Interferometry with a photon-number resolving detector*

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Abstract: With photon-number resolving detectors, we show compression of interference fringes with increasing photon numbers for both Michelson and Fabry-Pérot interferometers. We also theoretically show supersensitivity for nonclassical light.

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In quantum interferometry, nonclassical states of light replace conventional laser light to achieve a sensitivity at the Heisenberg limit, and at resolution well below the Rayleigh diffraction limit [1, 2, 3, 4]. We verify experimentally the photon-number resolved statistics with a weak coherent laser beam incident on a Michelson (MI) (Fig. 1), and Fabry-Pérot interferometer (FPI) (Fig. 2). A coherent laser beam at $\lambda = 850\,\mathrm{nm}$, a repetition rate of 50 kHz, and a

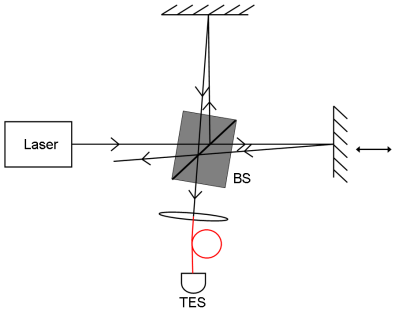

Fig. 1. Setup for the Michelson interferometer with TES detector.

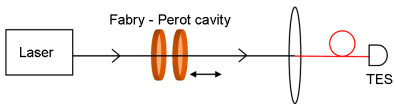

Fig. 2. Setup for the Fabry-Pérot transmission experiment.

pulse duration of 50 ps is attenuated to have the average photon number to be ≈ 4 as detected by our photon-number resolving transition edge sensor (TES) detector [5]. As can be seen in Fig. 3, our preliminary results agree with the theory and also confirm a previous investigation by Khoury *et al.* who also used coherent light, but a polarization Mach-Zehnder interferometer, and a visible light photon counter (VLPC)[3].

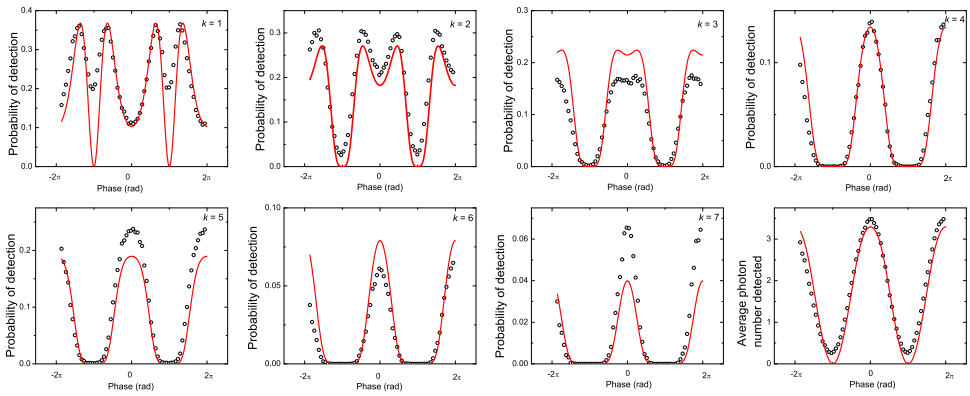

Fig. 3. Measurement of the photon-number resolved interference fringes for a weak coherent state with $|\alpha|^2 \approx 4$ measured at one of the output ports of the Michelson interferometer for different detected photon numbers, $k = 1, \ldots, 7$ and the averaged result; solid line is the theoretical prediction.

Similar features to the one observed with the MI may be obtained for a weak coherent laser beam incident on a Fabry-Pérot interferometer. The number resolved output of the FPI shows narrower transmission functions than for the

average photon number detection. However, the compression of the interference fringes does not improve the resolution of the device since it amounts to just taking the Nth power of the light intensity, which is basically equivalent to a classical post-processing of the data [4]. To obtain an improved sensitivity and resolution of the interferometer, we need to either send nonclassical light through the FPI or keep the classical input, but enable a complicated entangling measurement [2]. We follow the first approach and show that sending N-photon states through the FPI and observing the N-photon resolved transmitted light, results in beating the standard quantum (shot noise) limit. To calculate the transmission functions for quantum states of light, we use a fully quantized approach for the FPI. Loudon first considered a quantum theory of the FPI in the context of high-resolution length measurements [6]. We show that Loudon's results can be nicely related to an effective beam splitter transformation. The two incoming and two outgoing modes of the FPI can be quantized as displayed in Figs. 4, and 5.

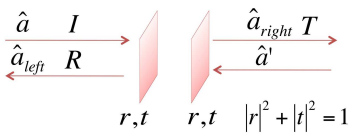

Fig. 4. Fabry-Pérot mirrors with complex amplitudes I, R, and T, for incoming, reflected and transmitted modes, respectively. Each mode can be assigned a mode operator to quantize the respective mode. Both mirrors have identical complex reflection and transmission coefficients denoted with r and t.

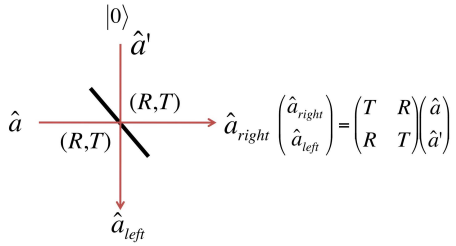

Fig. 5. Effective beam splitter for the Fabry-Pérot cavity with complex amplitudes I, R, and T, for incoming, reflected and transmitted modes, respectively.

It is now seen that the modes as described in Fig. 4 are transformed by an effective beam splitter transformation, displayed in Fig. 5. Figure 6 shows the theoretical results for a weak coherent state with average photon number $|\alpha|^2 = 2$ and a two-photon state $|2\rangle$ compared to the classical transmission function. The results for the sensitivity of

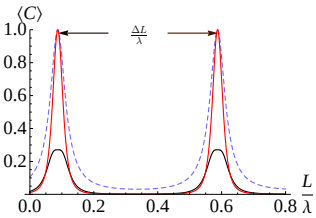

Fig. 6. Transmission function for a single-mode coherent state and an ordinary intensity measurement (dashes). The red narrow curve shows the two-photon state $|2\rangle$ and a two-photon detection. The small amplitude black curve is the result of a single-mode coherent state with average photon number $\bar{n} = 2$ with two-photon detection. The mirror reflectivity $|r|^2$ is 70%.

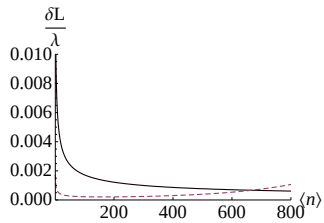

Fig. 7. Comparison of the sensitivity $\delta L/\lambda$ for a coherent state (solid line) versus a n-photon state with n-photon resolving measurement as a function of the photon number, slightly away from the transmission maximum.

a coherent state versus a n-photon state incident on the FPI (Fig. 7) show that a length measurement with n-photon states instead of coherent states provides us with a much smaller uncertainty δL in the few photon limit. Hence, the sensitivity of the FPI is increased. However, for large photon numbers the coherent state outperforms n-photon states with n-photon detection. The experimental verification of this effect is currently in progress and results will be presented at the conference.

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