Tilt angle dependence of the modulated interference effects in photo-elastic modulators

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The effect of the PEM tilt angle and incident polarization on the PEM interference is studied for a single axis photo-elastic modulator. The dc, 1\(\omega\), and 2\(\omega\) components of the detector signal vary periodically as a function of PEM tilt angle. Although it is possible to adjust the PEM tilt angle to minimize the 1\(\omega\) or 2\(\omega\) detector signal at small tilt angles, it is not possible to null both of them simultaneously. For the case where no analyzer is used, the ac detector signals can be minimized simultaneously by adjusting the polarization angle of the light incident on the PEM and the PEM tilt angle.

Direct observations of the detector signal indicate that the effects of refraction index and thickness variations are opposite consistent with a lower polarizability for compressive strain of the modulator. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

I. INTRODUCTION

Photo-Elastic modulators (PEMs)\(^1\) are often used to measure the magneto-optical Kerr effects of thin films and multilayers.\(^2,3\) The incident or reflected beam’s state of polarization are modulated by a standing sound wave in the optical head\(^4–6\) of the PEM and converted to an intensity variation using polarizers. This allows for a determination of the Kerr rotation and ellipticity with a S/N ratio limited by the shot noise of the light source. For single axis modulators the resonance condition is only fulfilled for one axis resulting in a time dependent refraction index for light polarized parallel to this axis (p-axis). Because of Poisson’s ratio, periodic strain variations are also expected perpendicular to this modulation direction resulting in a weak modulation of the refraction index for light linearly polarized perpendicular to the modulation axis (s-axis). In addition the modulation of the strain parallel to the optical axis will result in a time dependent thickness of the crystal, resulting in a time dependent of the optical path length. When using the modulator with a coherent light source this effect causes a time dependent interference of the laser beam in the crystal which can result in intensity variations several orders of magnitude larger than the intensity variations caused by the MO Kerr effect of the sample.\(^7\) These large signal offsets are undesirable as it forces one to use a higher range setting on the lock-in amplifiers losing measurement sensitivity. The interference effect can be avoided or suppressed by using incoherent light, by coating the PEM with anti-reflection coatings, by tilting the PEM with respect to the optical axis of the setup, or by using a special optical head design so input and output surface of the modulator are no longer exactly parallel.\(^7,8\) Polnau et al. showed that the interference effects also takes place in double axis modulators although those modulators do not have a time varying thickness. The modulation of the refraction index is sufficient to induce intensity variations. They concluded this from measurements of the 1\(\omega\) component versus the polarizer angle and from the time dependence of the detector signal.\(^9\) In this paper we investigate in more detail the PEM interference effect for a single axis modulator in particularly the dependence on PEM tilt angle and polarizer angles are investigated and the consequences for the MO Kerr technique are discussed.

II. EXPERIMENTAL PROCEDURE

A Melles Griot intensity stabilized HeNe laser (05 STP901) is used for the light source (633 nm, rms of the intensity < 1%, p-polarized). The optical components of the setup are a quarter wave-plate
(632.8 nm), a polarizer, a photo-elastic modulator, and a silicon photo-detector all mounted on top of a vibration isolation table. A Glan-Taylor prisms (MGTYS15, Karl Labrecht) is used for the polarizer. The polarizer prism is mounted in Newport servo motor rotator that can be controlled by a computer and whose orientation can be read out with a resolution of 0.0005 degrees. The orientation of the fast axis of the quarter wave plate is at 45 degrees with the horizontal so the linearly polarized laser light is converted into circularly polarized light just before the polarizer. Light reflected from the polarizer or PEM will once more pass the quarter wave plate and be vertical linearly polarized when heading back to the laser preventing it from entering the laser cavity and destabilizing the intensity control of the laser. The HINDS PEM-90 is mounted horizontally on a non-magnetic optical post that can be rotated by a computer controllable Melles Griot micro-encoder rotation stage. This allows us to change the angle between the laser beam and the optical axis of the modulator (PEM tilt angle) with a resolution of 0.2 mdegrees. A PDA50 Thorlabs photodetector that includes a pre-amplifier is used to convert the light into an electric signal which is monitored by a Tektronix scope. The AC and DC components of the signal are measured by an HP3457 multimeter and two SR830 lock-in amplifiers.

III. MEASUREMENT RESULTS

Fig. 1 shows the measured time dependence of the intensity for various orientations of the PEM’s tilt angle. All measurements were done without sample and analyzer. Note that the intensity variations decrease with the PEM tilt angle similar to the result reported by Oakberg.\(^8\) Note that the modulation depth for s-polarized light is larger than for p-polarized light. This is consistent with literature of others that shows that compressive strain in fused silica decreases the refraction index.\(^11\)

Fig. 2 below shows the DC, \(1\omega\), and \(2\omega\) signal as a function of the PEM angle. The phase of the lock-in amplifiers was adjusted at perpendicular incidence using the auto-phase button on the SR830 resulting in a positive signal. Prior to the measurement the phase of the lock-in amplifiers was adjusted at perpendicular incidence using the auto-phase button on the SR830 resulting in positive \(1\omega\) and \(2\omega\) signal at zero degrees. All three signals have an extreme at perpendicular incidence and are periodic with the PEM-angle. The \(1\omega\), and \(2\omega\) signals appear to be phase shifted with respect to each other at larger PEM angles: when the \(1\omega\) signal is maximum the \(2\omega\) component is zero and vice versa. An exception is perpendicular incidence where the \(2\omega\) signal has a minimum but does not become zero. The dc and \(2\omega\) signal have extremes at the same PEM tilt angles. The different values of the average DC component for both polarization directions are caused by a misalignment of the

![Fig. 1. Intensity as a function of the PEM orientation at 0.25 wavelength retardation depth for p and s-polarized light.](image-url)
FIG. 2. DC, $1\omega$ and $2\omega$ components as a function PEM tilt angle for p and s-polarized light.

broadband plastic quarter wave-plate which caused the light incident on the polarizer to be elliptically polarized ($I_v/I_h=0.8$).

Fig. 3 shows the normalized $1\omega$, and $2\omega$ components of the detector signal as a function of the polarizer angle for perpendicular incidence. Note that both the $1\omega$ and $2\omega$ zero at 51 degrees. This is off from the 45 degrees observed by Polnau et al. for a 2 axis PEM. Further investigations revealed that not for all retardation setting the $1\omega$ and $2\omega$ signals have a zero. For example no zeros were found for a retardation of $0.5\lambda$ while for $0.79\lambda$ only the $2\omega$ component has a zero.

IV. DATA ANALYSIS

We used the approach of Hecht\textsuperscript{10} to derive an expression for the transmission of the PEM that includes the interference effect.

$$T = \frac{E_i}{E_i} = \frac{1}{E_i} \sum_{k=0}^{\infty} E_k t_{ag} r_{ga} \left( 1 + e^{i(2k+1)\frac{2\pi nd(t)}{\lambda}} \right) = t_{ag} r_{ga} \frac{e^{\frac{2\pi nd(t)}{\lambda}} - 1}{1 - r_{ga}^2 e^{\frac{2\pi nd(t)}{\lambda}}}$$

(1)

Where $t_{ag}$ ($t_{ga}$) is the amplitude transmission coefficients for the air-glass (glass-air) interface, $r_{ga}$ is the amplitude reflection coefficients for the glass-air interface, $\lambda$ is the laser wavelength, $f$ is the PEM’s modulation frequency, $t$ is the time, and $nd(t)$ the optical path length upon one pass of the laser beam through the optical head. Since both the refraction index and the thickness of the optical head are modulated, the optical path length in radians is described by the product of two periodic functions:
\[ I_\phi \approx E_0^2 e \left[ c + \cos \left( a + a \frac{\phi^2}{2n_0^2} \right) \left( J_0 \left( b_\rho \right) \cos^2(\Phi) + J_0 \left( b_\sigma \right) \sin^2(\Phi) \right) + \right. \]
\[ + 2 \cos \left( a + a \frac{\phi^2}{2n_0^2} \right) \left( J_2 \left( b_\rho \right) \cos^2(\Phi) + J_2 \left( b_\sigma \right) \sin^2(\Phi) \right) \cos(2\omega t) + \]
\[ \left. 2 \sin \left( a + a \frac{\phi^2}{2n_0^2} \right) \left( J_1(b_\rho) \cos^2(\Phi) + J_1(b_\sigma) \sin^2(\Phi) \right) \sin(\omega t) \right] \]

Where \( a, c \) and \( e \) are constants which depends on the PEM properties, \( b_\rho \) and \( b_\sigma \) are related to the modulation depth setting of the PEM in \( p \) and \( s \)-direction, \( J_0, J_1, \) and \( J_2 \) are Bessel functions, \( \phi \) is the PEM tilt angle, and \( \Phi \) is the orientation of the polarizer with respect to the horizontal direction. Note that the proportionality constants of the \( d \)-, \( 1\omega \) and \( 2\omega \) components are cosine and sine functions of the PEM tilt angle in agreement with our experimental results of Fig. 2. Only for certain retardation depth values for which \( J_2(b_\rho) \) and \( J_2(b_\sigma) \) and or \( J_1(b_\rho) \) and \( J_1(b_\sigma) \) have opposite signs, it is possible to zero the \( 2\omega \) and/or the \( 1\omega \) components simultaneously as confirmed by our measurement results.

V. CONCLUSIONS

Intensity variation caused by the PEM interference effect can be minimized at small PEM tilt angles by adjusting the PEM tilt angle although in generally not simultaneously. For a 0.25 wave retardation depth, the \( 1\omega \) and \( 2\omega \) component can be minimized simultaneously by adjusting the polarizer angle. Nulling the \( ac \) signals originating from the PEM interference effect enables one to use a more sensitive range on the lock-in amplifiers and reduce measurement noise and drift.

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