National Aeronautics and Space Administration

Waveguide coupled high speed quantum well detectors for astronomy applications

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Program: FY23 R&TD Topics
Strategic Focus Area: Nano- and Micro- Devices/Systems

Project Objective:

The objective was to develop fast heterodyne mixers based on Quantum-Well Infrared Photodetectors (QWIPs). The development allows for detection of long-wavelength light around 9 μm with close to unity quantum efficiencies and quantum limited noise at unprecedented electrical bandwidths exceeding 30 GHz. Such detectors will be a game changing technology enabling long baseline heterodyne imaging of astrophysical targets.

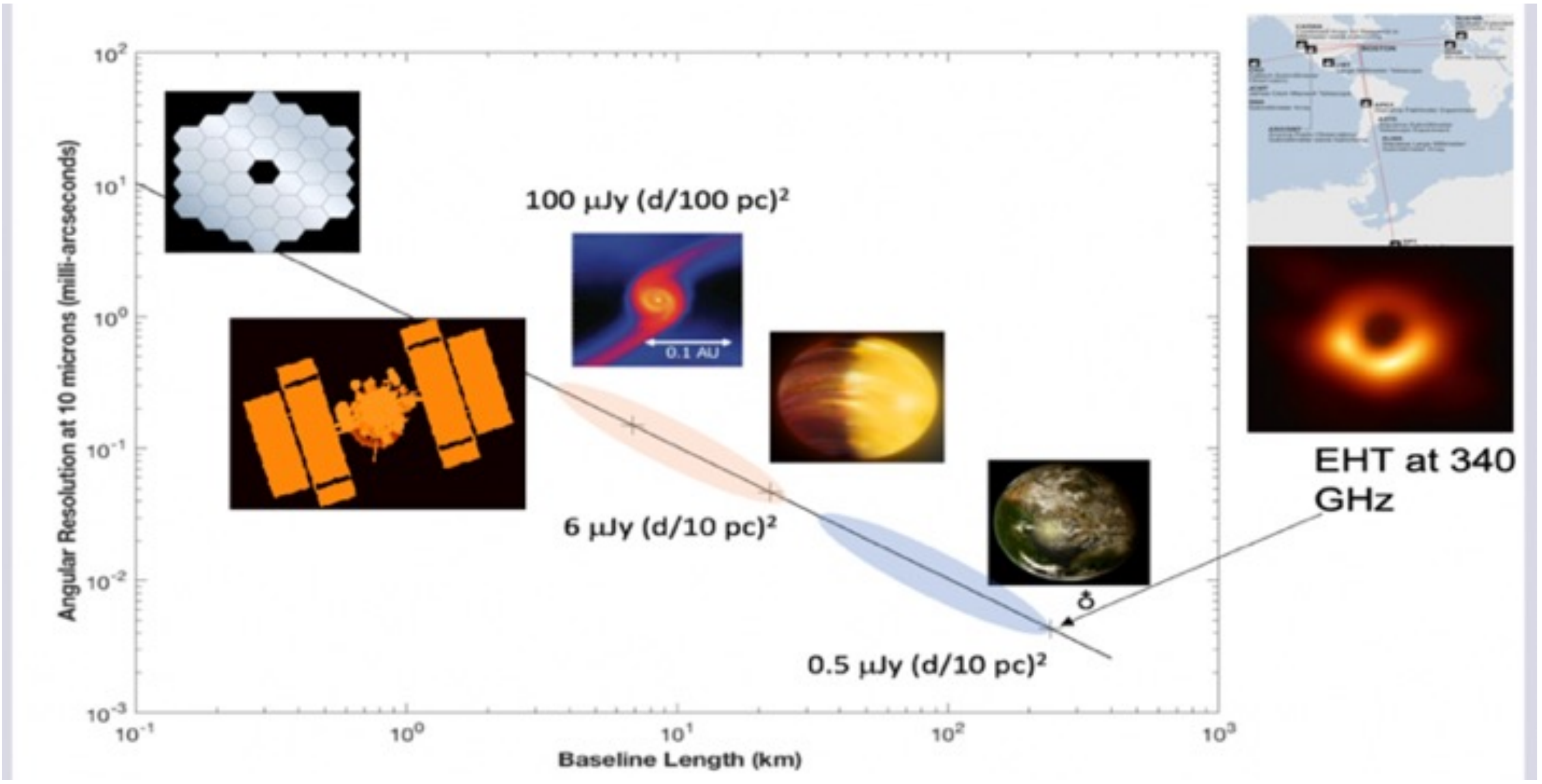

Figure 1-1: Interferometric baseline vs. imaging angular resolution of interest to NASA and DoD. GEOSATs are bright in the mid IR, and imaging them at small spatial scales requires baselines up to 1-2 km. In astrophysics, nearby giant (exo) planets and terrestrial planets can be resolved with longer 10-200 km baselines. The mid-IR is important for the study of planet formation in view of the high dust temperatures in the environments surrounding accreting protoplanets, along with the ~10^3 K temperatures of the young planets themselves [2].

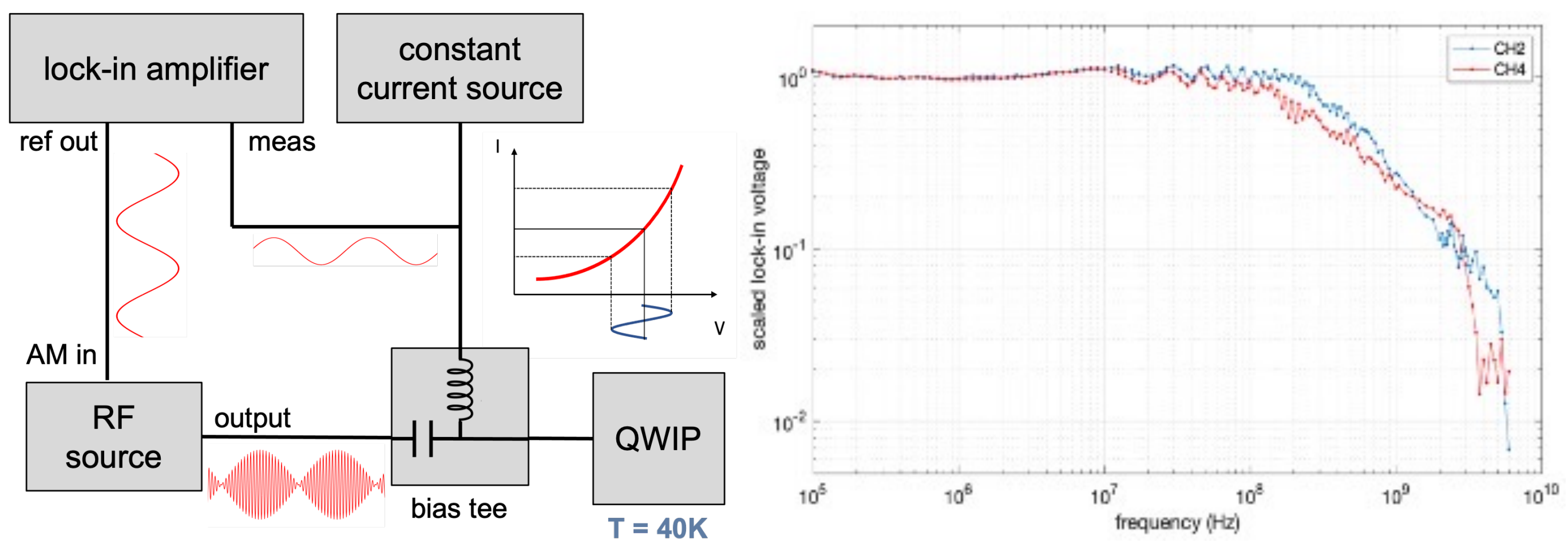

Figure 2: (a) Rectification set up and (b) the frequency measurement of the first round of fabricated devices. Sweep the frequency of the high-frequency RF source and measure the low-frequency change in voltage across the device.Measured 3-dB bandwidth is ~ 300-500 MHz, but is likely limited by wirebonds.

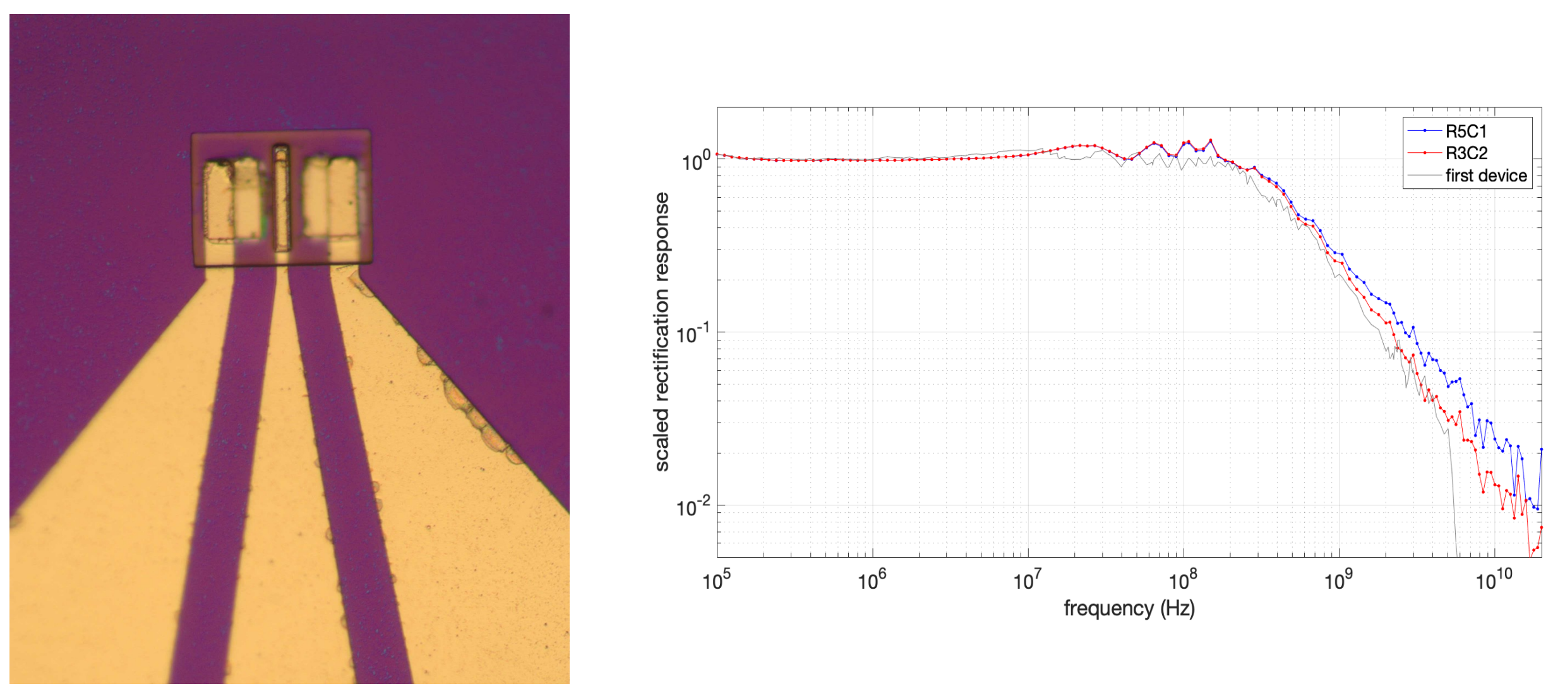

Figure 3: (a) 40 **μ**m fabricated QWIP device. (b) The frequency measurement of the second round of fabricated devices with the probe station.

Background and Significance of results to JPL/NASA

Infrared ultralong-baseline heterodyne interferometers with resolving powers on < 100 microarcsecond (μas) angular scales can allow a performance leap in astrophysical imaging, in particular, in exoplanet imaging. With baselines > 100 km and > 10^3 m^2 total collecting area, IR interferometers can reach few μas resolution (similar to that of the mm-wave Event Horizon Telescope) and resolve the planetary disks of the nearest Earth analogs. Resolving exoplanetary surfaces will be the core of NASA science in the so-called visionary era (post LUVOIR or HabEx). In the infrared and optical, direct detection interferometry has thus far ruled the roost. However, direct detection has severe limitations in achievable long baselines, and in optimally combining signals from multiple telescopes. Conversely, heterodyne detection has poor quantum-limited sensitivity at wavelengths shorter than ~9 μm, has had faced severe limitations in achievable signal bandwidth. The Infrared Spatial Interferometer (ISI) [1] on Mount Wilson was limited by the electrical bandwidth of a single HgCdTe photodiode / CO2 laser local oscillator (LO) combination to a relatively low ~ 3 GHz, which is a tiny fractional optical bandwidth (($\delta\nu/\nu$ ~10^{-4}). However, the rapid development of mid IR frequency combs allows us to envision highly broadband heterodyne receivers.

FY 22 Approach

Quantum well infrared photodetectors (QWIPs): Liquid-nitrogen cooled QWIPs provide high response and high-speed detection of 9 μm radiation. A highly favorable and little exploited intrinsic property of inter-subband QWIPs based on group III-V semiconductor materials is the very short lifetime of their excited carriers, typically of order a few picoseconds. This has two important consequences: the detector frequency response can reach ~100 GHz [2] and its saturation intensity is very high (1e7 W cm−2) [3]. These properties are ideal for a heterodyne detection scheme in which a laser LO can drive a strong photocurrent that can coherently mix with a signal shifted in frequency with respect to the LO. Notably, very high speeds are difficult to obtain in infrared inter-band detectors based on the state of the art mercury–cadmium–telluride (MCT) alloys currently at about < 5 GHz.

After material growth and material characterization, mesa devices were made using standard GaAs fabrication techniques and will be evaluated for electrical characteristics. The QWIPs were characterized by conventional I-V and spectral responsivity measurements. For the second year, we had to fabricate two sets of devices and had to build two measurement setups. The two sets of frequency response measurements were performed in these two setups. The first testbed was a pulse-tube cryostat, with the chip wire bonded into a sample package and installed on the 40K stage (figure 2). The second setup was a cryogenic probe station equipped with a 40-GHz probe arm. The probe station sample stage was temperature-controlled at 40K (figure 3). The frequency response was obtained using a rectification measurement technique (figure 2a): an RF source with a frequency of 100 kHz to 20 GHz was used to modulate the detector bias, and the resulting DC shift in the detector voltage was measured. We measured a 3-dB frequency roll-off of approximately 500 MHz for devices from both fabrication runs, despite their significantly different geometries. We are currently investigating the measurement systematics to ensure that the frequency response is not an artifact of the measurement.

References:

1 Townes and Wishnow, Proc. SPIE, 7013, 70130D (2008)., **2** J. Li et al., Proc. SPIE 2685, Photodetectors: Materials and Devices, (12 April 1996)., **3** Vodopyanov,et al.,. Semicond. Sci. Technol. 12, pp 708–714 (1997).

FY24 Plans

1. Characterization of passive waveguides coupled to QWIPs
2. Design, growth, fabrication and characterization (signal, noise and electrical bandwidth) of 9 μm QWIP linear array with 10 pixels
3.Integration and characterization of linear detector arrays with arrays of optical waveguides.

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Clearance Number: CL#
Poster Number: RPC#

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