

## Phase Shift for Thickness Measurement of Ta<sub>2</sub>O<sub>5</sub> using Modified Sagnac Interferometer

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### ABSTRACT

An optical non-contact measurement with Sagnac interferometer has been considered as the best option compared to Michelson and Mach-Zehnder ones for less sensitive to the external environment. Signal analysis produces errors due to frequency-time domain using single detection and a self-referenced polarization and phase-shifting technique for real-time thickness measurement is proposed. A beam splitter placed at the interferometer output separated the beam into two identical linearly polarized beams. One of the beams served as a reference, while the other served as a sensing arm. The output linear polarizer set at 45° relative to a reference plane was positioned anterior to the photodetectors to get rotating light intensities for phase shift measurement; hence, the intensities at various polarizations of 0°, 45°, 90° and 135° were automatically acquired without any polarizing device adjustments. These intensities were then transformed into a phase retardation introduced by a sample, and the resulting phase shift was eventually converted into film thickness. The samples were properly prepared, with pure BK7 substrate being deposited by Tantalum pentoxide (Ta<sub>2</sub>O<sub>5</sub>). The real-time phase shift is successfully realized at 0.2 rad. This shows the impact of state of polarization thickness thin film of 259.32nm. The mathematical theory was effectively demonstrated and empirically confirmed.

**Keywords:** Dual-beam; Interferometer; Photodetector; Phase-shift; Thickness,

### INTRODUCTION

Sagnac interferometer is insensitive to ambient disturbances; as a result, any movement or noise is avoided because all transmission paths interact with each other. It may be configured in a variety of ways, including lateral and radial shearing in cyclic or triangular forms. Lateral shearing is formed when one of the two mirrors is adjusted, while radial shearing uses a lens and a pinhole placed before the transmitted and reflected beams incident on the two mirrors. The most appropriate configuration for Sagnac interferometer is the triangular configuration with the help of polarization phase-shifting approach. Several phases stepping algorithms using modified Sagnac interferometer were reported, by replication of two coupling arrangements in (Lechuga *et al.*, 2017), by adjusting polarizing beam splitter (PBS) (Xu *et al.*, 2018). It was established that in the many phases shift technique, the linear polarizer at the interferometer's output is rotated. An automatic phase-shifting technique

was also realized using a piezoelectric transducer (PZT) to generate a path length difference by tilting the mirror attached to Piezoelectric transducer (PZT) for nanoscale tilt angle measurement. In this setup, the linear polarizer is fixed at an angle ( $\theta$ ). However, nonlinearity and unstable signal are the potential sources of systematic errors in the phase produced (García-Lechuga *et al.*, 2020). The phase shift using cyclic polarized is applied in (Bhaduri *et al.*, 2006), In (Pretheesh Kumar *et al.*, 2016), a nanoscale of tilt angle using Piezoelectric transducer (PZT) for an automatic phase shift, and further modified to (Joenathan *et al.*, 2016) and (Joenathan *et al.*, 2018). As in (Kaewon *et al.*, 2018), the measurement is observed with a single beam with the single detection at the output. The wave plate introduced does not have any effect in the measurement. In this paper, (Kaewon *et al.*, 2020) is modified with a real time measurement of reference and sample of Tantalum pentoxide (Ta<sub>2</sub>O<sub>5</sub>) by splitting the beam with beam splitter (BS). The intensity is obtained

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using four stepping algorithms for phase shift and thickness measurements. A self-referenced polarization and phase-shifting technique for real-time thickness measurement of single-layer Ta<sub>2</sub>O<sub>5</sub> using modified Sagnac interferometer is presented. The mathematical theory behind the four-step technique is proved and presented.

### MATERIALS AND METHODS

This section discusses the electric field vector determination in the absence of any samples. The Jones calculus is utilized here as it is the fundamental mathematical theory used to evaluate the polarization

$$E_{iT_s} = \frac{1}{2} \left\{ \begin{bmatrix} T_1 \\ -iT_1 \end{bmatrix} e^{i(\delta_2 x(t) + \delta_1 x)} \right\} \quad (1)$$

The electric field vector of reflected components.

$$E_{iR_s} = \frac{1}{2} \left\{ \begin{bmatrix} -iT_2 \\ T_2 \end{bmatrix} e^{i(\delta_2 y(t) + \delta_1 y + \Delta_s)} \right\} \quad (2)$$

where  $\delta_1$  and  $\delta_2$  are the phase retardations introduced by M1 and M2, respectively.  $T_1$  and  $T_2$  are transmission coefficients along the principal axes of the sample,  $t$  is time, and  $\Delta_s$  is the phase retardation introduced by the sample. A polarizer at the output is

$$I_{(0^\circ)} = \frac{1}{4} [T_1^2 + T_2^2 + 2T_1T_2 \sin(\beta - \alpha)] \quad (3)$$

$$I_{(45^\circ)} = \frac{1}{4} [T_1^2 + T_2^2 + 2T_1T_2 \cos(\beta - \alpha)] \quad (4)$$

$$I_{(90^\circ)} = \frac{1}{4} [T_1^2 + T_2^2 - 2T_1T_2 \sin(\beta - \alpha)] \quad (5)$$

$$I_{(135^\circ)} = \frac{1}{4} [T_1^2 + T_2^2 - 2T_1T_2 \cos(\beta - \alpha)] \quad (6)$$

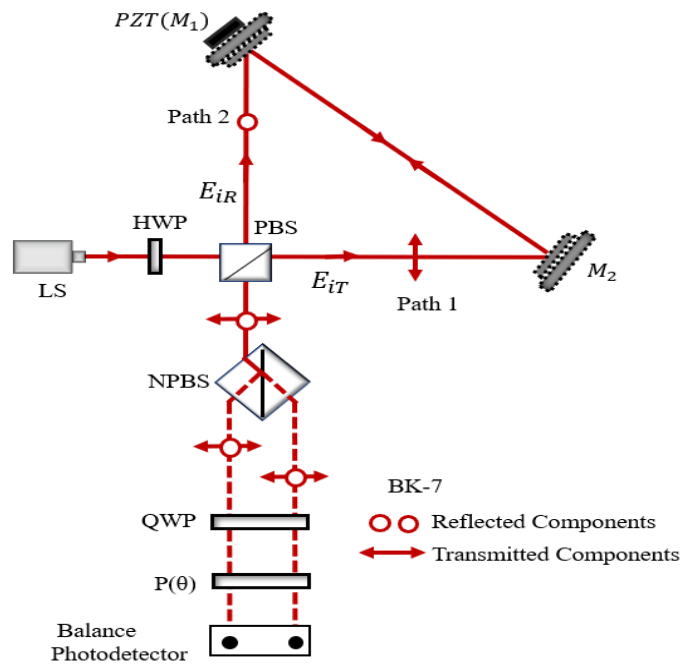
Where  $\alpha = \delta_2 x(t) + \delta_1 x$  and  $\beta = \delta_2 y(t) + \delta_1 y + \Delta_s$ . These forms of functions are further simplified and produce phase retardation relation  $\phi$  as

$$\phi = \tan^{-1} \left[ \frac{I_{(90^\circ)} - I_{(0^\circ)}}{I_{(135^\circ)} - I_{(45^\circ)}} \right] \quad (7)$$

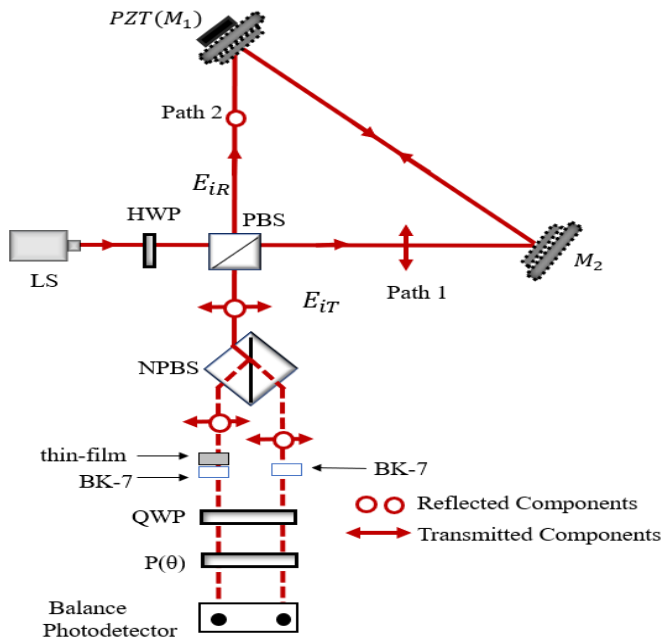
state of an optical interferometer. Prior to the setup of the interferometer, lights from a light source, all wave plates, and beam splitter were examined using software Polar VIEW to ensure states of polarizations. The schematic of a proposed modified Sagnac interferometer is depicted in Figure 1. A half-wave plate (HWP) oriented at 22.5° to the plane of incidence, known as a reference plane, was utilized to form a linearly polarized light at 45° relative to the reference. The Jones vector, representing an input electric field out of an HWP, is expressed as.

The electric field vector of transmitted components.

fixed at 45° relative to the reference axis. The polarization states are set at 0°, 45°, 90° and 135° to the reference. Thus, the intensities as a function of set angles can be found as:



**Figure 1:** Schematic diagram of the triangular Sagnac interferometer



**Figure 2:** Schematic diagram of the triangular Sagnac interferometer with sample

The samples are placed between a NPBS and QWP in the proposed system as depicted in Figure 2. One of the dual rotating linearly polarized lights travels through a pure substrate and it is stated as a reference arm, while the other propagates through a thin-film sample and is

called a sensing arm. The phase retardation and thickness relation are defined in (Usman *et al.*, 2021). The thin layer of Ta<sub>2</sub>O<sub>5</sub> is deposited on the BK-7 with thickness “d” and refractive index (n, 2.136). The thickness of the thin films can be evaluated using (8).

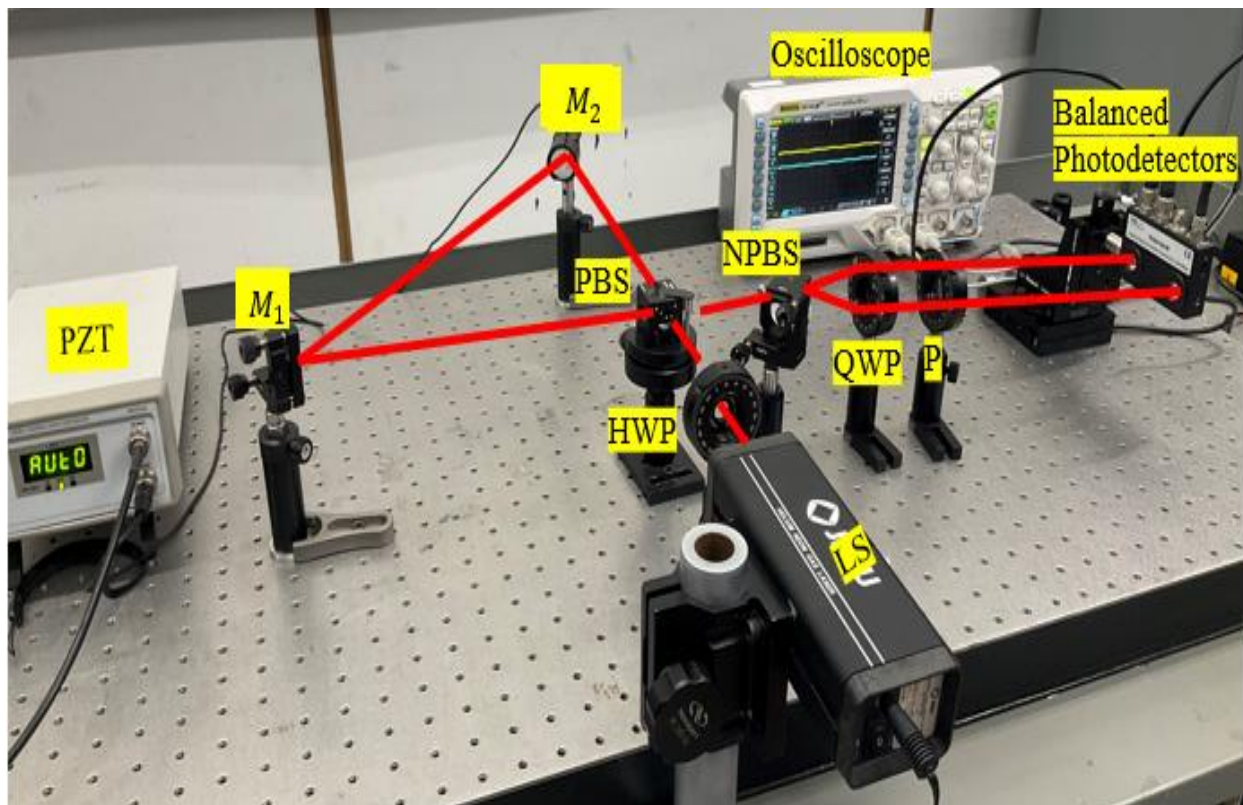
$$d = \frac{(\Delta + m\pi)\lambda}{2\pi n} \quad (8)$$

where  $\Delta$  is the difference between the phase retardation  $\phi$  introduced by the sample and the reference,  $\lambda$  is a light wavelength and  $n$  is a refractive index of the film.

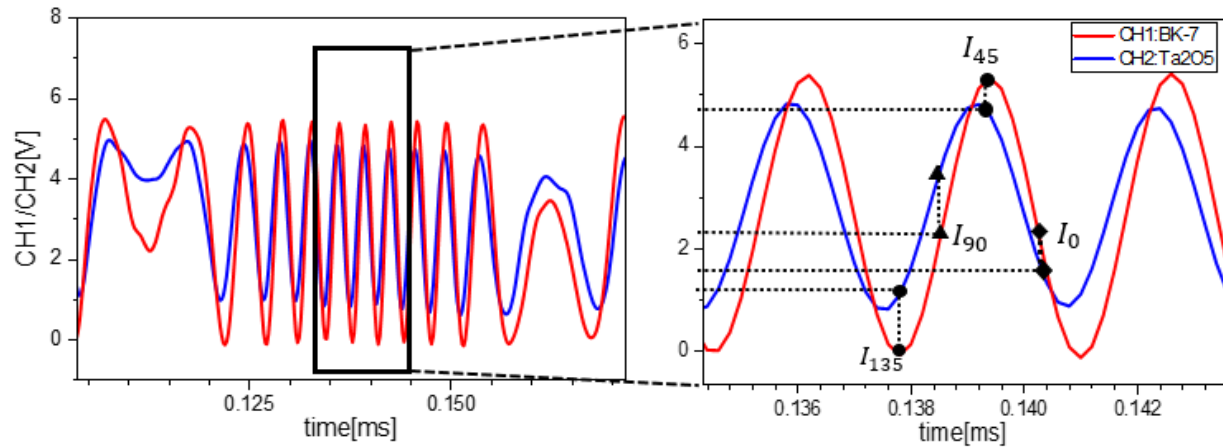
## RESULTS

The thin layer of Tantalum pentoxide (Ta<sub>2</sub>O<sub>5</sub>) ( $n = 2.136$ ) was deposited on the BK-7 substrate. The real-time intensities of the reference and sample beams at different polarizer settings were depicted in Fig. 4. The reference intensity at 45° could be derived from the peak shown in Figure 3, while those at 0° and 90° could

be acquired from the middle points. Then, the sample intensities were determined by drawing vertical lines from the points of each reference, as demonstrated in Figure 4. The obtained intensities were done with utmost caution. Eventually, the phase shift value  $\Delta$  with the presence of Ta<sub>2</sub>O<sub>5</sub> film was found to be 0.2 rad and it was then converted to thin-film thickness measurement using (8) and 259.32 nm is accomplished.



**Figure 3:** The experimental setup of the proposed modified Sagnac interferometer



**Figure 4:** intensities and comparison of BK-7 substrate deposited on  $Ta_2O_5$

## CONCLUSION

The simultaneous phase-shift and thickness of  $Ta_2O_5$  was found to be 0.2 rad and 259.32nm respectively, in real time by employing an automated self-reference. The four-step algorithms could genuinely minimize errors since more points at each polarization state were assessed for intensity. As a result, the proposed method has a lot of potential for real-time, multi-layer, non-contact thickness measurement without changing the orientations of polarizing devices. Sagnac interferometer is insensitive to external disturbances in comparison with other interferometric setup; any noise is avoided because all transmission paths interact with each other. The experimental results show that the proposed setup has a lot of potential for real-time, non-destructive thickness assessment of transparent thin films without the need to modify polarizing device orientations.

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