An All-Reflective Polarization Rotator

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ABSTRACT

The conceptual design and proof of principle experimental results of a polarization rotator based on mirrors are presented. The device is suitable for any-angle, online rotation of the plane of polarization of high peak intensity ultra-short laser pulses. Controllable rotation of the polarization vector of short laser pulses with a broad bandwidth requires achromatic retarding plates which have a limited scalability and the substantial plate thickness can lead to pulse broadening and inaccurate polarization rotation. Polarization rotators based on reflective optical elements are preferable alternatives to wave plates especially when used in high average power or high peak intensity ultra-short laser systems. The control of the polarization state is desirable in many laser-matter interaction experiments e.g., high harmonic and attosecond pulse generation, electron, proton and ion acceleration, electron-positron pair creating, vacuum nonlinear polarization effect. The device can also serve as a beam attenuator, in combination with a linear polarizer.

Keywords: polarization rotator, high peak intensity laser, ultra-short laser

1. INTRODUCTION

High peak intensity ultra-short laser pulses with complete control over the polarization states and pulse energy are highly desired for laser-matter interaction experiments. In most cases, changing the pulse energy is difficult without affecting the temporal and spatial properties and is usually done by rotating the plane of linear polarization of the laser beam and transmitting it through a polarizer. Most optical elements in high power laser systems are polarization sensitive and require a well-defined polarization state. Half-wave and quarter-wave plates are usually used to manipulate the polarization state but the wave plate's limitations prevent usage in high peak intensity ultra-short laser systems. The major advantages of a reflective polarization rotator are the wide range of available wavelength dependent mirrors; the device is scalable for large beam diameters and the damage threshold is only limited by the mirrors. A reflective polarization rotator, unlike wave plates, does not generate post-pulses and thus reduces the levels of generated pre-pulses after recompression.

At the ELI-ALPS research institute in Hungary, there is a need for a device that can convert between linear and elliptical polarization or can online rotate the polarization plane of high peak intensity ultra-short laser pulses. A polarization rotator based on mirrors is preferred with the further requirements of a stable and simple mechanical setup; a minimal number of mirrors to help alignment and reduce cost; good angular beam pointing stability and if possible collinear input and output beams. Such a device would give direct control over the azimuth angle of the plane of linear polarization, polarization purity and the laser pulse energy on a target.

2. REFLECTIVE POLARIZATION ROTATORS

This section provides a brief overview of the possibilities of polarization rotation with mirrors. An all reflective polarization rotator, consisting of three or four mirrors, was first proposed in ref. [1] and [2]. Geometric phase analysis showed that a three mirror setup is capable to rotate the polarization by an angle of $0 < \varphi < \pi$. It was proven that a minimum of four reflections is required to rotate the linear polarization, by any angle, for the final beam path to be collinear with the incident one. Elementary spherical geometry was used to determine the beam propagation vectors and necessary mirror orientations in case of arbitrary angle of rotation. The rotator proposed in [1] was used to rotate the

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polarization angle of $\varphi = \frac{\pi}{2}$ of CO_2 laser beams and, in principle, can be used for any wavelength at which the mirrors are reflective and polarization inactive[2]. Metal mirrors are virtually ideal mirrors in the mid- and far infrared region and show polarization-dependent phase shift in the visible[3, 10].

The majority of lasers at ELI-ALPS will work in the near infrared where pure, coated metal and multilayer dielectric mirrors have considerable phase shift and reflectivity difference between s- and p polarized components upon reflection. This is also true in the visible regimes and these effects depend on the angle of incidence (AOI). This phase shift difference converts the polarization from linear to elliptical if the incident light has p- and s-polarization components[3].

Ref. [2] proposes a compact configuration of a polarization rotator with three mirrors in the corners of a cube. A drawback of this proposed mirror configuration is that the input and output beams are antiparallel and a challenging mechanical setup would be required for rapidly changing the angle of rotation. A four mirror device is also proposed with collinear input and output beams but its challenging mechanical setup is also not suitable for fast and accurate working – key requirements in our applications. A polarization rotator is described in [4] and [5] that uses three mirrors and keeps the laser beam in the same plane after each reflection, furthermore the input and output beams are collinear. This is a promising development as such a device can be easily integrated into a given beamline and the angle of rotation dependence on the azimuth angle of the input polarization is not important.

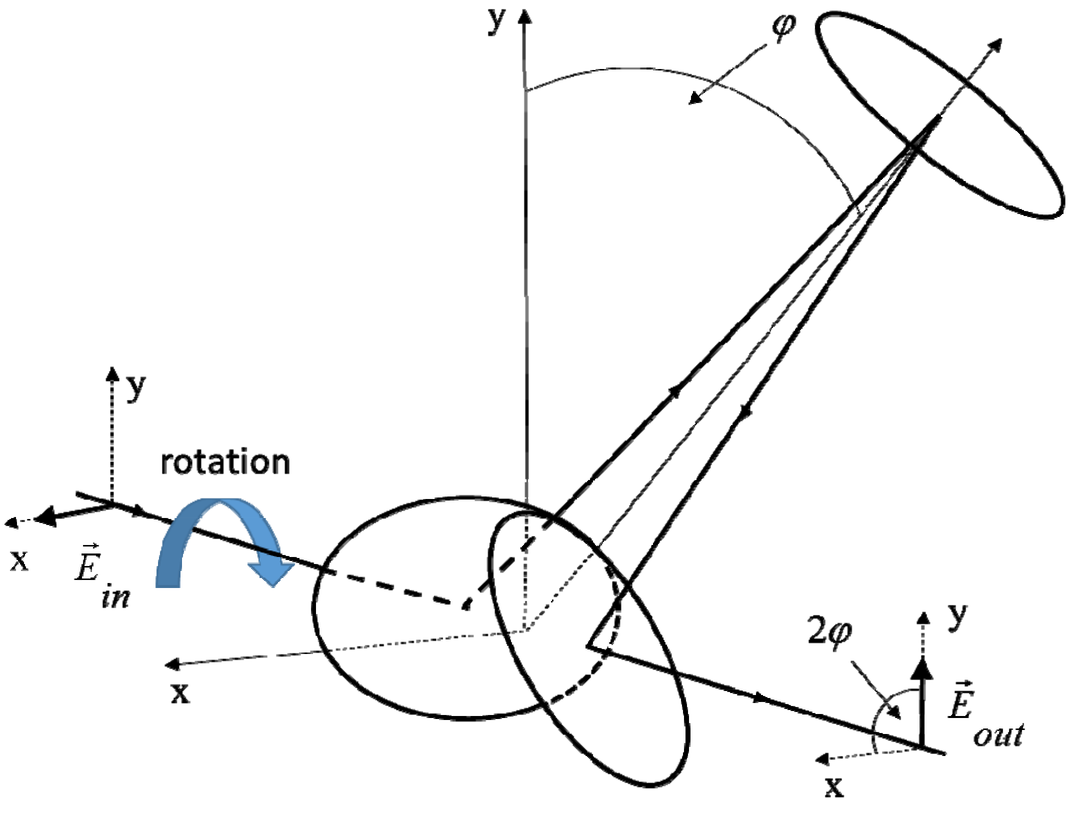


Figure 1. The principles of an all-reflective polarization rotator. The incident polarization $\vec{E}_{in}$ and the near field profile, are rotated by an angle of 2φ, while the mirror arrangement is rotated by φ.

A three mirror system with the output beam coaxial with the input beam was proposed in [4] (Figure 1.). The output angle of polarization is controlled by rotating the mirrors around the optical beam axis and rotating the mirror assembly through 180° enables continuous rotation of the polarization angle through 360°. The input and output beams are collinear and thus it should be easy to insert the device into any existing setup as long as the lengthened beam path is considered. This device is useful when the incoming linearly polarized beam has a stable polarization angle and there is a need for fast switching of polarization. The proposed device is a mirror analog of the Dove prism, which is able to rotate an image at any angle. The operation of the polarization rotator are shown in [4]. The work is based on the theorem that the rotation of polarization produced by an ideal mirror is exactly the same as the rotation of an image seen in the same mirror. It is also shown that the metallic mirrors in this type of polarization rotator will not significantly deteriorate the polarization purity of the beam for wavelengths longer than 5 μm due to the negligible polarization dependent reflective phase shift of metallic mirrors. However, the image rotation of the first and third mirrors cancel each other in the three mirror device[4].

The polarization rotator proposed in [6] is equipped with three dielectric zero-phase-shift mirrors, which have negligible phase shift difference between the s- and p-polarized components upon reflection and thus maintains the polarization purity of the beam. Such dielectric mirrors are available, with sufficient bandwidth, that are able to support short pulses (< 10 fs) centered at 800nm[6]. It has been shown using Jones matrix calculus[7,9], that a three mirror device, as shown in Figure 1, can rotate the plane of polarization by any desired angle[5]. Specifications for coated mirrors on the allowed reflectivity ratio and phase shift difference for the s and p polarization components in order to keep the polarization purity below a desired value are listed in [5]. The Dove prism can work as a very simple polarization rotator device but analysis shows that the polarization purity is very poor[8]. The design parameters for Dove prisms in [8] have a base angle which results in both the image and the polarization plane of the linearly polarized transmitted beam being rotated. This device is not suitable, especially in short pulse systems due to numerous problems, especially the material dispersion.

3. TEST MEASUREMENT OF A REFLECTIVE POLARIZATION ROTATOR

A polarization rotator device, based on the schematic proposed in [4], was chosen for its simplicity and compact layout and was subsequently built and tested. The device consists of three mirrors fixed on a common plate and this rigid mirror system is rotatable around the beamline. The light source in the experimental setup (Figure 2.) is a broadband (650 nm to 1000 nm) 7 fs Ti:Sa laser oscillator (Laser Quantum) with an average output power of 500 mW. Additional mirrors were used to fold the beam and collinearly align it with the axis of rotation. Proper alignment of the rotating mirrors and the incident laser beam with respect to the axis of rotation minimizes angular or displacement misalignment of the output beam during rotation. This is limited by the mechanical stiffness of the device. A nanoparticle linear film polarizer (Thorlabs LPNIR050-MP) was added to the beamline to improve the polarization purity of the incoming beam. The polarizing plane of the polarization analyzer (same type as the polarizer) was set to either parallel or perpendicular to the existing polarizer. The extinction ratio of the polarizers is greater than 1000:1 over the spectral range of the laser. The mechanical setup of the rotating assembly enables arrangement of the three mirrors so that the angle of incidence on mirrors #1 and #3 can vary between 48° and 66°. The power transmitted through the polarization analyzer was measured with a power meter (Gentec-EO XLP12-3S-VP) as a function of the rotation angle of the three mirror assembly. Multilayer dielectric, protected gold, protected silver and ultraviolet enhanced aluminum mirrors were tested. These dielectric mirrors were designed for a wavelength range of 700 nm to 900 nm and angle of incidence of 0° and 45°. These mirrors were tested in the polarization rotator at AOI=10° and 50° and therefore the spectral coverage was shifted to shorter wavelengths. No special features of the tested mirrors regarding the differential phase shift between s- and p-polarized components upon reflection were known before testing in the polarization rotator.

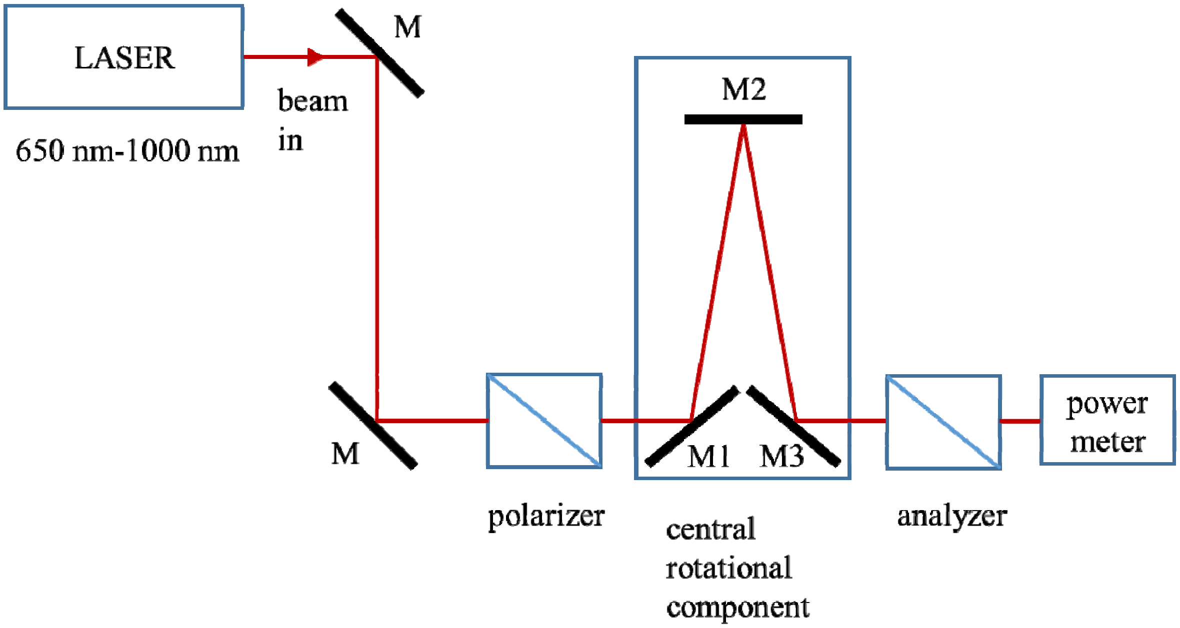
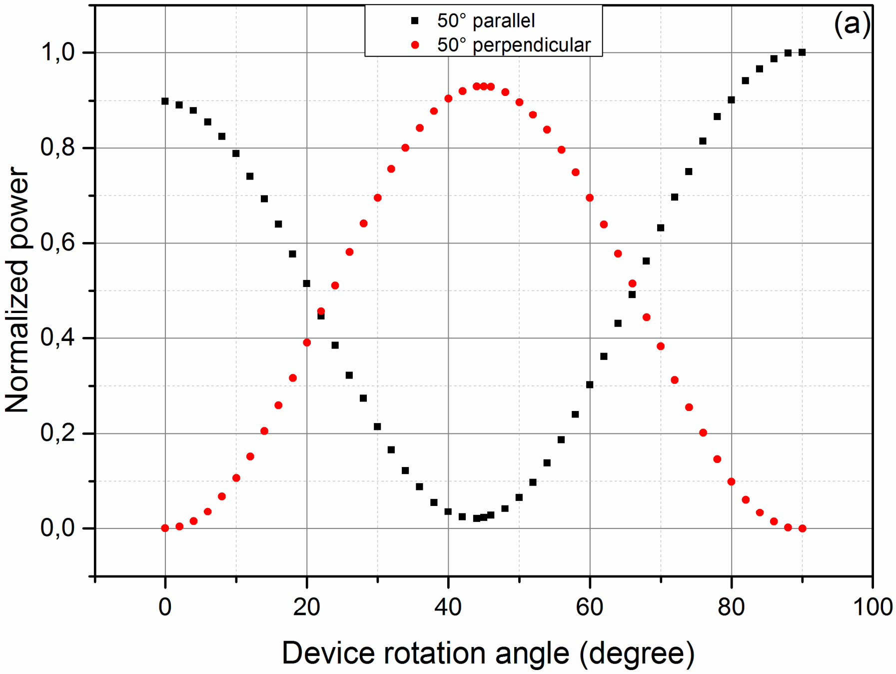
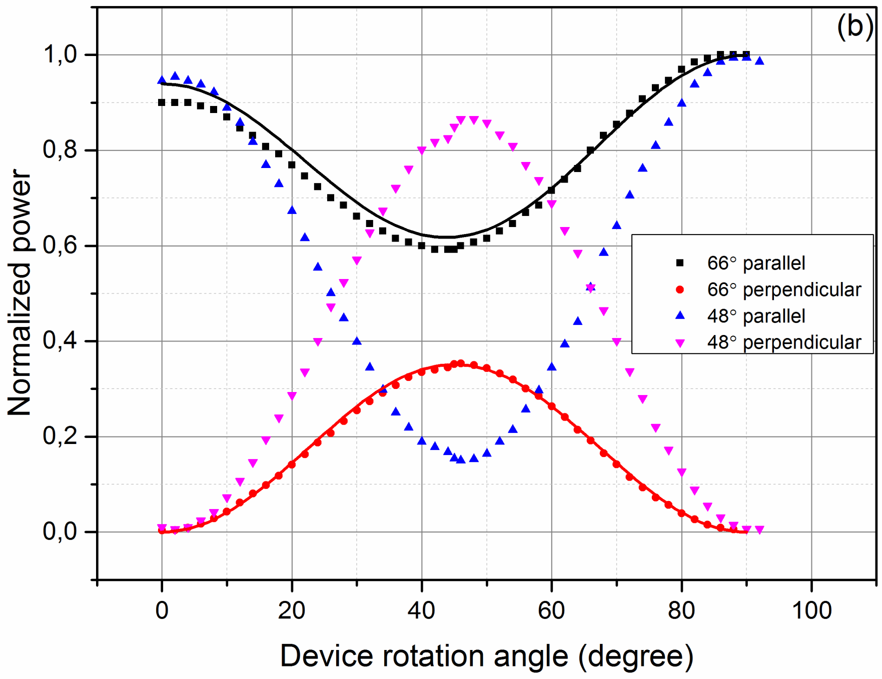
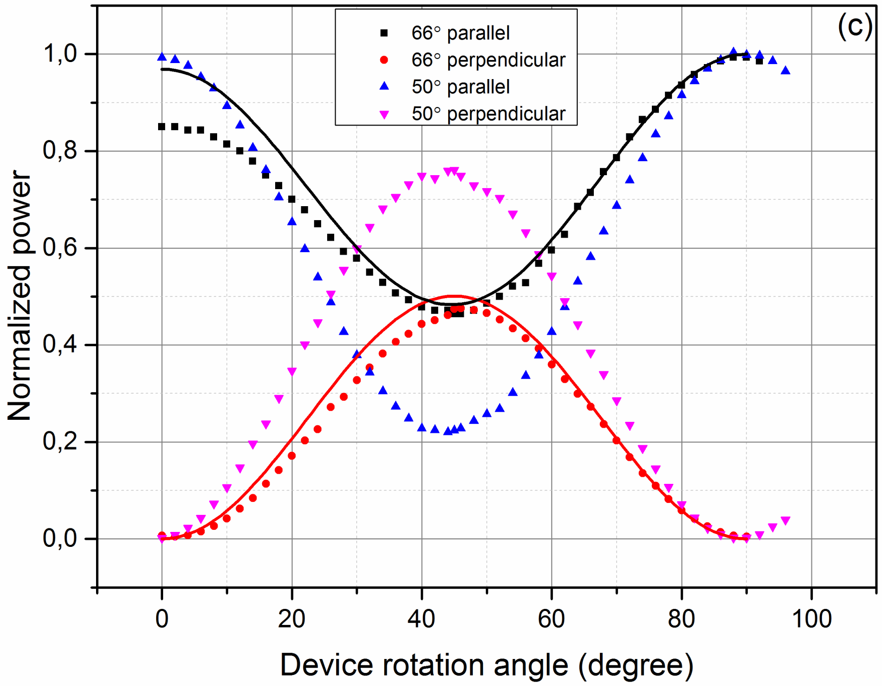


Figure 2. The proof of principle experiment setup for polarization rotating. The output power was measured as function of the angle of rotation of the rotating part.




(b)
Normalized power
Device rotation angle (degree)
1,0
0,8
0,6
0,4
0,2
0,0
0
20
40
60
80
100
■ 66° parallel
● 66° perpendicular
▲ 48° parallel
▼ 48° perpendicular


(c)
Normalized power
Device rotation angle (degree)
1,0
0,8
0,6
0,4
0,2
0,0
0
20
40
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80
100
■ 66° parallel
● 66° perpendicular
▲ 50° parallel
▼ 50° perpendicular

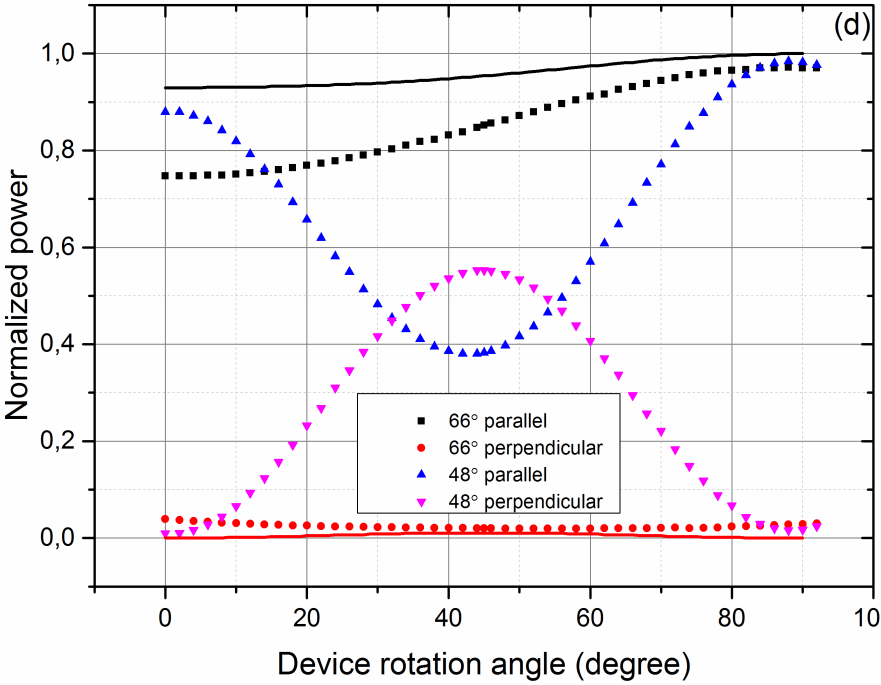

Figure 3. The measured (dots) and calculated (lines) power as a function of angle of rotation of the central rotational component (Figure 2.) from (a) dielectric (b) gold (c) silver, (d) UV enhanced aluminum mirror set. The polarizer and analyzer were set parallel or perpendicular. Both measured and calculated values were normalized to the sum of the output power of the two polarizations. Insets show the angle of incidence on mirrors M1 and M2 for the different curves.

The test results in Figure 3 show that dielectric mirrors (Figure 3d) result in the smallest loss of polarization purity. Aluminum mirrors are not suitable to rotate and maintain linear polarization and this is due to the phase shift modification of the enhancing protective layer upon reflection. Upon rotation from 0° to 90°, p polarization changes to s therefore the power recorded at 0° and 90° should not be equal in the case of parallel polarizer and polarization analyzer. Furthermore at 45° the signal does not tend to unity or zero due to the different phase shift for the s and p polarized components upon reflection. Therefore the originally linearly polarized beam becomes elliptically polarized. The difference between the measured and calculated curves of Figure 3 are due to the approximated reflectance values using the supplier’s data and the approximation that the calculations were performed with the differential phase shift between s- and p- polarized components upon reflection measured at the central wavelength of the laser.

4. CALCULATIONS

The optical properties of our device can be modelled using Jones calculus. The complex reflectivity for s- and p-polarized components determines the polarization purity of the rotated beam. The intensity reflectivity values for the metallic mirrors for s- and p- polarized components were taken from supplier data. The differential phase shift of the two perpendicular polarization components were measured using a Woollam M2000-F rotating compensator ellipsometer. The calculations start by considering an initially plane polarized beam and tracing it through the polarization rotator. The mirrors in the rotating assembly were aligned so that the normal of all three mirrors were in a common plane and the beam was aligned to propagate in that plane. The complex amplitude reflectivity r_p and r_s at the central wavelength of the test laser (λ = 825 nm), belonging to the current angle of incidence, were applied to the p- and s- polarized components of the incident field at each mirror. In [5] it is assumed that the complex reflectivity for the three mirrors are equal. However the angle of incidence on the mirrors in the rotating assembly are different therefore the phase shift of s- and p- polarized components are also different. The complex reflectivity for different angles of incidence on mirrors M1, M2 and M3 was calculated for a more precise analysis. The values of the reflectance and the differential phase shift for different mirrors used in calculation are summarized in Table 1.

Table 1. Intensity reflectivity for s- and p- polarization (R_s, R_p) using the supplier's data and measured differential phase shift between s- and p- polarized components upon reflection for different mirrors at angle of incidence of 42° and 66°, φ_p and φ_s are the phase shifts. φ_{total} is the sum of the differential phase shifts on M1, M2 and M3. The reflectivity was approximated to be the same at both angle of incidence.

mirror	R_s	R_p	$\varphi_p - \varphi_s$ AOI=42° (M2)	$\varphi_p - \varphi_s$ AOI=66° (M1, M3)	φ_{total}
gold	0.98	0.96	166°	134°	74°
silver	0.96	0.95	163°	152°	107°
aluminum	0.84	0.82	152°	98°	-12°

The sum of the differential phase shifts on mirrors M1, M2 and M3 for aluminum mirrors is around 90° for gold and silver mirrors and is closer to 0° for aluminum mirror. This is due to the unexpected behavior of aluminum mirrors at 66° and 42° angle of incidence in Figure 3d. Unfortunately, the minimum angle of incidence that can be measured on the ellipsometer is 42° and thus the angle of incidence of 6° and 10° on mirror #2 could not be checked with the calculation. The coordinate system of the beam for using Jones calculus is shown in Figure 4.

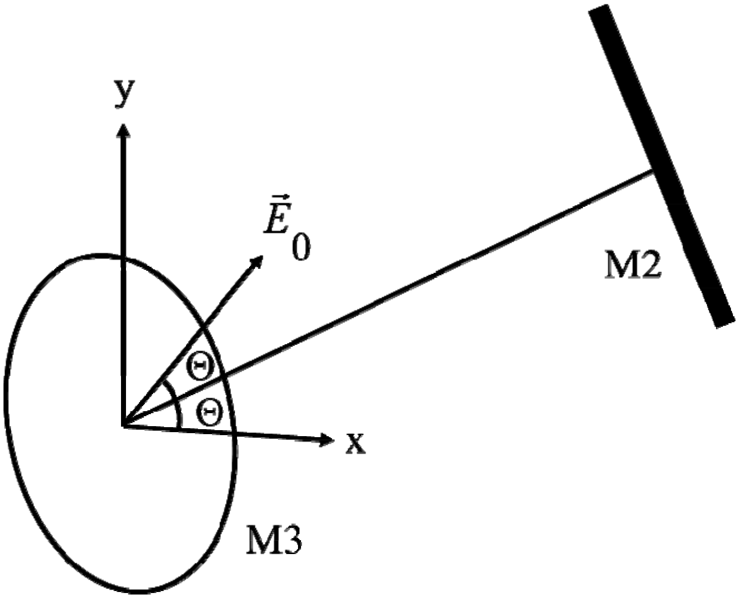

Figure 4. Beam coordinate system when viewing into the beam from the side of the third mirror (M3).

With 2Θ denoting the polarization angle of the incident field in this coordinate system, the Jones vector for the incident beam in the beam coordinate system is

$$\vec{E}_0 = \begin{pmatrix} \boldsymbol{cos}\, 2\Theta \\ \boldsymbol{sin}\, 2\Theta \end{pmatrix} \tag{1}$$

The Jones vector of the incident electric field can be transformed into the coordinate system of the mirrors, where reflection is simply a multiplication by the Jones matrix of the mirror, determined by the complex amplitude reflectances, and then return back to the original coordinate system. Coated metallic or dielectric mirrors introduce a phase shift difference between the p and s components of the electric field upon reflection[12]. The complex amplitude reflectance (r_p and r_s) can be expressed in the form $r_p = \rho_p\, \boldsymbol{exp}\left(i\varphi_p\right)$ and $r_s = \rho_s\, \boldsymbol{exp}\left(i\varphi_s\right)$[11], where $\rho_p \equiv \sqrt{R_p}$ and $\rho_s \equiv \sqrt{R_s}$ are the real amplitude reflectance for p- and s-polarized components. The overall Jones matrix for the experimental setup is[9]

$$M = \begin{pmatrix} \boldsymbol{cos}\,\Theta & \boldsymbol{sin}\,\Theta \\ -\boldsymbol{sin}\,\Theta & \boldsymbol{cos}\,\Theta \end{pmatrix} \begin{pmatrix} r_{p1,3} & 0 \\ 0 & r_{s1,3} \end{pmatrix} \begin{pmatrix} r_{p2} & 0 \\ 0 & r_{s2} \end{pmatrix} \begin{pmatrix} r_{p1,3} & 0 \\ 0 & r_{s1,3} \end{pmatrix} \begin{pmatrix} \boldsymbol{cos}\,\Theta & \boldsymbol{sin}\,\Theta \\ -\boldsymbol{sin}\,\Theta & \boldsymbol{cos}\,\Theta \end{pmatrix} \tag{2}$$

where $r_{p1,3}$ r, $r_{s1,3}$, r_{p2} r and r_{s2} are the complex amplitude reflectance for mirrors 1,3 and 2 respectively. The Jones vector at the input of the polarizing analyzer is

$$\vec{E} = M\vec{E}_0 \tag{3}$$

Finally, the intensity after the polarization analyzer regarding the two perpendicular positions can be simply determined by the components of $\vec{E}$.

5. CONCLUSION

A polarization rotator based on mirrors has been fabricated and tested. The device is suitable for online and continuous rotation of the polarization plane and conversion of linear polarization to elliptical. The polarization purity at the output of the device depends on the difference phase shift between s- and p- polarized components upon reflection on the applied mirrors. This directly depends on the mirror type and angle of incidence. The device has no transmissive optical elements therefore is highly suited for high peak intensity, ultra-short laser pulses and large beam diameters. This device is designed and will be use in the beamlines of ELI-ALPS.

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REFERENCES

[1] Luke, L. S. and Peter, M. K., “Use of four mirrors to rotate linear polarization but preserve input–output collinearity I,” Journal of the Optical Society of America A 13(10), 2102-2105 (1996).

[2] Galvez, E. J. and Peter, M. K., “Use of four mirrors to rotate linear polarization but preserve input–output collinearity II,” Journal of the Optical Society of America A 14(12), 3410-3414 (1997).
[3] Jenkins, F. A. and White H. E., [Fundamentals of Optics], McGraw-Hill, New York, 3rd ed., 520-526 (1957).
[4] Johnston, L. H., “Broadband polarization rotator for the infrared,” Applied Optics 16(4), 1082-1084 (1977).
[5] Greninger, C. E., “Reflective device for polarization rotation,” Applied Optics 27(4), 774-776 (1988).
[6] Keppler,S., Hornung , M., Bödefeld, R., Kahle, M., Hein, J. and Kaluza, M. C., “All-reflective, highly accurate polarization rotator for high-power short-pulse laser systems,” Optics Express 20(18), 20742-20747 (2012).
[7] E. Hecht, [Optics, (4th ed.)], Pearson, 376-385 (2001).
[8] Padgett, M. J. and Paul Lesso, “Dove prisms and polarized light,” Journal of Modern Optics 46(2), 175-179 (1999).
[9] Chipman, R. A., "Polarization Ray Tracing," Proceedings of the Society of Photo-Optical Instrumentation Engineers 766(53), 61-68 (1987).
[10] Refractiveindex.info
[11] Born, M., Wolf, E., [Principles of Optics 6th ed.], Elsevier, 615-624 (1980).
[12] Born, M., Wolf, E., [Principles of Optics 6th ed.], Elsevier, 627-633 (1980).