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V8 CONCEPT AND PHOTONIC CORRELATION FOR MID-INFRARED INTERFEROMETRY

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Abstract. The recombination of a large number of telescopes over kilometric baselines in an infrared interferometric array, such as proposed in the Planet Formation Imager (PFI) initiative, requires the investigation of renewed interferometric architectures. In the mid-infrared, heterodyne interferometry represents a potential solution, appropriate for the recombination of a large number of telescopes and the practical transport of interferometric signals. A major challenge of heterodyne interferometry is the limitation in terms of detection bandwidth, which requires the development of detectors and correlators handling detection bandwidth up to tens of GHz. Here, we report on the status of our technological demonstration in this direction. We present an update of the concepts of photonic correlation, including both phase and amplitude modulation schemes, and their proof-of-principle demonstration in the laboratory. Together with the advent of new mid-infrared high bandwidth detectors and Quantum Cascade Lasers (QCLs), the current state of mid-infrared technologies could be applied to the simultaneous combination of the eight telescopes of the VLTI, so-called V8 concept. We describe the first step in this direction, with the development of mid-infrared test bench at 10.6 μm with 2 detection channels, including a QCL, commercial high-bandwidth detectors and a photonic correlator.

Keywords: Planet Formation Imager, Heterodyne Interferometry, VLTI, Photonic Correlation, QCL

1 Introduction

The development of an infrared interferometric array recombining a large number of telescopes over kilometric baselines represents a major step in observational astrophysics, in particular for the study and the image reconstruction of protoplanetary environments with milli-arcsecond (mas) and sub-mas resolution in the infrared, such as proposed in the Planet Formation Imager (PFI) initiative (Monnier et al. 2018; Ireland & Monnier 2014). In the mid-infrared, heterodyne interferometry, which consists in detecting the amplitude of the field (coherent detection) as a radio-frequency (RF) signal and in correlating these RFs signal between each pair of telescopes, offers a practical solution while relaxing the requirement on a hard infrastructure. In this perspective, the V8 concept (this work and Berger et al. in the same proceedings) proposes to take advantage of the scalability of heterodyne interferometry and of the current state of mid-infrared technologies to combine the 8 telescopes of VLTI simultaneously in the VLTI lab through an heterodyne combiner, which handles the correlation and the delay function on the heterodyne signal, in order to exploit the full imaging capability of VLTI. In the following, we complement the photonic correlation proposed in this perspective and present a preliminary 2 beams combiner at 10.6 μm dedicated to the validation of a complete detection and correlation chain.

2 Photonic correlation

The principles of photonic correlation consists in encoding a wide band RF signal through a photonic modulator on a optical carrier, typically at telecom wavelength, which is then transported and combined on a photodiode. The scheme that enables to extract the correlation product of the signal can be based either on phase modulation or amplitude modulation. In both cases, the signal that is extracted is proportional to the multiplication product of the two input RF channels integrated in time i.e. the correlation product of the input RF signals at one delay. This principle is very similar to the analog RF correlator implemented on the Infrared Spatial Interferometer (Hale et al. 2000).

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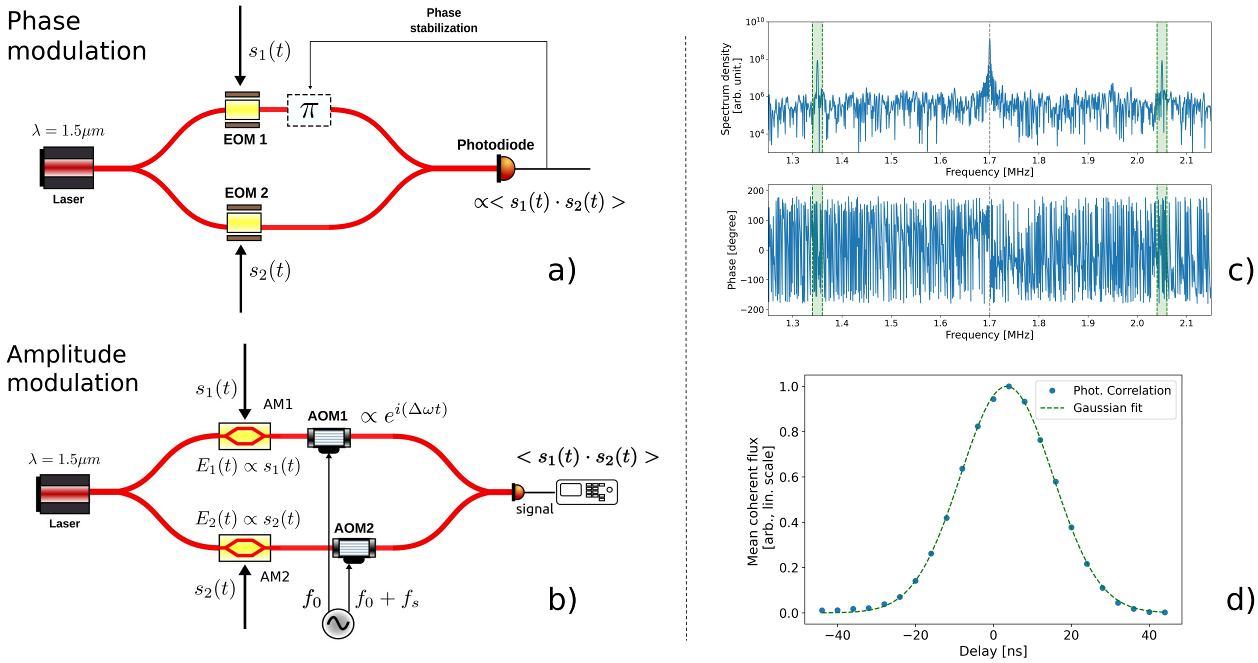

Fig. 1. a) : Phase modulation scheme (EOM : Electro-Optical Modulator) **b) :** Amplitude modulation scheme **c) :** Correlation of heterodyne signals in amplitude modulation (fringe peak in green area). **d) :** Coherence envelope of the correlated signals.

2.1 *Photonic correlation in phase modulation*

In the phase modulation scheme, the RF signal at the output of the rapid mid-infrared photodiode is encoded on the optical carrier through a phase modulator, placed at the level of each telescope. This signal then propagates in telecom fiber and is combined with an arm coming from an other telescope, which forms a Mach-Zehnder, as shown in Fig 1. The key idea of phase modulation consists in noticing that at a minimum or at a maximum of intensity of a Mach-Zehnder, the output intensity of the Mach-Zehnder varies as the square of the relative phase modulation between the arm. Since the phase modulation is proportional to the input RF signal, the output intensity contains the product term of the two input RF signals, which is the correlation product we seek to compute. A detailed description of the functioning principle as well as its experimental demonstration is given in Bourdarot et al. (2020). The stabilization of the Mach-Zehnder to a given functioning point (maximum or minimum of intensity) is an important constraint of this scheme. In the next section, we describe a second correlation scheme, based on *amplitude* modulation, which enables to relax the requirement on phase stabilization.

2.2 *Photonic correlation in amplitude modulation*

In the amplitude modulation, an amplitude modulator, on which is imposed the output RF signal of the heterodyne detection stage, is placed in each arm of the Mach-Zehnder, and used at the null of transmission. The optical field $E_k(t)$ in each arm (numbered k) after these two components is :

$$E_k(t) = E_0 e^{i\omega_0 t} e^{i\phi_k} \left(1 - e^{i\beta_k s_k(t)}\right) \approx -iE_0 \beta_k s_k(t) e^{i\omega_0 t + i\phi_k(t)} \tag{2.1}$$

where we have assumed that each modulator is at a minimum of intensity, with E_0 the amplitude of the optical carrier at telecom wavelength (carrier), ω_0 the angular frequency of the optical carrier, $\beta_k = \frac{\pi}{V_\pi}$ with V_π the half-voltage of the modulator, $s_k(t)$ the RF signals coming from the heterodyne stage, and $\phi_k(t)$ the phase perturbation in the fiber link. In addition, a fiber frequency shifter (Acousto-Optic Modulator abrev. AOM) can be placed downstream the amplitude modulator, and has the effect of shifting the central frequency of the optical field i.e. multiplying the electric field by $e^{i\Delta\omega_k t}$, with $\Delta\omega_k$ the angular frequency shift in arm k. The beating term at the output of the Mach-Zehnder (measured with a balanced detection for example) is finally :

$$I(t) = 4I_0 \mathrm{V}_i \beta_1 \beta_2 s_1(t) s_2(t) \cos\left((\Delta\omega_2 - \Delta\omega_1)t + \Delta\phi_{12}(t)\right) \tag{2.2}$$

with $I_0 = |E_0|^2$ and $\Delta\phi_{12}(t) = \phi_2 - \phi_1$. At the output of the correlator, the correlation product $\langle s_1(t)s_2(t)\rangle$ is thus encoded at a given (angular) frequency $(\Delta\omega_2 - \Delta\omega_1)$. In this way, the correlator does not require the stabilization to a given functioning point, but only a relative stabilization over the coherent integration time.

2.3 Experimental demonstration

Following the same methodology than in (Bourdarot et al. 2020), the amplitude modulation scheme was implemented with commercial fibred components, and enables to demonstrate the correlation of heterodyne signals that were previously registered and generated a posteriori with Arbitrary Waveform Generator (AWG). We measure the correlation fringes with a noise factor $> 90\,\%$, and we measure the coherence envelop of the incident signal by varying numerically the relative delay between each arm of the Mach-Zehnder. The results of this proof-of-principles are shown in Fig 1.

2.4 Extension to a large number of telescopes

The photonic correlation scheme described so far is adapted to the correlation of two channels. This scheme can be extended to the correlation of a larger number of telescopes. Different architectures can be envisioned, as in direct interferometry (Lebouquin et al. 2004). These beam combinations can be categorized in different type of flux encoding (spatial, temporal, static phase-shifting) and beam routing (pair-wise, all-in-one, hybrid), cf Fig. 2. In our photonic scheme, temporal techniques are favoured, as they are more suited to the temporal encoding of the fringes in the architecture presented so far, and to the integration of a metrology system in the same channel that the signal channel. In temporal techniques, all-in one combinations based on frequency multiplexing of the fringes, and pair-wise combination, are both compatible to the correlation of a large number of channels. Alternatively, direct-imager combiner, such as proposed in (Blanchard et al. 1999), could also be envisioned, but are less suited to the correlation of a large number of spectral channels, contrary to temporal techniques. These different techniques and the parallel with direct interferometry are summarized in Fig. 2.

3 Preliminary 2 channels heterodyne demonstrator at $10.6\,\mu$m

We propose the implementation of a 2 beam heterodyne combiner at $10.6\,\mu$m in order to demonstrate the detection and correlation architecture devised earlier, to produce a complete sensitivity analysis of this chain, and to validate in the laboratory the technological sub-systems required for V8. The current layout of the

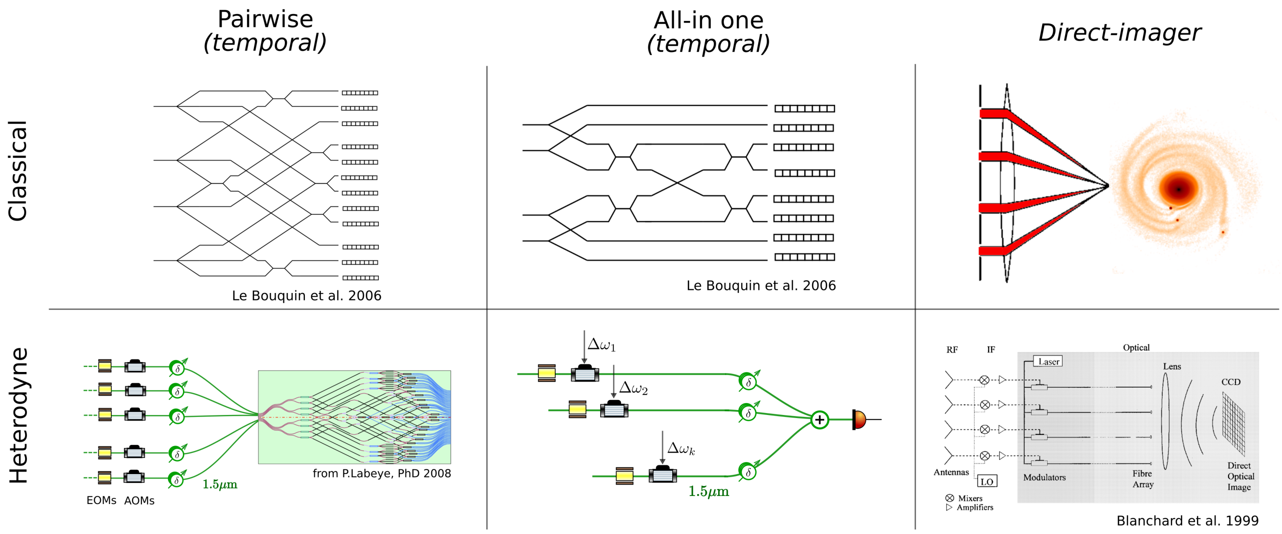

Fig. 2. Extension of the photonic correlation scheme to a larger number of telescopes.

demonstrator is shown in Fig. 3. In this demonstrator, the local oscillator (LO) is a Quantum Cascade Laser (QCL), splitted in two channels to two detectors, which naturally ensures the relative phase stability of the LO between the two channels. The signal channel can be either fed by a laser signal (e.g. the initial QCL) or an independent source (laser, black-body). The current detectors are commercial detectors (VIGO company, 1 GHz bandwidth) , and the correlator is a photonic correlator in amplitude modulation, identical to Sec 2.2. The demonstrator is currently under development, and is designed to observe an heterodyne interferometric signal on a black-body at 900K.

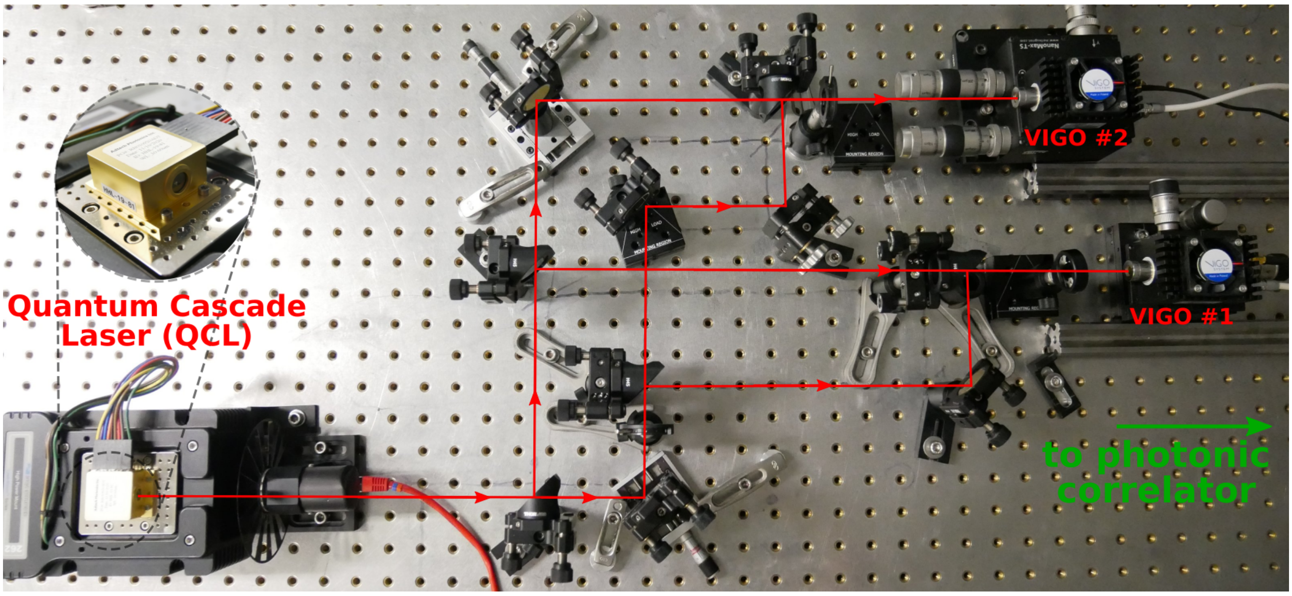

Fig. 3. Mid-infrared optics of the two beam heterodyne interferometric demonstrator at 10.6 μm.

4 Conclusions

The recombination of large number of telescope over kilometric baselines in the mid-infrared can benefit from the use of heterodyne interferometry. We complement the photonic correlation architecture proposed in this purpose with the introduction of amplitude modulation and the extension of this technique to the correlation of a larger number of telescopes. We present the preliminary implementation of a 2 channels heterodyne combiner at 10.6 μm whose goal is to validate the complete detection and correlation chain of our renewed heterodyne architecture, its sensitivity budget, and its essential technological blocks. Once demonstrated, this essential step could be scalable to the correlation of a larger number of telescopes and adaptable to existing infrastructures, in particular to the simultaneous correlation of the eight telescopes of VLTI in the mid-infrared, so-called V8 concept.

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