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An unbalanced interferometer insensitive to wavelength drift

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ABSTRACT

Frequency-modulated interferometry offers a unique way to create phase modulation in 2-arm interferometers with a small footprint and cost. However, this approach is not widely used in common interferometric devices due to its sensitivity to small wavelength fluctuations and the difficulty to handle intricated phase and amplitude modulation. In this paper, we tackle these issues by performing unbalanced interferometry immune to laser wavelength fluctuations via a slightly modified setup comprising an unstabilized laser source and an additional reference arm. High performances are obtained with minimal equipment by using a power modulated VCSEL and the "generalized lock-in amplifier" method: the slow phase drift due to temperature change is efficiently canceled out while the high frequency noise is divided by a factor of 2.4. The measurement of slow displacement (0.1–10 Hz) with a sub-nanometric resolution is demonstrated. The proposed approach can be used in a number of interferometric setups including slightly unbalanced interferometers for lasers having small coherence lengths.

1. Introduction

Two-arm interferometry offers extreme sensitivity for a large number of sensing applications [1–5]. However, its cost and its sensitivity to influence quantities still prevents a large implementation within commercial optical sensing systems. A major issue resides in the necessity of having bulky and costly phase or frequency modulators to perform unambiguous amplitude and phase measurement. Part of the problem is addressed by using an unexpensive and achromatic piezo-actuated mirror as phase modulator, but this option severely reduces the possible speed of operation and it is not easily compatible with integrated optics approach. In the eighties, unbalanced interferometry (UI) was proposed to solve this issue [6,7].

The approach is exemplified in Fig. 1A where the 2-arm interferometer simply consists in a Michelson system able to measure any displacement of the mirror in the signal arm. This setup is quite general however in the sense that the target mirror could be replaced by another system of interest such as an objective lens and a sample. As can be seen, the UI approach consists of having a sufficient optical path length difference between reference and signal arms so that a small wavelength modulation entails enough phase modulation to extract phase and amplitude from the resulting beating signal. For this purpose, most of the available singlemode solid state lasers can be used as a wavelength change of tenths of picometers is sufficient for a millimetric unbalance (in the visible domain). The initial idea in UI is to mimic a purely linear phase change by applying a sawtooth waveform to modulate the laser wavelength. To obtain the linear phase variation, the sawtooth amplitude is adjusted to obtain a modulation over an integer number of time 2π. Then, a simple phase-meter, such as a lock-in amplifier (LIA) can be used to obtain the phase [8]. However, as shown in Fig. 1B, a laser diode typically responds imperfectly to the sawtooth function, and the obtained beating is not a pure sine as we would ideally expect.

On the contrary, the modulation produces unwanted harmonic sidebands in the frequency spectrum and makes accurate phase determination difficult [9].

To improve the diode response, the discontinuous sawtooth-modulated approach has been replaced by a Sinusoidal Phase Modulation (SPM), induced by a sine modulation of the laser diode wavelength [10,11]. However, more than thirty years after its introduction, we can note that UI has received only moderate success. The main issue actually comes from the intrinsic sensitivity of such system to unwanted wavelength fluctuations, typically induced by temperature fluctuations that are unavoidable in a standard environment. As outlined elsewhere [12], common semiconductor laser diodes should be stabilized with a precision better than 1/1000 K to keep the fluctuations below the picometer range, in the most favorable case of millimetric unbalance. Facing such difficulty, only few attempts toward a drastic temperature control were reported [13,14], as the UI cost and simplicity benefits become seriously compromised. Because of wavelength fluctuation sensitivity, sta-

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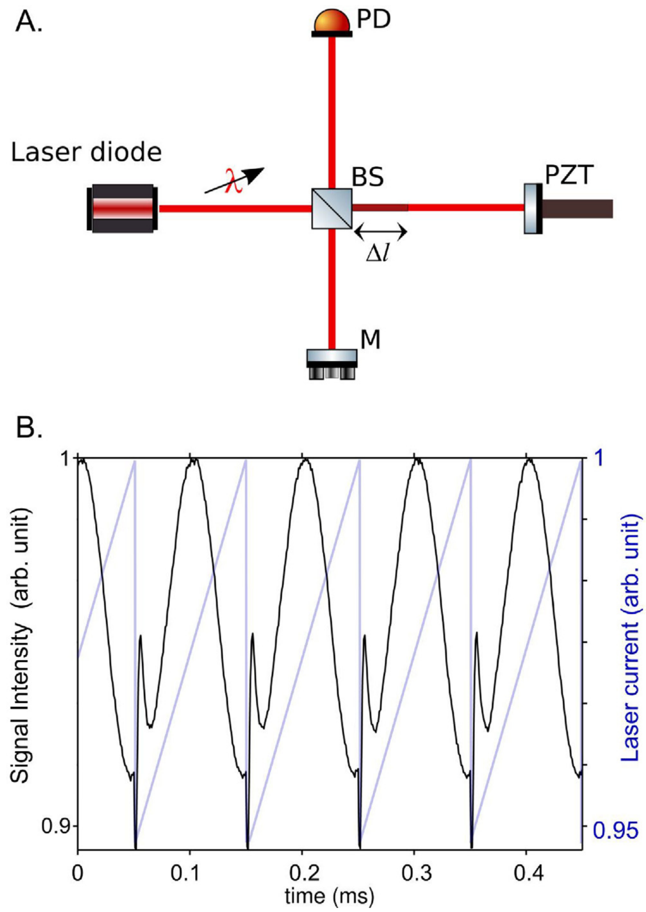

Fig. 1. (A) Classical unbalanced Michelson. BS: Beamsplitter, M: mirror, PD: photodetector, PZT: piezoelectric transductor. (B) Interferometric signal detected when applying a sawtooth current modulation at 10 kHz.

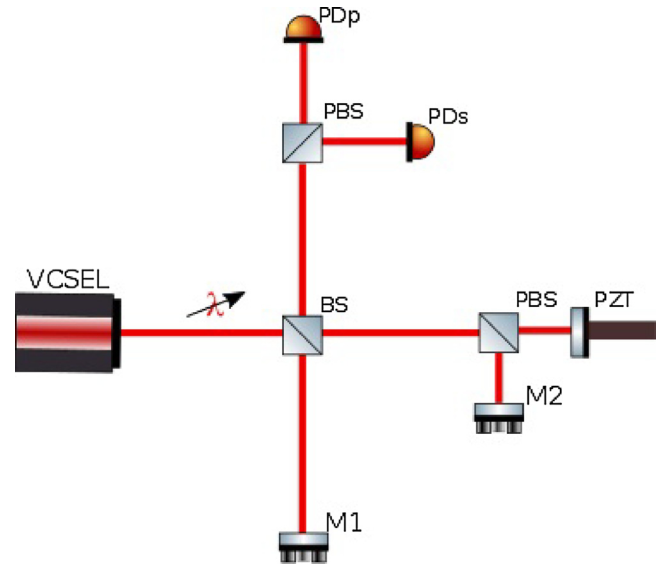

Fig. 2. Compensated unbalanced Michelson. PBS: polarizing beamsplitter, PDs: photodetectors for the s component of the field, PDp: photodetector for the p component of the field.

bilized single mode lasers have to be used and UI is now mostly devoted to vibrometry and fast measurements [15].

In addition, we note that a wavelength modulation typically involves a synchronized power-modulation, which is also triggered by the current waveform. Therefore, amplitude and phase modulation co-exist at the same modulation frequency. This amplitude modulation (AM) must be carefully considered [16] as it modifies the time-domain interferogram and it makes the analysis more complex by correlating amplitude and phase information. This effect can be minimized (1) by using a large unbalance or (2) by dividing the signal by the source power, using an extra detector (sometimes already embedded inside the laser diode case). In the first case, the signal phase becomes even more noisy. As for the second approach, the normalization is found to be particularly critical and difficult to achieve. The reason is that interferometric and monitor signals should not be DC-filtered before division and should not have any unwanted additional DC component as it is the case under ambient light conditions.

In this work, we show that UI can be made immune to wavelength fluctuation without temperature control, using a standard SPM and a Vertical Cavity Surface Emitting Laser (VCSEL). A compensation scheme is implemented by adding a second, fixed, signal arm to monitor the wavelength changes. In this demonstration, we use *s* and *p* polarisations to discriminate between the phase of the signal arm of interest and the phase of the additional, fixed, signal arm. In addition, it is shown that the method is robust to strong AM as it can be the case for millimetric or shorter unbalance. The algorithm of the phase extraction is based on a Generalized Lock-in Amplifier (GLIA) [17]. The GLIA has been used firstly in the context of scanning near-field optical microscope where the detected signal can be very weak. In this context, this technique was used to improve the signal to noise ration (SNR) by using all the available frequency components, which dependent on the employed modulation function (e.g. sawtooth, SPM, etc.). Herein we detail how the GLIA can be used to get rid of an AM at the SPM frequency.

2. Experimental methods

Fig. 2 shows the setup used to compensate for the unwanted wavelength fluctuations. Compared to Fig. 1A, the signal arm is further splitted into s-polarized and p-polarized sub-arms, both of them having the same unbalanced length $\Delta l_s = \Delta l_p = 4 \pm 0.06$ mm determined from the starting position where the optical path difference (OPD) vanishes. In practice, the zero OPD is precisely found when no more time-domain beating is observed while the VCSEL wavelength is modulated.

The interferences with the reference signal related to the two sub-arms are selectively recorded using a second polarizing beam splitter in the detection part. The laser diode is a multimode VCSEL (VC670M-TO46GL) emitting at $\lambda_0 = 674$ nm (Fig. 3).

The VCSEL, in series with a 1 kΩ resistor, is driven by a voltage $V = V_0 + \alpha \sin(\Omega t)$ at $V_0 = 7$ V coming from the analog output of a data acquisition card (National Instruments, NI USB-6363). The card resolution of 16 bits and the frequency sampling rate of 1 MHz are large enough to precisely define the sinusoidal modulation which is fixed at 10 kHz in our setup. For this V_o, the bias current is $i_0 = 4.7$ mA and the tunability in current is found to be $S = 0.178 \pm 0.002$ nm/mA.

The current flowing through the VCSEL $i(t) = i_0 + \beta \sin(\Omega t)$ induces: (1) a power modulation $P(t) = P_0 + \gamma \sin(\Omega t) = P_0(1 + \mu \sin(\Omega t))$ where it is convenient to introduce μ, the optical power modulation depth, and (2) a wavelength modulation $\lambda(t) = \lambda_0 + \delta \sin(\Omega t)$.

The beam of the VCSEL is collimated and launched into the interferometer as shown in Fig. 2. The signal mirror is glued on a piezo-actuator. The data acquisition card records the signal given by the two photodiodes (THORLABS, PDA36A-EC with 10 MHz bandwidth) at 1 MHz sampling rate and 16-bit resolution.