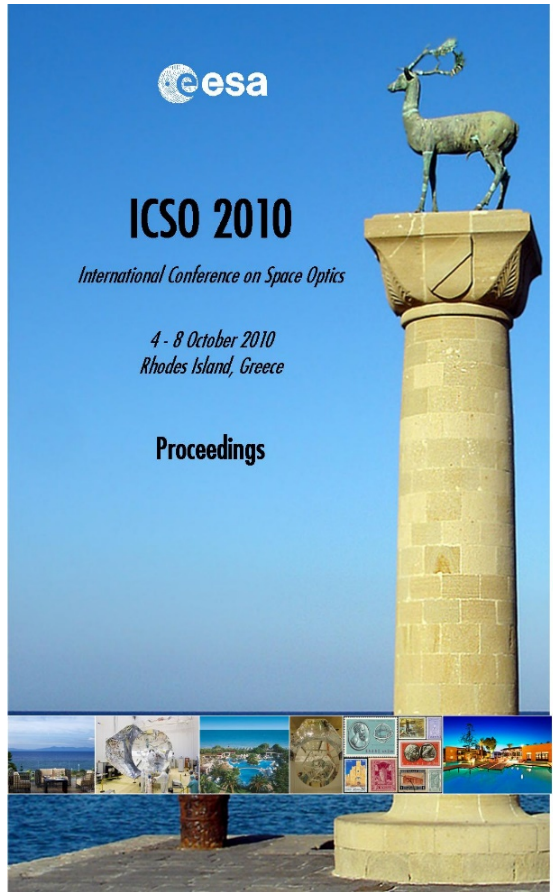
International Conference on Space Optics—ICSO 2010

Rhodes Island, Greece

4–8 October 2010

Edited by Errico Armandillo, Bruno Cugny, and Nikos Karafolas



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International Conference on Space Optics — ICSO 2010, edited by Errico Armandillo, Bruno Cugny, Nikos Karafolas, Proc. of SPIE Vol. 10565, 105655W · © 2010 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2552636

ABSOLUTE DISTANCE MEASUREMENT WITH SUB-FRINGE RESOLUTION

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ABSTRACT

A novel technique to measure absolute distances is presented. It is based on a Michelson interferometer where two tuneable lasers are superposed to create a synthetic wavelength. Relative and absolute interferometry theories are merged together. Its experimental realization allows absolute distance measurements with sub-fringe resolution. Preliminary results are presented in this work.

INTRODUCTION

Classical interferometers (mainly Michelson like) are relative interferometers and are known to be the best distance measurement instruments but suffer from the fact that are "incremental" instruments: i.e. since all optical fringes are identical, the only way to perform an "absolute" measurement is to count fringes while the target moves along the length to be measured. The issue of realizing an instrument capable of absolute distance measurement with low uncertainty has been afforded for several decades. Many technical solutions have been found, some of which have became popular commercial instruments. The two main approaches are the "time of flight" (TOF) and the "synthetic wavelength" (SW) methods, although most of the recently proposed solutions can be seen as a combination of the two [1]. TOF consists in sending a light pulse on a reflecting target and measuring time needed to the pulse to return back to the source. This method has been used since long for measuring very large distances (the most famous being the Heart to Moon distance) [2]. SW is basically a Michelson interferometer where the laser source is somehow modulated (amplitude, frequency, polarization etc.) with a given periodic signal and where the phase lag between the outgoing and the incoming modulating signal is measured. In other words, the system can be seen as a classical interferometer where the laser radiation acts as a carrier for an artificial wavelength (the synthetic wavelength) which in turn is used as the interferometer base wavelength. The difference with respect to classical interferometers is that the SW can be made as long as needed to solve the indetermination of integer number of wavelengths by analyzing the relationship between the SW phase and frequency. In practice the modulation of the carrier can be done in many different ways [3], [4], amongst which is the superimposition of two similar lasers [5], [6] and [7]. This technique consists in superimposing two lasers having same nominal wavelength where at least one of the two is tunable. In such a way, according to the interference theory, an amplitude modulated wave is obtained and the wavelength of the modulation can be changed from infinite (the two lasers having the same frequency) to a minimum limited by the maximum laser frequency detuning. With duplicated Nd:YAG lasers, it is possible to obtain tens of gigahertz detuning corresponding to few millimetres SW. Although SW interferometers allow absolute measurements, the resolution of these instruments is at present limited to at best a few micrometers: much worst of what can be obtained with relative incremental interferometry. This is mainly due to the scale difference between synthetic wavelength (tens of millimetres) and the "optical" wavelength (fractions of a micrometer). The realization of an absolute interferometer with nanometer resolution is a challenging task. A possible breakthrough could be the reduction of the absolute interferometer uncertainty down to less than an optical wavelength so that the optical fringes can be unambiguously numbered and the interferometer can be "switched" to the classical configuration eventually reaching nanometer resolution. In the present work we propose a simple interferometric set-up which allows to reach the aforementioned goal and experimentally demonstrate the feasibility of an absolute interferometer with subwavelength resolution.

PRINCIPLE OF THE EXPERIMENT

The experiment is based on the well known principle of feeding a Michelson interferometer with an amplitude modulated laser source made by superimposing two tunable lasers. If the two laser sources have equal intensity, the resulting radiation can be seen as a carrier having an optical frequency equal to the average of the two laser frequencies and modulated with a cosine function having frequency equal to the difference between the two laser frequencies.
Let us consider a simple Michelson interferometer with a 50:50 beamsplitter, two arms having length x_m and x_r and a single detector. The two laser sources have respectively amplitude E_1 and E_2 and wavenumber k_1 and k_2.

After the interferometer, we have four distinct fields: $E_{1m}\cos(2k_1x_m)$, $E_{1r}\cos(2k_1x_r)$, $E_{2m}\cos(2k_2x_m)$ and $E_{2r}\cos(2k_2x_r)$ that interfere to give a signal on the receiver limited in bandwidth:

$$I = \left(E_{1m}\cos\left(2k_1x_m\right) + E_{1r}\cos\left(2k_1x_r\right)\right)^2 + \left(E_{2m}\cos\left(2k_2x_m\right) + E_{2r}\cos\left(2k_2x_r\right)\right)^2 \tag{1}$$

In the particular case the amplitudes are equal, the interferogram signal simplifies to:

$$I = E^2\left[1-\cos\left(2\left(k_1+k_2\right)\left(x_m-x_r\right)\right)\cos\left(2\left(k_1-k_2\right)\left(x_m-x_r\right)\right)\right] \tag{2}$$

The resulting interferogram can be modelled as the product of the optical fringes (having frequency equal to the average of the two laser frequencies) and the synthetic fringe (having frequency equal to the difference between the two laser frequencies). The optical fringe is modulated by the synthetic wave and, every half a period, the latter reaches a zero amplitude point; at any of those points, the envelope of the optical fringes gets across the line of the average value of (2).

We can see the behaviour of the interferogram, by a numerical simulation, in Fig. 1:

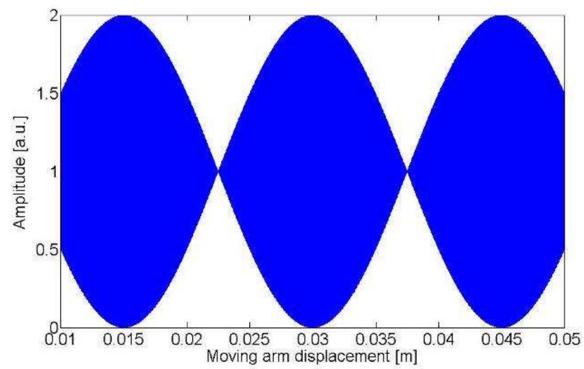

Fig. 1. Two laser beams theoretical interferogram

Fig.2 shows a detail of the interferogram close to the minimum amplitude region. On the left is the situation described in (2) with matched laser intensities. When the power of the two lasers is not balanced, we are in the case of a classical dual laser interferometer where the inversion point is not so clearly defined: in the right side we can see the simulated effect of a 0.1% power imbalance.

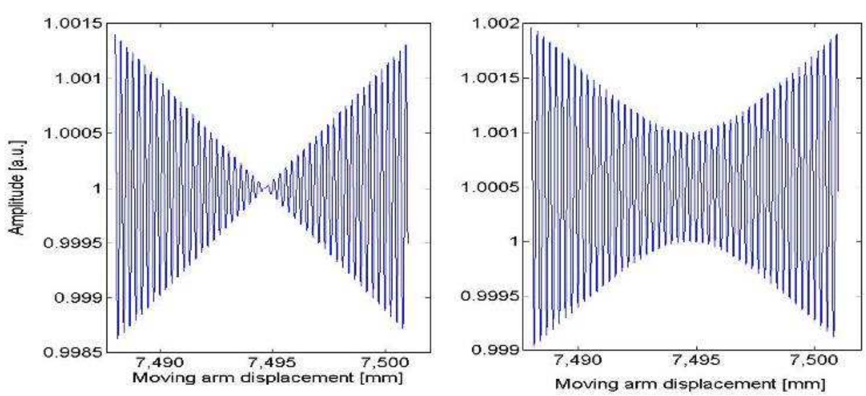

Fig. 2. Detail of a two laser beams interferogram around a zero amplitude point. In the left, the power of the two laser power is equal in the two arms, in the right, the power of the two laser differs by a 0.1%

When the power of the two lasers is well matched, it is easy to locate the inversion point with an uncertainty less than an optical fringe, so is possible to number the optical fringes contained in a synthetic fringe thus assigning an “absolute” value to the optical interferometer. This is the key point of the presented experiment.

EXPERIMENTAL SETUP

Let's refer to the experimental setup depicted in Fig. 3.

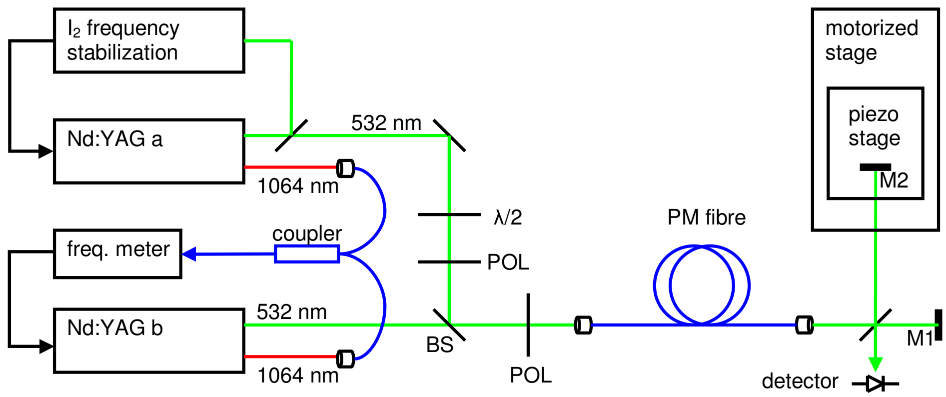

Fig. 3. Simplified experimental setup of the interferometer

Two single-mode doubled Nd:YAG lasers emit green light at around $\lambda = 532.4$ nm. Laser "a" is frequency locked to the a_{10}, R(56) 32-0, $^{127}I_2$ transition line, at $\nu_I = 563\ 260\ 223\ 513$ kHz [8]. Laser "b" frequency can be tuned. The frequency difference is measured by beating the infrared output of the two lasers. Laser "b" is frequency controlled to keep the frequency difference constant. The beam power of laser "a" is trimmed by means of a half wave plate together with a polarizer. The two lasers are superposed with a beam splitter and coupled to a polarization maintaining fiber. A polarizer serves to avoid unwanted polarization to be coupled to the fiber. The output coupler of the fiber feeds the Michelson interferometer. M1 is a fixed plane mirror, M2 is the moving plane mirror which is placed on a piezocapacitive translation stage with a range of 25 µm, in turn, fixed on a motorized translation stage having 100 mm range. The interference signal is detected with a photodiode and sent to the acquisition system (a 16 bit 1 MHz sampling board).

PRELIMINARY EXPERIMENTAL RESULTS

The preliminary results shown here have been obtained with the following procedure. The motorized stage is moved in order to find a minimum amplitude point in the interferogram. The mirror is then moved back and forth by means of the piezo stage in order to see on the oscilloscope the shape of the minimum amplitude region as in figure 2. Here the power of the laser "a" is manually trimmed to obtain a good intensity balance by rotating the half wave plate. The fine power balancing is obtained by acting on the temperature control of the doubling crystal of laser "b". Once the condition of laser power matching is reached, the piezo scan is stopped and the translation stage is moved while the interferogram is recorded. The frequency difference is recorded as well. The frequency difference ranges from 40 to 60 GHz corresponding to a distance between the minima of about 15 mm. Fig. 4 shows the two interferograms obtained while scanning the moving mirror at about 2 mm/s for two frequency differences.

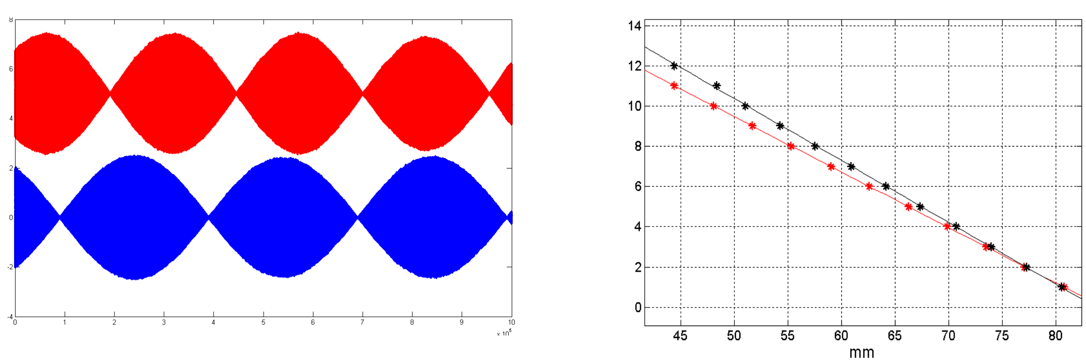

Fig. 4. Left: the two interferograms obtained while scanning the moving mirror at about 2 mm/s for two laser frequency differences. Right: position of the minima for two frequency differences. The zero optical path difference condition can be found around mm 78.

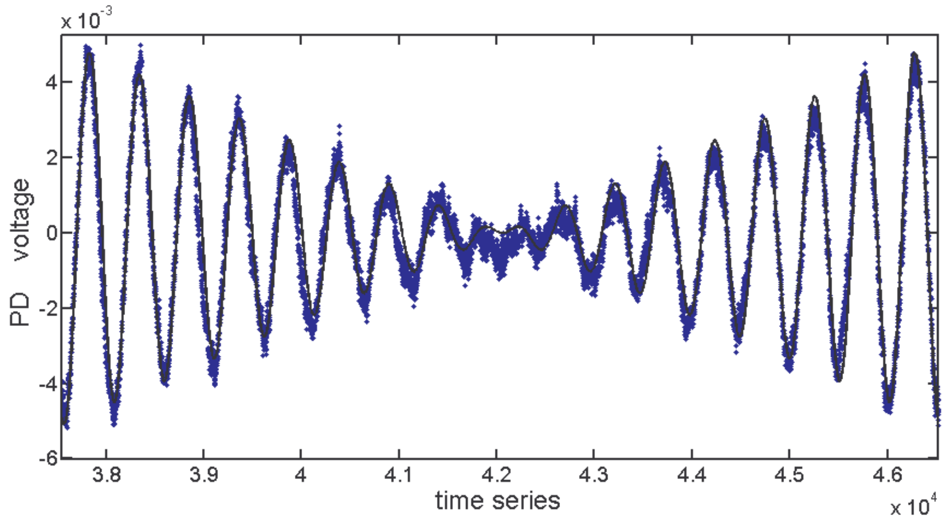

Fig. 5. Typical interferogram at the minimum amplitude region together with the fitting function (2)

Figure 5 shows a typical interferogram at the minimum amplitude region together with the fitting function (2). It is evident that the "inversion point" foreseen in (2) can be found and located with an uncertainty much less than one optical fringe. At present the experiment is made particularly difficult because of the non uniformity of the motorized translation stage which induces strong vibrations along motion axis. Indeed, in order to correctly fit the interferogram with function (2) it is necessary to have a constant speed scan. Improvements in the translation stage will be next step. Then a comparison with a reference laser interferometer will allow to complete the validation of the method.

CONCLUSIONS

We have proposed a simple dual laser interferometer capable of absolute distance measurements with sub wavelength resolution. Although we have not performed absolute distance measurements yet, we have demonstrated the feasibility of the most critical point of the experiment: i.e. that it is possible to find the position of the synthetic wavelength (namely the minima) with an uncertainty better than an optical fringe. This possibility combined with an accurate knowledge of the absolute frequency of the two lasers will allow the accurate knowledge of the absolute optical path difference between the two mirrors.

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