Creating Broadband Circular Polarised Light by Reflection

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Introduction

In high-powered laser-plasma experiments it is commonly desired to shift the laser's polarisation from linear to circular. An example application of this is proton acceleration via radiation pressure acceleration (RPA) which is predicted to become dominate at lower intensities with circular polarisation compared to linear [1]. Conventionally, a transmissive mica waveplate would be inserted within the beam-line to alter the polarisation state. This method unfortunately becomes impractical for lasers among the petawatt power output range, such as the Vulcan Laser (and especially the Vulcan 10PW upgrade) due to the necessary thickness of such plates (~µm) in comparison to the beam width (~m. Furthermore, upon transmission through an optic, the short pulses' large bandwidth makes them susceptible to group velocity dispersion (GVD) resulting in pulse broadening. Although reflective polarisers have been available before [2], here we present work on a *broadband* circular polariser between 800nm and 1000nm.

Theory

Upon reflection from a conductor surface, light experiences a phase shift in polarisation, governed by the angle of incidence θ_1, the incident wavelength λ, and the mediums involved.

For a highly reflective conductor, we can treat its refractive index $\hat{n}_j$ as complex [3];

$$\hat{n}_j = n_j(1 + \boldsymbol{i}k_j) \qquad (1)$$

where k_j is known as the extinction coefficient – the imaginary part of the refractive index describing absorption through the medium. For light incident upon a conductor (medium 2) at angle θ_1 from air/vacuum (medium 1) we can set;

$$\hat{n}_2 \cos\theta_2 = u_2 + \boldsymbol{i}v_2 \qquad (2)$$

for real, calculable $u, v = f(\theta_1, n_1, n_2, k_2)$ with θ_2 being the angle of refraction.

Now, by using the Fresnel equations and substituting equation (2), the reflectivity coefficients between mediums 1 & 2 can be found. Then, by exploiting the complex components, we can find the complex argument φ, also known as the phase shift in polarisation:

$$tan\varphi_{s_{12}} = \frac{2v_2 n_1 cos\theta_1}{u_2{}^2 + v_2{}^2 - n_1{}^2 cos^2\theta_1} \qquad (3)$$

$$tan\varphi_{p_{12}} = \frac{(2n_1 n_2{}^2 cos\theta_1)\left(2k_2 u_2 - v_2(1-k_2{}^2)\right)}{\left(n_2{}^2(1+k_2{}^2)cos\theta_1\right)^2 - n_1{}^2(u_2{}^2+v_2{}^2)} \qquad (4)$$

with 's' & 'p' denoting the standard perpendicular EM polarisation components and the subscript '12' denoting the transition from medium 1 to medium 2.
In the case of an intermediate boundary (i.e. coating on a protected optic) we now call the conductor medium 3 and set medium 2 as the film.

$$tan\varphi_{13} = \frac{\rho_{23}(1-r_{12}{}^2)sin(\varphi_{23}+2\beta)}{r_{12}(1+\rho_{23}{}^2)+\rho_{23}(1+r_{12}{}^2)cos(\varphi_{23}+2\beta)} \qquad (5)$$

for r & ρ being the real reflection coefficients and $\beta = \frac{2\pi}{\lambda} h n_2 cos\theta_2$ [3] of a coating, thickness h. Equation 5 holds true for both EM components.

The coated optic creates an opposite phase shift dispersion to that of an air-metal boundary. A system built from a combination of optics with air-metal and air-dielectric-metal boundaries can be developed to give a uniform phase shift over a broader range of wavelengths. The effects of this can be seen most noticeably in figure 1, where the incident angles of two three-mirror systems are manipulated in such a way (using equations 4 & 5) that a 90° phase shift is induced about 910nm – the planned wavelength for the Vulcan 10PW upgrade [4].

For light at $\lambda = 910nm$, solving equations 3-5 such that the system allows for an unaltered beam path with 90° phase shift, finds the required mirror parameters to be two of $\theta_{Au} = 65.50° \pm 0.25°$ with $\theta_{AgSiO2} = 14.00° \pm 0.50°$ [5].

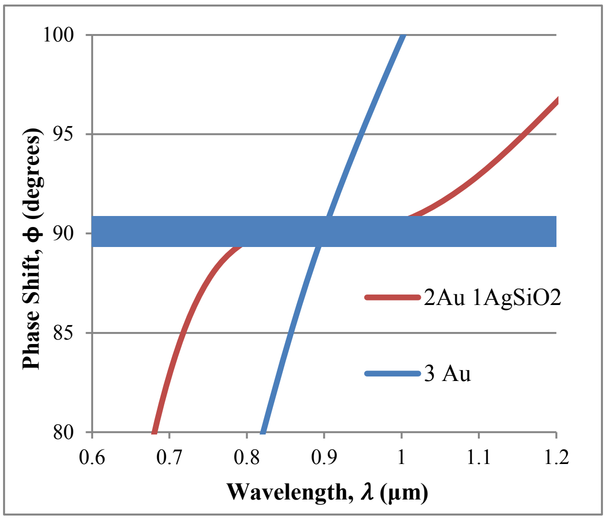

Figure 1: A comparison of reflection-induced phase shifts for two different combinations; one of 3 gold coated mirrors and one of 2 gold coated and 1 silver with silicon dioxide coating – with angle parameters aimed at producing φ=90° at λ=910nm.

Method & Setup

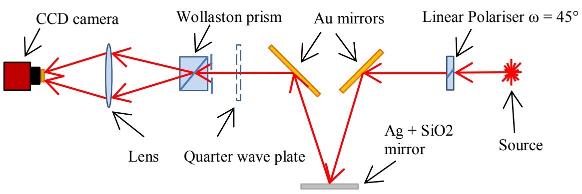

Figure 2: Optical polarisation measurement setup with reflective polariser.

The experimental setup, shown in figure 2, was designed to assess the reproducibility of equations 3-5. For the purposes of testing, a laser of wavelength 532nm was used. This was sent through a linear polariser to ensure initial fixed linearity at 45° to the vertical and then continued to a three mirror system – two gold-coated on mounts rotatable in the horizontal plane, one silver with a silicon-dioxide overcoat on a sliding mount which maintained beam directionality. After reflections, the beam continued in its original course towards a quarter wave plate (QWP) and a Wollaston prism (WP) (angles referenced from the vertical); both used to manipulate and separate perpendicular EM components such that upon examining at the CCD, the polarisation state of the wave can be ascertained.

To interpret information gathered by this technique, Stokes parameters (I, Q, U, and V) were used. These together fully describe the polarisation state of any electromagnetic wave by mapping it onto the Poincare Sphere (figure 3). The most notable vectors are shown in table 1.

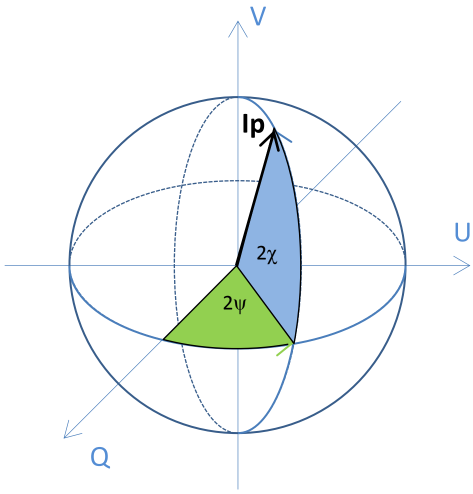

Figure 3: The Poincare Sphere, used for visualising polarisation characteristics.

Stokes parameters (I,Q,U,V) (normalised intensity)	**State of polarisation**
(1, 0, 0, 0)	Unpolarised
(1, ±1, 0, 0)	Linearly polarised (0°/90°)
(1, 0 , ±1, 0)	Linearly polarised (45°/135°)
(1, 0, 0, ±1)	Circularly polarised (Right/Left)

Table 1: Brief descriptions on significant Stoke's vectors.

By adjusting the Wollaston prism between 0° & 45° the magnitudes of 4 components (2 pairs of perpendiculars) can be recognised. This was exploited to find normalised relative Stoke's parameters:

- WP at 0° (and no QWP) showed the beam's 0° & 90° components.
- WP at 45° (and no QWP) showed the beam's 45° & 135° components.
- WP at 45° with QWP at 0° showed the beam's ellipticity.

To attain this information, images of the separate components were taken with the CCD and the mean intensities were found using the Image-J software. Subtracting these values from each other and normalising with respect to the total intensity (found by the summation of the two values) gave the Stoke parameters. These values were compared with theoretical values found from equations 3-5.

Results & Analysis

The recorded, relative Stoke's parameters for green light at $\lambda = 532nm$ are shown in figure 4.

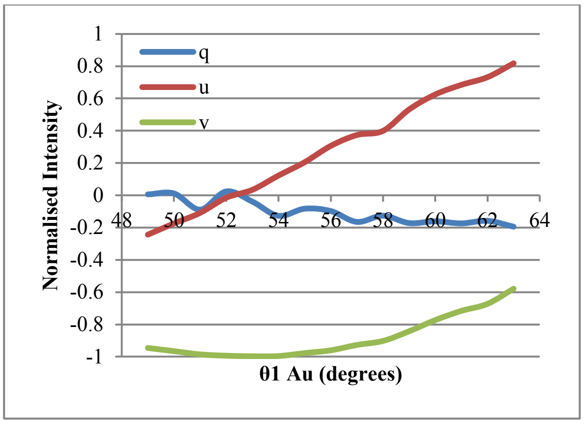

Figure 4: Recorded data for normalised Stokes parameters as a function of incident angle on gold mirrors.

To translate the recorded Stoke's Parameters into a magnitude of phase shift the following relationship was used [6].

$$\varphi = \mathrm{acos}\left(\frac{u}{1-q^2}\right) \quad (6)$$

Figure 5 compares the results obtained experimentally with the predicted values found through equations 3-5, highlighting the consistency and validity of the method.

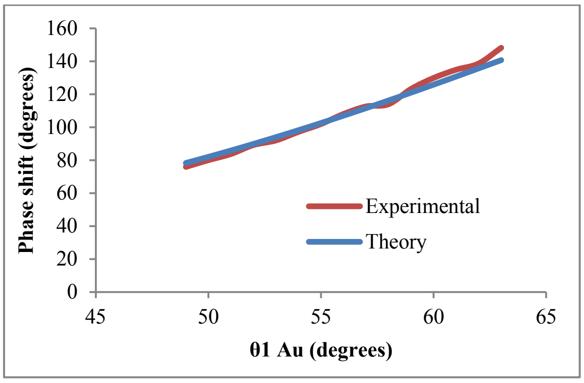

Figure 5: Recorded data interpretation compared with the expected calculated phase shift; with varying angle of indices, at λ=532nm.

Conclusion

A mock setup of a three mirror polarisation system was built and used to show the plausibility of creating a circular polariser through reflection for high powered lasers. Results were found to match the theory at $\lambda = 532nm$ requiring two gold-coated mirrors at 52° and one silver with a silicon-dioxide coating mirror at 14°. Following from the validity of the experimental results taken, we can look closer towards interpreting this design onto a real life scale for the Vulcan and/or Astra-Gemini lasers. The derived relationships demonstrate large bandwidth capabilities of the design for $\lambda = 910nm$ – the Vulcan 10PW wavelength.

Future Work

Adding a second silver coated mirror allows a degree of flexibility that can be used to tune a 90° phase shift over a wider range of central wavelengths, although this may sacrifice the bandwidth size (and reduce transmission efficiency).

To further test the mathematics behind the technique, a tuneable wavelength source would be useful – to verify the broadband capabilities shown in figure 1.

References

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