National Aeronautics and Space Administration

3D-HIFI: "A 3x On-Chip Diplexed Heterodyne Instrument for the Far-Infrared"

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Program: FY21 R&TD Topics **Strategic Focus Area: Direct/Coherent Detectors and Arrays**

Background and significance to NASA/JPL

Powered by the exceptional scientific findings from the HIFI instrument on Herschel [1], high-resolution (>1E6) submillimeter-wave receivers continue to be essential to answer key questions on the Decadal Survey: How did we get here? How did our galaxy form? NASA's Astrophysics Roadmap recognized the need for an Origins Space Telescope (OST) mission with enhanced measurement capabilities relative to those of Herschel. OST, one of the four Science and Technology Definition Studies selected for the 2020 Astronomy and Astrophysics Decadal survey, might include a heterodyne instrument (HERO) [2]. HERO would be an ambitious upgrade of HIFI, featuring very large focal plane arrays (>64 pixels) covering an extremely wide frequency range from 468 to 2700 GHz (641 to 111 microns) in only 5 bands. A key science driver for HERO or other future missions is tracing the path of water from interstellar clouds to habitable planets in order to understand how they came to have significant water to enable life (see Fig. 1). Eventually, the goal should be to produce the first detailed and complete census of the ISM ecosystems in the Milky Way with the aim of understanding the evolution of the ISM phases and its relation to star formation.

Having successfully delivered local oscillators and receivers for HIFI/Herschel, MIRO/Rosetta, MLS/Aura EOS and STO-2, JPL is at the forefront of THz technology. However, JPL has not led any of these missions. Even if NASA's COBE found that 50% of the luminosity and 98% of the photons emitted since the Big Bang are in the submillimeter-wave range, large area surveys of key species at high spectral resolution (1E6, ~0.3 km/s) is still missing in this range. This is mostly due to the lack of broadband receivers, limiting the scope of each mission to a few lines and specific astronomical targets. As of today, there is no technological solution that addresses the RF bandwidth issue, and consequently, these science requirements cannot be met in an affordable way. With enhanced RF bandwidth, high-spectral resolution far-infrared instruments would be capable of tuning to all key tracers of star formation ([CII], [NII], water, OI, HD, OH, HDO, HF, HD, CO, etc.). Hence, it is crucial for this field to increase the bandwidth of current receiver technology from ~12% to ~40%. If this limitation is overcome, JPL will lead the field during many years to come, owning an extremely powerful technology ready for future suborbital and space missions.

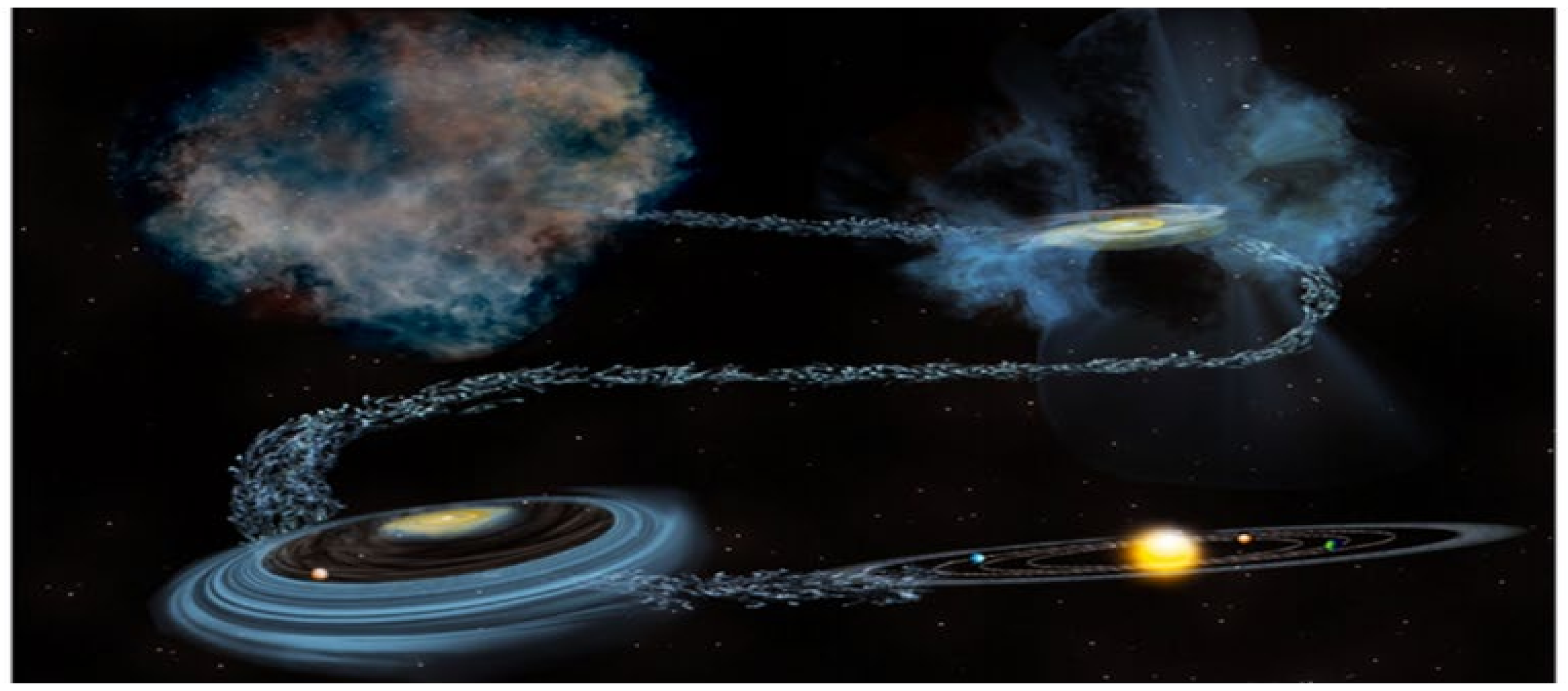

Fig. 1. Artist conception of the phases of star birth beginning in the "pre-stellar" phase where a cloud of gas collapses (top left) into a still-forming star surrounded by disk near the size of our solar system and a collapsing envelope of material (top right). Over time the envelope dissipates, leaving being a young star and a disk that is beginning to form planets (bottom left) eventually leaving being a new planetary system (bottom right). (Image Credit: Bill Saxton, NRAO).

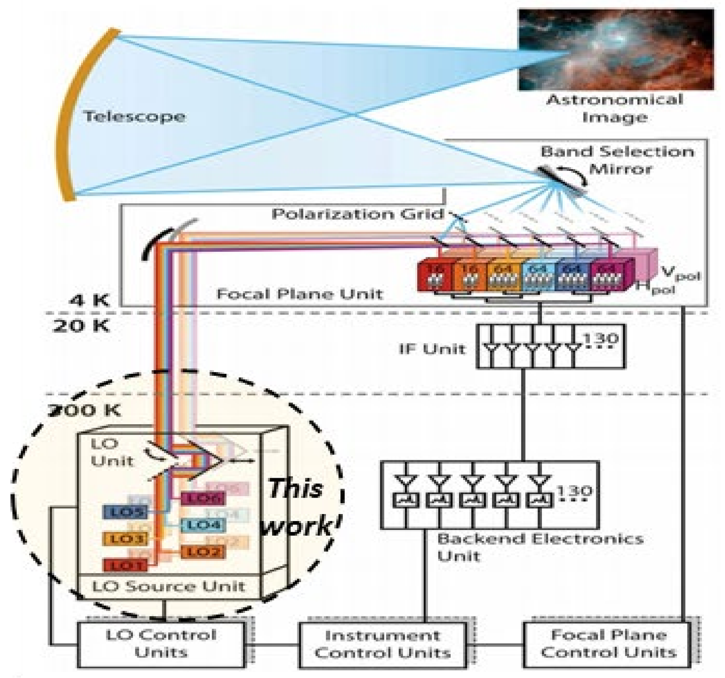

Fig. 2. HERO heterodyne architecture closely follows the successful HIFI one. The LO Source represents the bottle-neck for RF bandwidth. A factor of 3 increase over the SOA is needed to achieve ~40% bandwidths and fulfill the science requirements (Credit: Britt Griswold, NASA.)

Objectives

Herschel/HIFI has been an enormously successful space instrument, contributing to our understanding of the ISM and star formation [1]. The GREAT/SOFIA , GUSTO and ASTHROS are continuing this legacy with modest array receivers. However, future missions will require focal plane arrays covering the entire submillimeter-wave spectrum, which are impossible with state-of-the-art heterodyne receivers. A typical high-spectral resolution heterodyne receiver consists of an antenna, a frequency mixer (SIS or HEB, based on frequency), a Schottky diode-based frequency multiplied LO source, and the IF processor, see Fig. 2. Since the HEB mixers are inherently broadband, as long as the proper antenna structure is used, the bottleneck is the RF bandwidth of the LO (~15% only). We propose to maximize the LO bandwidth up to the limit (full-band waveguide coverage, i.e. 40% RF bandwidth) by using a radically new concept consisting in on-chip diplexing three bands into one with a novel design in which a single frequency multiplier chip can cover three bands (3OCDM), see chips on Fig. 4, left. With a thorough joint design of the multiplier diodes and matching circuitry, three different multiplier "cells" on a chip can work together as one, multiplying the bandwidth by a factor for 3 (from 15% to 45%).

The proposed work will be a game changer in the field of high-spectral resolution terahertz spectroscopy, establishing JPL far ahead as the leader in the field. The impact on science return will be enormous, and it will provide a path forward for the HERO instrument on OST, ASTHRO/FIR balloon facility, SmallSat missions, or any other Herschel follow-up mission. 3D-HIFI would be able to cover the key part of the submillimeter range (400-2700 GHz with just three channels, instead of the 14 used by Herschel or the 15 that would be required for OST if current SOA LO technology is used, see Fig. 3).

Approach and Results

The approach consists in implementing a novel and very innovative "3x on-chip diplexed frequency multiplier" concept. It is based on a single-substrate multiplier chip with one third of the diodes tuned to the lower side of the target frequency band, and the rest tuned to the mid and upper part of the band, as shown in Fig 4, resulting in the on-chip diplexing and an increase in bandwidth from 10-15% (current state-of-the-art) to at least 40%. Depending on the target frequencies, each subset of diodes within the chip can be designed to work either as a doubler or a tripler.

HIFI LO Subsystem Bands (Herschel Space Observatory - 2009)																	
1a	1b	2a	2b	3a	3b	4a	4b	5a	5b	6a	6b	7a	7b			Channel BW bandwidth	Channels with current SOA
487-554	562-629	634-718	722-794	807-852	866-953	957-1053	1054-1114	1116-1236	1236-1272	1430-1558	1578-1698	1701-1794	1793-1902			6-13%	14
HERO LO Subsystem (Origins Space Telescope Concept – 2020 Decadal Survey) or ASTHRO/FIR balloon facility or future Probe-Class Missions																	
1		2				3				4			5			Channel bandwidth	Channels with current SOA
468-648		648-900				900-1260				1242-1836			1836-2700			32-38%	15
3D-HIFI LO Subsystem (this work)																	
1A			2B			3				4A			5B			Channel bandwidth	Channels with new SOA
456-684			630-900			912-1368				1368-2052			1890-2700			35-40%	≤5*

Fig. 3. Comparison of the Local Oscillator Bands required for HIFI (top, blue), a next generation instrument like HERO suitable for OST, ASTHRO/FIR or a future Probe-Class mission (middle, orange), and the 3D-HIFI concept proposed here (bottom, green). With the current state of the art (~10-15% LO bandwidths), HIFI required 14 LO channels to fulfill the science requirements. HERO would need 15 with the current State of the art to cover the 5 bands proposed. The 3D-HIFI concept (this work), based on the 3x-on-chip-dpilexed multiplier concept, would need only between 3 and 5. This is because the "B" bands can be obtained from the intermediate frequency multiplication stages of the "A" bands. See next figures. ***Note: frequency units are in GHz.***

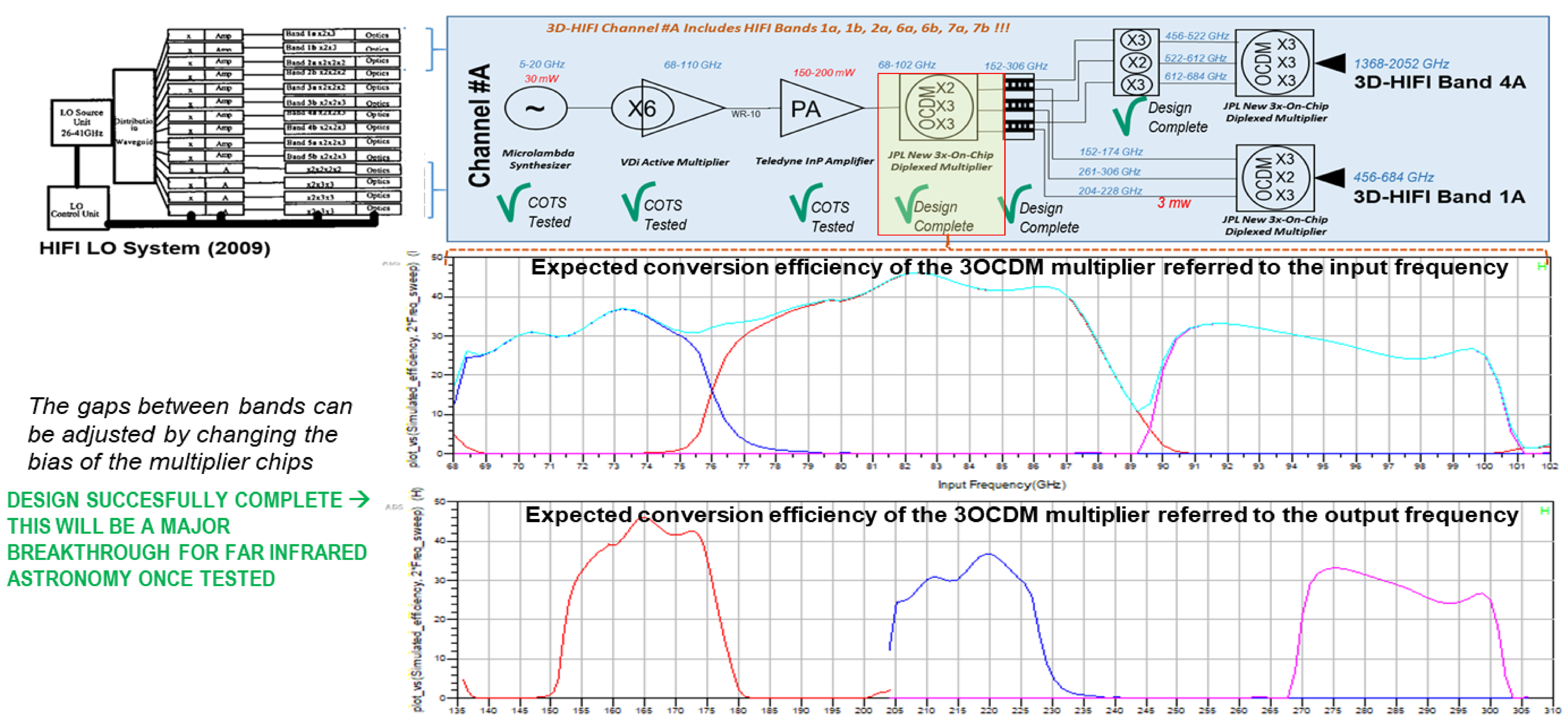

Fig. 4. A major milestone (M1 in schedule) was the successful design of the 3x-On-Chip Diplexed Multiplier than enables the 3D-SCIFI concept (3OCDM). 3 bands are combined on a single multiplier without compromising efficiency (the chip selectively routes the input signal to a certain number of diodes, doubling or tripling the signal depending on the frequency sub-band).

The major milestone completed in FY21 has been the successful design of the 3x-On-Chip-Diplexed Multiplier chips (3OCDM), which combine three multiplier structures into a single chip effectively increasing the bandwidth of traditional multipliers by a factor of 3, reaching full waveguide band operation without compromising conversion efficiency. This milestone confirms that the 3D-HIFI concept is indeed viable. Once fabrication and test are complete, this will be a major breakthrough for far infrared astronomy. The complexity of the design was huge though, which was expected since a single input waveguide matching structure is used for three multiplying structures operating simultaneously. The three bands are combined on a single multiplier. The chip selectively routes the input signal to a certain number of diodes, doubling or tripling the signal depending on the frequency sub-band. The fact that some of the diodes need to act as doublers and some as triplers, adds an additional complexity to the design. The crossover between bands at the right frequency is achieved by carefully designing the on-chip matching structures and the diode characteristics, taking advantage of the nonlinearities. Fig. 4 shows the 3D model of the chip and the predicted performance for the first 3OCDM stage, highlighted in green in the 3D-HIFI Channel "A" (Fig. 4, top). Fig. 4 also shows all the stages that have been completed for Channel A. All the LO early stages: synthesizer, active frequency multiplier and power amplifier have been tested. The 10-dB couplers required to obtain Band 4A and 1A from a common LO (Channel A) have also been designed and are in fabrication.. Once the devices are tested, the TRL will be 4. With this 3OCDM design complete, the chip can be easily adapted to other frequencies to finalize the high frequency multiplier stages of 3D-HIFI, in process now.

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Clearance Number:
RPC/JPL Task Number: R21123