Compact motorized circular wheel of polarization optics for ultra-broadband polarization state generation

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ABSTRACT

This study proposes an innovative optical mechanism with a miniature motorized circular wheel for polarization optics for an ultra-broadband polarization state generator. The proposed apparatus can be suitable for a polarimetric microspectrophotometer for measurements of micro optics and metamaterials with circular dichroism and linear dichroism. Different types of micro optics have their own wavelength dependence, meaning different curves in the broadband range of light. This study presents an ultra-broadband platform for measuring and identifying micro optics such as chiral metamaterials, plasmonics, micro polarizers, and patterned retarders. The key component of a polarimetric microspectrophotometer is a polarization state generator (PSG). A simple PSG consists of a polarizer and a waveplate. An arbitrary polarization state can be created by rotating either the polarizer or the waveplate. Sheet polarizers and achromatic waveplates have a limited bandwidth range. For the ultra-broadband measurement range of 400 nm to 1700 nm, the PSG needs at least three sheet polarizers and three achromatic waveplates: 400 nm-700 nm, 700 nm-1000 nm, and 1000 nm-1700 nm. This optical mechanism, which consists of only one control motor and two high precision unidirectional bearings, includes several polarizers and waveplates arranged in a matrix on a circular wheel. This apparatus can shift one of the polarizers and waveplates to a predetermined position and rotate all the polarizers to change the polarization status. An ultra-broadband polarimetric microspectrophotometer with a compact motorized wheel is an advanced polarization optical instrument for research on chiral metamaterials, plasmonics, micro polarization optics, green optics, and bio optics.

Keywords: circular dichroism, linear dichroism, circular wheel, polarimetric microspectrophotometer, polarization state generation, ultra-broadband

1. INTRODUCTION

A microspectrophotometer (MSP), which combines light sources and optical spectrometers in a microscope, is an instrument designed to measure the spectra of microscopic samples by transmittance, reflectance, fluorescence, and emission. An MSP can measure and identify samples non-destructively, and is widely used in numerous applications such as forensic science [1], new materials science, thin-film technology, nano- and micro-optics, bio-optics [2], and plasmonics and metamaterials [3-4]. Applications involving plasmonics and metamaterials are currently some of the most attractive topics for MSPs because of their negative refractive index and cloaking. Because of their various artificial patterns or shapes with different alkali metals, plasmonics and metamaterials have spectroscopic and polarimetric characteristics. Anisotropic metamaterials exhibit the characteristics of linear polarization sensitive resonance, such as linear dichroism (LD), because of their non-symmetric structure. Anisotropic metamaterials can be used as polarizers because of their strong LD effect. Densemetamaterial arrays with various patterns have great potential for applications involving high data storage [5]. Because of their chirality structure, chiral metamaterials exhibit circular polarization dependence in the form of circular dichroism (CD). Circular dichroism (CD) is characterized by the differential absorption of right circularly polarized (RCP) and left circularly polarized (LCP) light, and is related to optical activity. Chirality is needed for the creation of a perfect lens, and provides a demonstration of a negative index. The resonant frequency of metamaterials has recently shifted from the microwave range to the optical range. The visible and near infrared range is a suitable range for real applications. Most designed metamaterials currently operate in the range of near infrared to visible light. Different applications have their own wavelength dependence, meaning different curves in the broadband range of light. Most conventional MSPs provide the ability to measure spectra in the range of 400 nm -

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900 nm (visible to short wavelength near IR, VIS-SWNIR) and lack the ability of polarization identification. However, it is difficult to measure the spectrum of a microscopic area in the ultra-broadband range from 400 nm - 1700 nm because of the chromatic dispersion of optics. By improving the modern optics design and fabrication, an apochromatic lens can reduce the chromatic problem in broadband MSPs. An apochromatic microscope can be produced easily at a reasonable cost. Therefore, this study presents a broadband MSP created by modifying a conventional microscope with two spectrometers which are si based one cover from VIS to SWNIR and the InGaAs based one cover from SWNIR to LWNIR. An ultra-broadband polarimetric MSP is needed to measure chiral metamaterials and micro polarization devices. The MSP system requires a polarization state generator (PSG) and a polarization state analyzer (PSA) for the polarimetric analysis of a microscopic sample. The PSG and PSA have the same configuration, but different arrangements. The PSG can produce any arbitrary polarization state, whereas the PSA can analyze any arbitrary polarization state. Together, a PSG and a PSA can be used as a polarimeter. Commercial PSGs or PSAs do not have such a broadband range, and are not so suitable for microscope applications. There are two orthogonal polarization states for measuring the polarimetric characteristics of a micro polarization device or metamaterial: vertical and horizontal polarization states are needed for LD measurement, and RCP and LCP states are needed for CD measurement. A simple PSG consists of a polarizer and a quarter-waveplate (QWP). Rotating either the polarizer or the QWP with a high-precision rotator creates an arbitrary polarization state, including horizontal polarization, vertical polarization, RCP, and LCP. A sheet polarizer and thin achromatic QWP are easily installed in a microscope, making them suitable for high-quality microscopic imaging and microspectrophotometry systems without introducing too much aberration, which distorts the image quality and decreases the signal to noise ratio. However, the bandwidth of a sheet polarizer and achromatic QWP is limited by the dispersion of polarization optics. The purpose of this study is to develop an apparatus for an ultra-broadband polarimetric MSP system with CD and LD measurement. For the ultra-broadband measurement range from 400 nm to 1700 nm, the PSG needs at least three sheet polarizers and three QWPs for different ranges: 400 nm - 700 nm, 700 nm - 1000 nm, and 1000 nm - 1700 nm. This study proposes an innovative optical mechanism with a miniature motorized circular wheel for the polarization optics of an ultra-broadband polarization state generator (PSG). This apparatus can be used in a polarimetric microspectrophotometer for measurements of micro optics and metamaterials with CD and LD characteristics.

2. COMPACT MOTORIZED CIRCULAR WHEEL OF POLARIZATION OPTICS

In most industrial applications for power output, a drive unit, such as a motor, drives a set of transmission devices, such as gears or pulleys. A movement, such as a transverse shift or rotation, can be performed by one drive unit. If it is necessary to complete two or more movements, it is necessary to install more drive units, and each drive unit must drive a transmission device to operate and complete each movement. For example, a polarization device positioned in an optical mechanism includes several polarizers and QWPs arranged in a matrix on a circular wheel. One drive unit is provided to operate the transmission device, switching one of the polarizers and QWPs to a predetermined position. If it is necessary to adjust the relative angle of a set of polarizers or QWPs, then another drive unit and another transmission device are required. This design incurs a higher cost, and increases the volume of the transmission device. For a manual transmission device, the increase of components and total weight hinders the operation and transportation of the device, causing inconvenience to users. Based on these drawbacks, this study proposes a novel mechanism with a component position adjusting function that overcomes the drawbacks of previous designs and improves the industrial use of the mechanism.

A filter wheel is a good apparatus for switching multiple optics devices. A motorized filter wheel is ideal for automated index applications requiring spectral selection or light intensity control. Suitable optics devices include different objective lenses, multi-spectral filters, and multiple neutral density filters. However, filter wheels are unsuitable for polarization optics applications that must be aligned with the azimuth angle or orientation angle for polarization state modulation. Therefore, this study proposes a new type of circular wheel mechanism for generating an ultra-broadband state. This new wheel mechanism is called a compact motorized circular wheel of polarization optics (CMCWPO). To achieve the objectives described above, this design provides a CMCWPO mechanism with a component position adjusting function. Fig. 1 shows a schematic view of the mechanism with a component position adjusting function in the present design. The mechanism with a component position adjusting function includes a drive motor, a drive shaft, a plate body, a drive wheel, at least one passive component, and a brake. The drive unit provides a forward or reverse rotating shift. One end of the drive shaft is fixed to the drive motor, which rotates the drive shaft. The plate body has a unidirectional component positioned at its center, and the unidirectional component has a through hole. The other side of the drive shaft, which passes through the through hole, extends beyond the other side of the plate body, and the unidirectional component limits the drive shaft to synchronously drive the plate body to rotate in a counterclockwise direction (channel switching). The drive wheel fixed to the drive shaft is exposed from an end of the plate body, and the drive shaft synchronously rotates the drive wheel. At least one passive component is positioned on the plate body and contacts the drive wheel, and the drive wheel synchronously drives each passive component to rotate in a clockwise direction (self-rotation). The brake is placed at a position corresponding to the height of the plate body. Through the rotation of the unidirectional component and the contact of the brake with the plate body, the plate body remains still. For example, when the drive motor drives the drive shaft to perform a counterclockwise direction, the plate body switches to the predetermined position (channel switching). A pair of polarizers and QWPs with the same optical bandwidth is then chosen. In contrast, when the drive motor drives the drive shaft in a clockwise direction, the plate body does not move, but the drive shaft synchronously drives the drive wheel to rotate all the polarizers (self-rotation) with different bandwidths. In this case, none of the QWPs move or rotate. By rotating the polarizer at a predetermined position of the passive component to match the QWPs in the fixing component, a predetermined light source is passed from the polarizer and the QWP to produce any arbitrary polarization state of a predetermined wave band.

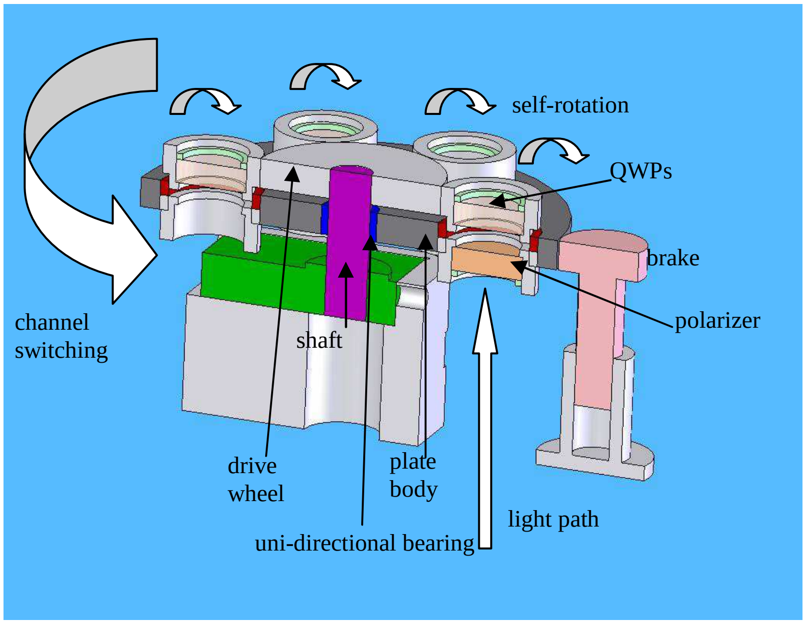

Figure 1. Schematic view of CMCWPO.

Fig. 2 shows a top-view picture of the CMCWPO. For the purpose of flexible applications in the future, this apparatus has 6 channels for 6 QWPs in the upper plate and 6 polarizers in the lower plate. For the ultra-broadband LD and CD measurement in the polarimetric MSP from 400 nm to 1700 nm wave band, the PSG based on CMCWPO needs at least three sheet polarizers and three achromatic QWPs for three ranges: 400 nm - 700 nm (VIS), 700 nm - 1000 nm (SWNIR) and 1000 nm - 1700 nm (LWNIR). The high precision motor is Newport 50PP, with a rotation angle resolution of 0.01°. The speed is 20°/s. The sheet polarizers were obtained from Thorlabs Company. The LPVISE100, LPVIS, and LPNIR series were used for the VIS, SWNIR, and LWNIR ranges, respectively. Achromatic QWPs also have wave band limitations. This study also surveys the retardations of the many QWP products worldwide, and selects Newport products. The 10RP54-1, 10RP54-2, and 10RP54-3 series were used for VIS, SWNIR, and LWNIR ranges. These products are achromatic Zero-Order Quartz-MgF2 waveplates. Fig. 3 shows the product specifications. The retardation for VIS is approximately $0.25\lambda \pm 0.015\lambda$, whereas the retardation for both SWNIR and LWNIR is approximately $0.25\lambda \pm 0.005\lambda$. The retardation error for VIS is much larger than SWNIR and LWNIR because the material is more dispersive in the visible range. The CMCWPO module is driven by a precision motor and controlled by LabVIEW software.

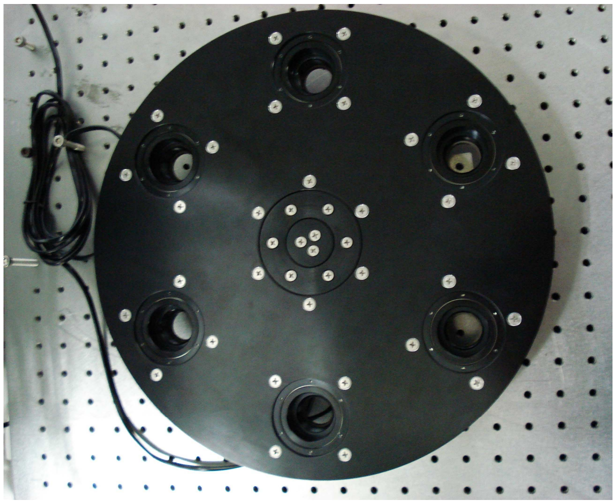

Figure 2. Top-view of CMCWPO module.

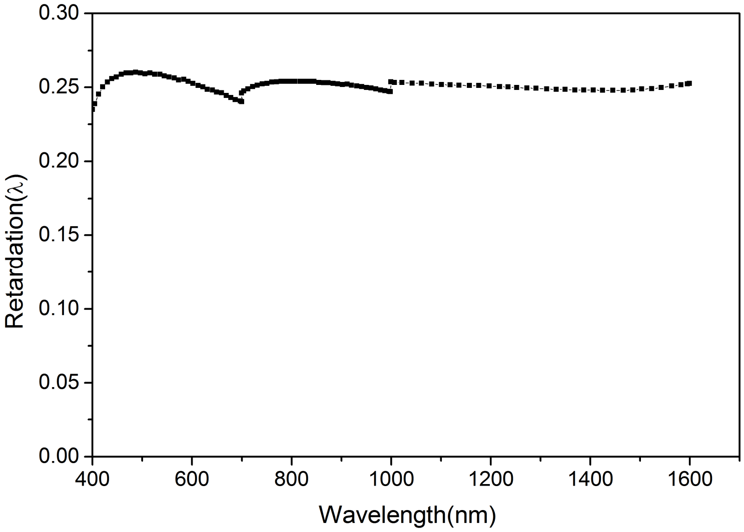

Figure 3. The retardation data of QWPs for Newport products.

3. EXPERIMENTAL RESULTS AND DISCUSSION

To characterize the mechanical performance of the CMCWPO module, six sheet polarizers with a visible band in the module were used to measure the error of channel switching and each channel's self-rotation. An analyzer was used to monitor both the switching angle and rotation angle using Malus's law. Fig. 4(a) shows the experimental results for the repetition measurement of a 360° switching angle. The motor drives the plate body to switch a wheel in a counterclockwise direction for each measurement. Fig. 4(a) shows that the error of repetition testing for channel switching is under 0.3°. The repetition errors are caused by the mechanical gap and intensity variation of the light source. The major error is from mechanical gap, whereas the error due to intensity variation is only approximately 0.05°. The error from switching two adjacent channels is also under 0.3°. Experimental data show that the error of channel switching is small. Therefore, the error of channel switching can be neglected when switching polarizers or QWPs with different bandwidths. Conversely, the same method is applying for measuring error from e channel's self-rotation. The drive wheel synchronously drives each sheet polarizer to rotate in a clockwise direction. Fig. 4(b) shows the experimental results. The error of repetition testing for self-rotation is under 1.2°. The major error is from the mechanical gear gap, which can be improved by applying a higher resolution gear set. The change of the function between channel switching and self-rotation causes another shift error. Experimental results show that the error is approximately 0.8°, and this error can be eliminated through LabVIEW calibration because of its repeatable characterization. The error from different sources degrades the maximum extinction ratio of both LD and CD when measuring samples. To achieve better performance, the mechanical device will be upgraded and improved in the next generation design, which will provide a higher resolution unidirectional bearing and a pulley for substitution of gear gap. The repeatable shift error can be calibrated by predetermining the value embedded in the LabVIEW software. The total error can be suppressed under 0.5° in the next design to achieve better measurement performance.

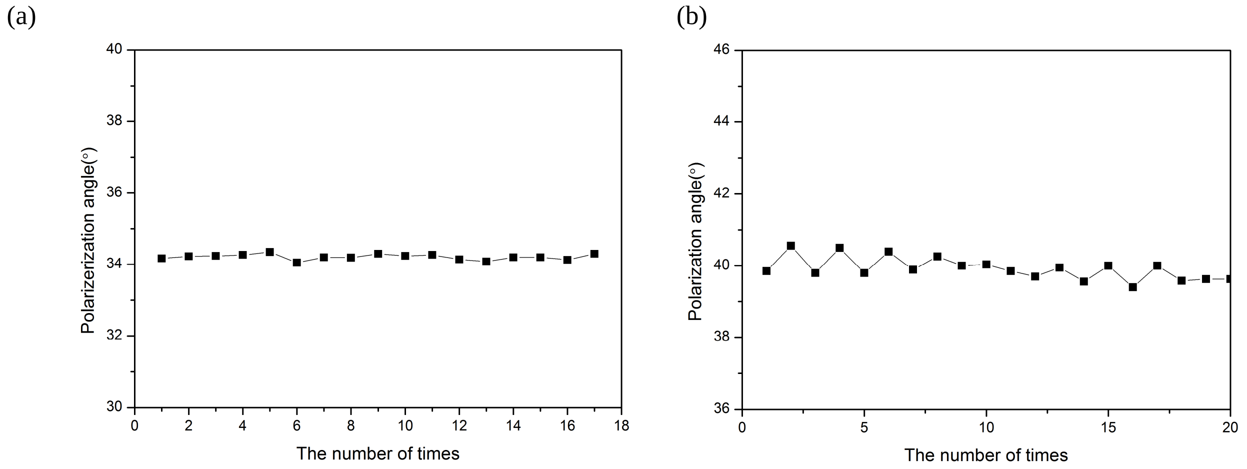

Figure 4. The error of repetition testing (a). Channel switching. (b). Self-rotation.

Fig. 5 shows the experimental results of extinction ratio for two orthogonal linear polarization. This figure shows three curves: VIS, SWNIR, and LWNIR. Compared with the other two curves, the extinction ratio for VIS is the biggest. The maximum extinction ratio for VIS can reach 725 at 615 nm, and the minimum extinction ratio can reach 85 at 400 nm. The maximum extinction ratio for SWNIR can reach 400 at 700 nm, and the minimum extinction ratio can reach 110 at 1000 nm. The extinction ratio for LWNIR ranges from 75 to 100. The reason why the extinction ratio is smaller in the near infrared range is because of the lower light source intensity and lower detector responsivity.

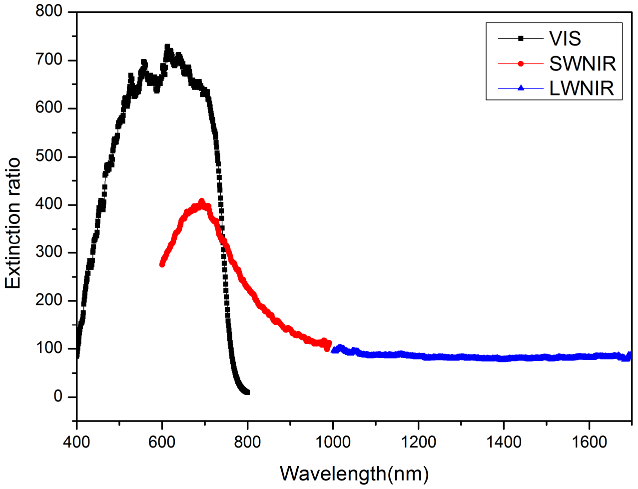

Figure 5. Extinction ratio for two orthogonal linear polarization.

Conversely, the QWP performance was measured by the three step measurement method [6]. The zero-order quartz QWP of 632.8 nm (Meadowlark) was measured to test the accuracy of the proposed method. Fig. 6 shows the experimental results of the three step measurement. The curve shows the retardation value is almost linearly proportion to the wavelength. The retardation value is 0.2485λ at 632.8 nm, and the retardation value from the original specification is 0.2511. The error between the measured and designed value is only approximately 0.0026λ. Therefore, the three step measurement method [6] is suitable for retardation measurement for QWPs. The same procedure can be used to measure three achromatic QWPs with three sheet polarizers in the CMCWPO. Fig. 7 shows the measured retardation curve. This figure shows three curves for the bandwidth from 400 nm to 1700 nm: VIS, SWNIR, and LWNIR. The VIS curve varies more obviously than the other two curves. This is because the material is more dispersive in the VIS range because of refractive index variation. The SWNIR and LWNIR curves are flatter, indicating adequate achromatic compensation. The retardation for VIS is approximately 0.25λ±0.02λ, whereas the retardation for both SWNIR and LWNIR is approximately 0.25λ±0.01λ. Compared to the designed value in Fig. 3, the error between measured result and designed value is under 0.01λ for the entire ultra-bandwidth from 400 nm to 1700 nm. The main reason for this error is the imperfect collimation of the ultra-broadband light source.

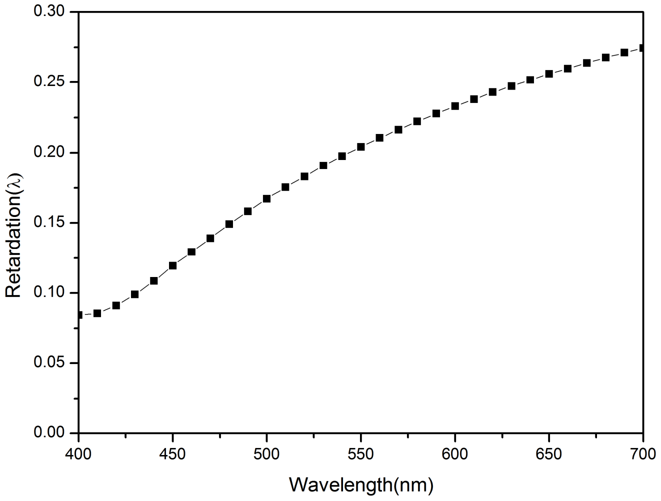

Figure 6. Retardation data for Meadowlark's zero order quartz QWP of 632.8 nm.

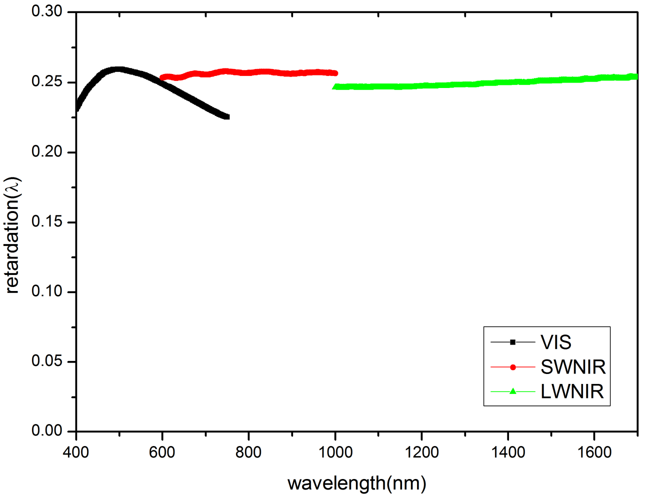

Figure 7. Retardation curves for VIS, SWNIR and LWNIR range.

4. CONCLUSION

This study introduces a compact motorized circular wheel for polarization optics. The proposed design is an innovative optical mechanism that is introduced successfully for an ultra-broadband polarization state generator. The polarization measurement method enables the measurement and characterization of the mechanical gap errors. The next design will improve and calibrate these errors. The errors from different sources degraded the polarization. The value of extinction ratio ranges from 85 to 725 in the VIS range and from 75 to 400 in the SWNIR and LWNIR range. The retardation for VIS is approximately $0.25\lambda \pm 0.02\lambda$, whereas the retardation for both SWNIR and LWNIR is approximately $0.25\lambda \pm 0.01\lambda$. In the near future, we will build a polarimetric MSP with an ultra-broadband PSG/PSA based on the current CMCWPO apparatus. We will use this polarimetric MSP to fully characterize micro polarization optics using both LD and CD measurements. The proposed instrument can be used for frontier research in areas such as chiral metamaterials, plasmonics, micro polarization optics, green optics, and bio optics.

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