Demonstration of a highly-sensitive tunable beam displacer with no movable elements based on the concept of weak value amplification

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Abstract: We report the implementation of a highly sensitive beam displacer based on the concept of weak value amplification that allows to displace the centroid of a Gaussian beam a distance much smaller than its beam width without the need to use movable optical elements. The beam’s centroid position can be displaced by controlling the linear polarization of the output beam, and the dependence between the centroid’s position and the angle of polarization is linear.

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6. For example, the tweaker plate from Thorlabs model XYT-A is a 2.5 mm thick plane-parallel plate that allows sub-mm level precision beam displacement.
7. II-VI UK LTD offers thin film polarizers made of either ZnSe or Ge that can be used to split or combine an input beam into two components with orthogonal polarizations. The polarizer is oriented at Brewster’s angle with respect to the input beam so that the vertical polarization is highly reflected whereas the horizontal is transmitted.
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1. Introduction

A polarization beam displacer (BD) is a device that splits an input polarized beam into two spatially separated beams that propagate parallel with orthogonal polarizations. Commercially available BD are made of birefringent materials like Calcite crystal, Barium Borate ($\alpha$-BBO) crystal, Rutile crystal or Yttrium Vanadate (YVO$_4$) among others. In these devices, due to the intrinsic birefringence of the material, the propagation direction of the ordinary polarized beam is unchanged whereas the extraordinary component deviates inside the crystal [1]. The beam separation is fixed and its maximum value depends on the crystal material and length.

A BD can also be used to displace spatially the position of a single optical beam, for example by using an input beam with vertical polarization at the input. However, in many applications it is desired to move the position of a single beam over a given interval [2]. To the best of our knowledge, a scan of the position of a single beam can be implemented either by using an arrange of moving mirrors [3, 4], a plane-parallel plate or a tunable beam displacer (TBD) [5].

In the first case, a set of mirrors are arranged in a configuration that allows to change the position of the output beam when one or various mirrors are rotated. In the second case, a transparent plane-parallel plate of certain thickness such as a tweaker plate [6], a thin film polarizer [7] or a plate beam splitter [8] is rotated with respect to an axis parallel to the surfaces offsets the position of the input beam after consecutive refractions in the air-plate and plate-air interfaces. The beam displacement is proportional to the plate thickness and the rotation angle. Finally, in a TBD, two mirrors fixed to a platform are rotated with respect to a polarizing beam splitter (PBS). When the angle is different from zero, the input beam splits into two parallel propagating beams with orthogonal polarizations separated by a distance proportional to the rotation angle. If the input beam polarization is horizontal or vertical, a single beam is obtained at the output.

For all the cases mentioned above the beam shift results from the mechanical rotation of an optical element. This condition imposes a technical limitation on the sensitivity of the beam displacer since it directly relates to which sensitivity we can achieve when performing the rotation. In a plane-parallel plate displacer one can obtain a typical beam shift of $\approx 12.5 \mu$m/deg, where the proportionality factor depends on the thickness of the plate and its index of refraction. For a TBD, the proportionality factor is $\approx 5$mm/deg which depends mainly on the distance from the mirrors to the PBS.

In this paper we demonstrate an optical device that can outperform the limitations imposed by the use of movable optical elements. In our scheme, we do not make use of the tunable reflections or/and refractions induced by the rotation of a specific optical element. Instead, we make use of the concept of weak value amplification [9, 10], that allows to convert two beams with orthogonal polarizations that slightly overlap in space into a single beam whose center can be tuned by only modifying the linear polarization of the output beam.

2. Scheme for a highly sensitive tunable beam displacer

Fig. 1 (a) shows the general scheme of the beam displacer. It is based on the device described by Feldman et al. [11] with the difference that our device does not use quarter waveplates that limit the spatial quality of the beam and the wavelength range of operation. A laser generates an input Gaussian beam with amplitude $E_{in}(x, y) = E_0 \exp \left[ -\frac{(x^2 + y^2)}{2w^2} \right]$, where $E_0$ is the peak amplitude, and $w$ is the $1/e$ beam width. The polarization of the input beam is selected to be $e_{in} = (x + y)/\sqrt{2}$, with the help of a polarizer. A polarizing beam splitter (PBS), rotated a small angle $\theta$ with respect the direction of propagation of the input beam, splits the input beam into two output beams with orthogonal polarizations, where the horizontal component is shifted a small distance $+\Delta x$ with respect to the input beam centroid, while the vertical component is shifted a distance $-\Delta x$. Fig. 1(b) shows the beam centroid displacement for each polarization as
Fig. 1. (a) General scheme of the tunable beam displacer. A polarization-dependent beam displacement is introduced by rotating the polarizing beam splitter (PBS) an angle $\theta$ with respect to the direction of propagation of the input Gaussian beam. Input and output polarizers (POL) control the corresponding polarizations. (b) Beam displacement before traversing the second polarizer for the horizontal (solid line) and vertical (dashed line) components of the optical beam as a function of the rotation angle $\theta$. The shaded region indicates the region where the beams with orthogonal polarizations still overlap.

After recombination of the two orthogonal beams, slightly displaced one with respect to the other a distance $2\Delta x$, and projection into the polarization state $e_{\text{out}} = \cos \beta x + \sin \beta y$ by using a second polarizer, the amplitude of the output beam writes

$$E_{\text{out}}(x,y) = \frac{E_0 \cos \beta}{\sqrt{2}} \exp \left\{ \left[ -\left( (x-\Delta x)^2 + y^2 \right) / (2w^2) \right] + i \phi \right\} + \frac{E_0 \sin \beta}{\sqrt{2}} \exp \left\{ -\left[ (x+\Delta x)^2 + y^2 \right] / (2w^2) \right\},$$

where $\phi$ takes into account any optical path difference between the orthogonal polarizations that could have been introduced, i.e., due to misalignment between the optical beams that leaves the PBS through different output ports.

Since the spatial shape of the beam in the $x$ and $y$ directions are independent, and the displacement is only considered along the $x$ direction, for the sake of simplicity we will be looking only at the beam shape along the $x$ direction. The intensity of the output beam, $I_{\text{out}}(x) = |E_{\text{out}}(x)|^2$ writes

$$I_{\text{out}}(x) = \frac{I_0}{2} \left\{ \cos^2 \beta \exp \left[ -(x-\Delta x)^2 / w^2 \right] + \sin^2 \beta \exp \left[ -(x+\Delta x)^2 / w^2 \right] + \exp \left( -\Delta x^2 / w^2 \right) \sin 2 \beta \exp \left( -x^2 / w^2 \right) \cos \phi \right\}. \quad (2)$$

We fix the angle $\theta$, which generates a certain displacement $\Delta x$, as shown in Fig. 1(b). Fig. 2 shows the output intensity, after traversing the second polarizer, for three different angles: $\beta = 30^\circ$, $\beta = 45^\circ$ and $\beta = 60^\circ$. An angle $\beta = 45^\circ$ corresponds to choosing the polarization of the output beam equal to the polarization of the input beam. Inspection of Fig. 2 shows that $I_{\text{out}}(x)$ corresponds to a single peaked Gaussian-like distribution whose center is slightly
shifted with respect to the input beam centroid by an amount smaller than $\Delta x$, far less than the beam width. We also observe that this small shift is polarization-dependent, i.e., it depends on the value of the angle $\beta$. This effect can be easily visualized by calculating the beam’s centroid $\langle x \rangle = \int x I_{\text{out}}(x) \, dx / \int I_{\text{out}}(x) \, dx$. We also show the insertion loss (expressed in decibels) $L = -10 \log_{10} \left[ \frac{P_{\text{out}}}{P_{\text{in}}} \right]$ where $P_{\text{in}}$ and $P_{\text{out}}$ designate the input and output power of the beams, respectively. The polarization-dependent shift is always associated with a similarly polarization-dependent insertion loss.

Making use of Eq. (2), the centroid of the output beam can be written as

$$\langle x \rangle = \frac{\cos 2\beta}{1 + \gamma \sin 2\beta \cos \phi} \Delta x,$$

(3)

where $\gamma = \exp(-\Delta x^2/w^2)$ is close to unity since $\Delta x \ll w$. Similarly, the insertion losses is given by

$$L = -10 \log_{10} \left[ \frac{1}{2} (1 + \gamma \sin 2\beta \cos \phi) \right].$$

(4)

Figs. 3(a) and Fig. 3(b) show the beam centroid position and the insertion loss as a function of the output polarizer angle (post-selection angle $\beta$). The displacements $\pm \Delta x$ for each polarization are indicated by horizontal dashed lines.

Equation (3) shows that the beam centroid $\langle x \rangle$ is related to the polarization-dependent displacement $\Delta x$ by a relationship of the form $\langle x \rangle = A \cdot \Delta x$, where $A = \cos 2\beta \left[ 1 + \gamma \sin 2\beta \cos \phi \right]^{-1}$ is the amplification factor. Most applications of the weak value amplification concept (see, for instance, [12] and [13] for two recent reviews about this topic) are interested in a regime where $A \gg 1$. However this is not the only regime where weak value amplification can be of interest [14]. Here, on the contrary, we are interested in the regime $A \ll 1$, where beam displacements much smaller than the beam width of the input beam are observed. In this regime, close to $\beta = 45^\circ$ (input and output polarizations are similar) the centroid position of the output beam varies almost linearly with respect to the postselection angle over the range $-\Delta x \leq \langle x \rangle \leq +\Delta x$ [see Fig. 3(a)], and the insertion loss is small for the same interval [see Fig. 3(b)], making the weak value amplification scheme described in Fig. 1(a) suitable for implementing a low-loss highly sensitive tunable beam displacer where the spatial shift is controlled by projection into a given polarization state, with no movable optical elements.
3. Experimental demonstration

In order to demonstrate the feasibility of the tunable beam displacer discussed above, we implement the set-up shown in Fig. 1(a). The input beam is a He-Ne laser (Thorlabs HRP005S) and the input beam is Gaussian with a beam waist of \( \sim 600 \mu m \left( 1/e^2 \right) \). Two Glan-Thomson polarizers (Melles Griot 03PT0101/C) are used to select the initial and final states of polarization before and after the TBD. The initial state of polarization is selected by rotating the first polarizer at \(+45^\circ\), and the output polarization is selected by rotating the second polarizer an angle \( \beta \) with respect to the horizontal direction.

The TBD is composed of two aluminum mirrors, positioned equidistantly from a 1.0 cm polarizing beam splitter (PBS), and fixed to a L-shaped platform that is free to rotate an angle \( \theta \) with respect to the PBS center. For a given angle, the separation between the two output beams depends on \( \theta \), the distance from the mirrors to the PBS, and the sizes of the input beam and the PBS. In the setup, the distance from each mirror to the PBS is set to 7 cm and the platform is rotated with a motorized rotation stage.

The output beam cross section is detected by a CCD camera (Santa Barbara Instruments ST-1603ME) with 1530 \( \times \) 1020 pixels (9 \( \mu m \) pixel size). With the data measured, the corresponding centroid position is calculated using a simple MATLAB program. To avoid CCD saturation, neutral density absorptive filters (Thorlabs - Serie NE-A) are used.

Before running the experiment an initial alignment is carried out without using the output polarizer. This preparation consists of two steps. Firstly, the input beam enters the TBD, \( \theta \) is set to zero and the angle for each mirror is set such that each beam reflected on the mirrors propagates towards the PBS center and only one beam is seen in the camera. The centroid of this image sets the reference point from which the new beam’s centroid position, \( \langle x \rangle \), will be measured. Secondly, the L-shaped plaque is rotated by an angle \( \theta \) to define the small initial displacement, \( \Delta x \), between the components with orthogonal polarization. For our experiment, \( \Delta x = 120 \mu m \), which yields \( \gamma = \exp\left( -\Delta x^2 / w^2 \right) \) equal to 0.96. Once the reference centroid is defined, the output polarizer is introduced. A set of images are recorded for different values of \( \beta \), and their corresponding centroids are calculated.

The experimental results are presented as dots in Fig. 4. Panel (a) depicts the measured beam displacement \( \langle x \rangle \) as a function of the output polarizer angle (\( \beta \)). The error bars take into account the uncertainty introduced by the CCD camera pixel size of 9 \( \mu m \). The solid line in Fig. 4(a)
corresponds to the best data fit using Eq. (3) where $\phi$ is the fitting parameter. From the best fit we obtain $\phi = 54^\circ$, which corresponds to a difference in optical path of $\sim 0.094 \mu m$, mainly due to misalignment. In the region $0^\circ \leq \beta \leq 90^\circ$ we observe that the beam’s centroid varies almost linearly with respect to the output polarizer angle. In this interval, the best fit gives $\langle x \rangle = -2.32 \beta \pm 114.24 \mu m$, which demonstrates a region of operation that goes approximately between $-120 \mu m$ to $+120 \mu m$, in agreement with the initial displacement of $\Delta x = 120 \mu m$. The sensitivity of the shift is limited by the angular resolution achievable when selecting the output polarization. As an example, if a manual rotation mount with resolution of $10 \text{arcmin}$ is used to select the output polarization, a minimum beam displacement step of $380 nm$ can be obtained without using opto-mechanical components. In panel (b) we show the measured (dots) and theoretical (solid line) insertion loss, given by Eq. (4) for $\phi = 54^\circ$ and $\gamma = 0.96$. The maximum insertion loss in this region is $\sim 3\text{dB}$.

4. Conclusions

In conclusion, we have implemented and demonstrated a low-loss tunable beam displacer based on the concept of weak value amplification that allows to displace the centroid of a beam with very high sensitivity. Interestingly, the relationship between the beam’s centroid shift and the output polarization is almost linear, and the sensitivity of the beam displacement is limited by the sensitivity available for selecting the output polarization. From the measurements, we were able to shift the centroid of a Gaussian beam with a beam waist of $\sim 600 \mu m$, over an approximate interval that goes from $-120 \mu m$ to $+120 \mu m$ in steps of less than $\sim 1 \mu m$.

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