Adjustable phase control in stabilized interferometry

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We report an optoelectronic feedback loop that permits the active stabilization of an interferometric setup for any chosen value of the phase between the interfering beams. This method is based on phase modulation and homodyne detection techniques. The phase can be stabilized with a precision of better than 1 deg for our experimental conditions.

Stabilization techniques are important for interferometric systems for which environmental phase perturbations must be compensated. One can treat phase perturbations by using a passive phase-compensation scheme,[1] in which the use of circularly polarized light in one of the interfering beams allows a phase-insensitive amplitude signal to be produced. Passive schemes, however, will not be effective for applications to holographic recording and the characterization of photosensitive materials[2] because phase perturbations are in any case always deletereous for the recording process. Actively stabilized systems[3–6] are therefore of the highest importance for holographic recording and for practical applications to image processing.[7] All reported stabilization systems of which we are aware, however, operate for particular phase values (0, π, $\pm\pi/2$ rad) in the output interferometric pattern of light.

In this Letter we report, for the first time to our knowledge, an actively stabilized interferometric setup in which the phase between the interfering beams can be kept fixed at arbitrarily chosen values. This method is based on the passive scheme described in Ref. 1 and on the actively operated system described in Ref. 6. The simplified setup is depicted in Fig. 1, where one of the interfering beams is phase modulated with an amplitude ψ_d and angular frequency Ω by a piezoelectric-supported mirror. The overall irradiance of the coherent addition of beams I_R and I_S is represented by $I = I_S + I_R + 2\sqrt{I_S I_R}\cos\phi$, where $\phi = \psi + \psi_d \sin(\Omega t)$ is the phase between the wave fronts of the two beams. Because of the nonlinear relation between I and ϕ, the Ω-frequency modulation in ϕ results in a number of harmonic terms in Ω, where the first (I^{Ω}) and the second ($I^{2\Omega}$) such terms are described by

$$I^{\Omega} = 4J_1(\psi_d)\sqrt{I_S I_R}\,\sin\psi\,\sin(\Omega t), \qquad (1)$$

$$I^{2\Omega} = 4J_2(\psi_d)\sqrt{I_S I_R}\,\cos\psi\,\cos(2\Omega t). \qquad (2)$$

The signals above are separately detected by suitable bandpass filters. The Ω-frequency signal is frequency doubled and phase shifted, whereas the original 2Ω-frequency signal is amplified (with gain A), so that a couple of 90°-shifted equal-amplitude signals can be obtained:

$$V_1 = V_0 \sin(\psi)\sin(2\Omega t + \epsilon), \qquad (3)$$

$$V_2 = V_0 \cos(\psi)\cos(2\Omega t + \epsilon), \qquad (4)$$

where $V_0 = 4k_E J_1(\psi_d)\sqrt{I_S I_R} = 4Ak_E J_2(\psi_d)\sqrt{I_S I_R}$, k_E is the photodetector and signal-processing electronics response constant, and ϵ is a phase delay arising from the optoelectronic circuitry. The signals represented by Eqs. (3) and (4) are then added so the following signal results:

$$V_+ = V_0 \cos(2\Omega t - \psi + \epsilon). \qquad (5)$$

Note that the interference phase shift ψ is now included as a phase delay in the argument of the temporal cosinusoidal function. The lock-in amplifier allows measuring the x-component $V_X = V_0 \sin(\psi - \epsilon - \theta)$ and (or) the y-component $V_Y = V_0 \cos(\psi - \epsilon - \theta)$ amplitude of the 2Ω-frequency signal V_+ in Eq. (5) in comparison with an arbitrarily θ-shifted lock-in reference signal. From these data the amplitude V_0 as well as the phase $\psi - \epsilon - \theta$ can be computed. The

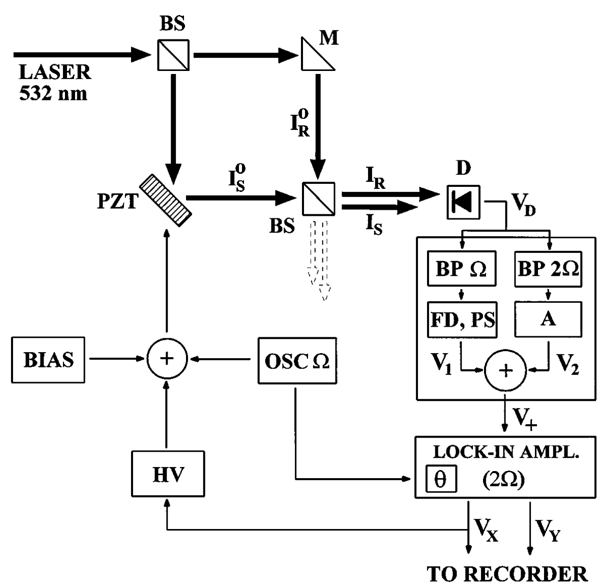

Fig. 1. Stabilized interferometer scheme: BS's, beam splitters; M, mirror; PZT, piezoelectric-supported mirror; D, photodetector; OSC, function generator; HV, high-voltage source; BP's, bandpass filters; PS, phase shifter; FD, frequency doubler; A, amplifier.

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reference system's phase θ can be chosen to cancel the remaining phase delay term ϵ ($\epsilon + \theta = 0$), where the value of ϵ to be offset can be computed from the lock-in measurement of V_1 or V_2 in Eqs. (3) and (4). The value for θ can still be chosen to impose a preset value θ_S ($\theta_S = \theta + \epsilon$), so the outputs from the X and Y channels in the lock-in amplifier are described by

$$V_X = V_0 \sin(\psi - \theta_S)\,, \qquad (6)$$

$$V_Y = V_0 \cos(\psi - \theta_S)\,. \qquad (7)$$

If V_X is used as the error signal in the negative feedback loop in Fig. 1, the interferometric setup is actively fixed for $\psi = \theta_S$ (or to $\psi = \theta_S + \pi$, depending on the way in which the electronics in the loop is set): Each time a phase perturbation in the interferometer shifts ψ away from the preset value θ_S, a correction signal ($V_X \neq 0$) is applied to the piezoelectric mirror through its high-voltage source amplifier, and the optical path length in the interferometer is modified until the stable equilibrium condition ($\psi = \theta_S$) is restored. This means that we are now able to stabilize the interferometric pattern of light at any arbitrarily chosen value for ψ. The performance of the stabilization system is shown in Figs. 2 and 3.

Figure 2 shows the evolution of the overall irradiance I measured with the detector for nonstabilized (0–1.7-min) and for stabilized (1.7–6.0-min) conditions. The steps from A to J represent the stabilization for different preset values of θ_S. In the first part of this figure the stabilization had been switched off and the signal was rapidly varying under the influence of environmental noise: the peak-to-peak modulation amplitude for I is computed from these data, and the ψ values corresponding to the preset θ_S are indicated by the dashed lines. For $\psi_d \approx 0.05$ rad and $\Omega = 2\pi \times 2$ kHz the stabilization system was experimentally shown to operate with a precision of better than 1 deg for the value of ψ.

The same experiment represented in Fig. 2 is described in Fig. 3, where the evolution of the lock-in signals, V_X and V_Y, is shown. In the stabilized regime V_X is used as error signal ($V_X = 0$), and therefore $V_Y = V_0$ independently of the value for θ_S.

The value of ψ_d is generally chosen small enough so as not to reduce the visibility of the fringes in the interferometer. However, if a reduction in the visibility of the fringes can be tolerated, ψ_d can be increased to amplify the I^{Ω} and $I^{2\Omega}$ terms in Eqs. (1) and (2). The first- and the second-harmonic terms, represented by Eqs. (1) and (2), can be directly measured by the use of adequately tuned lock-in amplifiers, without further processing, and used as error signals for stabilization purposes,[6] but, as we pointed out above, in this case the stabilization is limited only to discrete phase values: $\psi = \pm\pi/2$ for $I^{2\Omega}$ and $\psi = 0,\ \pi$ for I^{Ω}.

In conclusion, we have demonstrated the practicality of an active stabilization system to operate at any chosen value of the phase between the interfering beams. The continuously adjustable interferometric phase is the main feature of the stabilization method proposed in this Letter. Additional characteristics are the use of one single detector and the fact that the method is not restricted to a particular light polarization condition. We have employed an interferometric setup to illustrate the operation of the system, but this method can be straightforwardly applied to dynamic recording experiments. The possibility of recording a hologram in stabilized conditions with a continuously adjustable phase is useful for the Fourier synthesis of holographic optical components[8] and is particularly attractive for photorefractive crystals for which the recorded hologram phase shift depends on the external electric field applied to the sample.[2] The fact that the setup is not restricted to circularly polarized beams[1] is quite interesting, because some photosensitive materials are differently affected by the chosen polarization direction of the incident light,[2] and their performance may vary considerably accordingly.[9]

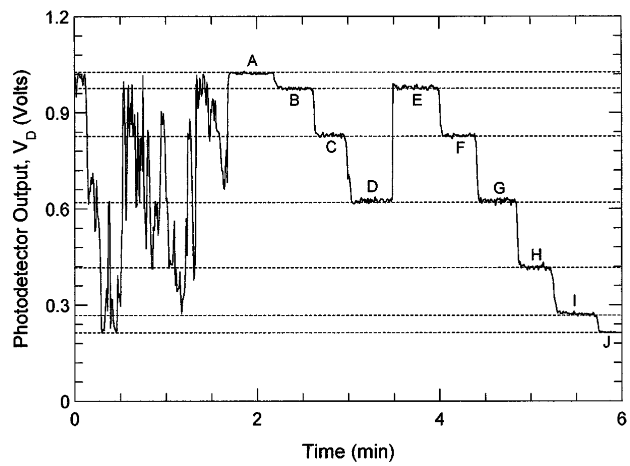

Fig. 2. Stabilized evolution of the photodetector output V_D (in volts) for θ_S equal to A, 0; B, 30°; C, 60°; D, 90°; E, 30°; F, 60°; G, 90°; H, 120°; I, 150°; and J, 180°. The first part of the figure (0–1.7 min) shows the evolution of I without stabilization: The peak-to-peak amplitude for I permits computation of the actual value for ψ for each one of the steps from A to J and is represented by the dashed lines.

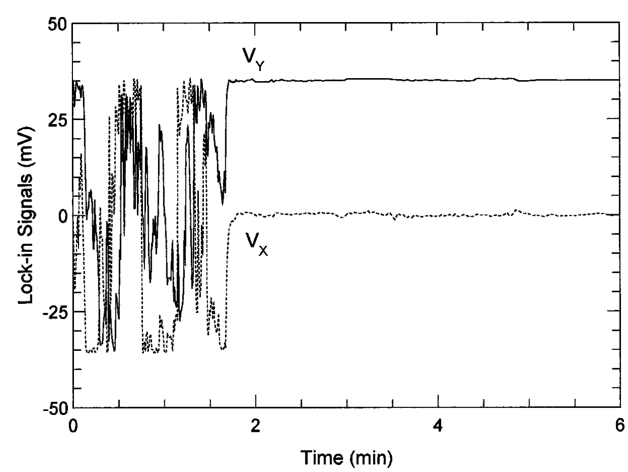

Fig. 3. Evolution of the lock-in output signals, V_X and V_Y, without stabilization (0–1.7 min) and in the stabilized mode (1.7–6.0 min) for the same preset values of θ_S chosen for Fig. 2.

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