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Mid-Wave InfraRed metrology using Quadriwave Lateral Shearing Interferometry wave front sensing with low coherence quantum cascade laser sources

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ABSTRACT

We show that metrology at the working wavelength is possible with a wave front sensor in the Mid-Infrared range (MWIR, 3-5µm). We demonstrate the implementation of an Interband Cascade Laser for double-pass optical qualification with a quadriwave lateral shearing interferometer. To avoid any parasitic interference fringes, which limit the phase accuracy, we modulate the diode driving current with an external analog signal. While the power stability is kept constant, the phase noise is reduced and no artefact limits the measurement accuracy.

Keywords: optical metrology, wave front sensing, quadriwave lateral shearing interferometry, quantum cascade laser, interband cascade laser, space optics

1. INTRODUCTION

Current space optical components explore specific spectral bands and the infrared range contains valuable information to understand physical processes taking place either in space or on earth. The recently launched James Webb Space Telescope is a good example of the interest for infrared radiations. In addition, payload constraints lead to compact optical design and sometimes monolithic optics. For such systems, standard metrology methods based on double-pass interferometric schemes and on single-frequency lasers have reached their limits. In the contrary, wave front sensing is often an obvious solution where flexibility on wavelength is requested or single-pass measurement leads to easier, less expensive, and faster metrology.

We propose to use quadriwave lateral shearing interferometry (QLSI) to qualify Mid-infrared (MWIR) optical systems. QLSI is a wave front sensing technique where the impinging wave front is sampled by a sophisticated 2D diffraction grating. It splits light into 4 diffraction orders which interfere on a focal plane array, which in the MWIR infrared is an uncooled microbolometer. The deformations of the interference pattern are proportional to the wave front gradients in two spatial directions. After numerical integration, the light phase is recovered.

One advantage of QLSI is that it is achromatic, since the interferogram deformation is independent upon the wavelength. Therefore, it can be used with any source of light with sufficient spatial coherence. For instance, we developed an optical metrology bench that uses a 10.6 µm CO2 laser and a 3.39µm HeNe laser to characterize optics with a single wave front sensor, based on a dual-band microbolometer.

However, using highly coherent lasers induce noise, much higher than the instrument limit, which is around 1 nm RMS. For instance, we could reach a measurement repeatability of less than 15 nm and an SFE accuracy of less than 25 nm RMS. This is clearly limited by coherent noise and parasitic interference fringes.

To overcome this limitation, we propose to use Quantum Cascade Lasers (QCL) and Interband Cascade Lasers (ICL), emitting from 3µm to 5µm. These laser diodes are available as single-frequency or large-spectral band emitters (Fabry-Pérot). Their time coherence is therefore greatly reduced and we could expect less noise on phase measurements. Thanks to optical fiber technology development, such sources are now easily fiber-coupled and the light source can be taken away from the OGSE or the unit under test (UUT). The large choice of wavelengths now offered makes it possible to test an optical system at is nominal and/or optimal wavelength.

In the end, we developed at PHASICS, a metrology instrument working at 3.8µm with phase noise below 3 nm RMS. We were also able to control the beam divergence so that it is kept below 5 nm RMS.

In this paper, we will first present the involved QLSI technology. We will then describe the optical set-up where the wave front sensor and the source were implemented. We will show how the laser coherence was controlled to achieve the best wave front measurements. Finally, we give experimental results when the wave front sensor and the source work together.

2. QUADRIWAVE LATERAL SHEARING INTERFEROMETRY IN THE MWIR RANGE

Quadriwave Lateral Shearing Interferometry is a wave front sensing technique invented by Jérôme PRIMOT at ONERA [1]. It was developed to overcome limitations of the Shack-Hartmann technology, mostly in terms of spatial resolution. It replaces the microlens array by a 2D phase and amplitude grating, which diffracts the impinging beam into 4 replicas. After a short propagation, the replicas interfere on a detector (see Figure 1). The interferogram fringes are deformed proportionally to the phase gradient and the distance between the grating and the detector, like for the Hartmann and Shack-Hartmann method. Here the main difference is that the signal recorded by the detector is a sinusoid, which does not require a high number of pixels to be sampled. Therefore, only 4x4 pixels are necessary to determine a phase pixel in comparison to 16x16 pixels for a Shack-Hartmann.

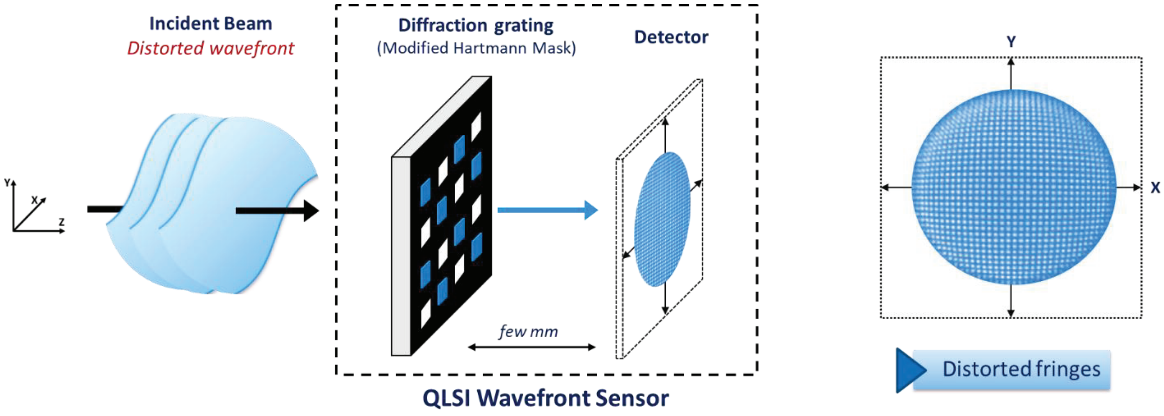


Figure 1- Principle of a QLSI wave front sensor device

The signal $I(x,y)$ acquired by the detector can be linked to the optical path difference W derivatives $\frac{\partial W}{\partial x}$ and $\frac{\partial W}{\partial y}$:

$$I(x,y) = I_0(x,y)\left(1 + cos\left(\frac{2\pi}{p}x + 2\pi\frac{z}{p}\frac{\partial W}{\partial x}\right) + cos\left(\frac{2\pi}{p}y + 2\pi\frac{z}{p}\frac{\partial W}{\partial y}\right)\right)$$

Here $I_0(x,y)$ is the intensity on the detector if they were no diffraction grating, p is the grating period, z the distance between the grating and the detector. The derivatives are processed from the interferogram thanks to a Fourier analysis in the vicinity of the 1/p frequencies (see Figure 2). They are finally numerically integrated to recover the optical path difference.

From this equation, we see that the sensitivity of the interferometer can be tuned just by changing the z distance. We also see that recorded signal is independent upon the wavelength, as long as the wave front is achromatic. All the parameters are wavelength independent, since the system does not include any refractive optics. This is not intuitive because the set-up includes a diffractive optics. However, it is known that interferometry with gratings make the fringes achromatic. If we also look close to the grating geometry, we see that the fringe deformation follows the same law as for the Hartmann test, which is intrinsically achromatic.

To work in the infrared range (MWIR and LWIR), the detector is a dual-band uncooled microbolometer. Though it is less sensitive to light than MCT detectors, its bandwidth is larger and it is possible to place the grating close the focal plane array, whereas the cooling system of the MCT detectors makes it very hard.

Though wave front sensors based upon an uncooled microbolometer and QLSI proved to work well with black body sources, the signal level on the camera is low and the phase noise is over 20 nm RMS, after averaging for 1s. In the contrary, with a laser source, the camera dynamic range is fully used and the phase noise reduces below 5 nm RMS, without any averaging.

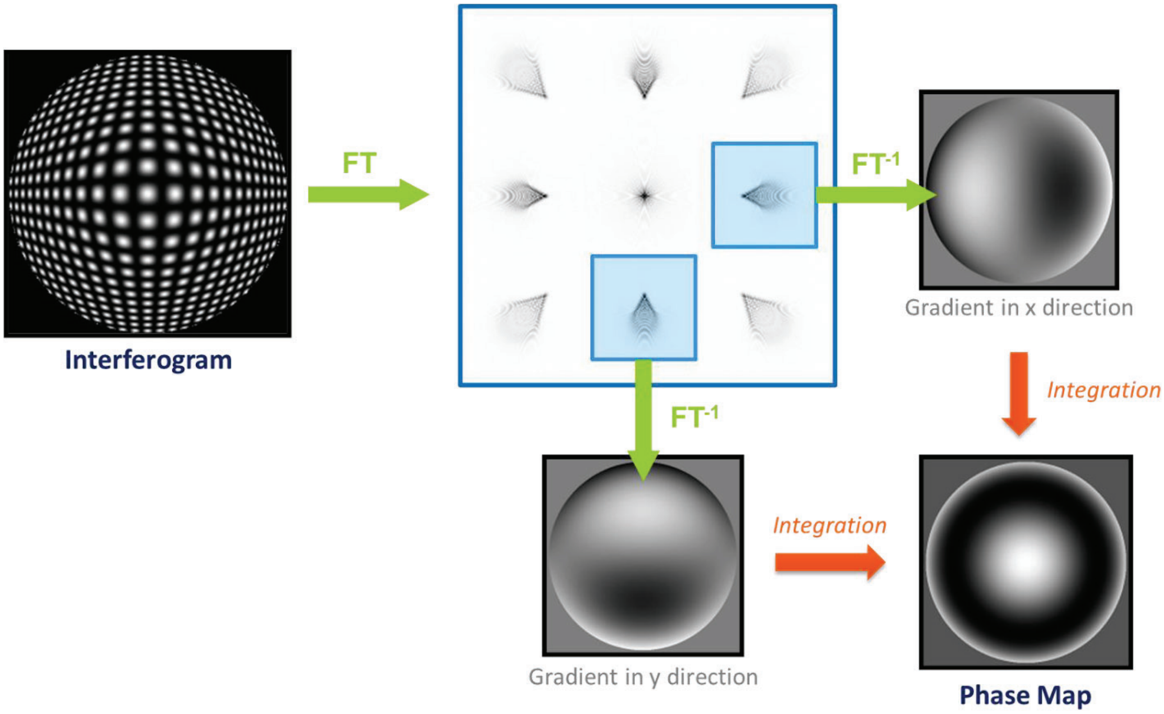


Figure 2- Principle of the interferogram process used to recover the phase map from a detector acquisition

3. DOUBLE-PASS OPTICAL METROLOGY AT THE WORKING WAVELENGTH

Metrology with wave front sensors is very versatile since optics can be qualified in double-pass (like with an interferometer) or in single-pass (unlike with an interferometer). The single-pass configuration is recommended for focusing optics where the wave front sensor is placed in the diverging part of the beam after the focal plane. In this paper, we focus on applications where the double-pass measurement is easy to implement, whereas a single pass measurement does not bring any advantage to double-pass.

In this configuration (see Figure 3), a light source is collimated, passes through a beam splitter and is sent to the unit under test (UTT). This reflects the light back to the beam splitter which redirects the beam to the wave front sensor. To make accurate and absolute measurements, it is necessary to make a preliminary acquisition with a reference optics (surface or transmission reference). The recorded wave front is subtracted to the UUT wave front.

For infrared radiations in the range around 4 µm, diffraction effects are much stronger than for visible light, since the depth of focus is inversely proportional to the square of the wavelength. Therefore, it is mandatory to image the optics pupil onto the wave front sensor detector plane to avoid artefacts due to diffraction rings at the pupil edges.

Space instruments are now designed and meant for narrow bandwidths. Their transmission range in which they can be probed is therefore limited. HeNe and CO2 laser wavelength is fixed and does not automatically match the optics working wavelength. Metrology is then complicated and sometimes almost impossible. In the best cases, the optics is tested at wavelengths outside of the optics working range and results are extrapolated. To overcome this issue, we propose using laser diode sources, which emission lines can be tuned when produced (long range) or during their use by changing their driving current or temperature, for a fine adjustment.

Quantum Cascade Lasers (QCL) are now a standard technology to address infrared radiations with laser diodes. They are commercially available and fast to integrate in optical set-ups. For wavelengths smaller than 4µm, Interband Cascade Lasers (ICL) are based on a variation of the Cascade Laser principle. For the results presented here, we used an interband cascade laser emitting at 3.8µm. QCL and ICL diodes are available in at least two configurations: DFB (Distributed FeedBack) which has narrow line emission and FP (Fabry-Pérot), which allows multiple laser lines to emit leading to a wide spectrum (> 50 nm). To reduce the laser coherence, we chose to use a FP configuration so that the coherence length is expected to be less than 300 nm. We thus expect no parasitic interference fringes would disturb the measurements.

$$l_c = \frac{\lambda^2}{\Delta\lambda}$$

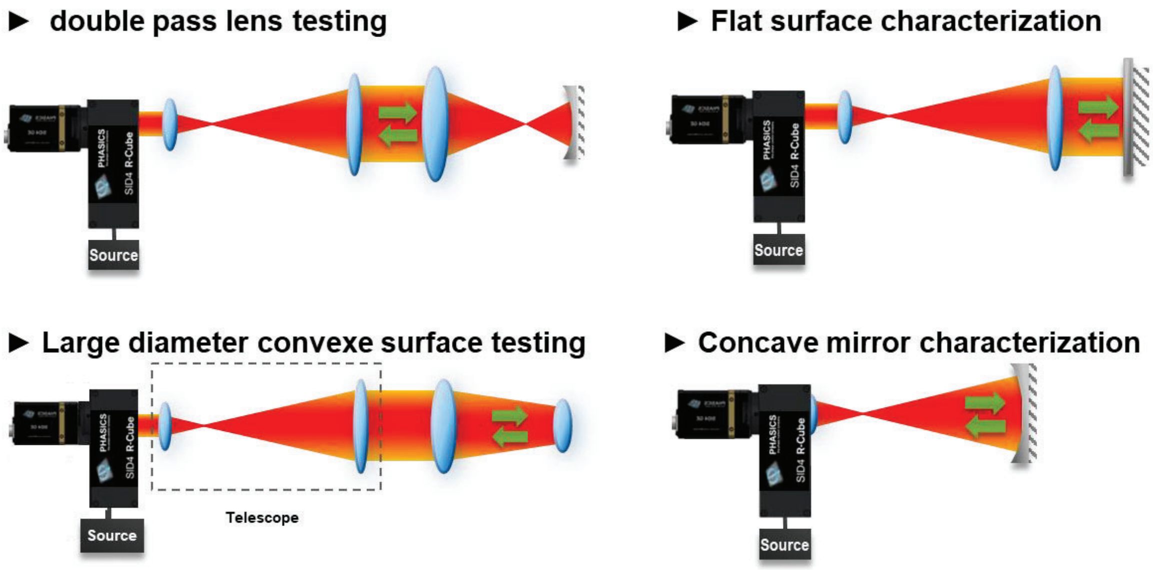


Figure 3 – Various configurations for double-pass measurement with a wave front sensor

4. LOW COHERENCE QUANTUM CASCADE LASERS FOR WAVE FRONT SENSING

The Figure 4 shows a typical FP-ICL emission spectrum. This shows a series of peaks which cover a range of around 50 nm. As reported before, we expected to see no fringe artefact in our wave front measurements. However, this was not the case (see Figure 5). We clearly see fringes which change with time and make the measurements unstable. For instance, we could not assess the beam quality with an accuracy better than 40 nm RMS, whereas the expected quality from simulations was below 10 nm RMS.
Looking closer to the ICL spectrum, we realized that it was an assembly of individual peaks, which alone make highly coherent beams and induce parasitic interferences. To overcome this unexpected limitation, we decided to modulate the ICL driving current. It is well known that the diode wavelength changes with the driving current. The modulation would enlarge the individual peaks until their coherence length is small enough to avoid any parasitic fringes.

We studied two methods to modulate the laser current. The first one does not require any additional hardware. To drive the current, we used a Thorlabs T-Cube driver, which current is changed thanks to a USB connection. We connected the driver to a computer and could modulate the current at a frequency of no more than 10 Hz. In this condition, it is mandatory to average acquisitions since the modulation frequency is smaller than the acquisition frequency (50 Hz). It is further called "internal modulation".
The second one requires the use of signal generator hardware, which is linked to the T-Cube driver with a co-axial cable. The analog signal modulates the driver current for frequencies up to 20 kHz. Since the modulation is much faster than the camera acquisition frequency, single frame processing remains possible. It is further called external modulation.

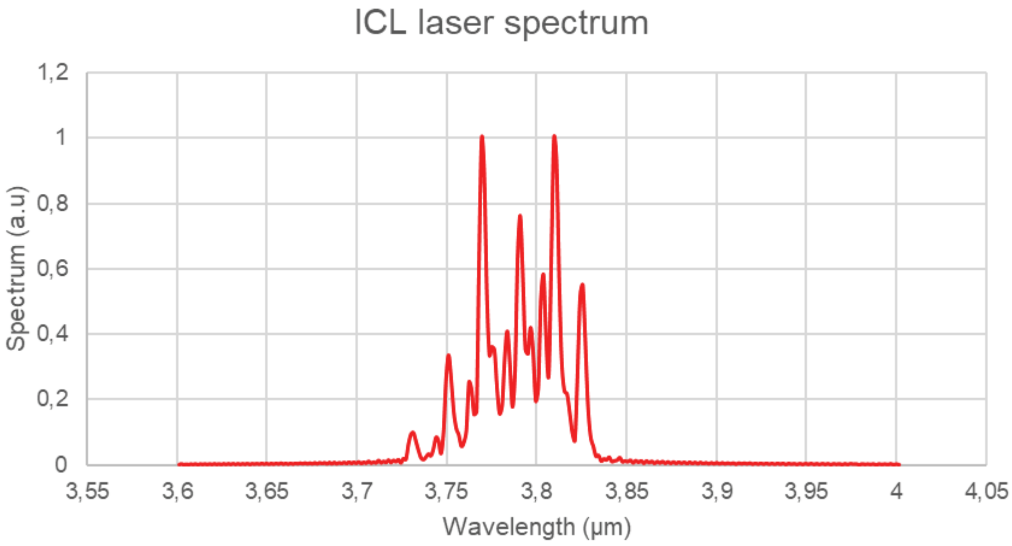


Figure 4 – Spectrum of the ICL used in our experiments. Its bandwidth is roughly 50 nm.

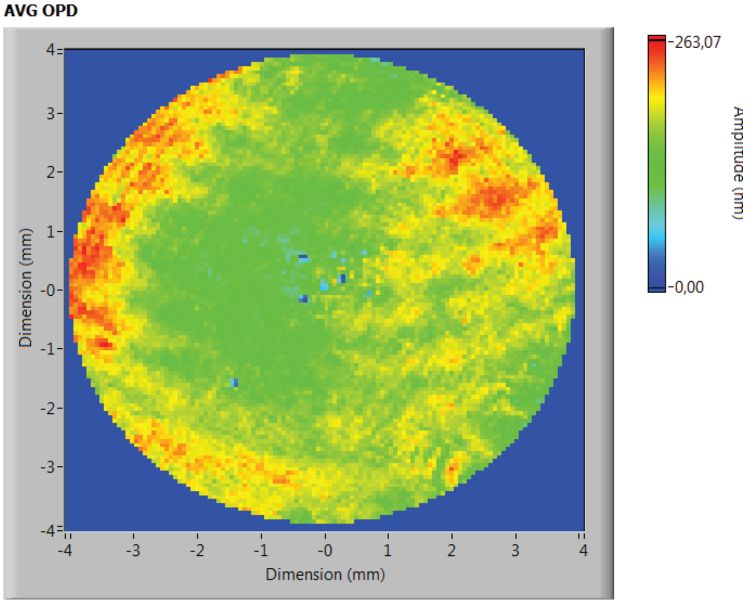


Figure 5 – Wave front measurement of a ICL laser beam, without modulation

When we apply both types of modulation (see Figure 6), we observe that the spectrum is changed. For internal modulation, the peaks are still visible and slightly enlarged. For the external modulation, the peaks are washed out. In both cases, we used the same modulation depth. More importantly the wave front measurements exhibit reduced fringes with the internal modulation (see Figure 7) and none with the external modulation.

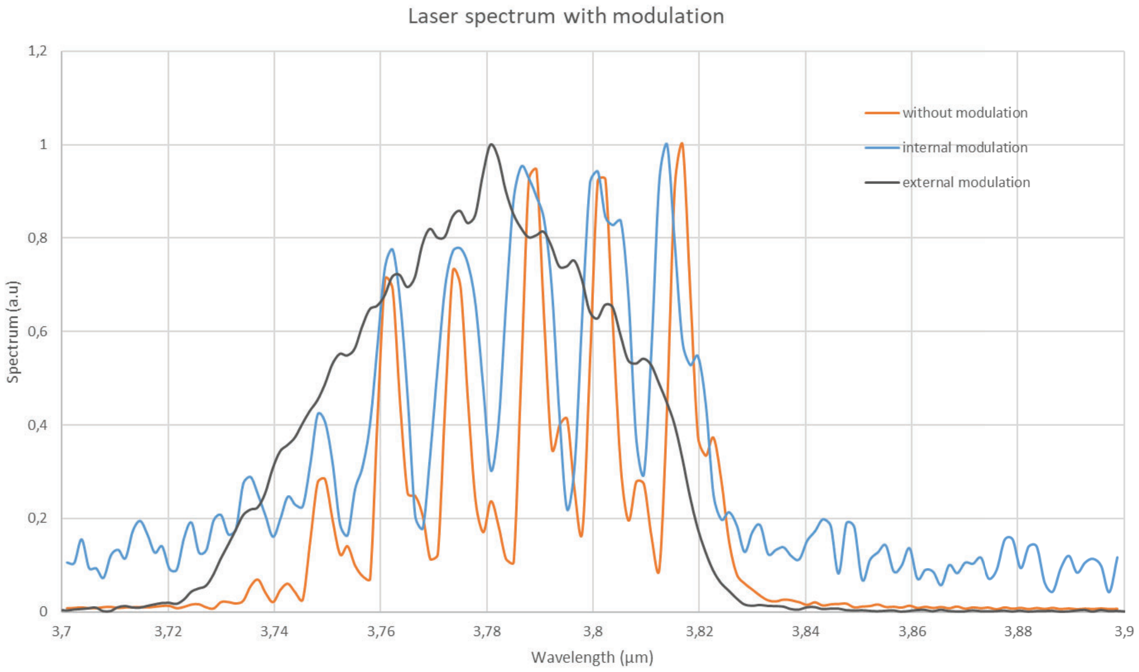
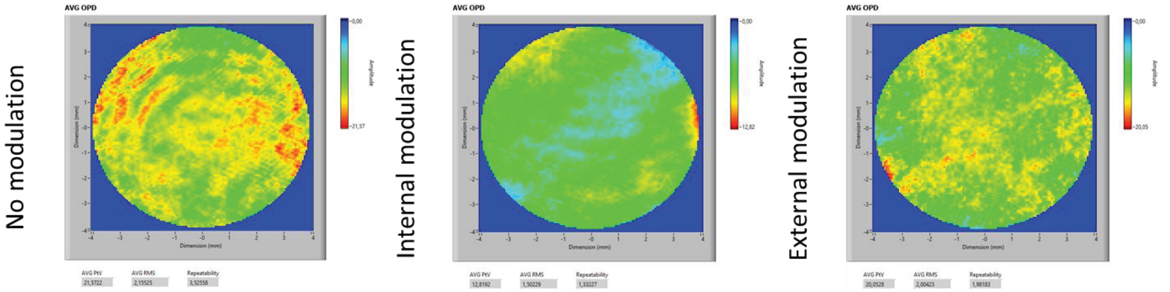


Figure 6 – Examples of spectra acquired with different modulation conditions: without modulation, with "internal modulation" and "with external modulation"



AVG PtV 21,5722 AVG RMS 2,15525 Repeatability 3,52558

AVG PtV 12,8192 AVG RMS 1,50229 Repeatability 1,33227

AVG PtV 20,0528 AVG RMS 2,00423 Repeatability 1,98183

Figure 7 – Wave front measurement of the same ICL beam with three different modulation configurations: without modulation, with "internal modulation" and "with external modulation"

5. QUALIFYING SPACE OPTICS WITH QCL AND A QLSI WAVE FRONT SENSOR

We finally had to test whether the modulated lasers were compatible with optical metrology for space applications. One constraint is that the source power should be kept constant at the 1% level. Since we modulate the laser current, we also modulate the laser power. If the modulation is fast enough, we could expect that it is not "seen" by the wave front sensor. For this purpose, we measured the power at the out of the laser for the three modulation configurations (see Figure 8). We first observe that the laser power is lower with the modulation, which is expected since we sinusoidally change the laser power. We then show that the power stability is kept below 1% for all configurations, though small spikes were visible for the internal modulation. This is certainly due to the slow modulation speed (10 Hz).

We measured the phase measurement stability (see Table 1). The internal modulation noise is obtained after averaging 20 images per acquisition, which is necessary to handle the slow modulation frequency. To compare to other noise, we should multiply its value by $\sqrt{20} = 4.5$. The internal modulation requires averaging to keep the same phase noise as without modulation. The external modulation reduces the phase noise without averaging, though the average power is 30% lower than without modulation. For all configurations, the phase noise is below 3 nm RMS, which corresponds to λ/1266.

From all these results, we decided to implement the external modulation for further experiments and bench products.

	No modulation	**External modulation**	**Internal modulation**
Phase noise (nm RMS)	2,9	2,3	1,0
	3,5	2,0	1,3
	2,1	2,1	1,2
Average	**2,9**	**2,1**	**1,2 (*)**
Std Dev	0,71	0,14	0,14

Table 1 – Phase noise for the three different modulation configurations. For the internal modulation, 20 images were averaged to make a phase measurement.

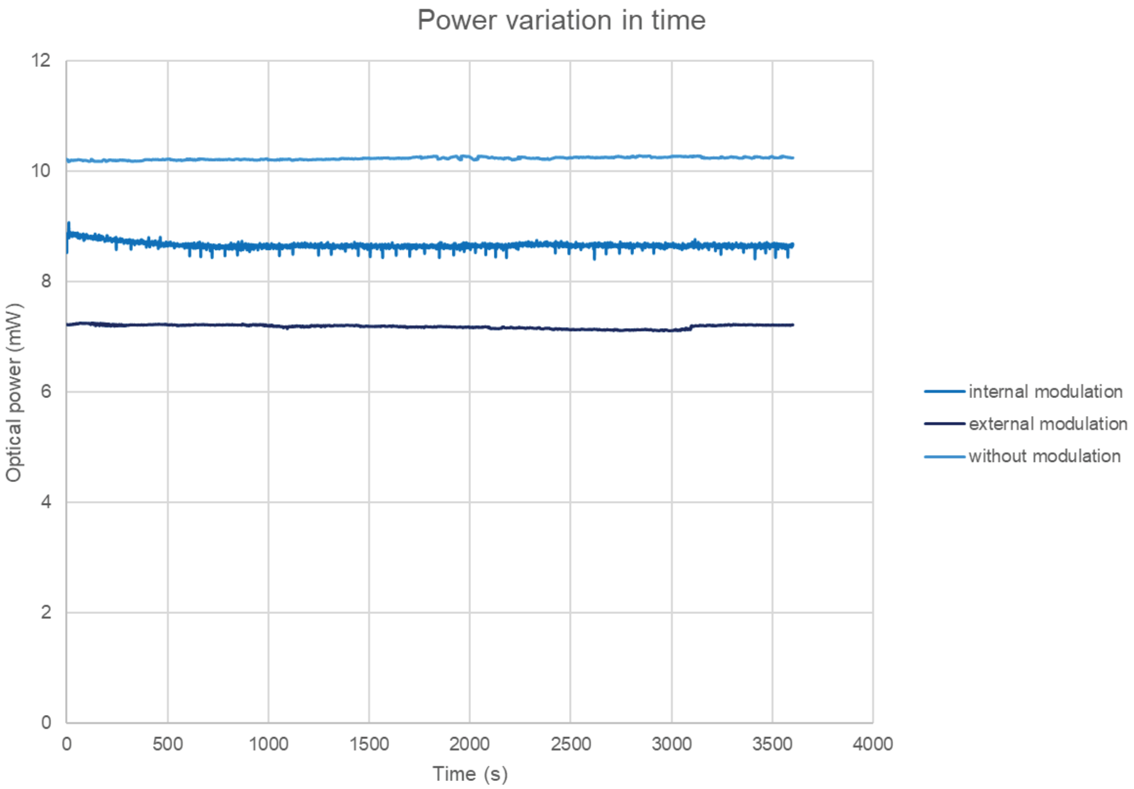


Figure 8 – Laser power stability for the three modulation configurations

6. CONCLUSION

In this paper, we showed that metrology at the working wavelength is possible with a wave front sensor. We demonstrate the implementation of an Interband Cascade Laser for double-pass optical qualification with a quadriwave lateral shearing interferometer at a wavelength of 3.8µm. To avoid any parasitic interference fringes, which limit the phase accuracy, we modulate the diode driving current with an external analog signal. While the power stability is kept constant, the phase noise is reduced and no artefact limits the measurement accuracy.
The extension of this method to LWIR (8-12 µm) QCL sources is under study.

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[1] Jérôme Primot, and Nicolas Guérineau, "Extended Hartmann Test Based on the Pseudoguiding Property of a Hartmann Mask Completed by a Phase Chessboard", Appl. Opt. 39, 5715-5720 (2000)