Achromatic polarization-preserving beam displacer

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We present a novel device based on four orthogonal reflections that displaces an optical beam while preserving the state of polarization. The principle of operation is the overall compensation of the phase shifts that s and p polarization components of the light acquire at each reflection. This compensation, which relies on the use of four identical reflectors, is independent of the actual values of the s and p reflection coefficients and thus is independent of the wavelength. Measurements of the polarization-preserving properties with different sets of reflectors and tolerances to misalignments are presented. © 2001 Optical Society of America
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In many applications it is necessary to displace an optical beam. The widespread use of lasers for research and technology demands the steering of collimated beams from one spatial region in which the optical beams are prepared to another in which they are applied. In many of these situations the prepared beam is not aimed in the proper path, and beam displacers are necessary. The simplest solution, a two-mirror beam displacer, may be inadequate because the reflections may alter the state of polarization of the light. It is well known that s- and p-polarized waves acquire phases upon reflection that in general are not equal. Therefore the additional phases introduced by the reflections may leave the light beam in an undesirable polarization state. In addition, if the amplitudes of the s and p reflection coefficients are different, pseudorotations occur. If an application requires that linear polarization be preserved, then the two-mirror beam displacer will work only if the state of polarization is perpendicular or parallel to the plane that contains the beam and mirrors; reflections must be s and p polarized, respectively.

If the input state of polarization is not linear, or if the input plane of polarization is not parallel or perpendicular to the plane of the beam displacer, then the solution requires a more complex system. One solution is to use reflectors coated with thin films designed specifically to make the phase and amplitude differences of the s and p reflection coefficients zero. Several schemes for this are possible, including forcing each reflection to preserve the state of polarization[1,2] and forcing the combined reflections to preserve the state of polarization.[3,4] The coating specifications of the former are more restrictive than those of the latter. Another possibility is to coat one of the reflectors so that the s and p reflection coefficients are reversed.[5] However, since the reflection coefficients of a coated reflector rely on interference, these solutions are wavelength dependent. The degree to which these solutions are monochromatic or broadband depends on the number of layers and the materials used. In general, these types of optical component are specialty items and are not readily available from commercial vendors.

Here we present a simple and inexpensive beam displacer based on four reflections that preserves the state of polarization at any wavelength. The reflectors can have arbitrary characteristics, including dispersion, as long as they are identical and properly aligned. This application is particularly useful for beams with multiple wavelengths and for tunable laser systems. The achromatic and polarization-preserving features rely on the compensation of the s and p reflection phases and amplitudes in a series of orthogonal reflections. This principle, called the compensating phase shift (CPS), was used previously in the design of polarization-preserving rotators.[6] Figure 1 shows diagrams of mirror-based and prism-based CPS beam displacers. The system is based on four orthogonal reflections. If the normalized input wave vector in Fig. 1 is (0, 0, 1), then the subsequent wave vectors are (1, 0, 0), (0, −1, 0), (1, 0, 0,) and (0, 0, 1). An optical beam initially polarized along the x direction (y direction) will be p polarized (s polarized) in the first and fourth reflections and s polarized (p polarized) in the second and third reflections. Both orthogonal components of the polarization of a beam (i.e., in the x and y directions) will then acquire the same accumulated reflection
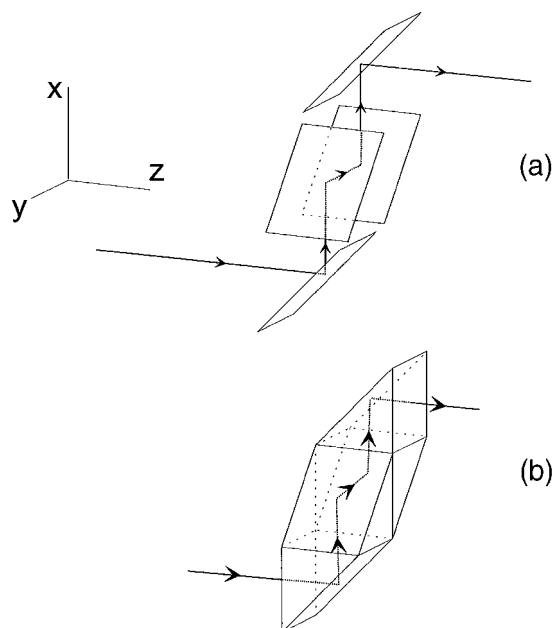

Fig. 1. Diagrams of the (a) mirror-based and (b) prism-based CPS beam displacers.

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phase shift, resulting in a phase-shift difference of zero after the four reflections. The accumulated attenuation will also be the same for both components. Since the cancellation is independent of the actual value of the s and p reflection phases and amplitudes, the system is inherently achromatic.

To verify the achromatic property of the CPS beam displacer and compare it with conventional two-mirror beam displacers we performed the following test: We obtained a measure of the ellipticity e of a linearly polarized beam after it passed through the beam displacer. We computed $e^2 = I_{min}/I_{max}$, where I_{max} and I_{min} are the maximum and minimum intensities of the optical beam, which are proportional to the squares of semimajor and semiminor axes of the ellipse described by the electric field vector of the beam, respectively. In the measurements the input linear polarization was oriented at 45° relative to the plane of the two-mirror beam displacer or to the x axis of the CPS beam displacer (see Fig. 1). At this angle the input linear polarization acquires the greatest ellipticity or pseudorotation after each reflection. The wavelength dependence was measured by use of the individual lines of argon-ion and He–Ne lasers. Two Glan–Thompson polarizers (Optosigma Model 066-0150 with a quoted extinction ratio of 1×10^{-5}) placed before and after the beam displacer were used in the measurement of I_{max} and I_{min}. The circles in Fig. 2 represent the data for the CPS beam displacer. The squares are the measurements for a conventional two-mirror beam displacer that had commercial UV-enhanced aluminum mirrors (CVI Model PAUV). The uncertainties in the measurements for the CPS device were typically 2%, much smaller than the symbols (circles) in the figure. The CPS beam displacer was composed of four uncoated right-angle BK-7 glass prisms (Edmund Scientific Model 32596) cemented together with refractive-index-matching epoxy, as shown in Fig. 1(b). The angle tolerance of the prisms quoted by the manufacturer was 44 arc sec. The results for two-mirror beam displacers using either the uncoated right-angle BK-7 glass prisms or broadband dielectric mirrors sets were too large to be included in the graph. For example, at 632.8 nm the values of e^2 for beam displacers that used the uncoated glass prisms and the broadband dielectric mirrors (Balzers VIS BD10307905) were 0.61 and 0.43, respectively. Figure 2 indeed shows the dramatic difference between the two types of beam displacer and the remarkable cancellation of phases effected by the CPS system. The achromatic properties are reflected by values of e^2 that varied from 2×10^{-6} to 5×10^{-5} across the visible spectrum. Deviations from the 45° azimuth in the emerging beam were within the resolution of the polarizer's rotation stage (30 arc min).

The tolerance to misalignments depends on the type of mirror. Shown in Fig. 3 are the tolerances for a prism-based system. These measurements were made with a linearly polarized He–Ne beam with the polarization axis oriented at 45° relative to the x axis of the beam displacer. The symbols correspond to tilts of the beam displacer about the x axis. Ellipticities of comparable magnitude were observed for tilts about the y axis.

We also made measurements on mirror-based CPS beam displacers [Fig. 1(a)] that had either broadband dielectric (Balzers VIS BD10307905) or protected aluminum (Edmund Scientific 43406) sets of mirrors. (For the latter, $e^2 < 0.15$ in the two-mirror beam-displacer measurement in the 450–670-nm range.) With our optical hardware we were able to align the mirrors to within 2 arc min. The metallic-mirror beam displacer remained achromatic to $e^2 < 5 \times 10^{-4}$; the dielectric-mirror beam displacer, to $e^2 < 5 \times 10^{-3}$. At a given wavelength either device could be angle tuned by tilting it (less than 1°) to reduce e^2 below 10^{-4}. This underscores that misalignments in the individual mirrors result in high sensitivity of the polarization-preserving properties to the overall alignment of the device.
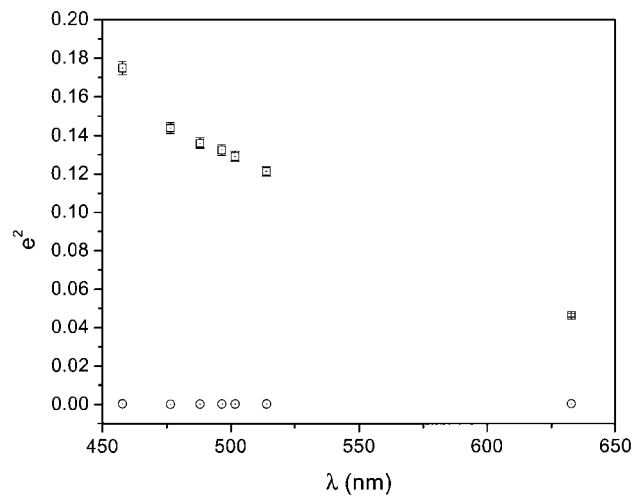

Fig. 2. Ellipticity acquired by a linearly polarized beam of wavelength λ in a conventional two-mirror beam displacer that used aluminum mirrors (squares) and in a prism-based CPS beam displacer (circles).
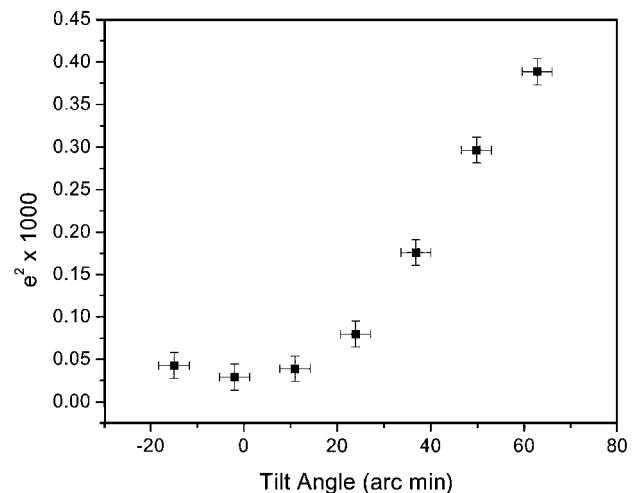

Fig. 3. Ellipticity acquired by a 632.8-nm linearly polarized beam as a function of the misalignment of the CPS beam displacer relative to the light beam. The measurements correspond to the tilting of the beam displacer about the x axis shown in Fig. 1.

A system similar to the one shown in Fig. 1 but with the third wave vector being (0, 1, 0) is also a CPS beam displacer. Since the wave vector and the helicity vector of the beam describe a zero solid angle in configuration space after the beam passes through the device, the CPS beam displacer introduces no geometric phase to the optical beam.[6] Since the concept of geometric phase applies to image-bearing optical beams as well,[7] the CPS system displaces optical beams while preserving both image orientation and polarization.

In another variation of the CPS system the light beam with input wave vector (0, 0, 1) has the following subsequent wave vectors: (1, 0, 0), (0, $\pm$1, 0), ($-$1, 0, 0), and (0, 0, 1). That is, the third reflection in Fig. 1 sends the beam down (negative x axis) instead of up. This system introduces a geometric phase of π to the light beam. In terms of polarization, such a transformation is trivial since it leaves the state of polarization unchanged, but for images it results in a 180° image rotation. Thus, by preserving the polarization while rotating images, the device may provide an advantage over the classic Porro system for some modern applications.

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