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Phase-shifting interferometry by an open-loop voltage controlled laser diode

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ABSTRACT

The paper presents a simple and straightforward procedure for determining the phase of an interferogram by exploiting the specific behavior of laser diodes—i.e., the small variation of the operating wavelength attainable by varying the forward current of the diode. The proposed procedure was developed by using a laser diode for feeding a quasi-balanced Michelson interferometer, by which the optimal operating conditions were investigated—i.e., the proper unbalancing and the proper variation of the supply voltage of the diode. The selected operating conditions were then used for evaluating the phase-steps by a simple algorithm developed on purpose for the present application. The phase measurements carried out by the proposed method have shown a very good accordance with those obtained by a conventional temporal phase-shifting procedure performed by a high-end commercial PZT actuator with quasi-nanometric accuracy.

1. Introduction

The implementation of phase-shifting procedures [1,2] in the field of interferometric measurements provides a powerful tool for carrying out accurate and actual full-field experimental data analyses. The significant step forward occurred with the spread of the these procedures encouraged several researches to work on this topic, as evidenced by the high number of texts and articles published in the scientific literature. In particular the effort of the researchers was focused on: defining innovative procedures for calculating the phase [3–5]; simplifying and reducing the cost of the experimental setups required for the application of the phase-shifting procedures [6–8]; reducing the number of steps necessary for retrieving the phase [5,9,10]; improving the spatial phase-shifting approaches [11–13].

Among the different phase-shifting procedures proposed in literature, the most popular are those usually named "temporal", thanks to their accuracy and ease of application. However, the temporal methods require the acquisition of the light intensities in not less than three different configurations when known phase variations are applied. This last operation demands a device able to accurately control the optical path length, and it is usually performed by a piezoelectric actuator, which could represent a limitation in term of cost and complexity of the whole experimental apparatus.

In the present paper authors propose a phase-shifting procedure based on the control of the forward current circulating in a low-cost laser diode. In fact, thanks to the high number of their applications (e.g., optical disc drives, optical mice, laser pointers, barcode scanners, laser meters, etc), this type of light source is nowadays rapidly spreading. Furthermore, although the most common laser diodes emit in the red band of the visible light ($0.62\ \mu m \le \lambda \le 0.75\ \mu m$) and in the near infrared ($0.75\ \mu m \le \lambda \le 1.40\ \mu m$), the diffusion of the blue-ray technology is making available, at highly competitive costs, sources emitting in the blue band ($0.38\ \mu m \le \lambda \le 0.49\ \mu m$). The use of a laser diode as light source, however, implies some drawbacks: low temporal coherence (normally the coherence length hardly exceeds 1 mm), astigmatic and elliptical beams, high sensitivity of electro-optical properties to the operating temperature.

In particular, with regard to this last drawback, the datasheets provided with the laser diodes usually report the variation of the wavelength with the case temperature [14]; this property represents the serendipity which allows to apply phase-shifting procedures simply by controlling the thermal conditions of the diode. The idea of exploiting this distinctive feature is not new. Several applications are proposed in literature [15–19], with the aim of controlling and stabilizing the phase of a laser beam, normally by acting on the forward current circulating in the diode laser. The most of these applications proposes more or less complex electro-optical equipment able to control the phase of the emitted light, often based on feedback systems designed on purpose for the specific application. In addition, laser diodes have high sensitivity to optical feedback, as shown in [20], where this peculiar behavior has been exploited for directional discrimination in Michelson interferometer.

By the present paper the authors proposed a complete phase-shifting procedure based on the wavelength variation of a laser

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diode. The wavelength variation was attained by controlling, in open-loop fashion, the supply voltage of an electrical circuit, consisting of a resistor connected in series with a laser diode. The experiments were carried out by using a laser diode as light source in a Michelson interferometer, by which the influence of the operative parameters (i.e., entity of the voltage steps and unbalancing between the arms of the interferometer) was properly investigated. Finally a novel numerical procedure able to identify the phase steps was assessed and successfully applied. It was proved that the accuracy of the proposed procedure is comparable with that attainable by using as phase-shifter a commercial high-end PZT actuator with quasi-nanometric accuracy.

In spite of the several approaches proposed in literature on this topic, our procedure allows to work without a feedback signal, which represents a significant hardware complexity. In fact, according to the proposed procedure, after the identification of the proper operating parameters, the voltage variations are applied without any control of the wavelength variation, and the consequent phase variations are evaluated only a posteriori. Eventual unwanted phase variations due to the thermal drift caused by the environmental conditions can be definitely neglected; in fact all the steps are acquired very quickly (about 1 s, and it is possible to decrease significantly this time), while thermal drift caused by the environmental conditions implies phase gradient much lower. The evaluation of the phase variations were performed by an original algorithm implemented on purpose, which just requires that the phase is a monotonic function and the input of a starting parameter, easily estimable—i.e., the number of steps necessary to cover a full cycle of the phase. Furthermore, the algorithm neither requires the knowledge of the actual wavelength, nor evaluates the wavelength variation induced by the voltage variation. Instead, it directly determines the single phase variations induced between the arms of the interferometer by applying, on the interferograms, a non-iterative even if non-linear calculation method.

Finally it should be emphasized that the proposed procedure was assessed with the aim of obtaining a cheap and self-contained equipment for carrying out any kind interferometric experiments, when it is possible to use, as light source, a low-cost laser diode.

2. Theory

The possibility to apply a phase-shifting procedure simply by controlling the forward current of a laser diode relies in the variation of the wavelength occurring when the thermal regime of the device is altered. This operative principle, normally used for applications concerning with profilometry [21,22] of fiber Bragg sensor [23], can be advantageously used for varying the relative phase between the arms of an interferometer, according to the following arguments.

If the interferometer is perfectly balanced, a variation of the wavelength λ does not produce any effect on the relative phase between the two beams of the interferometer. On the other hand, for a given unbalancing δ, the relative phase (in term of fraction of a cycle) is equal to the fractional part of n:

$$\delta = n\lambda, \tag{1}$$

where n is a real number evaluated by the previous relation and represents the number of wavelengths necessary to cover the unbalancing δ when the wavelength is equal to the initial value λ. For an adequate variation of wavelength ($\Delta\lambda$), a phase variation of 2π occurs when the following relation holds:

$$\delta = (n+1)(\lambda - \Delta\lambda), \quad \text{with} \quad \Delta\lambda > 0. \tag{2}$$

by combining Eq. (1) with Eq. (2), and by considering as unknowns δ, n and $\Delta\lambda$ (λ is supposed to be known), we obtain a relation between two out of the three unknowns. In particular, by calculating n from Eq. (1) and by substituting this expression in Eq. (2), the following equation, providing the relationship between δ and $\Delta\lambda$, is obtained:

$$\Delta\lambda = \frac{\lambda^2}{\delta + \lambda} \approx \frac{\lambda^2}{\delta}, \tag{3}$$

where the approximation holds if (as often happens) the unbalancing is much greater than the wavelength.

Eq. (3) provides the variation of the wavelength $\Delta\lambda$ necessary for obtaining a phase-shift (between the two arms of an interferometer unbalanced of an amount δ and fed by a light source whose initial wavelength is λ) equal to 2π. A phase shift of any value can be evaluated proportionally: for instance, for performing a conventional four-step algorithm, a phase shift of $\pi/2$ occurs for a wavelength variation equal to $\lambda^2/4(\delta+\lambda)$, and so on. Eq. (3) is used in the present work for selecting proper operative conditions of the experimental setup—i.e., the variation of the diode current necessary for varying the wavelength and the unbalancing entity between the arms of the interferometer; on the other hand the phase steps are evaluated by the procedure described in details in following sections, which is not based on the determination of the wavelength variation and, therefore, it does not require the use of Eq. (3).

3. The light source

The light source adopted for the development of the application proposed in the present paper is the laser diode *opnext* (powered by *Hitachi*) model HL6545MG, based on the semiconductor material *AlGaInP* (*Aluminium Gallium Indium Phosphide*) with *MQW* (*Multi-Quantum Well*) structure. The nominal wavelength (i.e., at room temperature) is equal to 0.66 μm, whereas the optical output power is 120 mW in continuous emission and 300 mW in pulsed emission. The complete set of optical and electrical features is available in the website of the manufacturer [14]. The choice of this particular diode is motivated by its very low price (available at less than 20 euros) together with its high optical power; nonetheless, the proposed method can be applied to other similar types among the hundreds available on market.

Among the different phase-shifting procedures proposed in literature, the most popular are those usually named ″temporal″, thanks to their accuracy and ease of application. On the other hand the temporal methods require the acquisition of the light intensities in not less than three different configurations when known phase variations are applied. This last operation requires a device able to accurately control the optical path length – i.e., a piezoelectric actuator – which could represent a limitation in term of cost and complexity of the whole experimental apparatus.

Fig. 1 reports the wavelength vs the case temperature of the laser diode used in the present study; the graph, scanned from the datasheet of the device, shows a wavelength variation up to about 16 nm when the temperature varies from 0 to 75 °C, with the upper limit representing the maximal operating temperature of the device. It is possible to notice a staircase trend of the wavelength, which represents the effect of mode hops of the laser diode. However possible phase shifts induced by discontinuous mode hops are negligible, due to the small unbalancing used in the experiments. In fact, as shown in the following sections, the phase variations was proven to vary smoothly, for any entity of the voltage steps and unbalancing. In conclusion we can rely on $\Delta\lambda$ significantly smaller than 16 *nm* to apply at least three known phase steps in the range $[0, 2\pi]$.