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Philippe Delaye, Gérald Roosen

Eur. Phys. J. Appl. Phys. **40**, 119–123 (2007)
DOI: 10.1051/epjap:2007118

THE EUROPEAN PHYSICAL JOURNAL APPLIED PHYSICS

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P. Delaye[a] and G. Roosen

Laboratoire Charles Fabry de l'Institut d'Optique, CNRS, Université Paris-Sud, Campus Polytechnique, RD128, 91127 Palaiseau Cedex, France

Received: 9 May 2005 / Received in final form: 15 May 2007 / Accepted: 14 June 2007
Published online: 12 July 2007 – © EDP Sciences

Abstract. We present the operating principle and a first experimental characterization of a holographic rangefinder, that couples a two wave mixing phase demodulation set-up with a frequency modulated laser source. In its first implementation, the system allows millimetre sensitivity on tens of meters measurement range with the ability to work with scattering surfaces.

PACS. 42.40.Kw Holographic interferometry; other holographic techniques – 42.65.Hw Phase conjugation; photorefractive and Kerr effects – 42.70.Nq Other nonlinear optical materials; photorefractive and semiconductor materials

1 Introduction

Optical measurement of distance is an important industrial stake with applications as various as the measurement of the distance of target (range finding) or the mapping of complex objects (3D vision). Optical range finding techniques belong to three main families: triangulation, time of flight pulsed techniques and interferometry [1]. Triangulation, based on the analysis of a structured illumination pattern (such as a line) projected on the object, is particularly adapted to the measurement of decimetric to decametric distance and is insensitive to the surface state of the target. In the time of flight technique one determines the propagation time of a laser pulse from the reception unit towards the target, from which the distance is deduced. Taking into account the speed of light, this technique is efficient with long distance in the kilometre range and operates with scattering target. The interferometric techniques, such as the frequency modulated continuous wave laser radar, couple an interferometer with a frequency modulated laser source that gives to the interferometric system the ability to access to the exact value of the interference order and thus gives an evaluation of the absolute value of the distance. The control of the characteristics of the laser source allows to have a measurement range that can be in the millimetre as well as in the kilometre range. Nevertheless these techniques have the major drawback to be very sensitive to the alignment and to the surface state of the target. This limitation of the aperture of the collection optic is given by the antenna theorem [2] that fixes the optimum collecting power to a speckle grain, what greatly reduces the performances of this kind of interferometric set-up. Such a constraint had already been encountered in optical vibrations measurement systems (ultrasonic or acoustic vibrations) for which an holographic solution was proposed [3–11]. We will now show how those holographic set-ups can be adapted to range finding for the measurement of absolute distance of scattering targets.

* This paper has been presented at "3[e] colloque interdisciplinaire en instrumentation (C2I 2004)", École Normale Supérieure de Cachan, 29–30 janvier 2004.

[a] e-mail: Philippe.delaye@institutoptique.fr

2 Presentation of the holographic range finder

2.1 Principle of the phase demodulation using dynamic holography

The holographic rangefinder uses the now well-known phenomenon of two wave mixing in a dynamic holographic material. This architecture has already been successfully used to realize a photorefractive laser ultrasonic sensor [3,7,9,11]. In this device, a laser beam illuminates the measurement point on a target. The scattered light forms the signal beam that is sent on the dynamic holographic media with a pump beam issued from the same laser (Fig. 1). These two waves interfere and write in the holographic media an hologram of the signal beam wavefront. Both writing beams read this hologram and in the direction of the transmitted signal wave the diffracted pump beam generates a local oscillator that has exactly the same structure than the signal beam. Both beams are then sent on a detector where they realize an homodyne transformation of the phase modulation, carried by the signal beam, into an intensity modulation whatever the

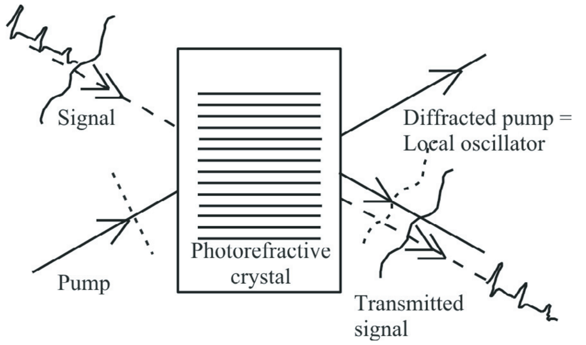

Fig. 1. Principle of the phase demodulation holographic set-up.

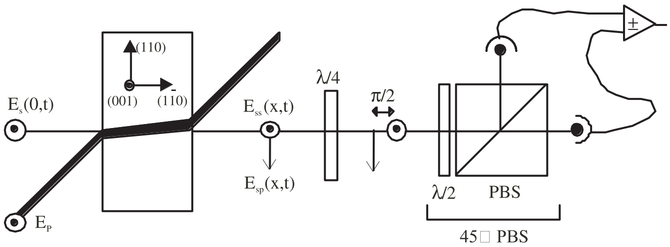

Fig. 2. The "anisotropic diffraction" configuration. The p-polarized diffracted beam E_{sp} is phase shifted, compared to the transmitted signal beam E_{ss}, by the quarter wave plate. Both beams interfere after the 45° polarisation beam splitter (PBS).

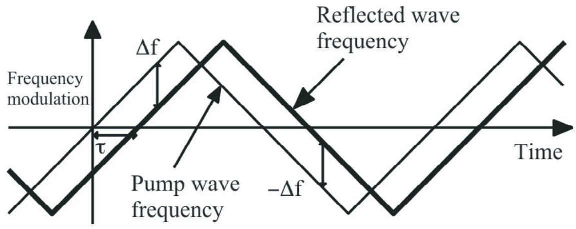

Fig. 3. Principle of the frequency modulated laser radar rangefinder.

wavefront structure of the signal beam, giving a large field of view homodyne detection.

When a transient phase modulation appears between the two interfering beams due, for example, to a vibration of the target, two cases occur depending on its evolution time compared to the response time of the transient media. If the vibration is rapid the holographic media cannot react and the hologram is static what leads to the creation of a static local oscillator. The detected signal is then proportional to the phase modulation and thus to the displacement of the target. This behavior is used for the laser ultrasonic holographic sensor [10,11]. On the other hand, if the phase modulation varies slowly, the hologram can follow the displacement of the fringe pattern. Then the local oscillator originating from the diffraction on this running hologram carries a phase modulation dependent on the displacement of the hologram and thus carries a part of the information on the initial phase modulation. One can then show [12] that the detected signal is proportional to the derivative of the phase modulation of the signal beam. This principle is used in the realization of a holographic velocimeter for acoustic vibration measurement [12] and will be used for the holographic rangefinder.

To implement the two wave mixing experiment we simply use a fast holographic media such as a semiconductor crystal of GaAs. With such a crystal and a high power CW laser, it is easy to reach response time as short as some tens of microseconds. This short response time is reached with a crystal used in the diffusion regime, i.e. without an applied field, and with a relatively large grating spacing. To use the resulting $\pi/2$ phase shifted grating, we have to be in the anisotropic diffraction configuration [11] that, coupled to polarization elements, allows to realize quadrature between the signal beam and the local oscillator giving a linear detection of the phase modulation (Fig. 2). In that configuration the signal detected on the differential detector, when the phase modulation evolution time is slower that the crystal response time, equals [12]:

$$S(t) = 2\gamma x \tau_0 I_{S0} \frac{\partial \varphi}{\partial t} \tag{1}$$

where γ is the photorefractive gain in amplitude of the crystal (supposed here real as the grating is $\pi/2$ phase shifted), τ_0 is the response time of the crystal and x is the crystal thickness (the absorption of the crystal is neglected in the present study). I_{S0} is the signal beam intensity incident on the photorefractive crystal, and $\varphi(t)$ is the phase modulation that it carries.

More generally, if both incident signal and pump beams are phase modulated ($\varphi_S(t)$ and $\varphi_P(t)$ respectively), the detected electrical signal is proportional to the derivative of the phase modulation difference, $S(t)\alpha\partial(\varphi_S(t)-\varphi_P(t))/\partial t$. The instantaneous frequency of each incident wave being given by the relation: $2\pi\nu_{S,P} = \partial\phi_{S,P}/\partial t$, that means that the detected signal at the output of the two wave mixing set-up is then:

$$S\left(t\right) = 4\pi\, \gamma x \tau_0\, I_{S0}\, \left(\nu_S\left(t\right) - \nu_P\left(t\right)\right). \tag{2}$$

It is this operating regime that is used in the holographic rangefinder, where the two wave mixing holographic set-up will be used with a frequency modulated laser source such as the one used in frequency modulated continuous wave laser radar [1].

2.2 Principle of the interferometric measurement of distance using a frequency modulated laser source

The use of interferometry for measurement of shape or displacement of objects is now well-known. Unfortunately usual systems are not able to measure the absolute value of the distance of the target because of the periodicity of the interference pattern regarding the phase difference between the two arms of the interferometer. A variation of the path difference of $\lambda/2$ gives back the same interference pattern. To suppress this indetermination of the interference order of the analyzed fringe pattern, the known solution [1] is to couple the interferometer with a sawtooth frequency modulated laser source (Fig. 3). With such a source the two waves interfering on the detector at a given instant do not have the same frequency anymore and their frequency difference is directly proportional to the time of flight difference between the two arms of the interferometer, what allows to retrieve the information on the absolute distance of the target. The distance is then simply given by the measurement of the beating frequency of the signal delivered by the detector. This technique is very precise with a large measurement range, that can be controlled by a simple change of the amplitude of the modulation frequency of the source [1].

2.3 The holographic rangefinder

In the case of the holographic rangefinder, we will couple two wave mixing in a fast photorefractive material with a frequency modulated laser source. If the frequency modulation of the laser source has a sawtooth shape (Fig. 3), the frequency difference ($\nu_S - \nu_P$) between the two interfering beams is constant, proportional to the delay between the paths and changes its sign between the positive and negative slope part of the frequency modulation. Then according to equation (2) the detected signal is a bipolar square modulated signal with the same period than the frequency modulation of the laser, with an amplitude given by the frequency difference between the two interfering beams and then proportional to the delay between the two beams and to the distance of the target.

For a frequency modulation having a sinusoidal shape, the incident beams on the holographic media have instantaneous frequencies that writes as:

$$\begin{cases} \nu_P\,(t) = \nu_0 + \nu_{\,\mathrm{mod}}\;(t) = \nu_0 + \nu_M\;\sin\left(2\pi\, f\, t\right) \\ \nu_S\,(t) = \nu_0 + \nu_{\,\mathrm{mod}}\;(t+\tau) = \nu_0 + \nu_M\;\sin\left(2\pi\, f\;(t+\tau)\right) \end{cases} \tag{3}$$

where ν_0 is the laser central frequency and ν_M the amplitude of the frequency modulation, supposed here to be sinusoidal with a frequency f. The delay τ corresponds to the time of flight difference between the two arms of the interferometer ($\tau = d/c$, with d the path length difference between the two arms and c the speed of light).

Inserting these expression in equation (2), one finally obtains:

$$S\,(t) = \left(8\pi^{\,2}\nu_M f\right)\,\left(\gamma x \tau_0\right)\,\left(I_{S0}\tau\right)\cos\left(2\pi\, f\, t\right). \tag{4}$$

This expression shows that the detected signal is cosinusoidal (i.e. in quadrature with excitation) at the modulation frequency f, and that its amplitude is directly proportional to the delay τ. The measurement of the amplitude of this detected signal allows then to access simply to the absolute distance of the target. Besides as the set-up is based on holography the wavefront structure of the beam reflected by the target is of no importance and the device can operate with scattering targets.

In order to obtain these expressions, several approximations were made. First, we considered that the period of the modulation of the laser frequency was large (i.e. $T = 1/f \gg \tau_0$) and that the condition $\pi f \tau \ll 1$ was fulfilled. Moreover, previous relations are obtained when the condition $(\tau_0 \partial\phi/\partial t)^2 \ll 1$ is fulfilled [12], what imposes a condition on the maximum measurable distance (i.e. the measurement range that assures a linear response of the device) given by the relation:

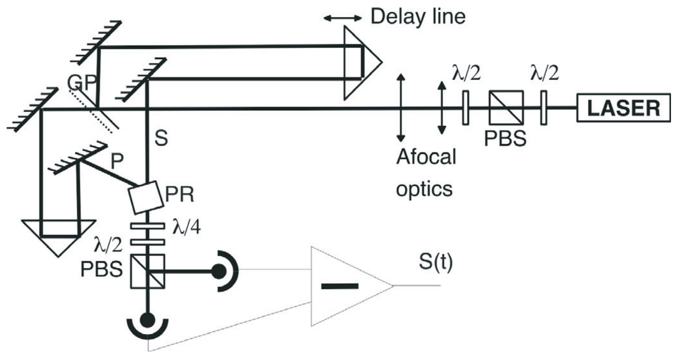

Fig. 4. Experimental set-up of the holographic rangefinder. PBS: polarisation beam splitter, PR: photorefractive crystal, GP: glass plate.

$$\tau < \tau_M = \frac{1}{12\,\pi^2\,\tau_0\,\nu_M\,f}. \tag{5}$$

The maximum measurable distance depends on the amplitude ν_M of the frequency modulation, it can thus be controlled by the used laser source characteristics. Thus if we use a Nd:YAG laser modulated at $f = 1$ kHz with an amplitude of the frequency modulation $\nu_M = 30$ MHz, with an holographic media having a response time of 10 μs (as can be obtained with photorefractive semiconductor materials), we obtain $\tau_M = 30$ ns, what corresponds to a maximum measurable distance of about 10 m. Increasing the amplitude of the frequency modulation until 30 GHz, using for example laser diode which emission wavelength is modulated through a modulation of the diode temperature, the maximum measurable distance becomes of the order of 10 mm, with an identical dynamic range.

3 Experimental characterisation of the holographic rangefinder

For the implementation of the experimental set-up of the holographic rangefinder, we use a high power (2.5 W) CW single longitudinal mode Nd:YAG laser operating at 1.06 μm. This laser can be frequency modulated with an amplitude of modulation of 1.5 MHz/V at a frequency that can reach 100 kHz. We typically use a modulation frequency of 1 kHz and an amplitude of the frequency modulation $\nu_M = 15$ MHz. A glass plate placed on the beam generates the signal beam that is sent on a 60 cm long delay line, as well as a 3 mm diameter pump beam with a power density of 6.4 W cm^{-2} (Fig. 4). Both beams are then combined in the holographic media (a 1 cm long GaAs photorefractive crystal used in the diffusion regime) with an half angle between the beams of 12° what gives a

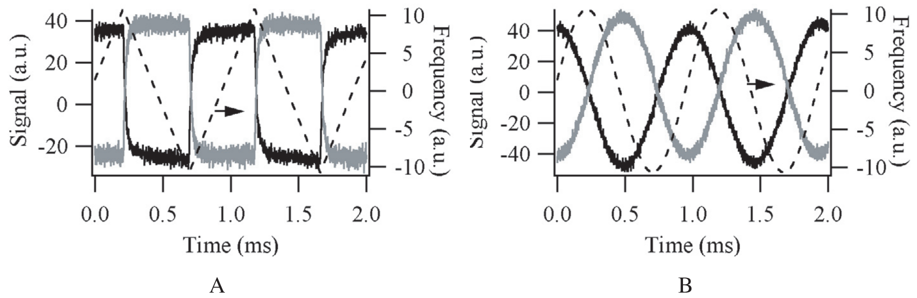

Fig. 5. Response of the differential detector to a triangular (A) and sinusoidal (B) frequency modulation of the laser source. For two positive (grey curve) and negative(black curve) position of the target regarding the zero delay position.

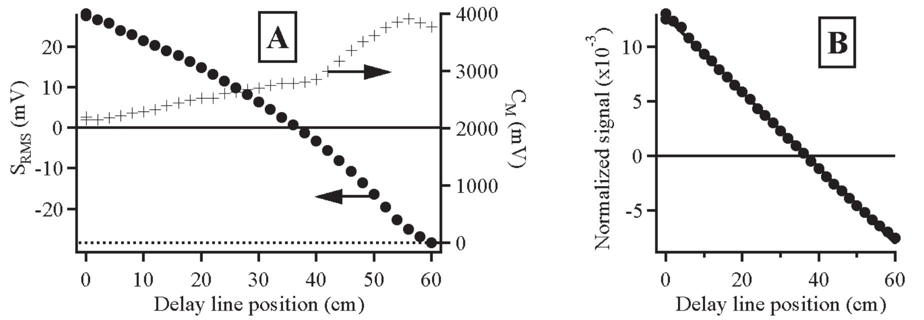

Fig. 6. Variation of the detected signal with the position of the delay line. (A) Rough signals, (B) normalized signal (S_{RMS} $/C_M$).

grating spacing of 2.5 μm. In these conditions the typical response time is 20 μs with a photorefractive gain that equals $\gamma = 0.1$ cm^{-1}. The photorefractive crystal is used in an "anisotropic diffraction" configuration with several polarizing components ($\lambda/2$ and $\lambda/4$ waveplates, polarisation beam splitter, differential detector) allowing to assure quadrature of the signal and local oscillator and optimal operation of the set-up [4]. The set-up operates with plane waves what allows to use a long delay line.

We first measure the temporal behaviour of the detected signal as a function of the modulation format and position of the target. For a triangular variation of the laser frequency, we observe the expected square shape signal (Fig. 5A) which changes its sign with the sign of the relative path difference between the two paths. The same expected signal is observed for a sinusoidal variation, with a $\pi/2$ phase shifted sinusoid for the detected signal that changes it sign with the delay sign. The further characterisation are performed in this sinusoidal regime that is easier to detect using a lock-in amplifier.

The signal of the differential detector is then sent on a lock-in amplifier in order to measure the RMS amplitude of the component of the detected signal in quadrature with the excitation signal. With a small adaptation of the experimental set-up (suppression of the $\lambda/4$ waveplate, we can access to a normalization signal C_M proportional to the incident power I_{S0} that may slightly vary with the position of the delay line. The results of the measurements are shown in Figure 6. The rms signal varies with the position of the delay line, but not strictly linearly, because of the variation of I_{S0} with the delay line position, that is shown in the same figure. When the ratio between the two curves is made, we obtain the expected linear variation (Fig. 6B).

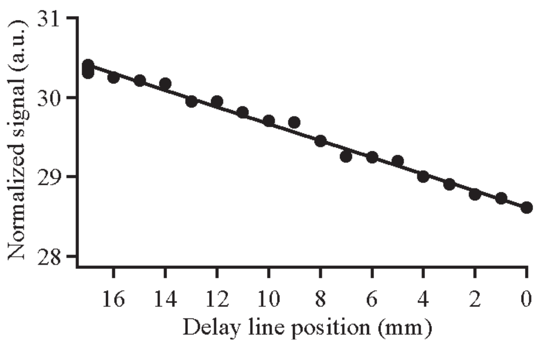

Fig. 7. Fine variation of the detected signal with the position of the delay line, around the 8 cm position.

The linear dependence of the detected signal with the delay shows that the approximation $t \ll \tau_M$ is always fulfilled. Using the set-up parameters we can estimate the typical value of τ_M that can be reached in our experiment, what gives a maximum measurable distance of the order of 50 m (a value not accessible with our delay line). In order to evaluate the precision of the measurement, i.e. the smallest measurable distance obtainable with our set-up, we place ourselves around a value of the position of the delay line of 8 cm, i.e. close to the highest attainable delay, and finely vary the position of the delay line. The normalized detected signal is shown in Figure 7, on which the linear variation can be seen with a millimetric measurement sensitivity. Extrapolating these results, one can estimate that this first non optimized set-up allows distance measurement with a precision of the order of 1 mm on a measurement range of 50 m, giving a dynamic range of the order of 10^{-4} to 10^{-5}. The characteristics of the present set-up are mainly limited by the electronic noise due to the not-optimized electronical system, the low intensity of the detected signal and the relatively low efficiency of the photorefractive crystal. The characteristics of the laser source such as its phase noise are not a strong limitation due to the low frequency lock-in detection. Indeed the system is sensitive to the derivative of the phase noise (Eq. (1)) at the relatively small frequency of the laser frequency modulation, which could be minimized in an optimized laser source if not already sufficiently small.

4 Conclusion

We have proposed and characterized a new type of rangefinder that combines the performances of frequency modulated laser radar with the ease of use of holography. Due to its holographic principle, this device allows to make precise measurement of the absolute distance of scattering targets. The first version of the realized set-up allows to have millimetric resolution on decametric distances. The obtained experimental results show a good accordance with simple models of the holographic rangefinder developed in parallel.

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