Frequency-stabilized moving interference patterns generated by a closed loop technique

A. A. Freschi [1]***, and A. C. C. Telles*** [2]

[1] **Departamento de Física, IGCE, Universidade Estadual Paulista – UNESP**
Caixa Postal 178, 13500-970 Rio Claro SP Brasil
afreschi@rc.unesp.br

[2] **Laboratório de Ensaios, Caracterização e Análise de Hardware**
Centro de Pesquisas Renato Archer – CenPRA
Rod. D Pedro I km 143,6 - 13082-120 Campinas SP Brasil
antonio.telles@cenpra.gov.br

Abstract

We present a closed loop technique and corresponding signal processing scheme that allows the control of the motion of interference patterns. The technique makes use of a small amplitude fast sinusoidal phase modulation introduced in one of the arms of the interferometer for detection and processing purposes. Two optical signals in phase quadrature are extracted, electronically processed and demodulated (using a lock-in amplifier) at a reference frequency slightly detuned to the frequency of the sinusoidal phase modulation. The resulting signal is integrated and fed back to the interferometer through a phase-shifting device. The scanning frequency of the optical fringes (which is proportional to their velocity) is then driven by the feedback loop to be equal to the detuning frequency (difference between the modulation and demodulation frequencies), which can be adjusted in our setup from some mHz to tenths of Hz. Therefore, noise-compensated frequency-stabilized moving interference patterns are generated. Experimental results are shown of an application where a piezoelectric actuator was used to produce linear scanning of optical fringes.

A common approach to generate moving interference patterns makes use of a phase-shifting device (such as a piezoelectrically transduced mirror - PZT) in open loop interferometers. Although simple and useful, this method is not effective when a stable movement of the optical fringes is required at very low velocities. In fact, when stable scanning motion of the optical fringes matters, it is required to consider both the phase disturbances acting on the interferometer and the (nonlinear) response of the phase-shifting device. Many systems have been proposed to control the phase of fringe patterns, but all of them are designed to operate at a constant phase value [1-5]. In this work we propose and demonstrate a closed loop technique that is capable of generating noise-compensated frequency-stabilized moving interference patterns by scanning the phase of interference patterns.

Let us consider two incident plane wavefront beams (*R* and *S*) creating an interference pattern, which optical intensity is described by,

$$I = I_R + I_S + 2\sqrt{I_R I_S}\cos\psi \qquad (1)$$

where I_R and I_S are the intensities of the beams *R* and *S*, respectively, and ψ is the phase shift between them. The phase ψ determines the position of the interference pattern, and can be expressed as $\psi = Kx$, where $K = 2\pi/\Lambda$ is the spatial frequency, with Λ the period of the interference pattern along the defined x spatial coordinate. Fig.1 shows the opto-electronic feedback loop and the signal processing circuit. The wave mixer is a component (like an hologram or just a piece of glass properly adjusted) that mixes two interfering beams towards the photodetector D. So, another optical interference pattern (that enables control of the phase ψ) is projected onto the active area of the photodetector D. A piezoelectric supported mirror (PZT), driven by an oscillator (QO), produces a small amplitude (δ = 0.2rad in our experiments) sinusoidal phase modulation of temporal frequency $\omega_0 = 2\pi\times1650$ rad/s in one of the incident beams. Therefore, the phase shift ψ between the mixed waves can simply be replaced by, $\psi \to \psi + \delta\sin(\omega_0 t)$. Because of the nonlinear relation between the light intensity projected on the photodetector and the phase difference between the interfering beams (see Eq.1), several harmonic terms in ω_0 are present in the output voltage V_D [2-3,5]. In order to generate a suitable error signal to operate the feedback loop, the voltage V_D is split in two branches: One of them is sent directly to the "A input" of a $2\omega_0$-tuned lock-in amplifier; In the other branch, the ω_0-component of V_D is filtered out and frequency doubled by mixing it with a sinusoidal wave from the same oscillator that drives the PZT. The mixed signal (called $\omega_0$2-component) is sent to the "B input" of the lock-in amplifier. The second harmonic signal (*A* input) can be written as $V_{2\omega_0} = V_0 \cos(\psi)\cos(2\omega_0 t)$, whereas the amplitude and phase of the $\omega_0$2-component can be adjusted to be $V_{\omega_0 2} = \pm V_0 \sin(\psi)\sin(2\omega_0 t)$. The reference circuit of the lock-in amplifier is driven at a frequency $\omega_0 \pm \omega_1$ slightly different to the frequency of the sinusoidal phase modulation ω_0 ($\omega_1 << \omega_0$). Two quadrature oscillators (QD), producing two sinusoidal outputs 90 degrees shifted to each other, are used to generate this slightly detuned signal. Therefore, when the lock-in amplifier is operated in the differential "A–B" input mode, it demodulates the signal,

$$V_\Delta = V_0 \cos(2\omega_0 t \pm \psi) \qquad (2)$$

that leads to the output,

$$V_{OUT} = V_0^{rms} \sin(\omega_1 t - \psi) \qquad (3)$$

with $V_0^{rms} = V_0 / \sqrt{2}$. Consequently, if V_{OUT} is used as an error signal to operate de feedback loop shown in Fig.1, the phase ψ will be forced to be $\psi = \pm\omega_1 t$ (or $\psi = \pm\omega_1 t + \pi$, depending on which condition makes the feedback negative) so as to have V_{OUT} operating around zero (equilibrium condition) [1]. In view of that, it is clear that we are able to scan the phase ψ at the detuning frequency ω_1, which can be selected in our setup from some mHz to tenths of Hz.

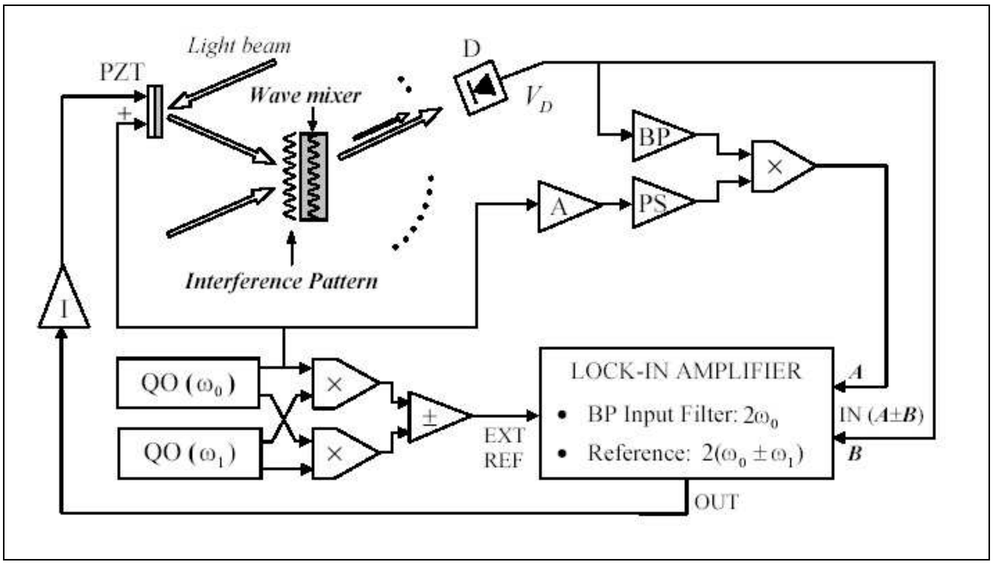

Figure 1: Opto-electronic scheme showing the interferometer and the electronic circuit. PZT: piezoelectric supported mirror; D: photodetector; BP: band-pass filter; ×: multiplier; A: amplifier; PS: phase-shifter; QO: quadrature sinusoidal oscillators operating at the angular frequency ω_0 and ω_1 ($\omega_1 << \omega_0$); ±: adder (or subtracter); *A* and *B*: lock-in inputs; OUT: demodulated output used as error signal to operate the feedback loop; I: integrator.

Fig.2A shows a typical time-evolution of the voltage V_D, which is proportional to the collected light intensity, when a linear ramp was applied to the PZT (without feedback – open loop condition). The maximum and minimum values of V_D correspond respectively to bright and dark fringes passing through D. The acquisition bandwidth of V_D is 60Hz. It is clear the influence of the phase disturbances acting on the interferometer, making the velocity of the fringes vary considerably during the scanning. The frequency of this modulation was set to be approximately 1Hz. With the aim of comparison, a similar fringe scanning was performed with the feedback on (Fig.2B). In this case, the signal from the integrator is fed to the PZT device (closed loop condition). Because the phase ψ is forced to be $\psi = \omega_1 t$ by the feedback loop, the noise is compensated by the system and appears in the signal applied to the PZT.

In summary, we have shown that a closed loop technique based on two-wave mixing and negative feedback can be used to produce running interference patterns with controllable speed. The remarkable feature of this technique is the ability of simultaneous compensation of environmental phase disturbances. In addition, a possible nonlinear response of the PZT is automatically corrected in order to get the selected fringe scanning.

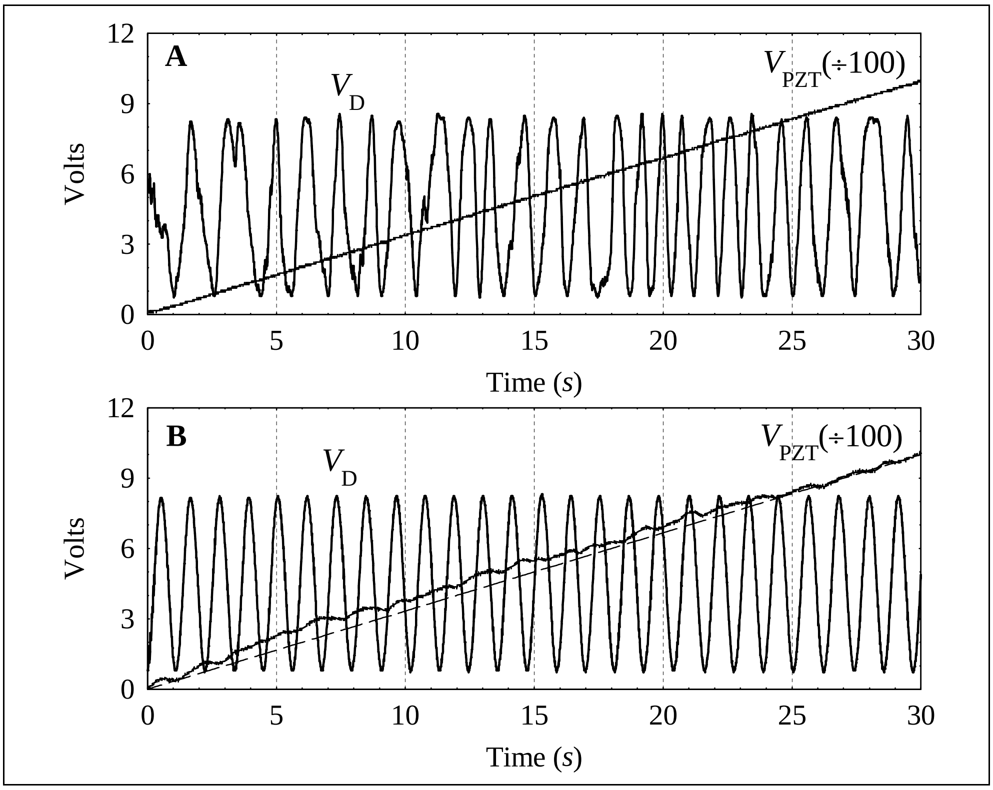

Figure 2: Experimental results, comparing the movement of the optical fringes with and without feedback. V_D is the output voltage of the photodetector and V_{PZT} is the voltage applied to the piezoelectric actuator (divided by 100). In Fig.2A, the interferometer operates in open loop (without feedback), whereas in Fig.2B the error signal is fed back to the interferometer.

The authors thank the **Conselho Nacional de Desenvolvimento Científico e Tecnológico** for the financial support (CNPq – PROFIX 540294/01-2).

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