Subnanometer absolute measurements by means of mixed synthetic-optical homodyne interferometer

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Abstract

A possible technique to measure absolute distances is presented. It is based on a Michelson interferometer where two tuneable lasers are superposed to create a very short synthetic wavelength. By exploiting relative and absolute interferometry theories merged together in a demonstrator experiment we have shown the possibility of absolute distance measurements with sub-fringe resolution.

1 Introduction

The classic use of a single wavelength interferometer is the measure of distance shifts between its two arms, because there is no a-priori knowledge of the integer number of optical wavelengths within the distance of the two arms. Hewlett-Packard built a single-wavelength interferometer [1] that can reach an accuracy down to one tenth of a micron and resolutions of the order of the nanometre.

Many papers can be found in scientific literature where new techniques and experimental setups for absolute distance measurements are presented. In [2 and 3], the International Laser Ranging Service is introduced and the time of flight method to measure the position of Earth satellites and the Moon is presented; accuracies and resolutions are usually limited to millimetres over ranges as long as thousands of kilometres. With the amplitude modulation technique ([4, 5 and 6]), the transmitted power is modulated and the phase of the carrier is measured at the receiver with respect to the phase at the source; the performance of this method allows an accuracy better than one part in 10^7 and a resolution around fractions of microns. This last method is affected by the unambiguity range, as the synthetic wave you are measuring the phase of can't be exactly determined. This experimental issue can be solved by double-wavelength interferometry; in double-wavelength interferometry, the phase measurement has a greatly reduced sensitivity to changes in path length and the unambiguity range is reduced to a single synthetic wavelength [7, 8 and 9]. A special type of double-wavelength interferometry is called frequency-sweeping: two phases are measured before and after a frequency sweep of a single laser and they are also unwrapped during the shift so that there is no more ambiguity on the synthetic wave [10 and 11].

Here we are presenting a new kind of double-wavelength interferometry where two lasers with different frequencies interfere in a Michelson interferometer. The unambiguity range can be reduced by unwrapping the phase and resolutions of less than an optical fringe can be obtained for an absolute distance measurement.

2 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 similar intensity, the resulting laser source 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 and a single detector. The two laser sources have respectively amplitude E_1 and E_2 and wavenumber k_1 and k_2. At the receiver, after the interferometer, we have four distinct fields: $E_{1m}\cos(k_1 x_m)$, $E_{1r}\cos(k_1 x_r)$, $E_{2m}\cos(k_2 x_m)$ and $E_{2r}\cos(k_2 x_r)$. The receiver has a finite band and cannot resolve the optical frequency, therefore the interferogram is

$$I = \left(E_{1m}\cos(k_1 x_m) + E_{1r}\cos(k_1 x_r)\right)^2 + \left(E_{2m}\cos(k_2 x_m) + E_{2r}\cos(k_2 x_r)\right)^2 \tag{1}$$

In the particular case E_1 and E_2 are equal, the interferogram becomes:

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

The resulting interferogram is 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 half 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 figure 1:

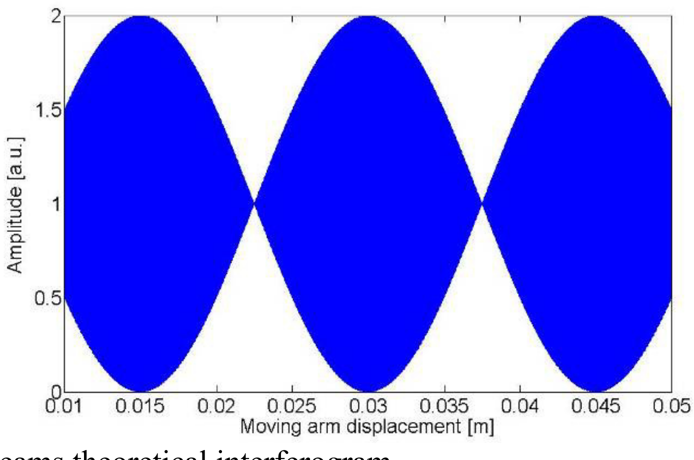

Figure 1: Two laser beams theoretical interferogram

Figure 2 shows a detail of the interferogram close to the minimum amplitude point. 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: the ambiguity of the inversion point is evident.

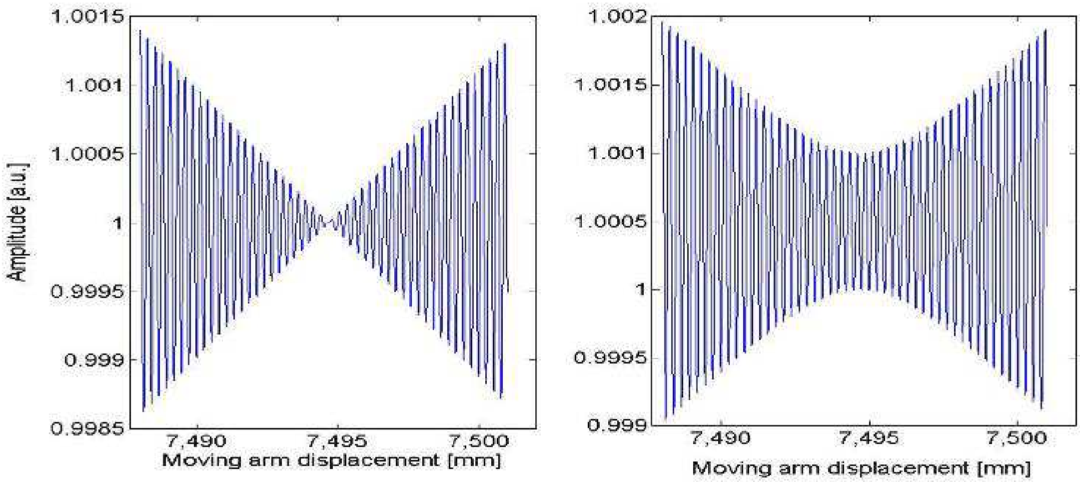

Figure 2: Simulation of a two laser beams interferogram around the zero amplitude point. in the left, the power of the two laser power is equal in the two arms, in the right, the power of the two laser differs by a 0.1%

It is easy to understand that if the power of the two laser 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.

3 Experiment and results

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

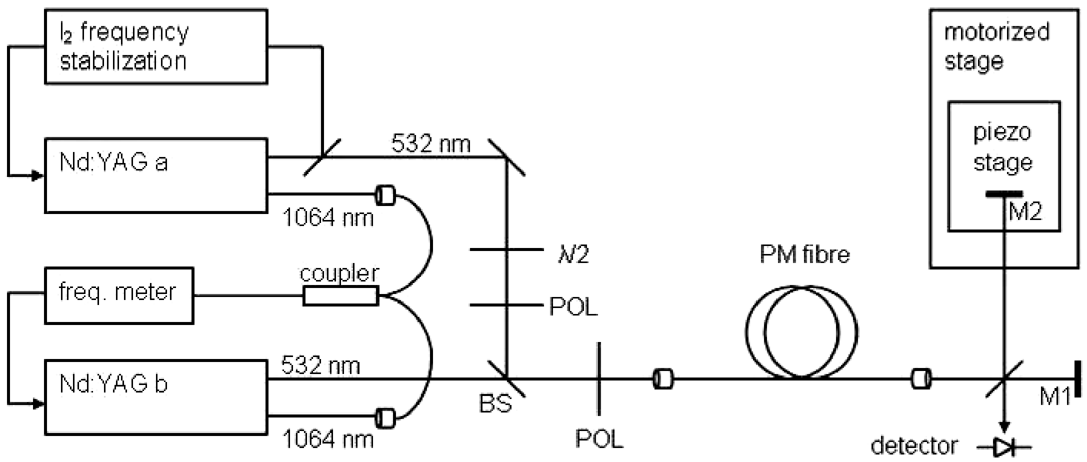

Figure 3: Simplified experimental setup of the interferometer

Two single-mode doubled Nd:YAG lasers emit green light at around λ = 532.4 nm. Laser "a" is frequency locked to the a10, R(56) 32-0, 127I2 transition line, that is λ = 563 260 223 513 kHz [12]. Laser "b" can be tuned. The frequency difference is measured by beating the infrared output of the two laser. 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).

The preliminary results shown here have been obtained with the following procedure. The motorized stage is moved in order to find a minimum in the interferogram. The mirror is than moved back and forth by means of the piezo stage in order to see on the oscilloscope the shape of the minimum. Here the power of the laser “a” is manually trimmed to obtain a good power balance by rotating the half wave plate. The fine power balancing is obtained acting on the temperature control of the doubling crystal of laser “b”. Once found the wanted condition 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 used for the experiment ranges from 40 to 60 GHz. Fig. 4 shows the interferograms obtained while scanning the moving mirror at about 2 mm/s for two frequency differences.

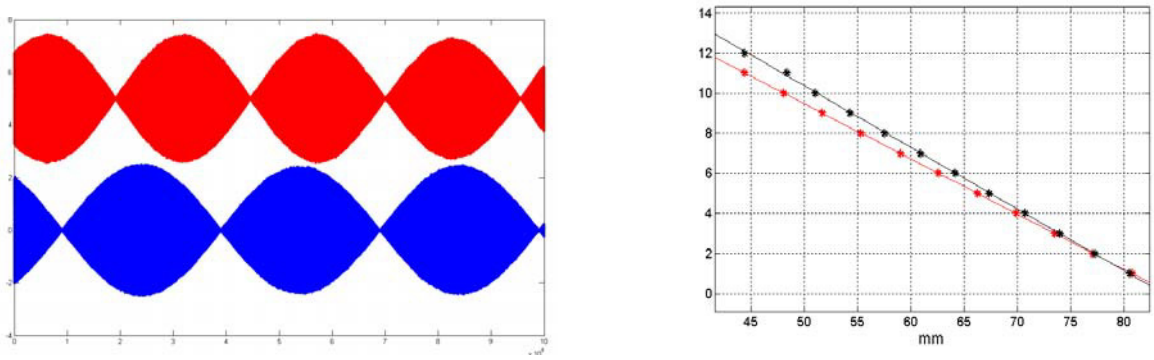

Figure 4: Left: the interferograms obtained while scanning the moving mirror at about 2 mm/s for two frequency differences. Right: position of the minima for two frequency differences. The zero optical path difference condition can be found around mm 78.

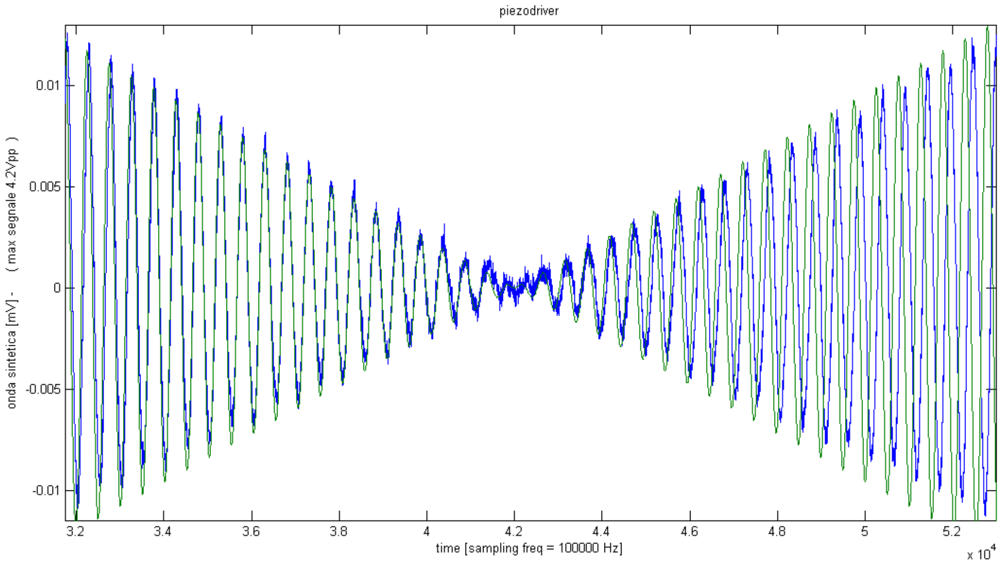

Figure 5: Typical interferogram at the minimum together with the fitting function (2)

Figure 5 shows a typical interferogram at the minimum 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. Furthermore the "balanced power" condition is very difficult to maintain to the required $1/10^5$ level. Improvements in the translation stage and a dynamic amplitude control will be next steps. Than a comparison with a reference laser interferometer will allow to complete the validation of the method.

4 Conclusion

We have proposed a simple dual laser interferometer capable of absolute measurements with sub wavelength resolution. Although we have not performed absolute 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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