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# Birefringence measurements of substrate materials and coatings for Einstein Telescope

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The birefringence that can occur in the optics that will be used in the Einstein Telescope (ET) interferometer is an essential phenomenon to be considered to ensure the desired sensitivity for gravitational wave (GW) detection.
The birefringence of the optics directly depends on the substrate and coating materials and is mainly induced by stress in these materials (residual internal stress, externally induced stress, intrinsic stress fluctuations).
Being experienced in sensitive birefringence measurements, the Ferrara ET Reasearch Unit (University of Ferrara and INFN - Ferrara) has been working on birefringence 2D mapping of different samples both in transmission and in reflection at 532nm and 1064nm.
Results of such measurements will be presented at the Symposium.

A medium of thickness $D$ with birefringence $\Delta n$ will induce a time dependent ellipticity $\psi(t)$ on a rotating linearly polarized beam given by
$\psi(t) = \frac{\pi}{\lambda} \int\limits_{\text{light path}} \Delta n\, dl \sin 2\vartheta(t) \simeq \frac{\pi}{\lambda} \Delta n D \sin 2\vartheta(t) \qquad (1) where, here, \vartheta(t)$ is the time dependent angle between the polarization and the birefringence axis.

The scheme of the polarimeter for transmission measurements is based on a linearly polarized beam (either 532 nm or 1064 nm wavelength) passing through two half-wave plates co-rotating at $\nu_w$. Between them is the sample whose birefringence is to be measured and a 2.5 T magnetic field rotating at $\nu_B$, for calibration purposes. Together these will generated a time dependent ellipticity $\psi(t)$. After the two half-wave plates an ellipticity time dependent photo-elastic modulator adds a known ellipticity $\eta(t)$ to $\psi(t)$ followed by an analyser placed at maximum extinction. The modulator ellipticity linearises $\psi(t)$ in the output power, $P_{\text{out}}(t)$, after the analyser. The precisely known sinusoidal time dependence of $\psi(t)$ also allows its separation from spurious harmonics generated by the two rotating half-wave plates and from slowly varying $1/\nu$ spurious ellipticity noise, always present due to the various optical elements, all contained in the ellipticity $\Gamma(t)$.

Finally, the output power $I_{\text{out}}(t)$ detected at the diode PDE will be $\mathrm{P}_{\text{out}} = P_0 \left[\eta(t) + \psi(t) + \Gamma(t)\right]^2 \simeq P_0 \left[\eta^2(t) + 2\eta(t)\psi(t) + 2\eta(t)\Gamma(t) + ...\right]$.

The total ellipticity $\psi(t) + \Gamma(t)$ is extracted by demodulating $I_{\text{out}}(t)$ at the modulator frequency. The main two harmonics of interest to us in the demodulated signal will be: the sample ellipticity at $4\nu_w$; the Cotton-Mouton effect of air at $4\nu_w \pm 2\nu_B$. Zero measurements can be made without the sample to minimize the contribution of spurious ellipticities generated by the half-wave plates at, in particular, the frequency of interest $4\nu_w$. The sample is mounted on a horizontal-vertical manual positioning system so as to acquire a 2D ellipticity map which can be converted to a birefringence (average $\Delta n$ over the thickness) map through Equation (1).

Measurements are also feasible in reflection to study mirrors and coatings with a minor modification of the transmission scheme. The beam enters through the output port of the analyzer. The beam then passes through the modulator, through the 'second' half-wave plate, the magnetic field and is then reflected by the sample and returns back along its path. The extinguished beam is then collected and analysed in the same way as in transmission measurements.

In this scheme a position sensitive detector (PSD) was introduced to ensure that during the mapping of the reflective surface, the reflected beam always returns through the same point on the half-wave plate. Given that no real zero measurements are possible (sample cannot be removed) in this configuration, for each position of the sample, two measurements were taken with the sample rotated by $90^\circ$. In this way the ellipticity of the sample changes sign whereas the spurious ellipticity induced by the rotating half-wave plate does not. By adding and subtracting the two measurements, the sample ellipticity can be extracted.

In both the transmission and reflection configurations the sensitivity to optical path difference is $calD = \int \Delta n\ dl \approx 5 \times 10^{-13}$ m, limited by the spurious ellipticity generated by the half-wave plates and not by noise.

We will present transmission maps for a 1 mm thick silicon plates in transmission measured at 1064 nm and reflection map measurements of various reflecting surfaces (silver mirror, coating, dielectric mirror, pure dielectric surface) at both 532 nm and 1064 nm.

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