A half wave retarder made of bilayer subwavelength metallic apertures

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(Received 26 January 2011; accepted 27 March 2011; published online 13 April 2011)

We demonstrate a half wave plate whose principle of operation is based on the strong evanescent field coupling between two metal layers with arrays of subwavelength slits. The device is divided into two kinds of pixels in which the slits are oriented in orthogonal directions. By tuning the phase delay of the transmitted light through the lateral displacement between the top and bottom layers, the polarization of linearly polarized light at 1.55 μm can be rotated by up to 90°. The polarization extinction ratio of the transmitted light exceeds 22 dB. © 2011 American Institute of Physics. [doi:10.1063/1.3579245]

Nano optical devices exploit the interaction between near field and far field radiations in subwavelength metallic and dielectric structures to achieve novel optical capabilities. For example, the excitation of surface plasmons is responsible for the remarkable transmission of polarized light at 1.55 μm. The polarization of linearly polarized light through bilayer subwavelength metallic slit arrays at here is a half wave retarder based on the enhanced transmission properties of periodic subwavelength metallic apertures. The subwavelength features on the metal surface can be engineered to control the strong evanescent fields associated with the surface excitations. Here, we describe the fabrication of a half wave plate where the retardation in one polarization is achieved through tailoring the evanescent field coupling between two metal layers with arrays of subwavelength apertures.

Polarization state controllers are essential components in optical systems. Conventional wave plates rely on birefringent crystals to impart a phase delay to one of the polarizations. The wavelength of operation is determined by the material properties and therefore is not readily tunable. Moreover, it is challenging to integrate them with other optical components due to their bulkiness. Alternative ways to control the polarization have recently emerged, including liquid-crystals, waveguides, micromechanical devices, and chiral metamaterials. In particular, chiral metamaterials offer a compact, planar platform to rotate the polarization of transmitted or reflected light. However, the difficulty in generating strong optical activity has limited the polarization azimuth rotation to ~30°. The device reported here is a half wave retarder based on the enhanced transmission through bilayer subwavelength metallic slit arrays at resonance. By utilizing the controllable phase delay of the transmitted light through the lateral displacement of the two arrays and the strong dependence of the transmission on the polarization of the incident light, the polarization of linearly polarized light at 1.55 μm can be rotated by up to 90° in the zero order transmission. The polarization extinction ratio of the transmitted light exceeds 22 dB.

Our sample is made of two 0.2 μm thick aluminum films separated by 0.34 μm, each with subwavelength slit apertures arranged in specific orientations. The slits in the aluminum layers are created by reactive ion etching with a photore sist etch mask defined by deep ultraviolet lithography. As shown in Fig. 1(a), the top aluminum layer is divided into a checkerboard pattern with two kinds of square pixels. Each pixel (25 × 25 μm²) consists of an array of long slits with width of 0.49 μm and periodicity of 1 μm. The orientations of the slits are perpendicular to each other in adjacent pixels. For pixels labeled as type 1 in Fig. 1(a), the slit array is oriented along the y direction. In the bottom layer, an identical array of slits is present, almost laterally aligned to the top array [Fig. 1(b)]. For type 2 pixels with slits along the x direction, the array of slits in the bottom layer is laterally shifted from the top layer by about half the period [Fig. 1(c)]. The two aluminum layers are completely surrounded by silicon oxide. Fabrication of the metal layers was performed on a silicon substrate. Completed structures were then transferred onto a quartz wafer for optical measurements.

To understand the working principle of the above structure as a half wave retarder, we first consider the transmission properties of a nonpixilated, single-layer structure with all slits oriented along the y direction. Linearly polarized light with electric field along the x (y) axis is denoted as E_x (E_y) polarized. We measured a transmission peak of up to 75% at 1.55 μm for E_y polarized light. Taking into account the refractive index of silicon oxide (n=1.47), the peak wavelength is slightly higher than the periodicity of the slit array (1 μm). It is well-known that when E_x polarized light impinges on metallic gratings oriented along the y direction, the transmission can exceed the diffraction limit at wavelengths comparable to the period of the slits. Such extraordinarily high transmission has been attributed to the excitation of surface plasmons, surface evanescent waves and/or guided modes. When two such single layers are placed in close proximity so that the strong evanescent fields on their surface couple, both the intensity and the phase of E_x.
polarized light can be controlled by the lateral shift in the two layers. The transmitted intensity for $E_x$ polarized light, in contrast, is lower by several orders of magnitude and is practically negligible. Therefore, the pixilated bilayer structure acts as a polarization beam splitter followed by a polarization beam combiner, in the sense that $E_x$ polarized light passes through type 1 pixels and $E_y$ polarized light passes through type 2 pixels. As we will explain below, the phases acquired by these two components in this process differ by $\pi$. Figure 1(d) shows the measured transmission through the pixilated structure for $E_x$ (red line) and $E_y$ (blue line) polarizations at normal incidence, measured with a Fourier transform infrared spectrometer. The transmitted intensity depicted by the red (blue) line originates from type 1 (2) pixels because light impinging on the other kind of pixels is entirely blocked. For instance, the maximum transmission of $\sim 32\%$ for $E_y$ polarized light in Fig. 1(d) originates from $\sim 64\%$ transmission through type 2 pixels. The transmission of both types of pixels for the corresponding polarization components remains strong due to the efficient coupling of the surface waves excited on the two layers. It should be noted that the lateral shift $s_1$ between the two slit arrays within pixel 1 is about $0.1 \mu m$ instead of exactly perfectly aligned. We choose a sample with this value of $s_1$ (out of many samples covering a wide range of $s_1$) so that the transmissions of the $E_x$ polarization through pixel 1 and the $E_y$ polarization through pixel 2 are identical at our laser wavelength of 1.55 $\mu m$ [Fig. 1(d)]. As described later, equal transmission intensity of the $E_x$ and $E_y$ polarizations is a crucial factor in determining the performance of this device as a half wave retarder. Figure 1(e) shows the transmitted intensity calculated with rigorous coupled wave analysis (RCWA) (Ref. 19) using the slit array dimensions of the two kinds of pixels and tabulated optical properties of aluminum. The calculated transmission is in good qualitative agreement with measurement.

The different lateral shifts in the orthogonal pixels produce a phase delay that is close to half-wave in the transmission of the two polarizations. Figure 1(f) shows that the calculated phase of the transmitted light varies by almost $\pi$ as the top array is laterally shifted from the bottom array between zero and half the period. To achieve a phase shift between light transmitted through pixels 1 and 2 that is closer to $\pi$, the sample was tilted about the $y$-axis by a small angle of 2.5°. The transmission intensity remains largely unchanged. Figures 1(g) and 1(h) compare the spatial distribution of the magnetic fields for the two pixels, showing the same field directions on the incident side (bottom) but opposite field directions on the transmitted side (top). Such phase delay can be understood in terms of the surface electromagnetic fields on the two individual layers coupling differently depending on whether the fields are parallel or opposite to each other, as explained in Ref. 18. The half-period lateral shift in the type 2 pixels reverses the direction of the electromagnetic field for the transmitted $E_x$ polarization relative to the $E_y$ polarization that was transmitted through the type 1 pixels.

We use a 1.55 $\mu m$ laser to demonstrate the capability of the pixilated structure to rotate the polarization. Through a shadow mask, the linearly polarized, collimated laser beam illuminated a sample area of $400 \times 400 \mu m^2$ (about 256 pixels). As shown in Fig. 2(a), the $x$-axis of the sample was oriented at an angle $\phi$ relative to the electric field of the linearly polarized incident light. A second linear polarizer in
front of a photodetector serves as an analyzer to measure the polarization of light transmitted through the pixilated sample relative to the polarization of the incident light. Depending on \( \phi \), the electric field of the incident light decomposes into different \( x \) and \( y \) components along the sample axis [Fig. 2(b)]. For \( \phi=0^\circ \), all the light is transmitted through the type 1 pixels. The polarization of the transmitted light remains unchanged, as shown in Fig. 2(c) by the square cosine dependence of the measured intensity at the photodetector on the angle \( \alpha \) of the second polarizer with respect to the first one. When \( \phi \) is changed to 45\(^\circ \), half of the incident light is transmitted through the type 1 pixels. The other half is transmitted through the type 2 pixels with the direction of the electromagnetic field reversed, as illustrated in Fig. 2(b). Consequently, the transmitted light remains linearly polarized with polarization rotated by 90\(^\circ \), as shown in Fig. 2(e). The structure therefore acts as a half wave plate that rotates the polarization of the incident linearly polarized light by 2\( \phi \). Figure 2(d) shows measured polarization rotation of 30\(^\circ \) for \( \phi=15^\circ \). For all our measurements at different \( \phi \), the polarization extinction ratio of the transmitted light is found to exceed 22 dB. It is important to note that since the maximum intensities in Figs. 2(c)–2(e) are largely independent of \( \phi \), the pixilated bilayer structure is not a simple polarizer that projects the polarization component along a certain direction, but is a polarization controller that imparts a polarization rotation to the transmitted light.

Unlike conventional wave plates, the half-wave retarder described here is not based on birefringence of the material. The wavelength of operation can be chosen by creating slit arrays with different periodicity to tune the surface wave resonance. Using similar principles, quarter wave plates can also be created to generate elliptically polarized light from linearly polarized incident light. Most importantly, it offers the possibility of dynamical control of polarization in future designs if one of the two metal plates can be suspended to allow controlled motion between the two layers. One such configuration involves a lower metal layer fixed to the substrate and a movable upper layer supported by springs. When the top layer moves in the \( x \) direction by half the array period, the top and bottom slit arrays become aligned in both types of pixels. As a result, the polarization rotating effect can be completely turned off. Such capability of dynamic polarization control by nanomechanical motion could prove to be useful in optical systems, telecommunication networks and interchip data communications.

This work was supported by the National Science Foundation under Grant No. ECS-0621944. Z. Marcet acknowledges support from South East Alliance for Graduate Education and the Professoriate. A portion of this research was conducted at the Center for Nanophase Material Sciences, which is sponsored at Oak Ridge National Laboratory by the Division of Scientific User Facilities, U.S. Department of Energy.