

Interferometric Amplification and Suppression of External Beam Shifts

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Interferometers are known for precise measurements of the effects inside of them. Here we show that placing a Dove prism in one of the interferometer arms allows for also detecting minute effects happening outside the device. We derive how the additional reflection in one arm can amplify small tilts or displacements of the input beam in the dark output port of the interferometer, in analogy to weak value amplification. The experiment demonstrates a clear improvement of the measurement signal. Moreover, in the bright output port, small disturbances in the input beam get largely filtered, thereby enabling beam stabilization with a fully passive device.

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Determining small displacements and tilts of light beams is crucial for many technological applications, and hence various approaches have been developed [1,2], including interferometric methods for enhanced sensitivity [3,4]. Similarly, motivated by the concept of weak value amplification techniques [5–10], small displacements, tilts, and rotations of the beam due to very weak interactions have been measured [11–18]. That formalism explains such amplification by the fact that the weak value of the projection on the location of the interaction, which corresponds to the amplification factor for the observed shift, has a value much larger than one, enabling significantly enhanced resolution to minute changes of light beams introduced inside interferometers.

Dove prisms [19], originally devised to mirror images, were used also inside interferometers, for example, to filter and manipulate the orbital angular momentum of light beams [20–23]. They have also been introduced into the discussion about the weak trace approach to infer the past of quantum particles inside nested interferometers [24–28], where they changed the location from where observable effects can originate [29–34].

Here, we combine these insights by designing a device consisting of an interferometer with a Dove prism inside, which is capable of amplifying and suppressing effects due to interactions of the light *external* to the interferometer, potentially far away from it. We show how the weak value formalism, introduced to explain the amplification of shifts inside an interferometer, can help to calculate the effect of such external, outside shifts. These beam shifts, whether displacements or tilts, are amplified in the dark output port (destructive interference) and suppressed in the bright port (constructive interference). As in the case of weak value amplification, in spite of the reduced brightness in the dark port, this method can be preferable in the presence of technical noise and especially if the critical resource is the number of detected particles and not the number of prepared ones [7,8,35,36].

The idea of using an interferometer to amplify or suppress changes to a light beam is schematically shown in Fig. 1 for a generic Mach-Zehnder interferometer with a Dove prism in one arm. External displacement δ_x and tilt δ_θ of a light beam can be introduced by changing the position and tilt of a mirror, respectively. This beam is input to the interferometer, tuned to zero phase difference. The final beams are analyzed in the output ports.

Consider an interferometer with an asymmetric input beam splitter. The preselected state of the path degree of freedom can be described as

$$|\psi_\xi\rangle = \mathcal{N} \left((1 + \xi)|A\rangle + (1 - \xi)|B\rangle \right), \quad (1)$$

with asymmetry parameter $-1 \leq \xi \leq 1$ [37].

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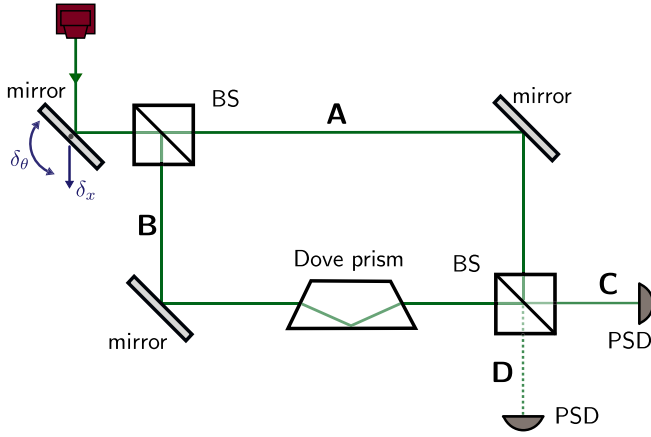


FIG. 1. Schematic Setup. A Dove prism is inserted into a Mach-Zehnder interferometer tuned to zero phase shift. The output beams in ports C and D are analyzed with position-sensitive detectors (PSD). A mirror introduces controllable displacements δ_x and tilts δ_θ to the input beam.

The states of the output beams are denoted by $|C\rangle$ and $|D\rangle$, which, for a 50/50 output beam splitter and zero relative phase difference between arms A and B, originate from the internal states

$$|\phi_\pm\rangle = \frac{1}{\sqrt{2}}(|A\rangle \pm |B\rangle), \quad (2)$$

respectively. For $|\xi| \ll 1$, arm C is the bright port and D is the dark port.

Consider now a lateral displacement δ_x of the input beam (the same derivation holds for lateral tilt δ_θ). For a standard interferometer, such a displacement propagates through the interferometer without change.

A Dove prism mirrors the beam about its central plane. Thus, for a beam in a symmetric mode $\chi(-x) = \chi(x)$, inserting a Dove prism aligned with the symmetry axis of the beam does not affect the output either. However, when the beam is displaced, the displacement is inverted by the Dove prism, $\chi(x - \delta_x) \rightarrow \chi(x + \delta_x)$ [38]. Using a hybrid notation for the joint state of path and spatial profile, the state before the output beam splitter in the interferometer with the Dove prism in arm B can be written as

$$|\Psi(x)\rangle = \mathcal{N}[(1 + \xi)\chi(x - \delta_x)|A\rangle + (1 - \xi)\chi(x + \delta_x)|B\rangle]. \quad (3)$$

The output state can be expressed, after Taylor expansion and rearranging terms up to the first order in δ_x (see Appendix C of the End Matter), as

$$|\Psi_{\text{out}}(x)\rangle = \mathcal{N}\left(\chi(x - \xi\delta_x)|C\rangle + \xi\chi(x - \frac{\delta_x}{\xi})|D\rangle\right). \quad (4)$$

The displacement is amplified by a factor of $(1/\xi)$ in the dark port D, while it is suppressed by a factor of ξ in the bright port C.

The amplification and suppression factors appearing in Eq. (4) were obtained via straightforward calculations of the evolution for an ideal interferometer. To consider also realistic cases when imperfections of the interferometer are present, the formal apparatus of the two-state vector formalism [5] turns out to be well suited. Let us start with the ideal interferometer without a Dove prism. It has been shown in an analysis of beam shifts introduced inside an interferometer [16] that a small shift δ (which can be any combination of δ_x and δ_θ) in, say, arm B is amplified in the output port by the real part of the weak value of the projector on this arm, $\tilde{\delta} = \delta \text{Re}[(\mathbf{P}_B)_w]$ [40].

An external shift δ of the input beam leads to *equal* shifts of the beams in arms A and B inside the interferometer. The effects of shifts in the arms are additive, i.e., $\tilde{\delta} = \delta \text{Re}[(\mathbf{P}_A)_w] + \delta \text{Re}[(\mathbf{P}_B)_w]$. For an interferometer with two arms, $\mathbf{P}_A + \mathbf{P}_B = \mathbb{1}$, and therefore $(\mathbf{P}_A + \mathbf{P}_B)_w = 1$. Thus, together with the linearity of weak values one obtains

$$\tilde{\delta} = \delta \text{Re}[(\mathbf{P}_A)_w] + \delta \text{Re}[(\mathbf{P}_B)_w] = \delta \text{Re}[(\mathbf{P}_A + \mathbf{P}_B)_w] = \delta. \quad (5)$$

The situation changes when a Dove prism is inserted into arm B. Since it mirrors the shift in arm B, $\delta \rightarrow -\delta$, the shift in the output ports is no longer described by the weak value of the sum of the projections but by their difference,

$$\tilde{\delta} = \delta \text{Re}[(\mathbf{P}_A)_w] + (-\delta) \text{Re}[(\mathbf{P}_B)_w] = \delta \text{Re}[(\mathbf{P}_A - \mathbf{P}_B)_w]. \quad (6)$$

For an ideal interferometer with a Dove prism and small shifts δ , we obtain, in agreement with Eq. (4),

$$\tilde{\delta}^C = \delta \text{Re}\left[\frac{\langle\phi_+|\mathbf{P}_A - \mathbf{P}_B|\psi_\xi\rangle}{\langle\phi_+|\psi_\xi\rangle}\right] = \delta\xi, \quad (7)$$

$$\tilde{\delta}^D = \delta \text{Re}\left[\frac{\langle\phi_-|\mathbf{P}_A - \mathbf{P}_B|\psi_\xi\rangle}{\langle\phi_-|\psi_\xi\rangle}\right] = \frac{\delta}{\xi}. \quad (8)$$

In a realistic implementation, decoherence effects have to be taken into account, which of course will limit the promised amplification factors. The various effects can be grouped into couplings to other quantum systems or degrees of freedom of the system itself described by the parameter η_I and the reduced mode overlap caused by the shifts δ , described by η_δ . Considering only the path degree of freedom $\{|A\rangle, |B\rangle\}$, the state directly before the post-selection becomes a mixed state

$$\rho = \mathcal{N}\begin{pmatrix} (1 + \xi)^2 & \eta(1 - \xi^2) \\ \eta(1 - \xi^2) & (1 - \xi)^2 \end{pmatrix}, \quad (9)$$

where the total decoherence parameter $\eta = \eta_I \eta_\delta$ can be measured as the maximal visibility for a symmetric interferometer ($\xi = 0$). Then, the suppression/amplification factors for the output ports are

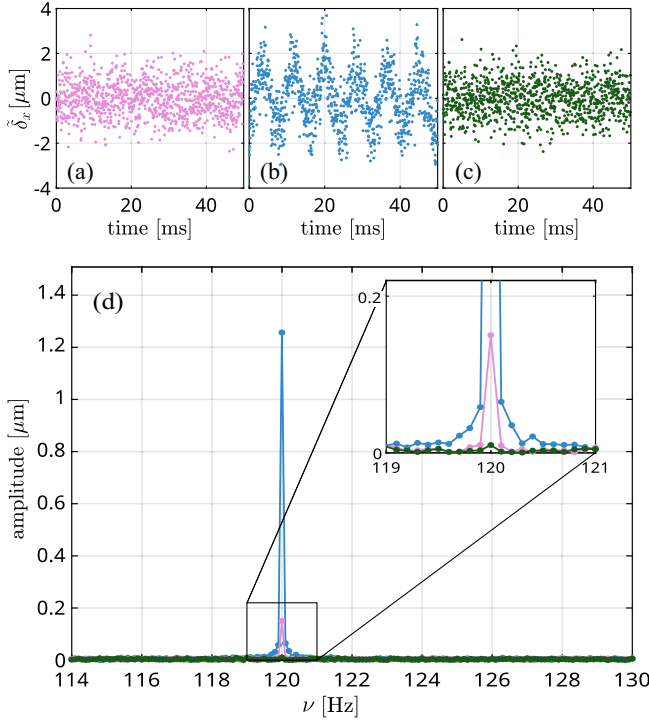


FIG. 2. Amplification and suppression of harmonic disturbances. (a)–(c) Examples of the measured signals in the time domain for three scenarios: (a) pink, displacement of the input beam measured after passing only one arm of the interferometer; (b) blue, displacement measured at the dark port; (c) green, displacement measured at the bright port. The noise of the position reading is dominated by electrical noise in the position sensitive detector. (d) The amplitude spectra of the signals measured over 10 s for the three cases.

$$\begin{aligned} \frac{\tilde{\delta}^{C/D}}{\delta} &= \frac{\text{Tr}[\langle \phi_{\pm} | \langle \phi_{\pm} | (\mathbf{P}_A - \mathbf{P}_B) \rho] }{\text{Tr}[\langle \phi_{\pm} | \langle \phi_{\pm} | \rho]} \\ &= \frac{2\xi}{1 + \xi^2 \pm \eta(1 - \xi^2)}. \end{aligned} \quad (10)$$

For Gaussian modes $\chi(x)$, this is a precise description of the shift of the beam-centroid in the output ports for arbitrary δ , while for general mode profiles there will be deviations increasing with δ [16].

While the amplification of shifts is maximal for non-vanishing ξ , see Appendix B of the End Matter for detailed analysis, the suppression of shifts is maximal for $\xi = 0$. In this case, due to the symmetrization by the Dove prism, the suppression of the centroid movement is independent of the coherence of the interferometer, i.e., it holds for arbitrary η , but, as $|\delta|$ increases, the shape of the output beam becomes distorted (see Appendix C of the End Matter). Provided coherence, all antisymmetric modes interfere destructively at the bright port. Thus, for small $|\delta|$, the interferometric method significantly reduces the disturbances of the input beam. Moreover, in contrast to conventional mode filters,

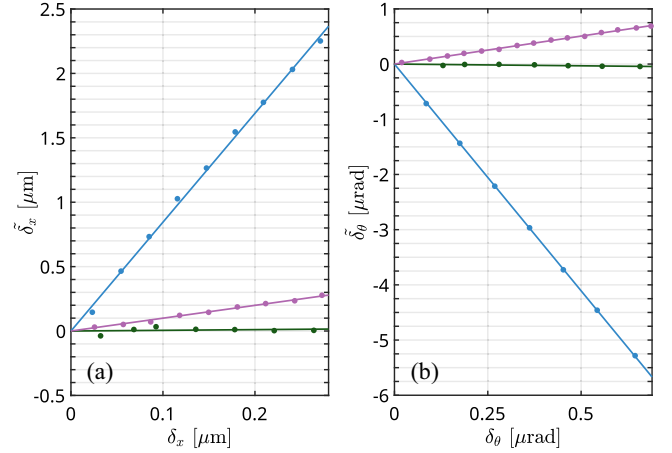


FIG. 3. Amplification and suppression of shifts (color coding as before). (a) Measured displacement $\tilde{\delta}_x$ for increasing position shifts obtained with asymmetry parameter $\xi = 0.065$. The straight lines represent the linear fit to the data points where the slope equals the amplification or suppression factors. (b) Measured displacement $\tilde{\delta}_\theta$ for increasing tilts with $\xi = -0.079$.

the interferometric device does not have to be tailored to the particular parameters of the input beam.

For the experimental demonstration we employ a folded Mach-Zehnder interferometer (MZI) in a displaced Sagnac configuration (Appendix A of the End Matter) for which we obtain a coherence parameter of $\eta = 0.993 \pm 0.001$. To demonstrate the full capability of the method, two Dove prisms are used, one in each arm, oriented in the x and y directions, respectively. We apply controllable displacements/tilts of the input beam, which are in the $\mu\text{m}/\mu\text{rad}$ range, and thus several orders of magnitude smaller than the waist w_0 /divergence angle Θ of our Gaussian input beam ($w_0 = 673 \pm 5 \mu\text{m}$ and $\Theta = 383 \pm 3 \mu\text{rad}$). The beam centroid in the output port is analyzed with position sensitive detectors. By controlling the input power, we set the same output power for all measurements.

For a first demonstration we introduce a periodically changing displacement $\delta_x(t) = \delta_{x0} \sin 2\pi\nu t$ in the input port, with a frequency $\nu = 120 \text{ Hz}$ and amplitude $\delta_{x0} = 0.15 \mu\text{m}$. This signal can be analyzed directly by blocking arm B (including the Dove prism orientated along x), but for small displacements it is hidden in electronic noise [Fig. 2(a)]. Contrary to this, with both arms open, the displacement is clearly visible in the dark output port [Fig. 2(b)], while no displacement is visible at the bright output [Fig. 2(c)]. Spectral analysis allows for isolating the signal from noise and makes the signal amplification in the dark port (blue) and the suppression in the bright port (green) relative to the input beam displacement (pink) more visible [Fig. 2(d)]. The amplification of signals is not restricted to a single frequency but can even be used to improve the transmission of audio recordings, as shown in Supplemental Material [41].

For a direct analysis of the effectiveness of the device, we measure the displacement $\tilde{\delta}$ of the output beam dependent on

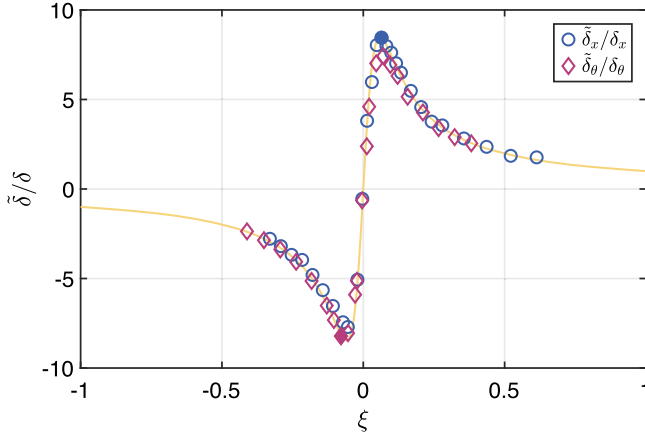


FIG. 4. Amplification factor measured in output port D as a function of the asymmetry parameter ξ for the decoherence parameter $\eta = 0.993$. Both displacement (circles) and tilt (diamonds) show the same dependence, fitting well with the theoretical description (10) (yellow line). The filled circle and diamond correspond to the data displayed in Figs. 3(a) and 3(b), respectively.

the shift δ of the input beam. Figure 3 compares the amplification in the dark output and the suppression of the shift in the bright output with the displacement of the input beam. Varying the beam splitter asymmetry, the highest amplification factor observed for the displacement was $(\tilde{\delta}_x^D/\delta_x) = 8.5 \pm 0.3$ [Fig. 3(a)] and $(\tilde{\delta}_\theta^D/\delta_\theta) = -8.2 \pm 0.2$ for the tilt [Fig. 3(b)]. Within errors, both values agree very well with the theoretical prediction (10) of $|(\tilde{\delta}^D/\delta)|_{\max} = 8.5 \pm 0.6$.

For these settings, the simultaneously achieved suppression in the bright port is shown with the green dots and lines in Fig. 3. With the same asymmetry parameters as before, displacements have been suppressed by a factor of $(\tilde{\delta}_x^C/\delta_x) = 0.05 \pm 0.04$ and similarly tilts by $(\tilde{\delta}_\theta^C/\delta_\theta) = -0.06 \pm 0.02$, consistent with the theoretical predictions $(\tilde{\delta}^C/\delta) \approx \xi$. As reference, for the beam just passing through one arm of the interferometer (pink) the slopes of the lines through the data points are very close to one in the cases of both displacement and tilt, $(\tilde{\delta}_x/\delta_x) = 1.00 \pm 0.04$ and $(\tilde{\delta}_\theta/\delta_\theta) = 1.01 \pm 0.02$.

To further demonstrate the general validity of Eq. (10), we determine the amplification factors in the dark port (Fig. 4) as a function of the asymmetry parameter ξ , which, contrary to (8), are finite due to decoherence. The experimental data match the theoretical prediction (yellow line) with very high accuracy. Both types of shifts show the same behavior, which represents a manifestation of the universality property previously observed for shifts inside an interferometer [16].

Although the suppression in the bright port was seen already in Figs. 2 and 3 for small but nonvanishing ξ , it is maximized by choosing $\xi = 0$. To demonstrate this effect, we simultaneously applied displacement along the x and tilt

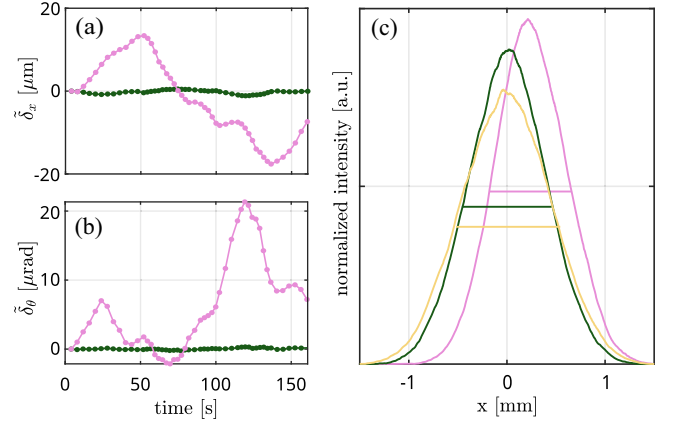


FIG. 5. Stabilization in the bright port. (a) The time-dependent displacement of the beam measured over a duration of 160 s (pink) is suppressed in the bright port (green). (b) The same is observed for a simultaneous time-dependent tilt. (c) Modification of the beam profile. The pink line shows the profile of the beam displaced by $\delta_x = 245 \pm 2 \mu\text{m}$. For better comparison, all profiles are normalized. Because of interference, the beam at the bright output port (green line) is only slightly broader compared with the initial undisturbed beam. Without interference, the output profile (yellow line) is clearly broadened further.

along the y direction, shown as pink lines in Figs. 5(a) and 5(b), respectively. In the bright output port (green lines), we observe only minute changes of the centroid position.

For small $|\delta|$ the changes of the beam profile are hard to resolve. (They can be estimated with an interference experiment [42].) Thus, to illustrate mode disturbance and its reduction, the beam was now shifted by a much larger displacement of $\delta_x = 245 \pm 2 \mu\text{m}$. We consider three cases of disturbance, the externally shifted profile passing through the interferometer (pink), the interference profile (green), and the profile obtained when the two arms were made fully incoherent via orthogonal polarizations [Fig. 5(c)]. The similarity of modes is demonstrated by comparing the widths of the respective profiles. The full width at half maximum of the undisturbed profile of $836 \pm 2 \mu\text{m}$ is increased to $915 \pm 2 \mu\text{m}$ in the case of constructive interference, which is significantly smaller than the increase to $1064 \pm 4 \mu\text{m}$, observed in the case without any coherence.

In conclusion, this letter introduces an interferometric amplification method which, in contrast to conventional weak value amplification schemes, allows for amplifying effects on the beam occurring *outside* the interferometer. While the design of this new device originates from discussions on interpretational questions about the presence of the photons in the arms of an interferometer [29–34], its practical advantage (which holds in both the quantum and the classical regimes) is independent of the particular interpretation of the effects discussed therein.

We showed that, due to an additional reflection in one arm, the new device amplifies external signals in the dark

port of an interferometer. In addition, our device provides a clear suppression of the centroid movement, along with a filtering of antisymmetric modes in the bright port with a fully passive device.

Our method concentrates information about the shifts of the incoming beam in the dark port, enhancing their measurability. One can use this information as feedback to further compensate the shifts, thereby enabling even better mode recovery. Finally, the concept of using additional “reflections” in one of the arms can be generalized to other degrees of freedom, e.g., for polarization of light using a half-wave plate, further extending the range of applications of the method introduced in this Letter.

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Data availability—The data that support the findings of this article are openly available [43].

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End Matter

Appendix A: Details of experimental setup—The actual experimental setup is a Sagnac-like MZI with the two arms displaced with respect to each other and operated at a wavelength of 810 nm (Fig. 6). Dove prisms are placed in each of the two arms, one oriented along the x direction and the other along the y direction, in order to achieve both a compensation of dispersion,

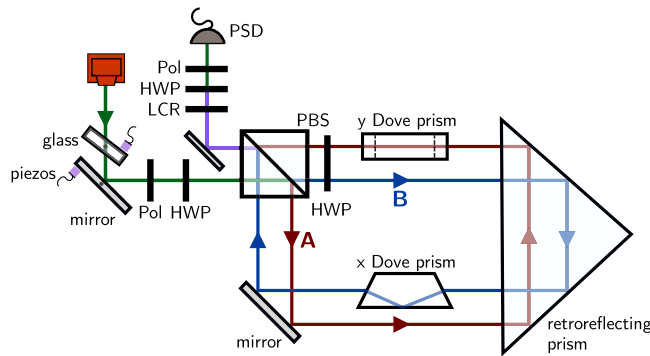


FIG. 6. Experimental Setup. Sagnac-like, folded MZI with Dove prisms oriented in the x and y directions in the arms. A polarizing beamsplitter is used together with a HWP to realize the asymmetry parameter ξ . The additional polarization encoding of the arms is further exploited to realize the bright and dark ports by projection onto certain polarization states before the lateral position sensitive detector (PSD).

as well as a sensitivity of the device to any transverse shift of the input beam. Because of the fact that only one mirror, one beam splitter, and one retroreflecting prism are used to realize both interferometer arms, this interferometer type naturally provides an improvement of phase stability.

The polarization degree of freedom is employed to realize the tunable asymmetry parameter ξ . For this, a polarizing beamsplitter (PBS) together with a rotatable half-wave plate (HWP) is used as the input beamsplitter, such that the state inside the interferometer (without the transverse modes) is given by

$$\mathcal{N}[(1 + \xi)|A\rangle|H\rangle + (1 - \xi)|B\rangle|V\rangle]. \quad (\text{A1})$$

To reduce the effects of imperfections, an additional HWP placed inside the interferometer was acting such that both beams in the interferometer exit the polarizing beamsplitter after one reflection and one transmission, but still with orthogonal polarizations. To obtain interference, this output beam is projected onto either $|P\rangle = [1/\sqrt{2}](|H\rangle + |V\rangle)$ or $|M\rangle = [1/\sqrt{2}](|H\rangle - |V\rangle)$, to realize the bright and the dark output port, respectively. (The case with full decoherence is observed when the polarizer is removed.) This projection is implemented via a liquid crystal retarder (LCR) set to act as

quarter-wave plate, a rotatable half-wave plate, and a polarizer.

The position of the centroid of the beam is measured by a silicon photodiode-based lateral sensing detector. Tilt is measured by comparing the centroid positions on two detectors at different positions.

In order to introduce controllable displacements and tilts of the input beam, piezoelectric actuators and a motor are employed to rotate a mirror and a 1.2 cm thick glass plate, respectively. Apart from observing the shift of the centroid of the output in bright and dark ports for arbitrary asymmetry parameters ξ , the shift of the input beam is measured by blocking one of the arms.

*Appendix B: Analysis of the maximal amplification—*According to Eq. (8), for vanishingly small ξ the amplification would be unbounded, but decoherence sets a limit to it. From Eq. (10) one obtains a maximal amplification factor of the beam shift in the dark port, which occurs for $\xi = \pm \sqrt{(1-\eta)/(1+\eta)}$ and is given by

$$\left| \frac{\tilde{\delta}^D}{\delta} \right|_{\max} = \frac{1}{\sqrt{1-\eta^2}}. \quad (\text{B1})$$

In our experiment, the initial mode $\chi(q)$ is approximately a Gaussian, for which $\eta_\delta = e^{-(\delta^2/2\Delta^2)}$, where Δ is the width of the intensity distribution either in position, $\Delta = (w_0/2)$, or in angle, $\Delta = (\Theta/2)$. The denominator in Eq. (B1) becomes $\sqrt{1-\eta_I^2 e^{-(\delta^2/\Delta^2)}}$, and the functional dependence of the maximally achievable amplification is described in Fig. 7(a).

For $\eta_I < 1$, there is a finite range of shifts, $|\delta| \ll \Delta\sqrt{1-\eta_I}$, for which the asymmetry parameter for maximal amplification and the amplification factor are approximately constant. The range of shifts in the runs of our amplification demonstrations is well inside this region; see Fig. 7(b).

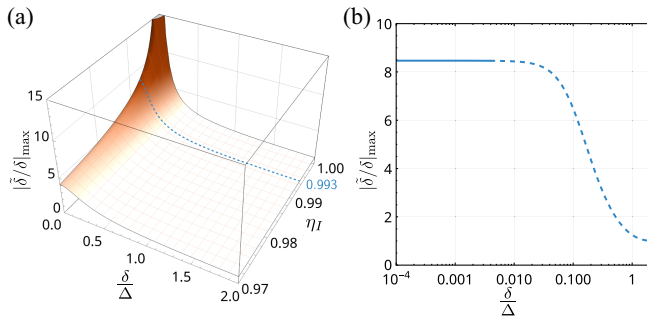


FIG. 7. (a) Maximally achievable amplification as a function of decoherence parameters (δ/Δ) and η_I . The blue line corresponds to $\eta_I = 0.993$ of our experiment. (b) The blue line of (a) in logarithmic scale. The continuous line corresponds to shifts of our experimental runs, while the dashed continuation corresponds to the theoretical prediction for larger shifts with the same η_I .

*Appendix C: Derivation of the spatial mode χ of the interferometer output—*For some shift δ (here representing any combination of δ_x and δ_θ) and the corresponding coordinate q , the state inside the interferometer after the action of the Dove prism can be written as

$$|\Psi(q)\rangle = \mathcal{N}[(1+\xi)\chi(q-\delta)|A\rangle + (1-\xi)\chi(q+\delta)|B\rangle], \quad (\text{C1})$$

which is a generalization of Eq. (3).

After the beamsplitter, the state of the system is given by

$$\begin{aligned} \mathcal{N} \Big[& \left(\chi(q-\delta) + \chi(q+\delta) + \xi[\chi(q-\delta) - \chi(q+\delta)] \right) |C\rangle \\ & + \left(\chi(q-\delta) - \chi(q+\delta) + \xi[\chi(q-\delta) + \chi(q+\delta)] \right) |D\rangle \Big]. \end{aligned} \quad (\text{C2})$$

The expressions for the ports can be analyzed by considering the Taylor expansion of χ at each point q ,

$$\chi(q \pm \delta) = \chi(q) \pm \delta\chi^{(1)}(q) + \frac{\delta^2}{2}\chi^{(2)}(q) \pm \dots, \quad (\text{C3})$$

where $\chi^{(k)}$ denotes the k th derivative of χ . With

$$\chi(q-\delta) + \chi(q+\delta) = 2\chi(q) + \delta^2\chi^{(2)}(q) + \mathcal{O}(\delta^4) \quad (\text{C4})$$

$$\chi(q-\delta) - \chi(q+\delta) = 2\delta\chi^{(1)}(q) + \mathcal{O}(\delta^3), \quad (\text{C5})$$

one obtains for the output state

$$\begin{aligned} \mathcal{N} \Big[& \left(\chi(q) + \frac{\delta^2}{2}\chi^{(2)}(q) - \xi\delta\chi^{(1)}(q) + \mathcal{O}(\delta^3) \right) |C\rangle \\ & + \xi \left(\chi(q) + \frac{\delta^2}{2}\chi^{(2)}(q) - \frac{\delta}{\xi}\chi^{(1)}(q) + \mathcal{O}(\delta^3) \right) |D\rangle \Big]. \end{aligned} \quad (\text{C6})$$

If one neglects all but the first order, the output state becomes

$$\begin{aligned} \mathcal{N} \Big[& \left(\chi(q) - \xi\delta\chi^{(1)}(q) \right) |C\rangle + \xi \left(\chi(q) - \frac{\delta}{\xi}\chi^{(1)}(q) \right) |D\rangle \Big] \\ = & \mathcal{N} \left(\chi(q - \xi\delta) |C\rangle + \xi\chi\left(q - \frac{\delta}{\xi}\right) |D\rangle \right), \end{aligned} \quad (\text{C7})$$

which directly leads to Eq. (4).

For a perfectly coherent and balanced interferometer, i.e., $\xi = 0$, all odd components interfere destructively in the bright port C , see (C2) and (C3), leading to the mode

$$\chi^C(q) = \mathcal{N} \left[\chi(q) + \frac{\delta^2}{2}\chi^{(2)}(q) + \mathcal{O}(\delta^4) \right]. \quad (\text{C8})$$

Thus, any distortions of the mode appear only in orders of δ^2 and higher. However, if imperfections are present, an incoherent contribution also remains in both output ports, which includes the first order of δ .

This effect can be quantified using η_I , (the δ -independent) decoherence, best described by some coupling to other degrees of freedom denoted by $|Q_k\rangle$, such that $\eta_I = \langle Q_A | Q_B \rangle$. The state in the interferometer can then be written as

$$\frac{1}{\sqrt{2}} [\chi(q - \delta) |A\rangle |Q_A\rangle + \chi(q + \delta) |B\rangle |Q_B\rangle]. \quad (\text{C9})$$

After postselection onto the bright port $|C\rangle$, the state of mode and additional degrees of freedom becomes

$$\frac{1}{\sqrt{2(1 + \eta)}} [\chi(q - \delta) |Q_A\rangle + \chi(q + \delta) |Q_B\rangle]. \quad (\text{C10})$$

By tracing out the other degrees of freedom, the mixed mode state in the bright port can be obtained. It consists of a mixture of the coherent superposition of the modes from the arms and of their incoherent sum. This can be illustrated by considering the intensity distribution at the bright port $I_{\text{out}}^C(q)$, which can be calculated by taking the modulus squared of Eq. (C10), leading to

$$I_{\text{out}}^C(q) = \frac{1}{2(1 + \eta)} \left(\underbrace{\eta_I |\chi(q - \delta) + \chi(q + \delta)|^2}_{\text{coherent part}} + (1 - \eta_I) \underbrace{[|\chi(q - \delta)|^2 + |\chi(q + \delta)|^2]}_{\text{incoherent part}} \right). \quad (\text{C11})$$

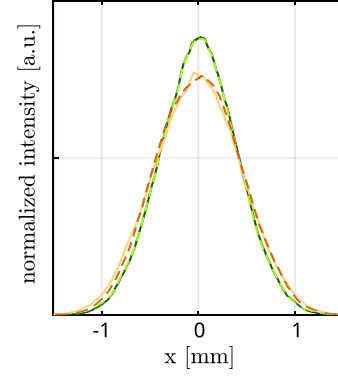


FIG. 8. Beam profiles in the bright port together with their theoretical description from Eq. (C11). Measured profile (dark green) and theoretical prediction (dashed light green) for the case with coherence, as well as measured profile (yellow) and theoretical prediction (dashed red) for the case without coherence.

The coherent and incoherent parts of Eq. (C11) are shown in Fig. 5(c). The dark green profile corresponds to an almost fully coherent case ($\eta_I = 0.993$), where the anti-symmetric components are removed and the mode is thus significantly restored. By contrast, the yellow profile corresponds to a fully incoherent case with $\eta_I = 0$, where the profile is given merely by the incoherent mixture of the two symmetrically shifted profiles from the two interferometric arms. For illustration they are plotted again in Fig. 8. Additionally, the red and light green dashed lines show the corresponding profiles calculated according to Eq. (C11), where the modes $\chi(q \pm \delta)$ have been obtained from the measured profiles from arms A and B.