Computer-generated infrared depolarizer using space-variant subwavelength dielectric gratings

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We present a novel method for the formation of a complete depolarizer that is based on a polarization-state scrambling procedure over the space domain. Such an element can be achieved by use of cascaded, computer-generated, space-variant subwavelength dielectric gratings. We introduce a theoretical analysis and experimentally demonstrate a depolarizer for infrared radiation at a wavelength of 10.6 μm. © 2003 Optical Society of America

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Depolarizers are optical elements that reduce the degree of polarization (DOP) of beams, independent of their incident polarization state. These components are essential for removing undesired polarization sensitivity in optical systems, for instance, in long-haul transmission systems that use erbium-doped fiber amplifiers,[1] and for optical measurement equipment.[2] Several approaches for depolarizing light based on the scrambling of the polarization state in the time or wavelength domain have been suggested and experimentally demonstrated. Lyot was the first to propose an approach for reducing the DOP of a beam.[3] His method relied on dispersion of the phase retardation of crystals in which the polarization scrambling was performed over the wavelength. However, the main drawback of the Lyot method is the need to use broadband sources to achieve as low a DOP as possible. Billings proposed the possibility of depolarizing monochromatic beams by use of a temporally varying retarder.[4] This method is based on modifying the polarization state of the beam faster than the typical time constants of the relevant optical components (e.g., detector, amplifier). In this case, the polarization scrambling is performed over the time domain.[5] The main disadvantage of this depolarization method is in its use of active elements, making it unsuitable for ultrafast applications or for optical systems having very short time constants. A crystal-based depolarizer was suggested for scrambling of the polarization state in the space domain.[6] However, this method is cumbersome, it is difficult to use for mid–far-infrared radiation, and the crystals are limited in size and must be cemented to form larger apertures.

We recently demonstrated the use of subwavelength gratings for the formation of space-variant phase plates (retarders).[7] In this Letter we present a novel design and realization procedure that allow the use of cascaded, computer-generated, space-variant subwavelength dielectric gratings to form complete depolarizers that are based on space-domain polarization-state scrambling. We discuss the theory behind our method, using Mueller–Stokes formalism, and experimentally demonstrate a continuous subwavelength-structured depolarizer for CO_2 laser radiation at a wavelength of 10.6 μm. The ability to utilize a single compact, space-variant subwavelength grating to depolarize beams of a known polarization state (pseudo depolarizer) is also demonstrated. Our spatial polarization-state scramblers are compact, passive components and are suitable for use with real-time applications and monochromatic laser radiation.

The analysis of the depolarizer is conveniently performed with the Stokes–Mueller representation, in which a Stokes vector of the form $\mathbf{S} = (S_0, S_1, S_2, S_3)^T$ describes the polarization state of a beam, where S_0 is the intensity.[8] Partially polarized light can be characterized by its DOP, defined as DOP $= [(\langle S_1\rangle^2 + \langle S_2\rangle^2 + \langle S_3\rangle^2)/\langle S_0\rangle^2]^{1/2}$, where the angle brackets $\langle\,\rangle$ denote the average value of the relevant time, wavelength, or spatial domain. In a Stokes–Mueller representation, the polarization state of a beam emerging from an optical system (e.g., wave plates, polarizers) is linearly related to the incoming polarization state through $\mathbf{S}^{\text{out}} = \mathbf{M}\mathbf{S}^{\text{in}}$, where $\mathbf{M}$ is a 4×4 real matrix called the Mueller matrix of the element and $\mathbf{S}^{\text{in}}$ and $\mathbf{S}^{\text{out}}$ are the Stokes vectors of the incoming and outgoing beams, respectively. A perfect depolarizer is an optical element for which the outgoing beam is completely unpolarized, independent of the incoming beam's polarization state. Light that is totally unpolarized is described by a Stokes vector of the form $\langle\mathbf{S}\rangle = (\langle S_0\rangle, 0, 0, 0)^T$. Therefore, for a uniform incident beam, the components of the Mueller matrix of a perfect depolarizer, $\langle\mathbf{M}^{\text{dep}}\rangle$, are given by $\langle\mathbf{M}_{ij}{}^{\text{dep}}\rangle = 0$, apart from $\langle\mathbf{M}_{11}{}^{\text{dep}}\rangle = 1$.

The Mueller matrix of a wave plate, for which the fast axis rotates periodically with respect to the position along the x axis, can be described by $\mathbf{M}(x) = \mathbf{R}(-\pi x/d)\mathbf{W}\mathbf{R}(\pi x/d)$, where $\mathbf{R}$ is the axis frame rotation matrix; d is the fast axis rotation period, which is larger than the incident wavelength λ; and $\mathbf{W}$ is the Mueller matrix of a wave plate.[8] Our depolarizer is composed of two sequential, spatially rotating wave plates, as shown in Fig. 1(a). The first is a space-variant quarter-wave plate (QWP), with a rotation period of $d_1 = d/4$; the second is a space-variant half-wave plate, (HWP), with a rotation period of

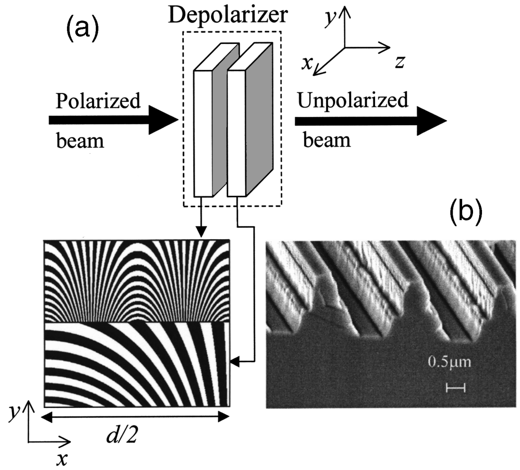

Fig. 1. (a) Schematic presentation of our concept for depolarizing over the space domain. The insets illustrate the geometry of the subwavelength gratings. (b) Scanning electron microscope image of a typical cross section of the grating profile of the QWP.

$d_2 = d$. The Mueller matrix of a composite optical element is provided by the multiplication of the Mueller matrices of the cascaded optical elements as follows:

$$\mathbf{M}(\theta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\theta \cos\theta & \sin 2\theta \cos\theta & \sin\theta \\ 0 & -\cos 2\theta \sin\theta & -\sin 2\theta \sin\theta & \cos\theta \\ 0 & \sin 2\theta & -\cos 2\theta & 0 \end{bmatrix}, \quad (1)$$

where $\theta = 4\pi x/d$. Calculating the average value along the x axis as $\langle \mathbf{M}_{ij} \rangle = (2/d) \int_0^{d/2} \mathbf{M}_{ij}(x)\, \mathrm{d}x$ yields the Mueller matrix of an ideal depolarizer. The averaging procedure represents an incoherent summation of the outgoing polarization states along the x axis; i.e., the depolarization effect is achieved by spatially scrambling the beam's polarization state. Figure 2 illustrates the local outgoing polarization states for different incoming beams, as well as the local polarization state as a trajectory on a Poincaré sphere. As shown in Fig. 2, the resulting space-variant polarization state includes polarization ellipses of different orientation and ellipticity. These polarization ellipses demonstrate the principle of the scrambling procedure. Note that other combinations of spatially rotating wave plates can be used to form a complete depolarizer. For example, a depolarizer scheme similar to that described above could be created using two spatially rotating HWPs with rotation periods of d and $d/2$, with a space-invariant QWP inserted between them. This scheme could serve as a depolarizer when the averaging process is performed over $d/2$. Alternatively, two spatially rotating wave plates, both having a rotation period of d but retardation phases of half- and quarter-wavelengths, and with a space-invariant HWP inserted between them, produce complete depolarization, as well. The averaging process in this case is performed over d.

The formation of spatially rotating wave plates can be achieved by use of dielectric subwavelength gratings. When the period of the grating is much smaller than the incident wavelength, only the zeroth order is a propagating order, and all other orders are evanescent. In this case, the subwavelength periodic structure behaves as a layer of uniaxial crystal, with the optical axes perpendicular and parallel to the subwavelength grooves.[9] Therefore, by controlling the structure, orientation and local periodicity of the grating, any desired space-variant wave plate can be formed. The design and realization of the subwavelength grating are described below.

We begin by defining a grating vector $\mathbf{K}_g = K_0(x,y)[\cos(\pi x/d)\hat{\mathbf{x}} + \sin(\pi x/d)\hat{\mathbf{y}}]$, which is oriented perpendicular to the grating grooves. $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ are unit vectors in the Cartesian coordinate system, whereas $\mathbf{K}_0 = 2\pi/\Lambda(x,y)$ is the spatial frequency of the grating (Λ is the local subwavelength period). To ensure the continuity of the grating, we require that $\nabla \times \mathbf{K}_g = 0$, by which $\Lambda(x,y)$ is determined. We then calculate the grating function ϕ (defined so that $\nabla\phi = \mathbf{K}_g$) by integrating $\mathbf{K}_g$ over an arbitrary path.[10]

We realize Lee-type gratings[10] that describe our grating functions. The first grating was a spatially rotating QWP with $d_1 = 2.5$ mm; the second was a spatially rotating HWP with $d_2 = 10$ mm. The subwavelength period of the elements, Λ, was varied from 2 to 3 μm along the y axis, where the physical dimensions of the gratings were 5 mm $\times$ 0.32 mm. First, we fabricated chrome masks of the gratings by use of high-resolution laser lithography. The chrome mask patterns are illustrated in the insets of Fig. 1(a). The patterns were then transferred onto 500-μm-thick GaAs wafers by use of contact photolithography, after which we etched the gratings by use of electron cyclotron resonance reactive ion etching with BCl_3. Finally, we applied an antireflection coating onto the back of the wafers. Figure 1(b) shows a scanning electron microscope image of a typical cross section of the grating profile of the QWP at a period of $\sim$2 μm. The measured phase retardations of the elements were 0.46π and 0.96π for the appropriate QWP and HWP, respectively. These results are in good agreement with the theoretical predictions

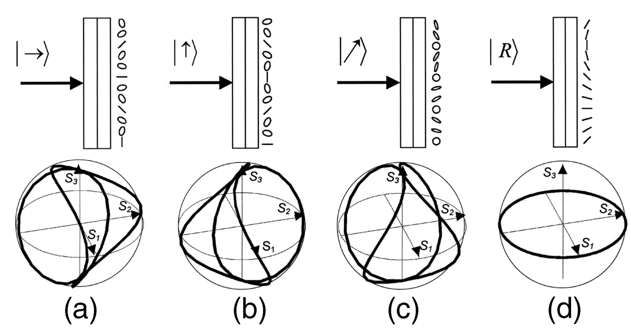

Fig. 2. Illustration of the outgoing beam's polarization state when the polarization of the incoming beam is (a) vertically linear, (b) horizontally linear, (c) linear at 45°, (d) circularly polarized light. The spheres show the trajectories of the outgoing polarization states onto the Poincaré spheres.

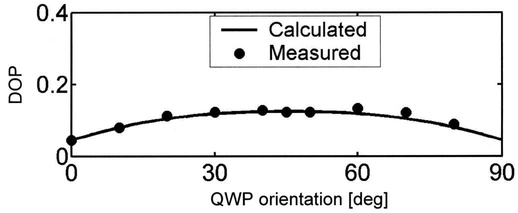

Fig. 3. Measured and predicted DOP as a function of the orientation of the QWP, through which the incident beam has been transmitted.

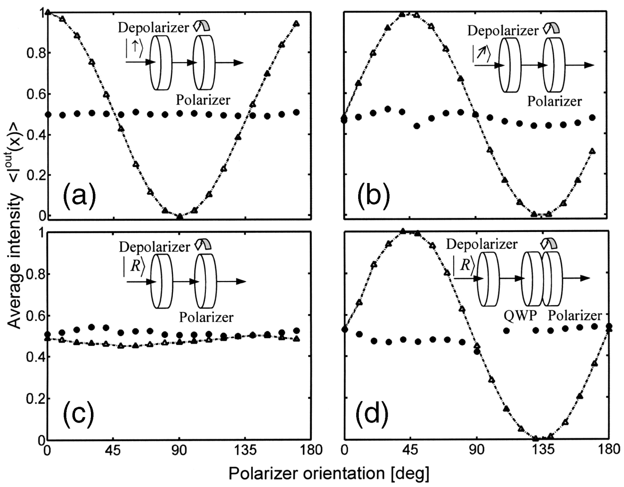

Fig. 4. Average intensity $\langle I^{\mathrm{out}}(x)\rangle$ of beams transmitted through (a)–(c) a rotating polarizer and (d) a QWP followed by a rotating polarizer. The incident polarization state is (a) linear (0°), (b) linear (45°), (c), (d) right-hand circular. Results having used the depolarizer are shown with dots, without the depolarizer are shown with triangles.

achieved by rigorous coupled-wave analysis, utilizing the measured profiles of the gratings.

Subsequently, our depolarizers were experimentally tested using linearly polarized CO_2 laser radiation at a wavelength of 10.6 μm. First, we manipulated the incoming polarization state by rotating a QWP and measured the Stokes vector of the beam emerging from the depolarizer. The Stokes vector was measured with the four-measurement technique.[8] The intensity of the beam was captured by a Pyrocam III camera, and each measurement was obtained by summing the intensity over the x axis in the range $0 < x < d_2/2$. Figure 3 shows the measured and predicted DOP as a function of the orientation of the QWP. The predicted DOP was calculated with Eq. (1), which was modified to reflect the influence of the retardation errors of the elements. The attained experimental DOP was less than 0.16. The desirable total depolarization (DOP of 0) was not achieved because of phase retardation errors. Nevertheless, our result provides strong experimental evidence for the validity of our polarization-scrambling technique.

We also demonstrated the performance of the depolarizer by illuminating it with beams having various polarization states and measured the spatial-average intensities, $\langle I^{\mathrm{out}}(x)\rangle$, transmitted through a polarization-sensitive medium. Figure 4 shows the experimental average intensities transmitted through a rotating polarizer, as well as through a QWP followed by a rotating polarizer. The polarization-sensitive media were illuminated with the range of polarization states resulting from incident light that was linearly (0°) polarized, linearly (45°) polarized, and circularly polarized. The modulations of the average intensities as a function of the orientation of the polarizer, both with and without use of the depolarizer, were measured. Figure 4 shows a small modulation of $\langle I^{\mathrm{out}}(x)\rangle$ ($\sim$0.02 standard deviation) while the spatial polarization scrambler was used, thereby indicating the effectiveness of the depolarization procedure independent of the incident beam's polarization state.

In a case where the incident beam's polarization state is known, the use of a simple pseudo depolarizer is sufficient. We have demonstrated that a single, spatially rotating QWP or HWP based on space-variant subwavelength dielectric gratings can completely depolarize incident light with a circular or linear polarization state, respectively. We used the same subwavelength grating as described above for the cascaded gratings. The experimentally measured DOPs for the QWP and HWP scramblers were 0.021 and 0.075, respectively.

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