Innovative Technologies for THz Heterodyne Detection

T.G. Phillips

California Institute of Technology, Downs 320-47, Pasadena, CA 91125, USA

Contact: tgp@submm.caltech.edu, phone +1-626-395-4278

***Abstract*— The "state-of-the-art" in the field of heterodyne receivers approaches (within a factor of a few) the quantum noise limit, for frequencies up to about 700 GHz, the band-gap of niobium. Such receivers use the SIS structure and the physics of photon assisted single quasi-particle tunneling. IF bandwidths are as large as 25 GHz. Above 700 GHz various loss mechanisms set in and above about 1.4 THz HEB devices are preferred, even though the IF bandwidth is usually only a few GHz.**

For the future, at frequencies <1 THz, improvement will probably be in the area of increased IF bandwidth and in the area of focal plane arrays, demanding large LO powers. At frequencies well into the THz range quantum noise is dominant and the receiver noise figure should not be a problem. However, constructing tuneable local oscillators with sufficient power becomes the problem. This talk will discuss possible solutions to this problem.

I. Introduction

It is clearly not possible to invent all the novel technology of the next few years even in a restricted field such as heterodyne detection. However, there are some required aspects which can be defined and which may possibly lead to new devices. The heterodyne detection process is invoked when high resolution spectroscopy is needed. It has a major disadvantage in that the detection process involves quantum noise which cannot be avoided. This noise is proportional to frequency and is the dominant source of noise for heterodyne systems operating in the infrared or optical. When high resolution is not required direct detection processes may be preferred. In fact, when in the background noise limit condition, the signal to noise ratio is the same apart from the proportionality to the total bandwidth for both heterodyne and direct detection (Phillips, 1988). So, generally direct detection is preferred for large bandwidths. The best THz detectors for a given application are generally superconducting devices. This is because as an optical photoconductor uses the semiconductor band gap of about 1 eV, so the THz or submm detector uses the superconducting band gap of about 1 meV. Due to the relatively high frequencies involved the quantum noise limit is relatively easily achieved and the problem is to provide a suitable high power, spectroscopically clean, local oscillator source. So progress in the next few years will depend upon effective research into local oscillator techniques.

II. The Optimized Pixel

Before discussing the local oscillator problem we can ask whether the detector element problem has been completely solved. Surprisingly the answer is no! We are a factor of several away from an optimum pixel element in many cases. The first improvement which can be generated is the detection of both polarizations (Figure 1) for the one pixel. This costs two detector elements which could be coupled to the radiation field through lithographic crossed antennae. Secondly, we can use on-and-off pixels to improve on the switched antenna, single pixel device, costing another factor of 2 in SIS elements. Thirdly, the simple double-side band detector can be constructed as a side-band separation or image processing device, costing a further factor of 2 in SIS elements.

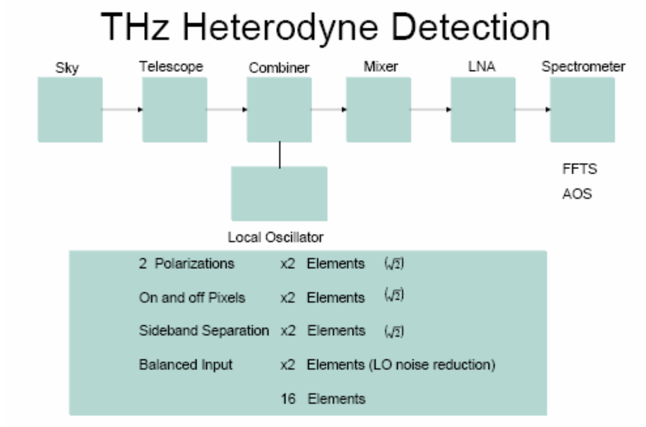

Figure 1. Components for heterodyne detection for a single pixel.

Finally, a balanced input device has the capability of rejecting local oscillator noise and costs a yet further factor of 2 in SIS elements. The total number of SIS elements is therefore 16, representing the optimized single pixel detector (see Figure 1). Of course, if this detector is incorporated into an array configuration it will only require 8 SIS elements per pixel since the off-pixel is provided by the array. To construct such a single pixel detector chip may have practical difficulties, but it seems likely that in the Nb frequency gap range, i.e. up to 700 GHz, it should be possible using Nb components. Due to the availability of non-superconducting micro-elements in the 700-1400 GHz range the Nb SIS detector can still be used but with reduced effectiveness. Generally above this range we switch to hot electron bolometer devices. The problem with these is not really the upper frequency limit which is hard to define but certainly in the several THz range. It is the difficulty in achieving a suitable high IF bandpass. In fact, the first hot electron bolometer in use in astrophysical applications had only about 1 MHz IF bandpass. Most people would have said this was not a useful detector but actually it made many of the initial discoveries which opened up the submillimeter field (Phillips and Jefferts, 1973). Modern receivers are mounted in accurately machined blocks with scalar-feedhorns, as shown in Figure 2, but at the highest frequencies employ dual-slot lithographic antennae and quasi-optical components rather than waveguides. (Zmuidzinas & Leduc, 1992) Figure 3.

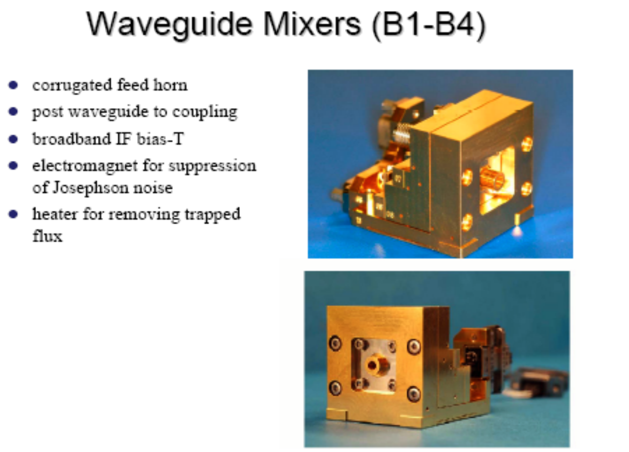

Figure 2. Bands 1-4 of HIFI employ waveguide circuits and scalar-feedhorns.

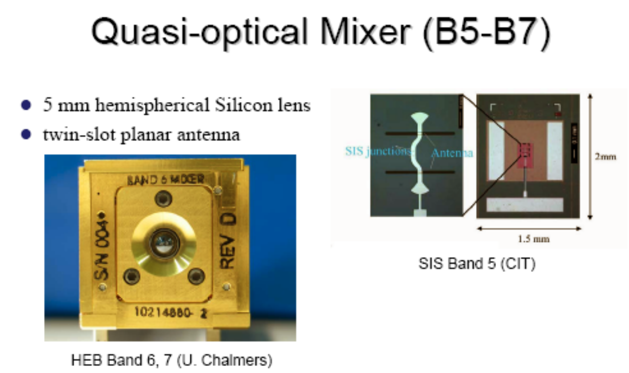

Figure 3. Bands 5-7 of HIFI use quasi-optic techniques and twin-slot antennae.

Returning to the question of quantum noise, this is an interesting question (see Figure 4) in that detectors in the SIS range have increasing noise roughly linearly as in quantum noise, whereas in the HEB range apparently the noise is roughly constant in frequency so will soon meet the theoretical quantum noise limit as the frequency increases. The problem then becomes achieving adequate local oscillator power and adequate IF bandwidth. The hot electrons are cooled by phonons or leave the system mechanically thereby requiring very small lithographic sizes in order to have sufficient speed to allow a wide IF. In terms of local oscillator power a rule-of-thumb is that it should be approximately the same as the DC power which can be as small as 100 nW to achieve thermodynamic flexibility. However due to optical losses in the front-end the LO power required is usually of the order of 1 microwatt.

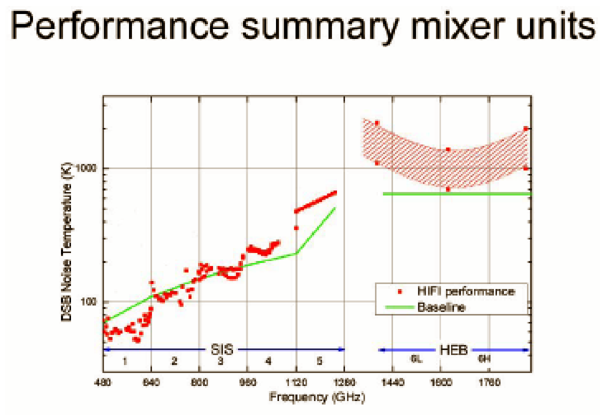

Figure 4. DSB receiver noise as a function of frequency for HIFI.

III. Local Oscillators

The classical THz local oscillator is a fundamental oscillator (e.g. Gunn) followed by a lithographically generated waveguide multiplier (Figure 5). We can list some of the potential LO devices. (1) Lithographic planar-diode multipliers, (2) Photonic schemes, (3) Josephson oscillators, (4) Quantum cascade lasers. Although modern devices such as quantum cascade lasers often appear to have plenty of local oscillator power it usually emerges that the output is not single mode but a combination of modes only one of which can be coupled to the mixer (Figure 7). This problem has been with us from the time of carcinotrons. The 4 schemes mentioned above each has its own problem. For instance, the planar-diode multiplier has to multiply up from a frequency at which power amplifiers can be implemented (about 100 GHz) which involves as many as 4 multiplier units. The LO power achieved by this technique for HIFI is adequate up to 1.9 THz, the frequency of the ground-state CII line. Josephson oscillators generally struggle to produce adequate power to drive an SIS detector and Quantum cascade lasers typically have multi-mode outputs and are hard to couple cleanly to detectors.

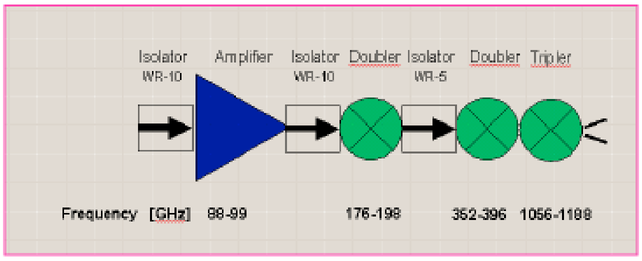

Figure 5. LO Chain Basic Layout

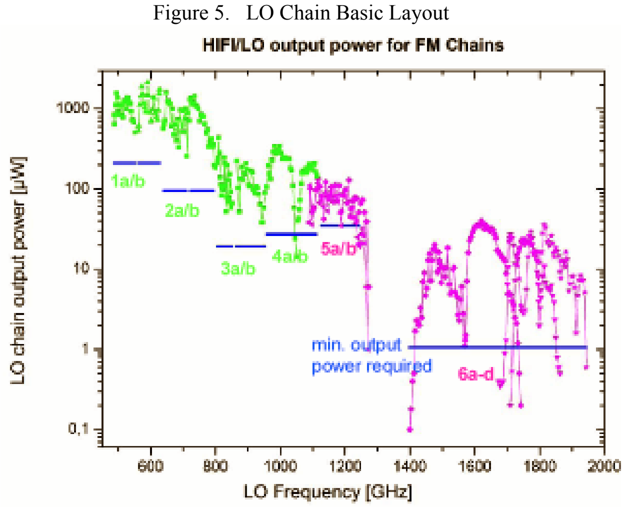

Figure 6. The HIFI LO power in the terahertz regime. The LO chain was maintained at temperature of 120 K for these measurements.

The multiplication technique becomes harder to implement as the frequency goes up, whereas some other techniques become easier with increasing frequency. An example of such a technique is the quantum cascade laser. An example of quantum cascade laser structure is shown in Figure 7 (after Williams, 2007). Of course, optically pumped molecular gas lasers produce considerable amounts of power but are not generally tuneable over a sufficient range required for astrophysics. Other lasers are often only available pulsed. Photonic devices seem attractive with the higher frequencies but are limited by the lack of appropriate impurity states of semi-conductors. On the whole it seems that the best device for astrophysics applications is probably the quantum cascade laser and if the single output coupling mode can be achieved then it is quite likely to be selected for future projects. Power problem will limit the size of the rays and implementation of the complex multiple SIS chip discussed above will exacerbate the power problem. In spite of all the difficulties, I expect within the long run quantum cascade lasers will become the standard LO for high terahertz work.

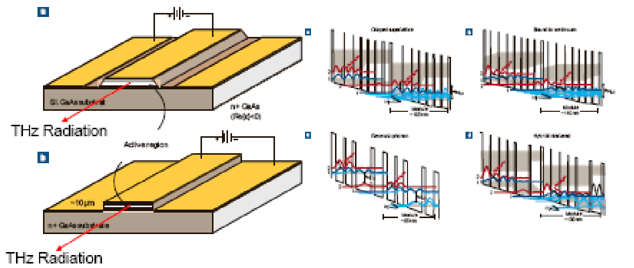

Figure 7. Quantum Cascade Laser as LO Sources

ACKNOWLEDGMENT

In terms of financial support, NSF supports the CSO through contract #AST-0540882. The work on HIFI is supported by NASA through JPL.

I would like to take this opportunity to congratulate the HIFI technical team which produced many of the results quoted here.

REFERENCES

[1] T.G. Phillips, *Techniques of Submillimeter Astronomy: Millimetre and Submillimetre* Astronomy; Summer School, Stirling, Scotland, Dordrecht, Kluwer Academic Publishers, 1988, p. 1-23.

[2] T.G. Phillips; KB. Jefferts, *A low temperature bolometer heterodyne receiver for millimeter wave astronomy*, Rev. Sci. Instrum., Vol. 44, p. 1009–1014, 1973.

[3] J. Zmuidzinas; H.G. Leduc; J.A. Stern, *Slot antenna SIS mixers for submillimeter wavelengths:* The Third International Symposium on Space Terahertz Technology: Symposium Proceedings p. 234, 1992.

[4] B.S. Williams, *Terahertz quantum-cascade lasers*, Nature Photonics, Volume 1, Issue 9, p. 517-525, 2007