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Accurate multipixel phase measurement with classical-light interferometry

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We demonstrate accurate phase measurement from experimental low photon level interferograms using a constrained optimization method that takes into account the expected redundancy in the unknown phase function. This approach is shown to have significant noise advantage over traditional methods, such as balanced homodyning or phase shifting, that treat individual pixels in the interference data as independent of each other. Our interference experiments comparing the optimization method with the traditional phase-shifting method show that when the same photon resources are used, the optimization method provides phase recoveries with tighter error bars. In particular, rms phase error performance of the optimization method for low photon number data (10 photons per pixel) shows a $>5\times$ noise gain over the phase-shifting method. In our experiments where a laser light source is used for illumination, the results imply phase measurement with an accuracy better than the conventional single-pixel-based shot-noise limit that assumes independent phases at individual pixels. The constrained optimization approach presented here is independent of the nature of the light source and may further enhance the accuracy of phase detection when a nonclassical-light source is used.

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Interferometric phase detection is one of the most important techniques in physics. Optical interferometers are being used routinely for metrology, biomedical applications, Fourier transform spectroscopy, and holographic three-dimensional (3D) imaging, to name a few applications [1]. Sensitive phase detection is at the heart of large scale collaborative efforts such as gravitational wave detection [2]. Our aim in this Rapid Communication is to examine the interferometric phase-detection problem with an optimization framework that effectively models the redundancy in the unknown phase signal. For given photon resources, we show that this approach gives phase measurements with an accuracy better than the conventional single-pixel-based shot-noise limit (SNL) even when a classical-light source is used. This conclusion, though somewhat surprising, suggests that limits such as SNL may be generalized to incorporate the multipixel structure of the unknown phase signal. While the quantum limits to the measurement of stochastically fluctuating time-varying phases have been studied before, our focus in this work is to exploit the redundancy in the phase signal to obtain enhanced phase measurement accuracy for experiments limited by low photon numbers.

When two complex fields R (reference field) and O (object field) interfere, the interference signal I detected by a square-law detector is represented by

$$I = |R|^2 + |O|^2 + R^*O + RO^*. \quad (1)$$

Given the prior knowledge about R, the typical methods for the analysis of the interference data are linear in nature. The first step in estimating the phase from the interference data is to get rid of the two intensity terms $|R|^2$ and $|O|^2$ in Eq. (1), followed by processing of the remaining cross terms to estimate the amplitude and the phase of the unknown complex field O. The removal of $|R|^2$ and $|O|^2$ may be performed by high-pass filtering of the interference signal I or by using multiple recordings of the interference signal with known phase shifts in R. When the phase of O is smaller than $\pi/2$ in magnitude, a balanced detection scheme such as homodyning [3] may be followed. However, if the phase of O can take any value in the interval $[-\pi,\pi]$, typically four interference signals are recorded with reference phase shifts of $\theta = 0$, $\pi/2$, π, and $3\pi/2$ applied to R [4]. The corresponding four interference records are sufficient to provide information about the two quadratures of the unknown object field O. Denoting the four interference records as I_θ, the phase ϕ_O of the object field relative to the phase ϕ_R of the reference field may be expressed as

$$\phi_O - \phi_R = \arctan\left(\frac{I_{3\pi/2} - I_{\pi/2}}{I_0 - I_\pi}\right). \quad (2)$$

Henceforth, we will refer to this procedure as the phase-shifting method (PSM). Improving the accuracy of the phase estimation is of great interest to all the associated applications, and this problem has been studied in detail in literature [5–8]. It is now well established that when classical-light sources are used, the phase-detection accuracy is ultimately limited by the shot noise or the $\sqrt{N}$ noise, where N is the mean number of photon counts registered by a point detector. This noise limit is often referred to as the SNL. Obtaining phase-detection accuracy below the SNL requires the use of nonclassical states of light such as squeezed or entangled states [9–12]. The introduction of a squeezed vacuum for sub-shot-noise

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