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

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Abstract: We report the implementation of a highly sensitive tunable 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 deflect the direction of propagation of the input beam with 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.

OCIS codes: (230.0230) Optical devices; (260.3160) Interference; (260.5430) Polarization.

References and links

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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.
8. For instance, Edmund Optics plate beam splitter model #49-684 is a 3 mm thick N-BK7 splitter that transmits 70% of the input power and operates in the visible regime.
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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 BDs 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 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 to offset 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 $\approx 12.5\,\mu\text{m/deg}$, where the proportionality factor depends on the thickness of the plate and its index of refraction. For a TBD, the proportionality factor is $\approx 5\,\text{mm/deg}$ 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

Figure 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 $E_{\text{in}}(x,y) = E_0 \exp\left[-(x^2+y^2)/(2w^2)\right]$, 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 $\mathbf{e}_{\text{in}} = (\mathbf{x}+\mathbf{y})/\sqrt{2}$, with the help of a polarizer.

A TBD set at an angle θ, 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 $-\Delta x$. Figure 1(b) shows the beam centroid displacement for each polarization as a function of the TBD rotation angle

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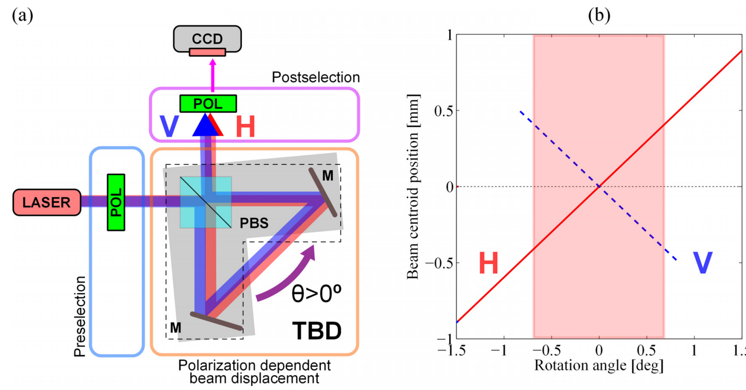

Fig. 1. (a) General scheme of the tunable beam displacer. A polarization-dependent beam displacement is introduced by a TBD set at an angle θ. Input and output polarizers (POL) control the corresponding polarizations. (b) Beam displacement before traversing the second polarizer for the horizontal (solid line) and vertical (dashed line) components of the optical beam a function of the rotation angle θ. The shaded region indicates the region where the beams with orthogonal polarizations still overlap.

(θ). The TBD is set to operate in the shaded region shown in Fig. 1(b), where the two output beams with orthogonal polarizations still overlap. i.e., the distance between the two beam centroids ($2\Delta x$) is small compared to the beam diameter (w).

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 $\mathbf{e}_{\text{out}} = \cos\beta\,\mathbf{x} + \sin\beta\,\mathbf{y}$ by using a second polarizer, the amplitude of the output beam writes

$$\mathbf{E}_{\text{out}}(x) = E_0 \left\{ \cos\beta \exp\left(-(x-\Delta x)^2/2w^2 + i\phi\right) + \sin\beta \exp\left(-(x+\Delta x)^2/2w^2\right) \right\}, \quad (1)$$

where ϕ 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

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

Figure 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 Δx, 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 β. This effect can be easily visualized by calculating the beam's centroid $\langle x \rangle = \int x I_{out}(x)\,\mathrm{d}x / \int I_{out}(x)\,\mathrm{d}x$. We also show the insertion loss (expressed in decibels) $L = -10\log_{10}[P_{\text{out}}/P_{\text{in}}]$ where P_{in} and P_{out} designate the input and output power of

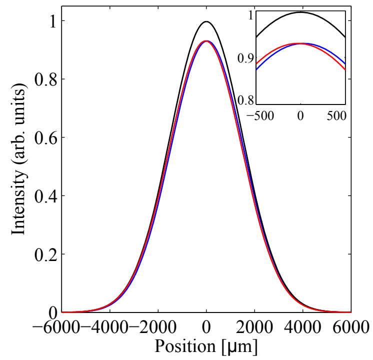

Fig. 2. Beam profile after traversing the second polarizer for three different output polarizations ($\beta = 30^\circ$, $\beta = 45^\circ$ and $\beta = 60^\circ$). The insets shows more clearly the small beam displacements for different post-selections of the output state of polarization.

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

$$\langle x \rangle = \frac{\cos 2\beta}{1 + \gamma \sin 2\beta \cos\phi} \Delta x \,, \tag{3}$$

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

$$L = -10 \log_{10} \left[\frac{1}{2} \left(1 + \gamma \sin 2\beta \cos\phi\right) \right] . \tag{4}$$

Figures 3(a) and 3(b) show the beam centroid position and the insertion loss as a function of the output polarizer angle (postselection angle β). 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 Δx 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. In a quantum context, this amplification A is equal to the real part of the weak value of the observable $\hat{A} = |H\rangle\langle H| - |V\rangle\langle V|$ defined by $\langle \psi_i|\hat{A}|\psi_f\rangle / \langle \psi_i|\psi_f\rangle$ where $|\psi_i\rangle = (|H\rangle + |V\rangle)/\sqrt{2}$ and $|\psi_f\rangle = \cos\beta |H\rangle + \sin\beta |V\rangle$ are the polarization states before and after the weak measurement.

Most applications of the weak value amplification concept (see, for instance, [12] and [13] for two recent reviews) are interested in the regime $A \gg 1$, obtained by setting $\beta = -45^\circ + \varepsilon$, with ε small (input and output polarizations quasi orthogonal) which leads to an amplification factor equal to $\sim 1/\varepsilon$. However this is not the only regime where weak value amplification can be of interest [14]. For example in this paper, 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, $\beta = 45^\circ + \varepsilon$ (input and output polarizations quasi parallel), and the centroid position of the output beam varies linearly with respect to the postselection angle over the range $-\Delta x \leq \langle x \rangle \leq +\Delta x$ [see Fig. 3(a)]. The insertion loss is small in 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 need of using deflecting optical elements.

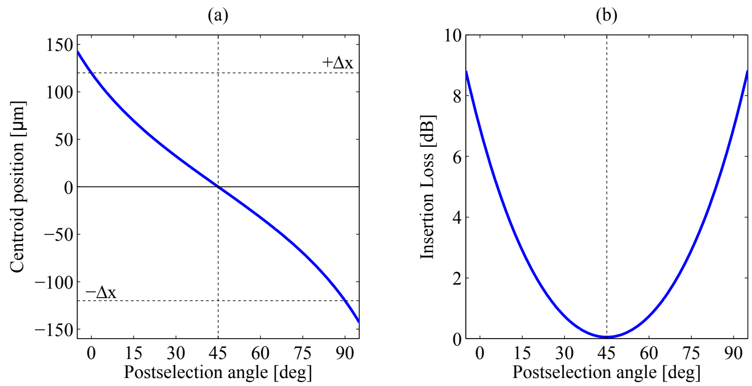

Fig. 3. (a) Centroid position as a function of the polarization selected of the output beam, given by the post-selection angle β. (b) Insertion loss as a function of the post-selection angle β. Data: $\Delta x = 120\,\mu$m, $\gamma = 0.9$ and $\phi = 0°$.

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 ($1/e^2$). 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 $+45°$, and the output polarization is selected by rotating the second polarizer an angle β with respect to the horizontal direction using a custom made rotating stage with resolution of 2 arcmin/step.

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 θ with respect to the PBS center. For a given angle, the separation between the two output beams depends on θ, 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 1530×1020 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, θ 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 θ to define the small initial displacement, Δx, between the components with orthogonal polarization. For our experiment, $\Delta x = 120\,\mu$m, which yields $\gamma = \exp(-\Delta x^2/w^2)$ 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 β, and their corresponding centroids are calculated.

The experimental results are presented as dots in Fig. 4. Figure 4(a) depicts the measured beam displacement $\langle x \rangle$ as a function of the output polarizer angle (β). The error bars take into account the uncertainty introduced by the CCD camera pixel size of $9\,\mu$m. The solid line corre-

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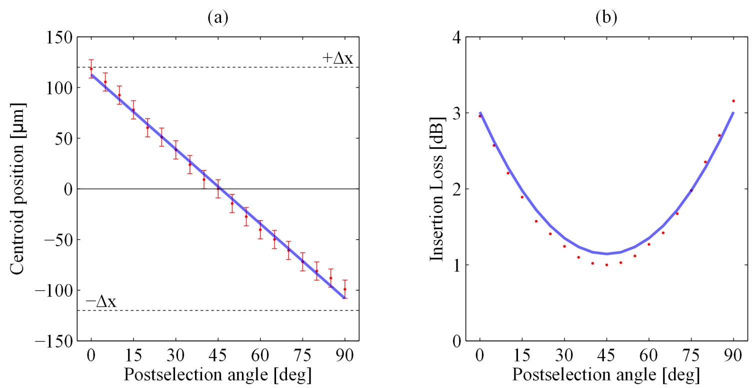

Fig. 4. (a) Measurement (dots) of the beam's centroid position as a function of the postselection angle β. The solid line corresponds to a linear fit given by $\langle x \rangle = -2.45\beta + 113\ \mu m$ with correlation coefficient $R = 0.998$. (b) Measured insertion loss (dots) and theory (solid line) obtained from Eq. (4) with $\Phi = 54^\circ$ as fitting parameter.

sponds to a linear fit given by $\langle x \rangle = -2.45\beta + 113\ \mu m$. The correlation coefficient of the linear fit ($R = 0.998$) indicates that our device exhibits a linear response over the interval $0^\circ \leq \beta \leq 90^\circ$. The minimum beam shift is limited by the angular resolution achievable when selecting the output polarization. As an example, if a rotation stage with resolution of 10 arcmin is used to select the output polarization, a beam displacement of 400 nm can be obtained since the sensitivity of our device is 40 nm/arcmin (2.45 μm/deg). If we compare this result with other commercial alternatives, such as the Edmund Optics plate beamsplitter #49-684, that provides a sensitivity of $\approx$ 360 nm/arcmin, or the Thorlabs tweaker plate XYT-A, with sensitivity $\approx$ 200 nm/arcmin, we observe that our device compares favorably since beam displacements with steps eight and five times smaller, respectively, can be obtained when using the same rotating stage to rotate the parallel-plane plate. In Fig. 4(b) we show the measured (dots) and theoretical (solid line) insertion loss, given by Eq. (4) for $\gamma = 0.96$ and the fitting parameter $\phi = 54^\circ$, which corresponds to a difference in optical path of $\sim 0.094\ \mu m$, mainly due to misalignment. The maximum insertion loss in this region is $\sim$ 3 dB.

4. Conclusions

We have 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 linear, and the sensitivity of the beam displacement is limited by the sensitivity available for selecting the output polarization. The presented experimental setup allows to shift the centroid of a Gaussian beam with a beam waist of $\sim$ 600 μm, over an interval that goes from $-120\ \mu$m to $+120\ \mu$m in steps of 80 nm. Interestingly, we achieve the sough-after beam displacement without the need to deflect the optical beam with movable optical elements.

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