Noise-free interference patterns of light with pre-determined movement

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Abstract

We report an opto-electronic feedback loop for generating self-stabilized interference patterns of light with arbitrarily pre-determined movement. A weak and fast (high-frequency) sinusoidal phase modulation is applied in one of the optical waves to produce two signals in double phase quadrature. By using a two-phase lock-in amplifier in a quasi-synchronous demodulation scheme we generate an error signal containing a phase term controlled by a slowly varying arbitrarily pre-selected voltage. The modulated phase term drives the feedback loop and can be used to control the dynamics of the moving fringes at arbitrary wave forms.

1 Introduction

Phase modulation is a widely used technique in optical interferometry [1]. Low-frequency phase oscillations have been applied in holographic interferometry to produce nonstationary dynamic photorefractive gratings with enhanced diffraction properties [2]. There are many sources of noise in a practical interferometer leading to annoying random fluctuations in the phase shift between the interfering beams. Environmental noise tends to be stronger at the low-frequency region of the noise spectrum and a number of feedback methods were developed or improved on different aspects for compensating these unwanted effects [1,3-10]. A known technique uses a weak and fast sinusoidal phase modulation in one of the optical waves to create harmonic terms of the fundamental frequency [4-6]. These terms are then synchronously recovered by tuned lock-in amplifiers and (error) signals suitable for stabilizing the fringe pattern at any desired position can be generated.

2 Experiment

This paper addresses the problem of disturbance compensation for generating controlled fringe movements at low frequencies. We use the fast phase modulation technique and propose a quasi-synchronous demodulation scheme to create stable low-frequency fringe oscillations. Fig. 1 illustrates the interferometer and the signal processing block diagram. A phase modulator driven by an oscillator produces a weak (low-amplitude, δ) and fast (high-frequency, ω) sinusoidal phase modulation in one of the interfering waves. Assuming that the light intensity is homogeneous over the detection area we can represent the output voltage as $\tilde{V} = V_0(1 + n\cos\tilde{\varphi})$, with $V_0\kappa(I_R + I_S)$ the average voltage, κ the irradiance-to-voltage conversion factor, I_R and I_S the irradiances of the R and S waves, m the contrast of the pattern ($0 \ll m \ll 1$), and $\tilde{\varphi}$ the phase shift between the interfering waves. Assume $\tilde{\varphi} = \varphi + \delta \sin\omega t$, with t the time and $\delta \ll 1$. Also, we write $\varphi = \varphi(0) + \varphi_N + \alpha$, with $\varphi(0)$ the initial phase, φ_N a noise term introduced by environmental disturbances, and α a slow feedback phase modulation applied in one of the interfering waves. Due to the fast phase modulation, the Fourier spectrum of voltage $\tilde{V}$ presents several

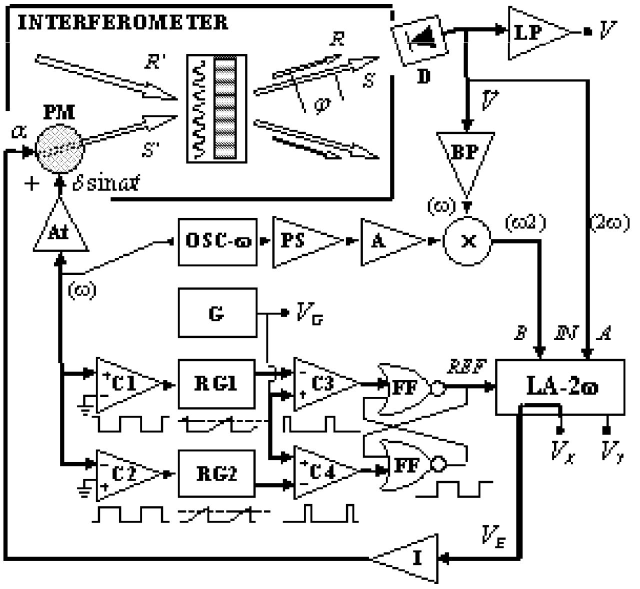

Figure 1: Opto-electronic feedback loop. PM: phase modulator; R', S': input optical waves; R, S: output optical waves; φ: phase shift between the R and S waves; D:photodetector; LP: low-pass filter; BP: band-pass filter; sign : multiplier; A: amplifier; PS: phase-shifter; $OSC-\omega$: sinusoidal oscillator operating at the frequency ω ; At: Attenuator; G: function generator; $C1$, $C2$, $C3$, $C4$: voltage comparators; $RG1$, $RG2$: ramp generators; FF: RS flip-flop; $LA-\omega$: Two-phase lock-in amplifier tuned at ω; I: integrator; V_E: analog output used as error signal (amplified V_X voltage).

harmonic terms of the frequency ω. Expanding up to the second order we write $\tilde{V} = V + \tilde{V}_1 + \tilde{V}_2$,

$$V = V_0[1 + m_0 \cos\varphi] \tag{1}$$

with V a relatively slow varying component, $\tilde{V}_1 = -2V_0 m_1 \sin\varphi \sin\omega t$ the first harmonic component, and $\tilde{V}_2 = -2V_0 m_2 \cos\varphi \cos 2\omega t$ the second harmonic component; $m_n = mJ_n(\delta)$ and $J_n(\delta)$ is the first-kind Bessel function of order n with argument δ. Voltage $\tilde{V}$ is split in two branches (see Fig.1): One is sent directly to the "A input" of a two-phase 2ω-tuned lock-in amplifier; in the other branch, $\tilde{V}_1$ is filtered out and mixed with an amplified and phase shifted sinusoidal wave from $OSC-\omega$. The mixed signal $\tilde{V}_\otimes = 2V_0 a m_1 \sin\varphi \cos(2\omega - \varepsilon)$, called $\omega2$-component, is sent to the "B input" of $LA-2\omega$. When the lock-in is operated in the differential "A-B" nput mode, with $a = m_2/m_1$ and $\varepsilon = \pi/2$, it demodulates the 2ω-signal $V_\Delta = 2V_0 m_2 \cos(2\omega t + \varphi)$. In our system, a delay line circuit [11] consisting of comparators, ramp generators, and a RS flip-flop generates an external signal to feed the reference circuit of the lock-in amplifier, which is operated in the 2F-reference mode. C1 and C2 produce two square wave signals $T/2$-delayed (π-shifted) at the frequency ω , where $T = 2\pi/\omega$. RG1 and RG2 generate ramp waves at the trailing edges of the square wave forms. The $T/2$-delayed ramp waves are compared to a slowly oscillating (Ω-frequency) voltage V_G. The output from C3 is connected to the Set input of the RS-FF and the output from C4 is connected to the Reset input of the RS-FF. Any one of the flip-flop outputs is a delayed square wave signal at the frequency ω; the time delay between the input and the output signals is proportional to V_G (within the ramp limits) and the proportionality factor depends on the slope of the ramp waves, which can be adjusted electronically. For the circuit shown in Fig. 1 the maximum delay is $T/2$ (π). It is worth mentioning that because the lock-in is operated in the external 2F-reference mode, the phase shift (θ) induced in the actual reference signal is twice the one originated by the delay circuit, so that 2π phase excursions can be achieved. In practice, it is useful to correlate θ to V_G through the expression $\theta = \rho V_G$, where ρ is a voltage-to-phase conversion factor (characteristic of the delay circuit) that can be easily and precisely measured; in the present case $\rho = (0.253 \pm 0.001)$ radians/Volt. The outputs from the lock-in demodulators, after filtering by low-pass filters, are slowly varying voltages. Most lock-in amplifiers are calibrated to give the root-mean-square amplitude of the input AC signal. Therefore, in the differential "A-B" input mode, it gives X and Y outputs that can be written as,

$$V_X = \sqrt{2} V_0 m_2 \cos(\varphi - \theta - \beta) \quad \text{and} \quad V_Y = \sqrt{2} V_0 m_1 \sin(\varphi - \theta - \beta) \tag{2}$$

with θ an oscillating phase term controlled by voltage V_G, and β a constant phase selected in the internal reference circuit of the lock-in amplifier. If an amplified V_X analog output is used as error signal (V_E) to operate the feedback loop we have $V_X = V_E = 0$ [3]. This means that an external phase $\alpha = -\varphi(0) - \varphi_N + \theta + \beta \pm \pi/2$ is applied in the optical setup so as to maintain the stable condition $\varphi = \theta + \beta \pm \pi/2$. The initial phase $\varphi(0)$ and the noise term φ_N are therefore compensated and the fringe pattern oscillates

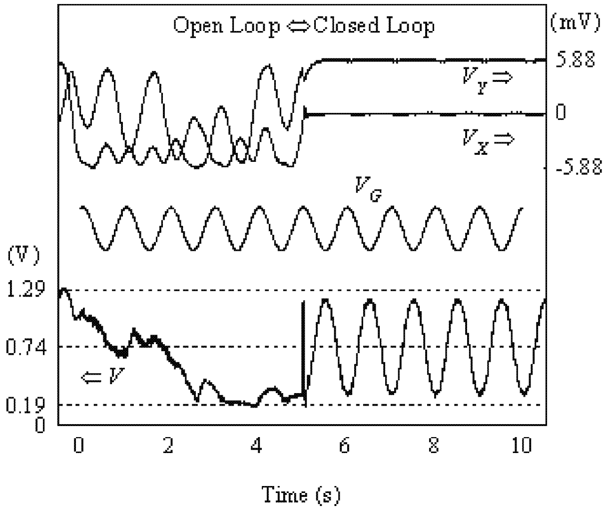

Figure 2: Generation of a noise-free slowly oscillating fringe pattern. Voltage modulates the error phase used to drive the control loop. When the loop is closed an external signal is applied in the interferometer in order to keep the stable condition , whereas measures the amplitude of the interference term. The fringe oscillation is illustrated by voltage V (see Eq.1).

around the position $\beta \pm \pi/2$. Note that although the oscillation amplitude is limited to π in the present case, larger phase excursions can be attained by simply connecting several delay line blocks in cascade. Also, the speed of the fringe pattern is proportional to the time derivative $\dot{\theta} = \rho \dot{V}_G$, which corresponds to the detuning frequency produced in the reference signal. During operation (closed loop) $\dot{\alpha} = \rho \dot{V}_G - \dot{\varphi}_N$ and $\dot{\varphi} = \dot{\theta}$.

3 Results and discussion

Fig. 2 illustrates the generation of a slow sinusoidal fringe oscillation around $\varphi = \pi/2$ ($\beta = 0$); the oscillation amplitude is 1 radian and the frequency 1 Hz. The light source is a double-frequency Nd:YAG laser operating at λ =532nm. A piezoelectrically-supported mirror (PZT) was employed to apply the fast modulation at the frequency $\omega/(2\pi) = 1.6$ kHz and the amplitude δ =0.25 radians. Outputs V_X, V_Y, V_G and V (acquired in a 100 Hz bandwidth) are shown. We make $V_G = (3.95 \pm 0.04) \sin \Omega t$ (Volts) to get $\theta = \theta_0 \sin \Omega t$ with $theta_0 = 1$ radian ($\pm 1\%$) and $\Omega/(2\pi) = 1$ Hz. In open-loop mode (first-half of Fig.2) the phase shift $\varphi = \varphi(0) + \varphi_N$ between the optical waves and voltage V varies from its maximum value $V_M = V_0(1 + m_0) = 1.29$ Volts (bright fringes) to its minimum $V_m = V_0(1 - m_0) = 0.19$ Volts (dark fringes). The average voltage $V_0 = (V_M + V_m)/2 = 0.74$ Volts and $m_0 = (V_M - V_m)/(V_M + V_m) = 0.74$. When the loop is closed $V_X = 0$ and $V_Y = \sqrt{2} V_0 m_2 = 5.88$ mV; during holographic exposures the product mV_0 evolves in time and voltage V_Y provides information on the diffraction efficiency evolution. Note that at small δ the contrast and the detection sensitivity of the technique is limited by $m_2 \approx m\delta^2/8$. The amplitude of the slow phase modulation can be estimated directly through voltage V as 1 radian ($\pm 5\%$), in accordance with the preset value.

4 Conclusions

We have shown the generation of a noise-compensated low-frequency sinusoidal fringe oscillation. Other wave forms, such as triangular (for linear scanning) and square (for step-like motion), can also be easily generated. In all cases, the dynamics of the fringe pattern is conveniently governed through a voltage signal. The oscillation amplitude is limited to the half-fringe in the present case, but larger excursions can be obtained by connecting several delay line blocks in cascade. The technique is suitable for applications in holographic interferometry and it is capable to generate stable fringe oscillations at very low frequencies; in our setup, phase modulations from the mHz range up to ≈10 Hz were successfully generated.

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