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Investigation of achromatic micro polarizer array for polarization imaging in visible-infrared band

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Abstract The design and fabrication of a micro polarizer array (MPA) for polarization imaging is described for visible-IR region. The MPA, composed of 1280×1024 elements, is designed to be integrated directly onto the CMOS chip. Each micro polarizer consists of a 200-nm-period Al wire grating with the dimension of 5.2μm×5.2μm, and the performance of gratings with finite number of periods and gradient ridge-length has been thoroughly investigated. The grating ridge of each polarizer orients four different directions offset by 45°, which determines different polarization directions correspondingly. Initial test and experiment for the MPA are performed and the crosstalk caused by diffraction is discussed.

Keyword Polarimetric imaging; Micro polarizer array; Subwavelength gratings.

1. Introduction

To compensate human eyes’ inability of identifying the polarization information, conventional imaging systems are designed to capture the intensity and wavelength information, when the polarization characteristic of the light is unfortunately ignored. Polarization is, however, an indispensable nature of light which indicates the vector information of the optical field. There are significant different polarization states of radiated and scattering light from different objects, or from the same object at different conditions. Analyzing the polarization images will bring us additional information, such as surface features, shape, shading, and roughness, which cannot be obtained from the conventional intensity image.1 As a result, by taking into account of the polarization characteristics of light, it is possible to improve the ability of information acquisition and analysis. And capturing the polarization properties has proven to be beneficial in diverse applications, such as haze/foggy imaging,2 underwater imaging,3 material identification,4 non-contact fingerprint detection5 and so on.

Generally, existing polarization imaging systems include the following categories: division of time polarimeters,6 division of amplitude polarimeters,7 division of aperture polarimeters,8 and division of focal plane polarimeters.9,10 The micro polarizer array polarimeter,11,14 a kind of division of focal plane polarimeters, is characterized with real time, high reliability and stability, but low power consumption. Each micro-polarizer of the MPA is essentially a sub-wavelength metal grating which obtains polarization variations of the light.15 Compared with the traditional polarizers, subwavelength metal gratings have much broader spectral width and smaller volume. Due to their superiority of small size, compact structure, and easy to be integrated, subwavelength metal gratings can replace the traditional optical polarimeters to reduce the optical components and increase system flexibility in the optical system.16 The advantage of the polarizing imaging device based on micro polarizer array in terms of volume, weight, power consumption, has greatly promoted the application field of polarization imaging.

Fig.1.Illustrative figure of MPA
The micro-polarizer array is designed to be integrated on the CMOS photosensitive chip. The size of the micro-polarizer array is exactly the same as that of the chip, and the micro-polarizer array is aligned strictly pixel to pixel with the chip. In a 2x2 unit of the MPA, as is shown in Fig. 1, the polarization direction of the micro-polarizer is different from each other, which is decided by the orientation of the ridges: 0°, 45°, 90° and 135°. Therefore, in the image captured by the camera, each pixel in a 2x2 unit records the intensity of light passing through polarization analyzer of a certain polarization direction. The advantage of the micro-polarizer array is that it can acquire images of four different polarization directions by simply acquiring one single-frame image.

2. Design

For subwavelength metal gratings, whose period is less than the wavelength of incident light, the traditional scalar diffraction theory is no longer suitable. Instead, the vector diffraction theory is used for detailed analysis of subwavelength structures. Some widely-used vector diffraction theories include Finite Element Method (FEM),

\[ n_{TE} = \left( f n_2^2 + (1 - f)n_1^2 \right)^{\frac{1}{2}}, \]

\[ n_{TM} = \left( f n_2^{-2} + (1 - f)n_1^{-2} \right)^{-\frac{1}{2}}, \]

in which \( n_1, n_2 \) are the refractive index of air and the grating medium respectively, \( f \) is the duty cycle, and \( f = w / p \), \( w \) is the width of the grating, \( p \) is the grating period. For metal gratings, \( n_k = n + i \kappa k \), where \( n \) and \( k \) denote the refractive index and extinction coefficient of the metal, respectively. For different duty cycles \( f \), the equivalent refractive index of TM polarized light and TE polarized light is different. Therefore, the grating exhibits polarization characteristic, that is, the incident TE polarized light (whose polarization direction is parallel to the grating ridge) is reflected, and the incident TM polarized light (whose polarization direction is perpendicular to the grating) is transmitted. The essence of this phenomenon is that the TE polarized light can excite the electrons of the nanowires to generate current, and is consequently reflected. While, due to the presence of the air gap between the nanowires, current cannot be excited by the TM polarized light, resulting in the transmission. The equivalent dielectric theory is utilized to understand the polarization characteristics of metal gratings and perform the preliminary parameter design.

Transmittance is the most important parameter to evaluate the performance of gratings, which reflects the utilization of the grating for light energy. The rate depends on the parameters of the grating itself and the incident light. The incident light is decided by its wavelength, angle of incidence, and polarization state. Main parameters of gratings are grating period, grating groove parameters, surface roughness, grating materials. For polarized gratings, there is one more parameter to evaluate the polarization effect, that is the extinction ratio. Extinction ratio is defined as the transmission rate of TE wave divided by the transmission rate of TM wave. To achieve high transmittance and high extinction ratio, it is necessary to optimize the parameters of the grating, in which the groove parameters are the most important factors affecting the transmittance and extinction ratio. The preliminary simulation and optimization of the structures are performed using the FDTD method. To calculate 3-dimensional models with a large simulation area, FDTD method is chosen because of its advantages of time-saving and accuracy.

Aluminum is used for its characteristic of easy processing and the simulated Al wire gratings are positioned on top of an infinite silica slab. Spectral responses were calculated using normal incidence plane wave excitation at a wavelength of 630 nm and tabulated dielectric functions for both aluminum and silica. Fig.2 presents the simulation results of Al wire gratings illuminated by normally incident light at 630 nm for varying grating period (\( p \)), duty cycle (\( f \)) and groove depth (\( d \)). The groove depth is fixed to be 160nm in Fig 2(a) and (b), while in (c) and (d) the duty cycle is set to be 0.4.

In Fig. 2(a) -Fig. 2(d), the transmittance and the extinction ratio decline with the raise of the grating period, which means the smaller period the better. However, considering the difficulty of the fabrication of structures with a too small period, the period is finally chosen to be around 200 nm. As can be seen from Fig. 2(a) and Fig. 2(b), with the increase of the duty cycle \( f \), there is an obvious decrease of transmittance but a clear growth of the extinction ratio at the same time. Consequently, a centered value of duty factor, such as 0.4 or 0.5, is selected to get a transmittance larger than 0.8 and a high extinction ratio larger than 100. In Fig. 2(c), there is no clear connection between transmittance and groove depth, while in Fig. 2(d), having a larger groove depth will get a better extinction ratio, and the depth should therefore be over 140 nm to feed the need. Thus, considering all above factors, the
period, groove depth and duty cycle are finally determined as 200 nm, 160 nm and 0.4 respectively. Fig. 3 presents the calculated spectra for the designed grating at the wavelength from 500 nm to 1200 nm. The transmittance is larger than 0.8 and the extinction ratio is over 100, which achieve our requirement perfectly.

Fig.2. The simulation result: (a) transmittance and (b) extinction ratio of the grating with varying p (nm) and f when d=160nm; (c) transmittance and (d) extinction ratio of the grating with varying p (nm) and d (nm) when f = 0.4.

Fig.3. Spectra calculated for Al wire gratings with p=200, d=160 and f=0.4

The calculations above are for infinite periodic structures, but the target structure cannot be extended infinitely. The size of the micro-polarizer array is designed to be the same with that of the CMOS chip. A chip consists of 1280×1024 pixels, and the size of each pixel is 5.2μm×5.2μm. Since the grating period designed is 200 nm, a basic unit consisting of horizontal or vertical (0° or 90°) ridges will have 26 periods. And for the unit consisting of oblique (45° or 135°) ridges, the periods number is 36. Thus, Al wire gratings with various finite periods are simulated at the wavelength of 630nm. As is shown in Fig. 4, the grating of smaller number of cycles does not exhibit good polarization characteristics with low maximum transmittance and low extinction ratio. While, it
performs well when the period number reaches 20 or more, and the polarization performance of the grating with 26 periods can be comparable to that of the infinite periodic structure. Furthermore, the structure with oblique ridges is also calculated, with grading length of the ridge strips, unlike straight gratings with stable length. Fig.5 presents the similar trend with Fig.4. Gratings with oblique grating ridges achieve the requirements of polarization characteristics with the periods number over 20. Hence the 5.2×5.2μm oblique grating with 36 periods can meet the requirements. But when the period number is the same, the performance of oblique gratings is not as good as that of straight gratings.

**Fig.4.** Calculation results of finite-periods straight Al gratings. (a) Structure diagram; (b) Transmission spectrum with various incident polarization angle; (c) Transmittance when the polarization angle is 0° (Maximum transmission angle); (d) Extinction ratio: Transmittance (0°) / Transmittance (90°).
Fig. 5. Calculation results of finite-periods oblique Al gratings. (a) Structure diagram; (b) Transmission spectrum with various incident polarization angle; (c) Transmittance when the polarization angle is 0° (Maximum transmission direction); (d) Extinction ration = Transmittance (0°) / Transmittance (90°).

3. Experiment

The micro polarizer array was fabricated on a fused silica substrate. First a 160 nm thick layer of aluminum was evaporated using DC sputtering. This was followed by an e-beam evaporation of SiO2 that acts as a hard mask for aluminum etching. For the electron beam exposure, the sample was coated with ZEP7000 electron beam resist. The micro polarizer array with different line orientations was then exposed using Raith (former Vistec) EBPG 5000+ HR system. The exposed resist was then developed in ethyl 3-ethoxypropionate (EEP) and rinsed in Isopropanol and DI-water. The pattern in the resist was then transferred to SiO2 layer and finally to aluminum using reactive ion etching.
Fig. 6. (a) SEM photos of the MPA; (b) Illustrative figure of the fabrication.

Fig. 6(a) presents the SEM photos of the 1080×1024 MPA. The overall structure matches the design perfectly, with each pixel of 5.2μm×5.2μm. The width of the grating ridge is 10nm wider than expected, because of the fabrication error.

A reference polarizer with the dimension of 5 mm×5mm is also fabricated to do characterization, since there is no effective method to do transmittance measurement though a micro structure of 5.2μm×5.2μm, as is shown in Fig.6(b). The reference structure is Al wire grating with only one ridge orientation, and the structural parameters are the same with the designed grating. The optical parameters were measured by a ellipsometry (J. A. Woolam). A comparison between experimental data and calculated data is made in Fig.7. The maximum transmittance of the grating is about 0.6 during the wavelength from 500nm to 1200nm, and the extinction ratio is about 100, which meets the usual commercial standards, though both data are lower than calculated results.

![Comparison of experimental and computational results](image-url)
Fig. 8. Photos of a polarization testing pattern: (a) the original picture in natural light, with an invisible fish in the red box; (b)–(e) are taken with four different polarization angles (the maximum transmission angle for fish pattern is defined as 0 degree). The exposure is automatically adjusted. Suppose the image intensity without a polarizer is \( I_0 \), and then the background intensity with a polarizer is \( \alpha \cdot I_0 \) (\( \alpha \) is the transmissivity of the polarizer and \( \alpha < 1 \)), and the intensity of a fish pattern will change with different polarization angles.

Imaging experiments were performed using a black and white visible light CMOS camera. Object light reaches the CMOS window through the imaging lens and the MPA polarizer, and the protective case of the CMOS is removed in order to get a close contact between the polarizer and the CMOS chip. Fig. 8 presents polarized images taken by the reference polarizer. The object is a polarization testing pattern for polarized glasses, as is shown in Fig. 8 (a), which is shot without the polarizer. There is a fish pattern with polarization selectivity in the red box, which is distinguished from the background. But the fish cannot be revealed in Fig. 8(a), because the fish and the background have the same light intensity in the natural light. The reference polarizer is rotated in front of the CMOS. With the polarizer rotating, the background intensity stays at the same level while the fish pattern will become bright and dark according to the rotation angle. The angle when the fish becomes brightest is defined as 0°, and it becomes darkest after the polarizer rotating by 90°. The contrast between the fish image and the background is not obvious when the polarizer is rotated by 45° or 135°, because they have similar intensity at this time. This phenomenon shows that, compared with the background, the fish pattern has an obvious polarizing effect depending on the incident light. And the polarizer presents good polarizability.
To get the experiment photos photographed with the MPA polarizer, each micro-polarizer of the MPA needs to be strictly aligned with each pixel of the CMOS chip. Pixel images which are taken by the same kind of micro-polarizer are extracted to form four final pictures, and the processing is presented in Fig. 9 (a). Pixel images obtained with 0° polarizers are marked with "I", and they are extracted from the original picture to form an image which can be regarded as photographed with a 0°-polarizer. Fig. 9 (b) presents the processed four pictures, which, however, shows no obvious polarization effect. There should be no problem of the gratings, since experiments of the reference polarizer have shown the expected performance. Two reasons are responsible for the failure of the experiment. One possible reason is the inaccurately alignment of the system. To get a good experiment performance, each micro polarizer should be strictly aligned with a corresponding pixel of the CMOS chip as designed. And that means the adjustment precision of the system should be accurate to micron level, which is beyond the equipment condition of our laboratory. While another reason may be the strong crosstalk caused by diffraction. 27,28

A pixel of Al gratings can be seen as a rectangle polarizer. Diffraction occurs when light passes through a polarizer, and the further the transmission distance is, the more obvious the diffraction phenomenon will be. Considering the thickness of the SiO2 base of the MPA, the glass protective layer of the CMOS and the air gap between these elements, the spacing between the MPA and the photosensitive chip of the CMOS is estimated to be 2 -3mm. The diffraction of the adjacent polarization will affect each other to produce crosstalk. In order to study the diffraction effect, the diffraction calculation model of a square hole is built. The side length of the square is 5.2μm. A beam of plane wave light at the wavelength of 630 nm is incident on the model. The field distribution is calculated at a distance of 2mm off the square hole, as is shown in Fig. 10. The field intensity along the straight line through the center is also specifically calculated.
Fig.10 (a) The field intensity (|E|) of the plane 2mm off the square hole; (b) Cross line at y=0mm, and the FWHM is 0.148mm.

Fig.10 (a) presents a nearly circular distribution of the diffraction field with a radius of about 100μm, far beyond the 5.2μm boundary limit of the square hole. And the full width at half maximum (FWHM) of the center optical filed is about 148μm, calculated by the cross line at Fig.10(b). The calculation result exhibits the strong influence of diffraction. The polarization of a micro polarizer has a significant effect on the surrounded polarizers within a radius of a dozen periods. As a result, there is no way to perform a good experiment for the MPA, since the performance of a polarizer if interfered and covered by others.

It is known that there is a layer of micro lens at the surface of the CMOS, and the micro-polarizer array is designed to be integrated on the CMOS photosensitive chip, in the position between the photosensitive chip and the micro lens. Because of the focusing action of the micro lens, the crosstalk of the diffraction effect will be reduced. As a result, the following work is to explore the method of integrating the polarizer directly on the chip.

5. Conclusion

In this paper, we have described the design and fabrication of a 1280×1024 MPA in visible-IR polarization imaging. The influence of the number of grating periods and grating shape on the polarization characteristics of the grating is discussed in detail. Each micro polarizer consists of a wire grating fabricated with Al on a SiO2 substrate. SEM evaluation indicates successful fabrication of the desired structures. The measurement result shows a maximum transmittance of 60% and an extinction ratio of about 100:1. The experiment of the reference group showed good polarization performance of the designed grating. The crosstalk caused by diffraction is analyzed. Future research will include integration of higher extinction-ratio wire grating structures into micro polarizer arrays, and efficient methods to integrate the MPA on a CMOS chip.

Acknowledgments

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