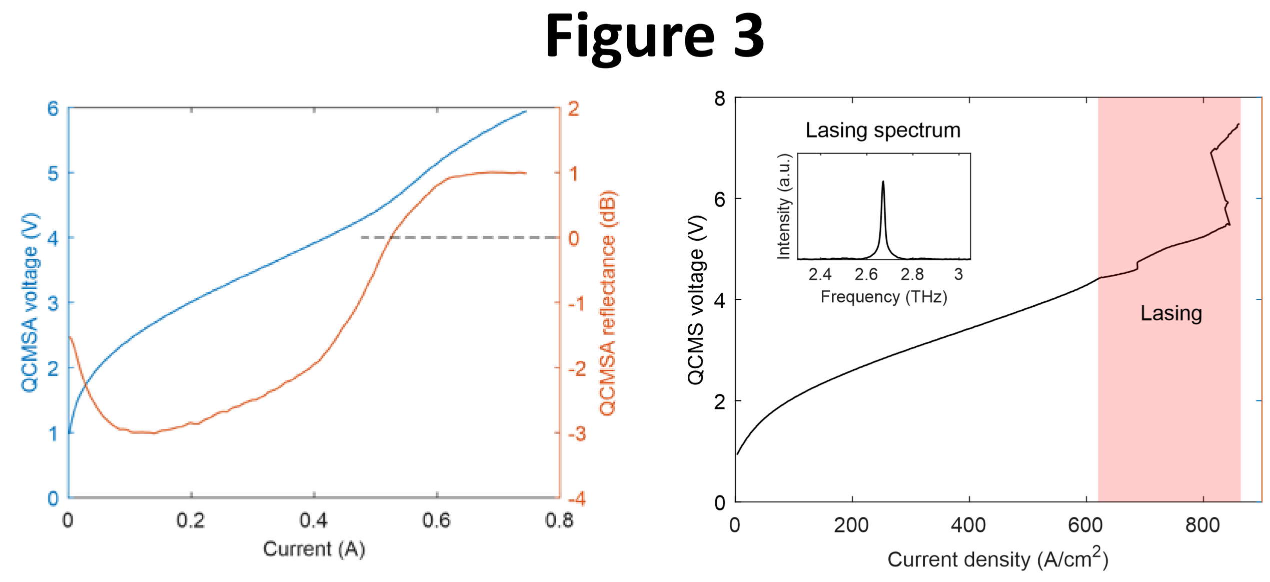


Figure 3



Above: Mask layout for a high-gain (5-10 dB) QCMSA. The active region is shown shaded in pink. The elements are periodic microstrip patches shown in SEM images.

Right: Current gain measurement set-up.

Above: A moderate gain design (2-3) dB exhibits the expected gain in preliminary measurements (left). High-gain devices exhibit self-lasing that renders them unsuitable as amplifiers (right).

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RPD-019 Clearance Number: CL#00-0000

Publications:

Christopher A. Curwen, Mohammad Shahili, Sadhvikas J. Addamane, John L. Reno, Boris S. Karasik, Benjamin S. Williams, Jonathan H. Kawamura "Measurement of amplification and absorption of a THz quantum-cascade metasurface free-space amplifier." AIP Advances 1 November 2022; 12 (11): 115205. https://doi.org/10.1063/5.0122154

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