A LOCAL OSCILLATOR SYSTEM FOR THE FIRST HETERODYNE INSTRUMENT

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Abstract

The Heterodyne Instrument for FIRST (HIFI) shall cover the full frequency range from 480 to 1250 GHz plus two additional parts of the spectrum around 1.6 and 2.6 THz. To be able to cover this frequency range, the Focal Plane Unit and the Local Oscillator Unit of HIFI will be split into 6 channels. The Local Oscillator Unit will be located at the outside of the satellite's LHe dewar and will be operated at a temperature of about 100 K. Each of the channels 1 to 5 consists of 2 chains of wide bandwidth HEMT power amplifiers in the 60 to 110 GHz range feeding wideband planar multipliers. To provide enough output power to pump two mixers at perpendicular polarizations wire grid beam splitters will be used. The amplifiers are fed by an actively multiplied tunable YIG oscillator which is located in the ambient temperature service module part of the satellite. The 6th channel is split into a 1.6 and a 2.6 THz part. Here, optical mixing in LTG GaAs will provide the LO power to feed a set of HEB mixers. The overall LO system design as well as the necessary development program are described.

Introduction

The ESA cornerstone mission 'Far-Infrared and Submillimeter Telescope' (FIRST)[1,2] will consist of a 3.5 m telescope that is mounted on a LHe cryostat. It will give the first opportunity to cover a large part of the submillimeter and far-infrared wavelength range with a sensitivity close to the quantum noise limit at high angular and spectral resolution and without damping absorption of atmospheric water vapor and trace gases. A heterodyne instrument on FIRST will allow to study the complex chemistry and dynamics in a variety of astronomical sources ranging from comets to distant galaxies[3]. Essential to achieve this goal will be a complete coverage of a wide frequency range. Therefore, (HIFI) shall cover the full frequency range from 480 to 1250 GHz plus the astronomically important spectral regions from 1410 to 1910 GHz and from 2400 to 2700 GHz. HIFI consists of four sub units, the Focal Plane Unit inside the cryostat, the local oscillator system, the IF section, and the control electronics. This paper describes the current baseline for the LO system.

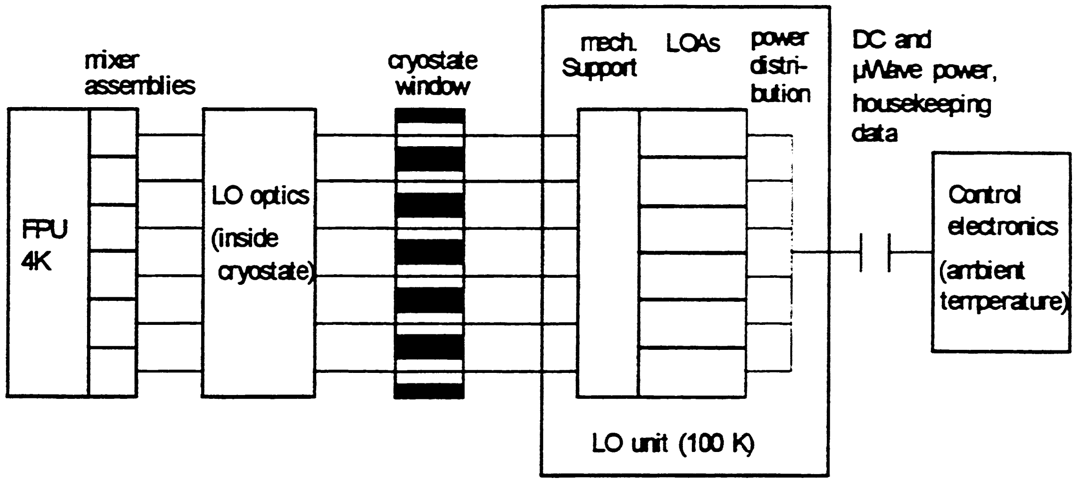

Figure 1: Schematics of the LO system with respect to the focal plane unit (FPU)

General Description

The design of the LO system is driven by the choice of mixer frequency bands and mixer properties, and by the spectroscopic requirements, i.e. maximum resolution and bandwidth. The HIFI frequency range is split into 6 mixer bands which are operated in double sideband (DSB) mode[4]. The lower five mixer bands are equipped with SIS mixers with an IF range from 8-12 GHz. Band 6, which is called the ultra-high frequency channel (UHF) will be equipped with hot electron bolometric mixers (HEBMs) with an IF range from 2-6 GHz.

The HIFI backend will consist of a high resolution spectrometer with a resolution of 0.1 MHz at a minimum bandwidth of 500 MHz and a wideband spectrometer with a resolution of 1 MHz and a bandwidth of 4 GHz.

An overview of the local oscillator part of

Table 1. Proposed mixer, local oscillator and amplifier frequency bands (* for band 6 the baseline is to use a photomixer LO source)

mixer		LO		multiplier	LO amplifier
band	operating range, GHz	band	tuning range, GHz	stages	frequency band, GHz
1	480–642	1a 1b	492–550 572–630	x2x2x2 x2x2x2	61.5–68.8 71.5–78.8
2	640–802	2a 2b	652–710 732–790	x2x2x2 x2x2x2	81.5–88.8 91.5–98.8
3	800–962	3a 3b	812–870 892–950	x2x2x3 x2x2x3	67.7–72.5 74.3–79.2
4	960–1122	4a 4b	972–1030 1052–1110	x2x2x3 x2x2x3	81.0–85.8 87.7–92.5
5	1120–1250	5a 5b	1132–1174 1196–1238	x2x2x3 x2x2x3	94.3–97.8 99.7–103.2
6	1410–1910 2400–2700	6a 6b	1414–1906 2404–2696	x2x2x2x3* x2x2x2x3*	58.9–79.4 100.2–112.3

the HIFI instrument is given in Figure 1. It consists of a coupling optics part inside the LHe vessel, the Local Oscillator Unit and the LO control electronics.

The Local Oscillator Unit will be arranged in 6 local oscillator assemblies (LOA's) with a spacing of about 50 mm between the optical axes of adjacent LOAs yielding one optical plane per mixer band which eases alignment and gives a high degree of modularity. The LOAs are fixed to a mechanical support structure. Each LOA feeds both polarizations of the Focal Plane Unit's mixer bands.

The LO control electronics, which is sited in the service module of the satellite and which also supplies the electrical and microwave signals needed by the Local Oscillator Unit, monitors the LO system, and reports its status to the instrument control unit.

For bands 1 to 5 the high IF frequency and DSB mixer operation is used to reduce the tuning range required from the LO, but to ensure a smooth transition between adjacent mixer bands a band overlap of 2 GHz was assumed. Further, due to the restricted tuning ranges of sub-mm LO sources, we have chosen to use two LO sources to cover each mixer band. Only one LO source is operational at any given time. This LO pumps two mixers operating on orthogonal polarizations.

Assuming equal tuning ranges for the upper and lower LO sources for each mixer band, the above leads to minimum LO tuning ranges of 58 GHz for bands 1 to 4 and 42 GHz for band 5. We expect that the tuning range of LO sources will be increased in which case we can use any overlap between the coverage of upper and lower LO sources for each band to increase the redundancy. An overview of the different frequency bands applicable to HIFI is given in Table 1.

LO Sources

For bands 1 to 5, the listed tuning ranges can only be achieved if a broadband, high-power mm-wave source is available to drive the varactor frequency multiplier chain. In our baseline design we propose

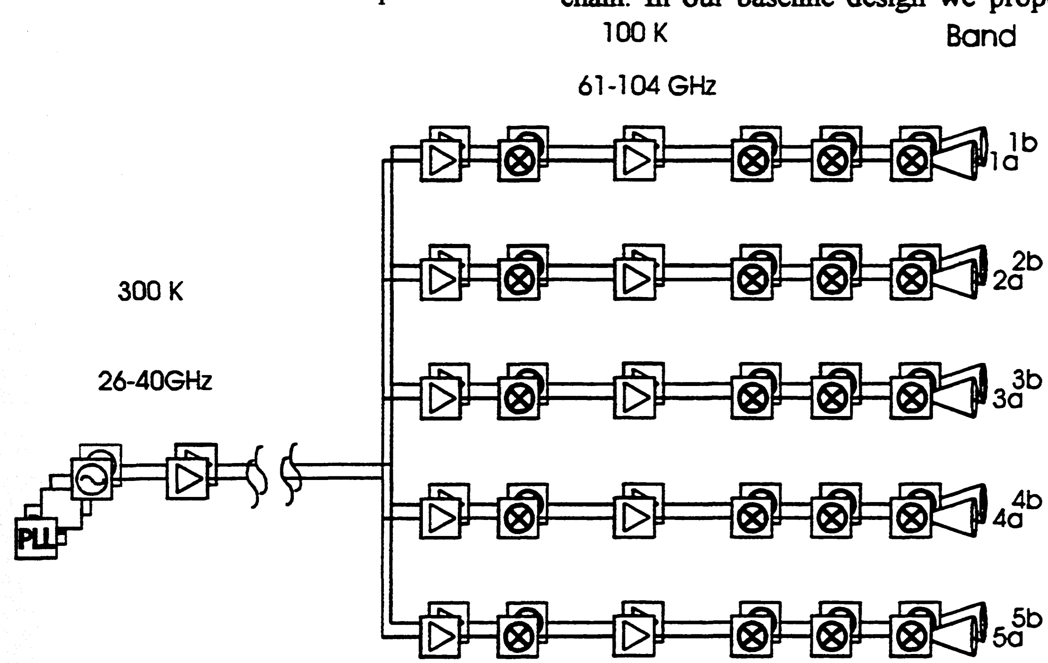

Figure 2: Schematic diagram of bands 1-5 of the LO system using power amplifiers

Table 2: Current performance of whisker-contacted and planar frequency multipliers

Type	Multiplication	Output Frequency GHz	Output Power mW	Efficiency %
planar	x2	160	77	22
whisker	x2	167	30	30
whisker	x2	190	15	15
planar	x2	240	6	15
planar	x2	320	9	13
whisker	x3	334	7	10
whisker	x2	384	1.5	10
whisker	x2	500	2 (est.)	20 (est.)
whisker	x3	800	0.04	4
whisker	x3	1000	0.06	1

to use custom high-power mm-wave amplifiers manufactured by TRW[5] to drive cascaded frequency multipliers. Such an LO source has already been demonstrated to work well at 500 GHz. A possible backup solution using mm-wave Gunn oscillators to drive the multiplier chains (as used in almost all ground-based submm receivers) is unlikely to have the required electrical tuning range. In this case we would either have to resort to mechanically tuned Gunn oscillators or use 4 LO sources per mixer band and a more complex optical setup employing fixed tuned diplexers. For band 6 laser photomixers are under development. A schematic diagram of the LO channels 1 to 5 is shown in Figure 2.

LO Sources for Bands 1 to 5

High Frequency Power Amplifiers

The successful development of GaAs p-HEMT MMIC power amplifiers in the 60-110 GHz frequency range makes it feasible to use them as the broadband sources to drive the frequency multiplier chains. Units manufactured at TRW have demonstrated output powers of 350 mW, an output power far exceeding what is available with Gunn devices. Presently, instantaneous bandwidths of 10 GHz are available but with modest further development this is expected to increase to 15 GHz.

Frequency Multipliers

An overview of state-of-the-art varactor frequency multiplier performance is given in Table 2. Generally, at lower frequencies, planar and whisker-contacted multipliers show rather similar performance. However, considering the reproducibility needed for a satellite project, the high power-handling capability and the wide bandwidth needed for the HIFI LOs, planar Schottky diodes will be used for at least the first stage of the varactor multiplier chains[6,7]. As backup, particularly for the high-frequency multiplier stages, whisker-contacted multipliers will be used[8]. Although the whisker contact is difficult to manufacture, it presents an important 'free' parameter for matching the diode to the embedding circuitry. Due to its extremely low mass it is not very vulnerable to vibration and such devices have flown on various satellites (e.g. MLS on UARS, MAS on the Space Shuttle).
For the final design, several LO chain and technology options will be considered.

Various multiplication schemes are feasible to generate an LO signal at THz frequencies. Best results are obtained with a cascade of multipliers with small multiplication factors (×2 or ×3), since they provide the highest efficiency and are easier to make broad band. A design goal is to cover a full mixer band with a single multiplier chain. This way we obtain full redundancy with the second chain.

As baseline we have chosen an amplifier driving a cascade of 2 planar frequency doublers followed by a whisker contacted final stage of frequency multiplication. As an option we will actively pursue a goal of integrating the first 2 doublers into an MMIC since development work in this area has already shown very promising results. This goal will open up the possibility of combining the amplifier and MMIC multiplier in a single package with consequent benefits of improved performance, reduced mass and smaller volume.

Band 6: Laser Photomixer Local Oscillator

In the Laser Photomixer Local Oscillator[9] two near-IR laser beams are combined in a photomixer to generate a difference frequency in the THz region. The current system concept is composed of four different components; the laser sources, the optical processing hardware, the control electronics, and the photomixer assembly (see Figure 3).

Two laser sources are currently under evaluation: a Distributed Bragg Reflector (DBR) laser diode with external optical feedback, and an external cavity diode laser. In both cases the laser source includes a laser with its respective optical feedback mechanism and the necessary isolation and optics to couple the radiation into Polarization Maintaining (PM) single mode fiber.

The optical processing unit is assembled from fiber-optic components, and includes two Electro Optic Modulators (EOM), a number of directional couplers, a wavemeter, a Cs reference cell, a number of photo detectors, an Ultra Low Expansion (ULE) high finesse cavity and an optical amplifier (MOPA). A MOPA amplifier has demonstrated the ability to amplify two laser signals separated by more than 10 GHz.

The control electronics supply the current and feedback to the lasers, and provide all the necessary signal processing to control the laser source frequencies. A microprocessor controls the operation of the laser frequency locking system. To date, a line width (FWHM) of 500 kHz has been demonstrated along with all-day lock times using 852 nm DBR lasers. The ability to generate any offset frequency to 100 kHz within the 1.5 THz tuning range of the lasers has been demonstrated. Optical feedback experiments at Caltech have demonstrated that a 100 kHz line width is possible.

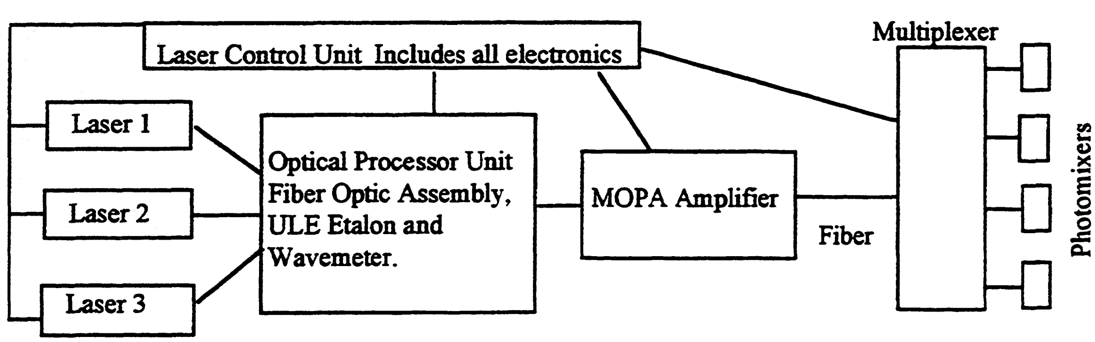

Figure 3. Laser photomixer LO source block diagram

Current etalons have free spectral ranges of ~3 GHz. The current baseline is to use a system with three external-cavity lasers. The reference laser and the offset laser would be fixed tuned gratings (tuning bandwidth ~60 GHz), while the second cavity locked laser would be a tuned grating device (tuning bandwidth ~10 THz). The two fixed tuned devices would lie near the 371 THz Cs line and would use that to determine the cavity order for the reference laser and tune the microwave frequency offset around the cavity order picked. The cavity order of the second laser would be determined by a wavemeter with better than a free spectral range resolution. The free spectral range of the etalon will be measured to better than the required part in 10^8 accuracy. Several suitable calibration methods are known and the actual calibration procedures will be developed and evaluated this year.

LO Assemblies

There are two types of local oscillator assemblies (LOA), the standard version for bands 1-5 using frequency multiplier chains, and a photomixer version for band 6.

LO Coupling Optics

The design drivers for the calculation of the detailed optical parameters of the LO beam-guide are the geometrical f/D ratio of the beams entering the mixer assemblies, the locations of the relevant components as defined by the satellite set-up (e.g. position of the Focal Plane Unit, position of cryostat window, etc.), and the requirement to minimize the IR heat load through the cryostat windows. In addition, the LO coupling shall be wavelength independent within a mixer band, and the optical path between the first mirror outside the dewar and the LO source has to be large enough to accommodate for the necessary optical components. This is especially important in the case of the backup solution with four LO sources per band that are coupled by fixed tuned diplexers. In that case, a third focusing element will have to be implemented.

To minimize diffraction effects, aperture diameters of the optical elements are chosen as four times the $1/e^2$ beam radius within the element.

A detailed study of the different design criteria resulted in the need of a minimum of 2 focusing elements along the optical path, one inside and one outside the cryostat. However, there is some flexibility in the choice of beam sizes and this will be exploited, for example, to reduce the size of the LO window in the cryostat or to relax the lateral alignment tolerances between the local oscillator unit and the focal plane unit.

Local Oscillator Assembly for Bands 1 to 5

The LOA for bands 1 to 5 (see Figure 4) consists of a small optics part with a focusing mirror and a wire grid beam combiner and two essentially identical LO sources oriented with orthogonal polarization. Together these two sources provide full frequency coverage of the particular mixer band. The chosen arrangement of two LO sources (one operational) pumping two mixers on orthogonal polarizations can be implemented with minimal

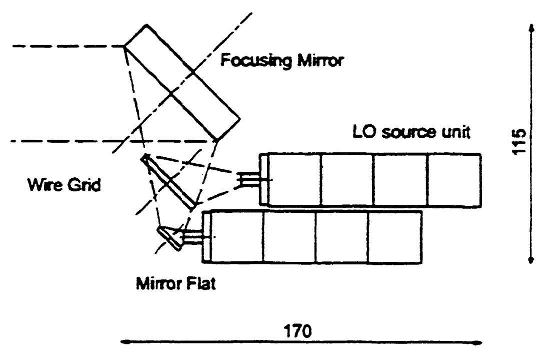

Figure 4. Layout of the local oscillator assembly for bands 1 to 5

loss.

Local Oscillator Assembly for Band 6

The photomixer assembly will include a fiber multiplexer feeding a set of fiber-coupled photomixers. Each photomixer will be integrated with a planar antenna on high resistivity Si lens to couple out the sub-mm radiation efficiently. Photomixers have been demonstrated to provide output power at 1.6 and 2.6 THz. However, this power is still not enough to drive the HEB mixers at the frequencies needed for band 6. Further photomixer development is currently focused on improving device performance and reliability by research in the areas of faster materials, increased output power and efficiency, and increased input power handling. The current plan is to use local heaters to warm the photomixers to above 250 K so that 852 nm lasers can be used.

All of the laser system except the photomixers will reside in the service module of the FIRST satellite. Transmission of the signal to the photomixer will take place in PM fiber which has a loss of less than 3 dB/km.

To minimize optical losses in the bands 6a and 6b, the two beams will be conducted separately through the window section of the satellite's LHe vessel and combined again inside the cryostat to feed the mixer assembly of band 6.

The LO Control Unit

The LO control unit will perform several functions. It will allow the selection of the proper LO band, provide the drive frequency for the local oscillator unit and adjust the power level to the LO to the mixers. In addition, the LO control unit will supply and monitor the bias for the multipliers and amplifiers and provide the DC/DC power conversion.

The LO control unit will provide the microwave signal to drive the power amplifiers (see Figure 2). The high stability oscillator will provide the reference frequency for a synthesizer which will have an output in the 26 to 40 GHz range. The output of this oscillator will be amplified, and fed to the Local Oscillator Unit via low loss coaxial cable. The step size of the synthesizer has to be small enough to have two steps within the 500 MHz minimum bandwidth of the high resolution spectrometer backend. With a maximum overall multiplication factor of 36 in bands 1 to 5 this leads to a step size in the order of a few MHz to a few tens of MHz. Within the Local Oscillator Unit, the 26 to 40 GHz signal will be distributed to the different LO assemblies. The feed signal will be further amplified and, depending on the frequency range of the LO assemblies, doubled or tripled for each band separately. With a second chain full frequency coverage and a high degree of

Table 3. Local oscillator spectral purity and stability.

Parameter	value	notes
Frequency accuracy	1 part in 10^8	
Linewidth	25 kHz	
Carrier-to-noise ratio	70 dB	0.1 MHz offset
	90 dB	1 MHz offset
	139 dB	2 GHz offset
	155 dB	10 GHz offset

redundancy will be obtained.
In order not to compromise the frequency resolution or sensitivity afforded by the instrument it is necessary that the LO signal is of high spectral purity and stable in frequency. Table 3 lists the necessary requirements.

The Interface to the Satellite

The local oscillator unit will be bolted to a plate or space-frame on the side of the satellite's payload module over 3 fixation points. The mechanical interface will mechanically support the Local Oscillator Unit and will be used to maintain its alignment with respect to the Focal Plane Unit. The LO unit is thermally insulated from the payload module by a low heat conductivity mounting structure and, optionally, by a thermal radiation shield. The heat generated by the LO unit will be radiated into deep space to achieve an operating temperature of 100–150 K.

Discussion

The HIFI LO system described above has some intriguing features. It is compact, shows a high degree of modularity, and is relatively simple considering the complexity of functions it has to perform.
To ensure the feasibility of the described LO system and to increase the redundancy, several items need further development. For channels 1 to 5, this holds especially for the MMIC power amplifiers and the planar and whisker contacted multipliers. The efficiency and output power of both items have to be increased as well as their bandwidth and reproducibility.
For the multipliers the development goal is broad band operation without mechanical tuners. To save cost, scaled planar doublers will be developed at least for the first multiplication stage We hope to be able to integrate up to the first two multiplier stages into the power amplifier module.
Concerning channel 6, the efficiency and output power of the laser photomixer LO has to be increased even considering the low power levels requested by the HEB mixers.
Finally, the layout of the LO optics will have to be refined to be able to relax alignment tolerances of the LO unit relative to the focal plane unit at minimized window losses and to further reduce the size and mass of the LO unit.
Summarizing, a compact LO system for the HIFI instrument is within reach. Current estimates of the size and mass of the most critical part of the LO system, the LO unit, yield dimensions of $200\times130\times300$ mm^3 and a mass of less than 10 kg. Since only one LO chain will be operational at any given time, the power consumption of the LO unit can be kept below the 6 W limit, that has been specified by ESA.

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