

1,000-fold amplification in time-holography phase metrology

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Abstract. Conventional interferometers provide uniform phase sensitivity across the measurement range. However, for applications involving small phase changes, amplifying the response within a specific phase range—at the expense of reduced sensitivity elsewhere—can be advantageous. A key example is the Gires-Tournois etalon, used in gravitational wave interferometers. In this work, we introduce an ultrasensitive phase measurement system based on time-holographic recording with a conventional Mach-Zehnder interferometer, operated near the intensity minimum at the dark output port. Phase fluctuations in the milliradian range around this point are converted into rad-sized dark output phases, with amplification factors exceeding 1,000. The adjustable imbalance between the interferometer arms controls this magnification, which is revealed by heterodyning the output with a frequency-shifted beam. Phase is digitally retrieved from the time-hologram using Fourier processing, with noise subtraction for correction. The system achieves phase sensitivities better than $\lambda/3,000$, enabling sub-nanometer precision for dimensional measurements. This versatile platform provides powerful tools for ultrasensitive phase measurements in a wide range of scientific and technological applications.

Phase sensitivity enhancement is necessary when phase changes are so minute that they cannot be detected or measured with conventional methods. This can be achieved selectively around some working ranges through various approaches, such as phase-shifting measurements using dual interferometers or double-passed configurations [1,2]. Similarly, Gires-Tournois etalons [3,4] exhibit such enhanced sensitivity, a property effectively exploited in gravitational wave observatories like VIRGO and LIGO.

In conventional interferometers, phase difference between two beams (call it input phase) is inferred from the intensity leaving from an output port. However, not only the intensity of the output but also its phase carry information about the input phase [1,3,5]. In some cases, the input-output phase relation is highly nonlinear and shows a steep slope around some input value (call it the zero). Thus, around those points, an input phase variation ϕ_{in} off zero is transferred to the output with large magnification. If that output phase ϕ_{out} , amplified to “macroscopic” levels, is measured, the sensitivity of the system is roughly enhanced by the phase magnification factor.

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We use this strategy to amplify mrad-sized ϕ_{in} into rad-sized ϕ_{out} using a conventional Mach-Zehnder interferometer. To measure ϕ_{out} , the output is mixed with a frequency-shifted beam, whose interferogram is recorded. The complex output field is reconstructed from the time hologram with standard Fourier techniques after noise subtraction.

By slightly unbalancing both interferometer's arms and working close to complete suppression in one output port (the dark port), the phase of that output displays a sigmoid-like response as shown in Fig. 1(left). Close to $\phi_{in} = 0$, the sigmoid is very steep, with slopes that can be adjusted from tens to thousands, depending on the unbalance level. Denoting by σ the difference in amplitude between arms, the output and input phase variations around the zero are approximately related as $\tan \phi_{out} = \phi_{in}/\sigma$, as follows from a simple theoretical analysis. We have experimentally demonstrated very large level of amplification, exceeding 1,000, as shown in the right panel of Fig. 1, where we show $\tan \phi_{out}$ (black symbols) for an input phase (a sinusoid with a Gaussian envelope) with 5 mrad of maximum modulation depth (continuous line).

Similar behaviour is observed in photorefractive two-wave mixing [5], extending the method to transient phase detection [6,7] with unprecedented sensitivity.

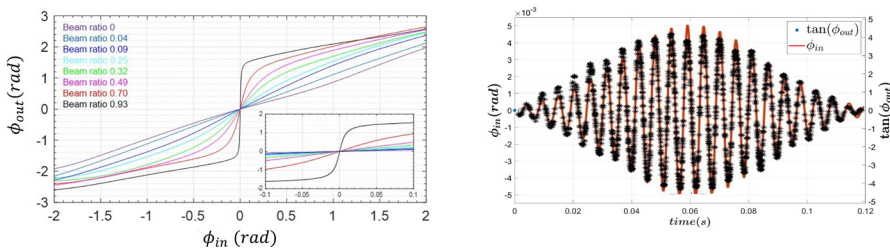


Fig. 1. Experimental results for phase amplification for input phase crossing zero for various beam balance ratios (left) and example of phase amplification ($\sim \times 1,000$) for a time modulated signal (right).

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