Babinet-Soleil interferometers with zero walk-off

Wei Liu (偉 劉)

weiliu.tsinhua@protonmail.com

Abstract

Babinet-Soleil compensators are routinely used in spectroscopy using Fourier Transform Spectroscopy principles to extract the spectral information of light sources. The Babinet-Soleil compensator allows for precise control and adjustment of the phase difference between two polarized light beams. It offers several advantages over other interferometer types such as excellent stability compactness and delay precision. However, the interference signal measured with this common path interferometer is usually degraded by the presence of a displacement between the two polarization replicas at the output of the interferometer. This is due to a splitting between the two polarization paths happening when the light passes through the air-gap of the wedge-shaped crystals inside the Babinet-Soleil interferometer. This paper explores various modifications to the Babinet-Soleil scheme to mitigate birefringence-induced displacement effects between two interfering replicas. The proposed schemes enhance the contrast of the interference signal, making it particularly advantageous for high-precision metrology, optical coherence tomography, and other interferometric techniques requiring high visibility and stability.

Discussion

The Babinet-Soleil compensator is a continuously variable, zero-order retarder that plays a crucial role in controlling the phase shift between orthogonal polarization components of a light beam. It consists of two primary components: birefringent wedges and a compensator plate as shown in Figure 1.

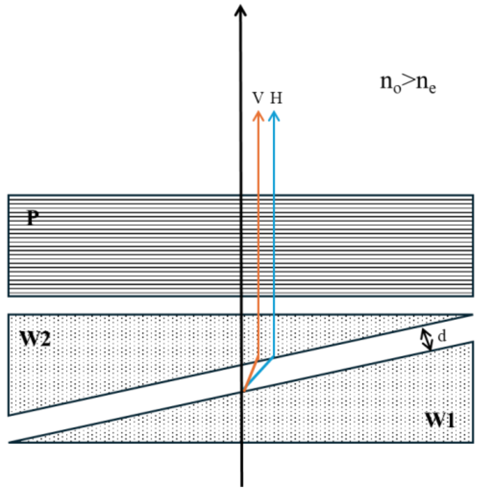

Figure 1 Babinet-Soleil compensator scheme comprising the Plate P the first wedge W1 and the second Wedge W2. The path of the vertical and horizontal polarizations is shown as a red and blue line in the figure. The gap in between the wedges is defined as d. The fill pattern on the crystal indicates the direction of the optical axis.

The birefringent wedges are crafted from a birefringent material such as quartz or calcite. These wedges are oriented such that their optical axes are perpendicular to the optical axis of the compensator plate. This orientation is essential for the proper functioning of the compensator. One of the wedges is fixed in place and might be attached to the compensator plate, ensuring stability and precision in the optical path. The other wedge is designed to be movable along the optical axis. This movement is facilitated by a finely adjustable mechanical system, often employing a micrometer screw or an electrical actuator, which allows for precise control over the position of the movable wedge [1].

Considering a polarized light beam entering the interferometer we can consider the beam to be composed of a superposition of two orthogonal polarization components directed vertically or horizontally with respect to the beam direction. Due to the birefringent nature of the wedges, these rays experience different refractive indices, resulting in a phase difference. By adjusting the position of the movable wedge, the optical path length difference between the vertical and horizontal polarizations can be finely tuned, enabling precise control over their relative phase shift. This precise control over the phase shift is vital in applications such as interferometry, polarimetry [2], spectroscopy, and optical coherence tomography, enhancing the accuracy and contrast of measurements and images in these fields.

The compensator plate's optical axis is oriented to be perpendicular to one of the wedges. The width of the plate is chosen so that it matches the width of the two wedges for a particular position of the movable wedge. This position corresponds to the zero-delay position where total constructive interference occurs between the two replicas.

4 wedges-Babinet-Soleil compensator

As it is possible to see from Figure 1, the path of the vertical and horizontal polarizations differs due to the presence of the air gap between wedges W1 and W2. This is because of Snell's law and the different refractive index mismatch at the glass-air interface of W1 between the vertical and horizontal components.

For this reason, the two beams are separated by an offset at the output of the interferometer and when the output light is measured by a single pixel detector it causes a loss of interference contrast of the interference signal which reduces the quality and signal to noise of the light spectrum after the signal is Fourier Transformed (FT).

For this reason, we propose an alternative configuration shown in Figure 2 where the plate is simply split into two identical wedges W1 and W2 retaining the optical axis orientation of the original plate. Figure 2 shows the path between the vertical and horizontal polarization as they travel across the air gap between W1 and W2 and P1 and P2. As shown in Figure 2 If the two gaps are equal the two components in this configuration overlap perfectly at the output of the interferometer. This is due to the relative orientation of the wedges and also to the different refractive indices experienced by the two components traveling through the wedges and the plate. As an example, the vertical component is the extraordinary beam in W1 and W2 but is the ordinary beam in P2 and P4. The opposite is true for the horizontal beam.

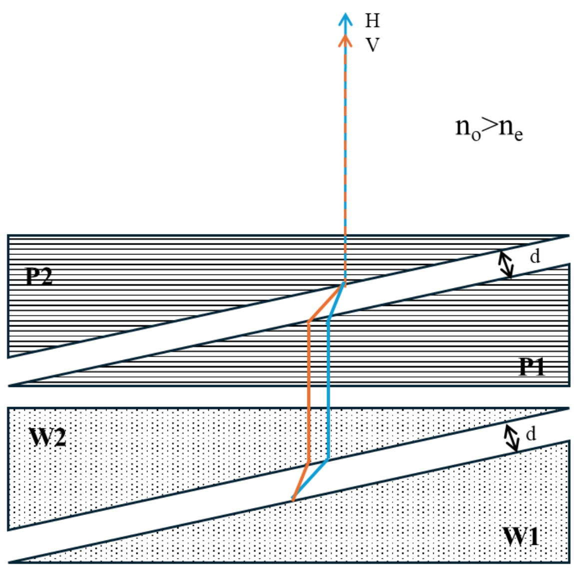

Figure 2 Modified Babinet-Soleil compensator where the plate is split into two additional wedges. The path of the vertical and horizontal polarizations is shown as a red and blue line in figure. The gap in between the wedges is defined as d. The fill pattern on the crystal indicates the direction of the optical axis.

Notably in this configuration, it is possible to glue together W2 and P1 and to build an assembly that can be moved together generating a tunable delay. In this case, considering the same later movement as in the case of the original configuration the imposed delay will be doubled.

Tilted optical axis Babinet-Soleil

To introduce the second configuration, we can consider the optical system of Figure 3 where we consider the propagation of a beam inside a birefringent block with the optical axis oriented with an angle with respect to the propagation direction in a way it is not parallel or perpendicular to the face of the crystal.

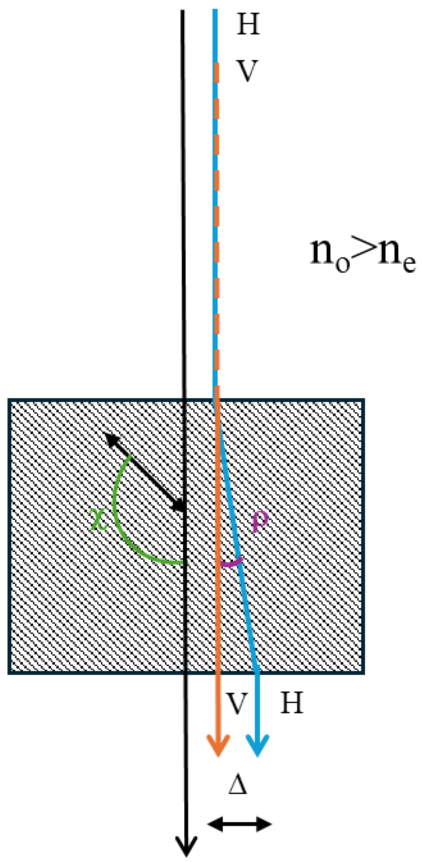

Figure 3 Birefringent beam displacer

This configuration is known as a beam displacer as the ordinary and extraordinary rays are split and the two rays are shifted by an offset at the output of the crystal. The separating angle between the ordinary and extraordinary ray is called birefringence angel or walk-off angle and it is given by [3]:

$$\rho = \pm \arctan(\frac{n_o^2}{n_e^2} \tan(\chi)) \mp \chi$$

Where ρ is the walk-off angle, n_o and n_e are the ordinary and extraordinary beams, and χ is the angle of the optical axis with respect to the propagation direction as shown in Figure 3. the upper signs refer to negative birefringent crystals ($n_o > n_e$) and the lower signs refer to the positive ones ($n_e > n_o$). The output displacement Δ depends on the thickness and is given by:

$$\Delta = L \tan(\rho)$$

Where L is the crystal thickness.

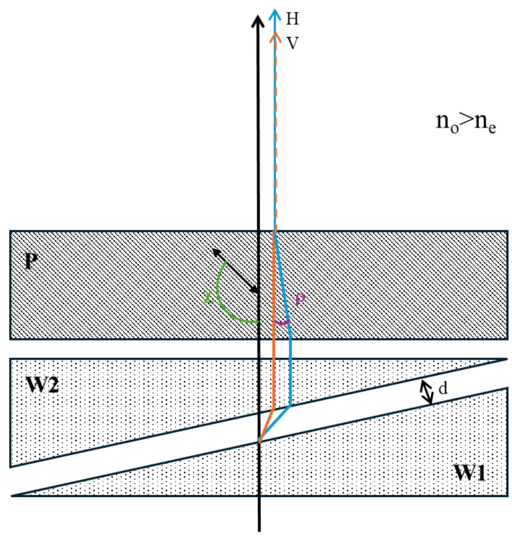

Figure 4 Alternative Babinet-Soleil configuration where the optical axis of the Plate P is shown in figure as a double arrow oriented in the direction of the fill pattern and with an angle χ with respect to the propagation axis. The angle ρ is the birefringence or walk-off angle.

In Figure 4 we propose an alternative modification to the original Babinet-Soleil compensator where we exploit the beam displacer effect and the optical axis of the plate is oriented with a tilt with respect to the propagation axis inside the interferometer. This tilt deviates from the horizontal polarization component which inside the plate behaves extraordinarily this is because the extraordinary beam does not respect Snell's law. The tilt of the optical axis of the plate does not perturb the operation of the common path interferometer. This tilt is exaggerated in the figure but can be properly designed and oriented to match the offset generated inside the air gap between W1 and W2. This configuration is particularly convenient as it reduces the number of crystals employed and the number of interfaces reducing Fresnel reflection losses and improving the light throughput of the system.

Conclusion

The Babinet-Soleil compensator is a vital tool in the precise control of phase shifts between orthogonal polarization components of a light beam, consisting of two primary birefringent wedges and a compensator plate. In the traditional configuration, one wedge is fixed while the other is movable, allowing for fine adjustment of the phase difference by altering the optical path length. This setup is essential for applications requiring high accuracy, such as interferometry, polarimetry, spectroscopy, and optical coherence tomography. However, the presence of an air gap between the wedges introduces an offset at the output, leading to a loss of interference contrast and a reduction in signal quality.

To address these limitations, we propose an alternative configuration where the compensator plate is split into two additional wedges, maintaining the original optical axis orientation. This design ensures that the vertical and horizontal polarization components overlap perfectly at the output, enhancing interference contrast and improving the overall signal quality. Additionally, the modified setup allows for the movable assembly of wedges, doubling the imposed delay for the same lateral movement.

Further, we introduce a second configuration utilizing a plate with a tilted optical axis, creating a beam displacer effect. This configuration leverages the walk-off angle to match the offset generated in the traditional air gap, reducing the number of crystals and interfaces, thereby minimizing Fresnel reflection losses and enhancing light throughput.

These innovative configurations of the Babinet-Soleil compensator offer significant improvements in performance and efficiency for optical interferometry and related fields. The precise control over phase shifts and enhanced interference contrast provided by these designs make them highly advantageous for a wide range of scientific and industrial applications.

References

[1] Françon, Maurice, and Shamlal Mallick. "Polarization interferometers: applications in microscopy and macroscopy." (1971).

[2] Otani, Yukitoshi, and Toru Yoshizawa. "Polariscope using the phase-shifting technique." *Polarization Analysis and Measurement II*. Vol. 2265. SPIE, 1994.

[3] Nikogosyan, David N. *Nonlinear optical crystals: a complete survey*. Springer Science & Business Media, 2006.