FY23 Topic Areas Research and Technology Development (TRTD)

Quantum-noise limited Terahertz Amplifier for Astrophysics and Planetary Science

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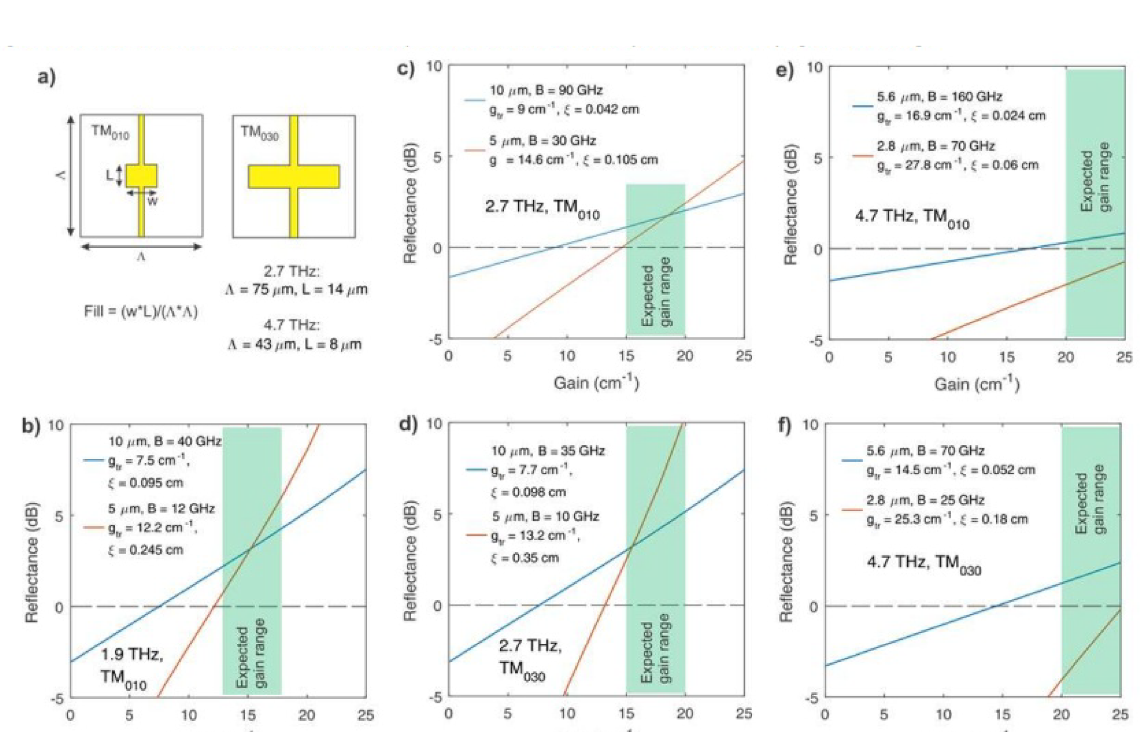
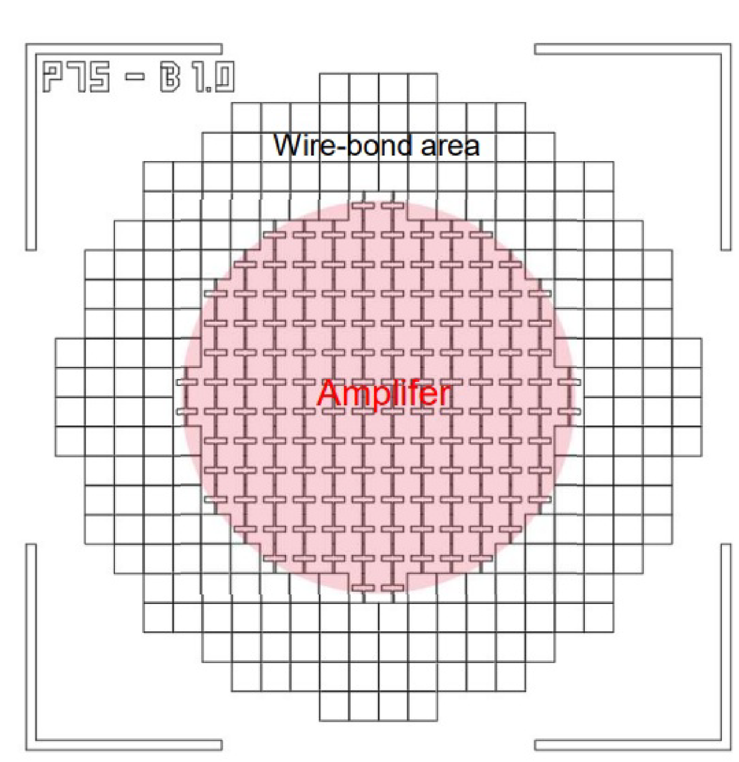
Objectives: We propose to demonstrate a near-quantum noise-limited amplifier operating at THz frequencies utilizing a free-space reflective quantum cascade metasurface. When such a device is optimized as an amplifier for gain and noise, it will enable a significant reduction of the overall input noise 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. Extending past this frequency bound may be possible with new material systems. 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 SmallSat-class (GEMS) concepts, which will be severely cost constrained, to longer-term Explorer-class (SOURCE) and Probe/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 operating temperature when used with either a moderately cold (e.g., MgB2 mixer operating at 20K) or a warm mixer (Schottky diode).

Approach and Results: Maser amplifiers have a rich history in radio astronomy and 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 a photomask including the designs for amplifiers at 2.7 THz and 4.7 THz. Devices were fabricated and measurement of lasing in these devices are on-going. An optical coupler was designed and fabricated at USI and evaluated during a visit in June 2023. Further work to develop a 2.7 THz receiver test-bed are in progress. Such a system is required in order to measure the input noise temperature of the amplifier.





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. Two recent controversial ideas have appeared in the literature for low-noise mixing. The first is an IR photonics device that requires an unlikely condition of substantial conversion gain from a classical mixer, and the evidence provided thus far involved an unusual mode of operation of modulating the local oscillator [Wang Nat Astronomy 3 2019]. The second involves a graphene-based device, which is predicted to have extremely poor conversion and must be operated at near-zero K temperature [Lara-Avila Nat Astronomy 3 2019]. 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.

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