SF2A 2024
M. Béthermin, K. Baillié, N. Lagarde, J. Malzac, R.-M. Ouazzani, J. Richard, O. Venot, A. Siebert (eds)

LABORATORY DEMONSTRATION OF MID-INFRARED HETERODYNE INTERFEROMETRY USING ANALOG PHOTONICS CORRELATION.

T. Allain[1], J.-P. Berger[1], G. Bourdarot[2] and H. Guillet de Chatellus[3]

Abstract. Studying the formation of planets and protoplanetary disks around young stars requires the access to extreme angular resolutions which can only be achieved using interferometry with typically kilometric baseline mid-infrared instruments. Direct interferometry uses bulky mid-infrared free space delay lines to recombine the light from separate telescopes and to recover the astronomical object interferometric observables. Heterodyne interferometry, which is widely used in radio-interferometry, relies on a different approach and consists in detecting the heterodyne beating between the astronomical signal and a local oscillator (laser) at each telescope. The resulting heterodyne signals are radio-frequency signals can be either digitized or analogically processed to retrieve the interferometric observables. We aim to demonstrate the interferometric recombination of two telescopes with a kilometric baseline in the N band using a heterodyne interferometry approach with photonic correlation. In the short term, we use a laboratory demonstration bench to test the different technological blocks that would be necessary for such a system and develop methods to operate a mid-infrared heterodyne interferometer. For the heterodyne detection stage, we use commercial 1 GHz bandwidth infrared detectors and 10.6 um quantum cascade lasers to detect a wide-band infrared source. For the correlation stage, we use commercially available photonic components at 1.5 um telecom wavelength. We are able to measure the coherent flux of a wide-band source down to a few 100 fW (limited by our infrared detectors) and to retrieve the coherence envelop of an infrared source. We also demonstrated the ability to compensate free-space delay by fiber delay directly inside the photonic correlator.

Keywords: interferometry, instrumentation, high angular resolution, mid-infrared

1 Introduction

From the birth of stars and planetary systems to supermassive black-holes, the recent observations of astronomical objects at the highest angular resolution have profoundly changed our vision of our surrounding universe. In this field, aperture synthesis with Very Long Baseline interferometry (VLBI) and optical infrared interferometry such as the Very Large Telescope Interferometer (VLTI) are currently the two techniques that provide the highest angular resolution achievable. With its shorter wavelength, infrared interferometry, still confined at 100m scale baseline, could be envisioned as one of the most promising technique to go even further. The extension of this technique to a large number ($N \geq 20$) of telescopes and kilometric baselines would represent a major step for observational astronomy. Nevertheless, such an infrastructure, as proposed in the context of the Planet Formation Imager (PFI) initiative (Monnier et al. 2018) which has the ambition to reach sub milli-arcsecond resolution in the mid-infrared (N and Q bands) would also require challenging technological developments that cannot be extrapolated simply from existing facilities such as VLTI.

Because 1) it provides a possible pathway for an infrastructure without a bulky and hard to maintain free-space propagation; 2) mid-infrared photonics research has considerably progressed and 3) the gain of direct interferometry at $\approx 10\mu$m is not so superior in the mid-infrared; heterodyne detection offers a still valuable and complementary path to explore the problem of kilometric baseline and aperture synthesis with a large number of telescopes. In the past, through the pioneering work of maser inventor and Nobel Prize C.H. Townes and his team, heterodyne interferometry was the first technique able to combine 2 telescopes in the mid-infrared and

---

[1] Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France
[2] Max Planck Institute for extraterrestrial Physics, Giessenbach-strasse 1, 85748 Garching, Germany
[3] Univ. Rennes, CNRS, Institut FOTON - UMR 6082, 35000 Rennes, France

to measure closure phases with 3 telescopes, on the Infrared Spatial Interferometer (ISI) in UC Berkeley (Hale et al. 2000; Hale et al. 2003). ISI provided valuable scientific results well ahead of its time.

We present here an innovative instrumental concept for mid-infrared heterodyne interferometry that has been assembled at IPAG and whose aim is to validate all the building blocks of an operational fibered link heterodyne photonics chain allowing the coherence to be measured over kilometric baselines. We have embarked in a characterization of the building blocks and global coherent efficiency of the link and to establish operational protocols for potential future instruments.

2 Principle

2.1 Heterodyne detection

Heterodyne interferometry relies on the ability to detect the electric field at each telescope of the array. In order to achieve that the celestial light is interfered with a so-called *local oscillator* in order to generate an intermediate frequency signal (radio-frequency) that can be digitized (ALMA, NOEMA) encoded into a laser carrier (this work) before being correlated. The measurement of the correlation (complex visibilities) carries the information on the object surface brightness which can be reconstructed provided that sufficient spatial frequencies have been measured (the so-called *uv* plane).

2.2 Challenges of the mid-infrared interferometry

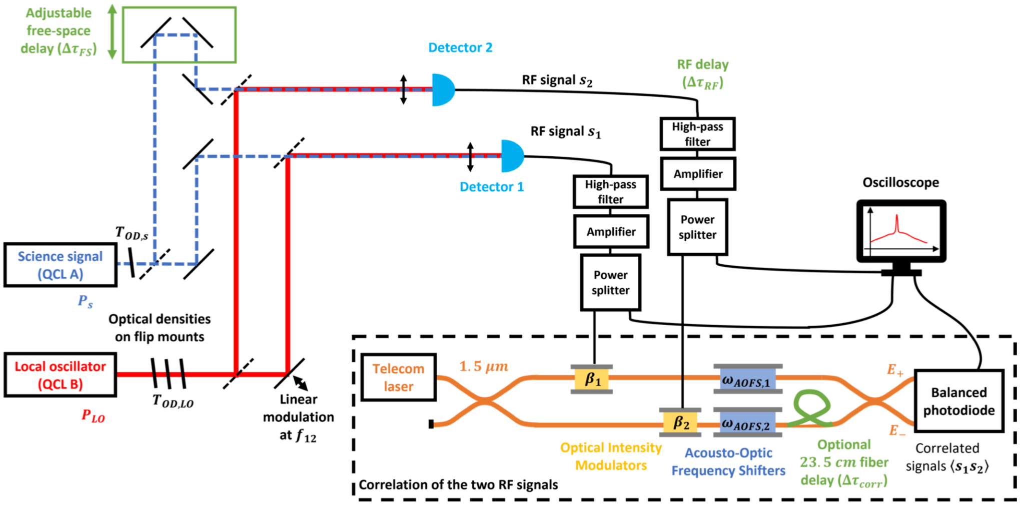

Fig. 1. Schematic of the mid-infrared heterodyne bench with its photonics correlator.

Unlike in the radio/mm regime, heterodyne interferometry in the mid-infrared suffers from a severe penalty in terms of number of photons per mode. This requires to combine several functionalities that are permitted by advances in mid-infrared photonics

1. High bandwidth high quantum efficiency detectors;
2. Mid-infrared laser frequency combs synchronized between telescopes in order to increase the wavelength coverage and provide a shared frequency reference;
3. Atmospheric piston fluctuations compensation;
4. High bandwidth correlation.

In the following we focus our effort on the proof-of-principle demonstration of analog correlation of mid-infrared coherent signals using off-the shelf photonics components. More detailed on the principles can be found in Bourdarot et al. (2021)

2.3 The bench

The schematic of the bench can be seen in figure 1.

Mid-infrared stage: generates wide-band mid-infrared signals to be simultaneously detected and correlated

1. The astronomical signal is emulated by a mid-infrared Quantum Cascade Laser (QCL) at 10.6 μm . This signal QCL can be set to the laser regime (i.e. the regular operating regime for a laser) or to the Amplified Spontaneous Emission (ASE) regime (a regime of broader emission below the laser threshold). The ASE regime is used to obtain a low-power wide-band source while keeping a simple procedure alignment.
2. The signal QCL is split and sent to two different infrared detectors (detectors 1 and 2), thus creating our two correlated E_1 and E_2 fields. A temporal delay between the two detectors can be manually adjusted to explore the coherence envelop of the science signal.
3. The signal QCL is superimposed with another QCL at 10.6μm playing the role of local oscillator (LO). The frequency of the local oscillator can be adjusted to match the frequency of the signal QCL.
4. A dither mirror moving back-and-forth at constant velocity is used to Doppler shift the frequency of the local oscillator.

Detection and RF stage: detects the intermediate frequency signals, adapting their RF power to the correlator requirements, filtering noise and measuring the RF power to normalise the coherent flux measurements.

1. The heterodyne intermediate frequencies between the signal and the local oscillator are detected on detectors 1 and 2. The two detectors output radio-frequency signals carrying the amplitude and phase information of the signal source. In the proper conversion regime they are the down-converted versions of the incoming electric fields.
2. The RF signals signals are filtered, amplified and split. Half of the signals goes to an oscilloscope to measure their average power while the other half goes to the photonic correlator.
3. The RF signals are encoded onto a 1.5 μm laser using Mach-Zehnder Intensity Modulators. The 1.5 μm laser is a telecommunication fibre laser that is divided in two channels, channels carrying the two heterodyne signals.

Photonic correlator: computes analogically the correlation between the two heterodyne beatings and allows to exact the coherent flux and its phase in order to provide a measurement of the complex visibility.

1. The 1.5 μm laser is shifted in frequency by Acousto-Optic Frequency Shifters (AOFS). The frequency shift is not the same for the two channels, inducing a angular frequency difference the two channels in order to encode the coherent signal at a predetermined frequency.
2. A internal delay can be added in the correlator to account for propagation time differences.
3. The two channels are recombined using a fibre coupler. A balanced photodiode is used to measure the intensities at the output of the coupler. The intensity frequency components at the proper frequency are proportional to the sum/difference of the heterodyne signals $|h_1 \pm h_2|^2$, enabling us to obtain correlation product $\langle h_1(t)h_2(t)\rangle_{\mathrm{Tavg}}$ which is proportional to the coherent flux of the astronomical source.
4. A digital oscilloscope in FFT mode is used to extract the correlation product. .

3 Results

We have demonstrated that "broadband" 300 MHz coherent signals can be correlated efficiently using our proposed photonics concept. Moreover, instead of bulky external delay lines we have shown that optical path compensation could be carried within the correlator fibers (see figure 2). Moreover, we have identified that our main sources of noise should in principle easily be corrected through the use of better detectors, and improved electronics.

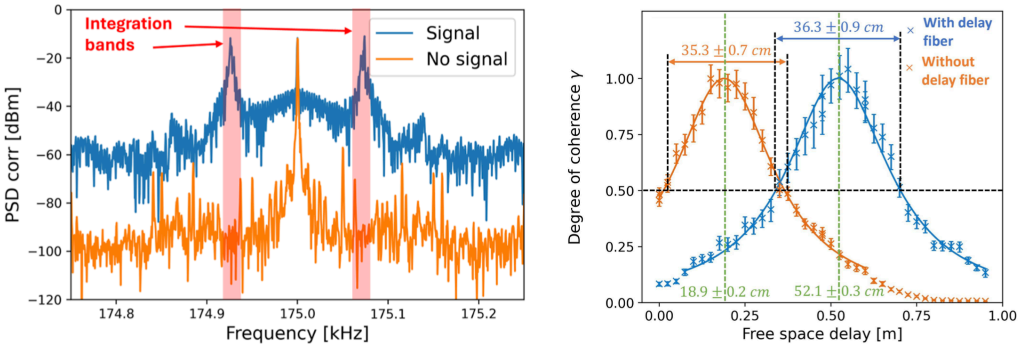

Fig. 2. Left: example of power-spectral density at the output of the photonics correlator. In the presence of a coherent wideband source the coherent flux appears as a peak. Right: Detection of the coherence envelop of a ”broadband” source and demonstration of optical path correction.

4 Conclusions

Heterodyne interferometry is an alternative to direct interferometry in mid-infrared with:

- Easier scalability to large baselines and high number of telescopes
- Limited sensitivity due to high density of frequency modes in mid-infrared

We wish to demonstrate that the essential building blocks for a kilometric baseline mid-infrared heterodyne interferometer exist. In this study we have focused on demonstrating the principle of high bandwidth analog correlation using off-the shelf photonics components.

We demonstrated the photonic correlation of infrared signals with:

- Up to 1 GHz bandwdith (only limited by 10.6 μm detectors), could in principle go up to 40 MHz
- A one σ detection limit of 100 fW in 0.2 seconds (limited by the detectors)

We estimate that the sensitivity could improve considerably by using

- better high bandwidth detectors such as the QWIPs developed at Laboratoire de Physique de l’Ecole Normale Supérieure ($\approx$ 100 gain in SNR, on going collaboration);
- frequency combs with $\approx$ 100 lines ($\approx$ 10 gain in SNR);
- Coherent integration ($\approx$ 10 gain in SNR) for 1 hour integration.

TA acknowledges financial support from ENS-THALES Chair. We acknowledge financial support from LabEx FOCUS ANR-11-LABX-0013, from INSU ASHRA and from INSU CSAA

References

Bourdarot, G., Berger, J.-P., & Guillet de Chatellus, H. 2021, Journal of the Optical Society of America B Optical Physics, 38, 3105

Hale, D. D. S., Bester, M., Danchi, W. C., et al. 2000, The Astrophysical Journal, 537, 998

Hale, D. D. S., Fitelson, W., Monnier, J. D., Weiner, J., & Townes, C. H. 2003, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4838, Interferometry for Optical Astronomy II, ed. W. A. Traub, 387–397

Monnier, J. D., Kraus, S., Ireland, M. J., et al. 2018, Experimental Astronomy, 46, 517