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THE INFLUENCE OF POLARISATION CHANGES INTRODUCED BY DEFLECTING ELEMENTS TO INTERFEROMETRIC MEASUREMENTS

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ABSTRACT

In a large variety of high precision measurement and positioning applications interferometers play an important role. When the object under test is not accessible in a straight line or such a layout would restrict the design of the device too much, the beam path can be folded. But the deflecting elements (mirrors and prisms) used for this purpose can introduce measurement errors to the system. Errors due to the mere presence of such an element or caused by slight movements of it have to be corrected for reliable measurement results. In this contribution we address changes that deflecting elements inflict on the polarisation of the interferometric measurement beam. We show the impact of these changes on the measurement and discuss a compensation method.

Index Terms – Interferometer, Measurement, Deflecting Element, Prism, Mirror System, Polarisation, Signal Contrast

1. INTRODUCTION

Interferometers are among the most precise and at the same time most versatile length measurement systems available. Their development has driven the advance of high precision technology in many different fields. Applications for laser interferometers reach from the semiconductor industry to measurement and positioning systems of the highest resolution.

An interferometric measurement setup requires the object under test to be provided with a reflective surface to reflect the measurement laser beam back to the interferometer device. The sample object needs to be arranged in a straight unobscured line with the interferometer head. This layout greatly restricts the design and installation space of respective measurement devices. Especially for large measurement volumes in several dimensions a large footprint of the machine is unavoidable.

We have suggested that folding the beam by use of deflecting elements (mirrors, prisms and systems thereof) can reduce the required installation space [1]. At the same time a more compact and more robust design becomes possible. The inserted deflecting elements, however, can introduce errors to the measurement that have to be accounted for. In [1] we have discussed deviations in beam direction, lateral beam position and optical path length resulting from a movement of a deflecting element during the measurement. All three quantities present errors that have to be understood and quantified in order to correct them.

One concept to avoid errors resulting from the presence of a deflecting element in the beam path is to prevent its movement. For this purpose a metrology frame designed for highest mechanical and thermal stability is used to connect the deflecting element with the interferometer head. Thus their relative position remains unchanged during the measurement process and the only effect is a constant offset in the measurement value. The drawback is the usually large and complex structure of the metrology frame, especially for multi-dimensional measurements. With increasing measurement volumes the effort to ensure the metrology frame's stability increases along with its size and weight.

A different strategy that we want to address in this paper is to mount the deflecting elements on a detached frame with lower demands on stability. Thus we allow the elements to move slightly in the range of arc minutes and micrometres. This greatly simplifies the mechanical design of the frame and increases the accessibility of the sample object. But it also allows errors to arise from the displacement of the deflecting elements during the measurement. These errors have to be analysed and compensated or corrected to ensure the precision of the measurement.

Beside the before mentioned changes of beam direction, lateral beam displacement and optical path length, deflecting elements also have an influence on the polarisation of the measurement beam. In this contribution we show the origin of these polarisation changes, explain their impact on the measurement and discuss a possible strategy for their compensation.

2. POLARISATION OF LIGHT

2.1 Characterisation of the polarisation of light

The polarisation of light accounts for the transversal character of the light wave. It describes the electric field $\vec{E}$ as a vector in space and time [3]. This vector follows the trajectory of an ellipse (elliptical polarisation) in the most general case. Special cases are a line (linear polarisation) or a circle (circular polarisation). A completely polarised beam can be described by its Jones vector [4]. An arbitrary polarisation state is decomposed into two orthogonal components that are for simplicity usually chosen to be a horizontal and a vertical linear state. The Jones vector is composed of two complex numbers giving the amplitude and phase of each component.

A general polarisation state can be characterised by three values [4]: amplitude, ellipticity and azimuth (Figure 1). The amplitude A is given by the length of the secant from the major to the

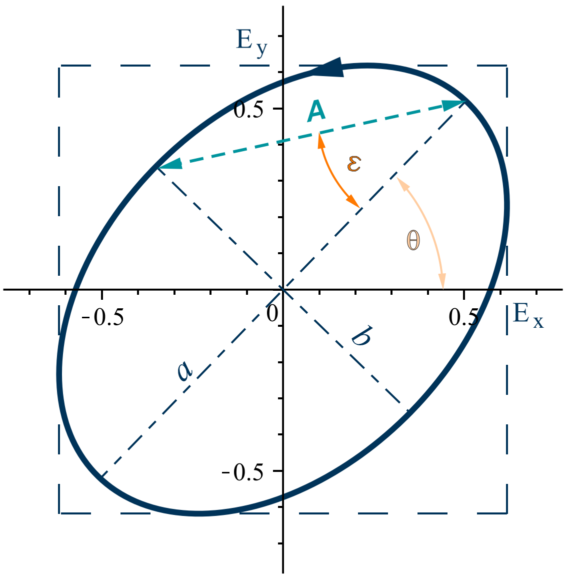

Figure 1. Parameters for the characterization of a general elliptical polarisation state;

minor half axis of the ellipse. Its square, the intensity I, is a measure for the power transported by the light wave. The ellipticity ε is given by the angle between said secant and the major half axis a. It can range from -45° to +45° where positive angles denote right-handedness. The azimuth θ is the angle between the positive x-axis and the major half axis of the ellipse in the range from 0° to 180°.

2.2 Causes of polarisation changes

The polarisation state can be affected by different elements in different ways. At each boundary surface of two different media where the beam is refracted or reflected, the amplitude and phase of the parallel and perpendicular components are altered according to the Fresnel equations [3]. The changes depend on the angle of incidence and the properties of the two bordering materials (i.e. their refractive indices). Furthermore, propagation through a birefringent or optically active medium can affect the polarisation state of the beam [5].

3. INFLUENCE OF THE POLARISATION ON THE INTERFEROMETRIC MEASUREMENT

To understand how polarisation changes affect the interferometric measurement, it is necessary to know how the measurement signal is evaluated in a polarising interferometer.

3.1 General structure of a polarisation interferometer

Figure 2 shows a common design for a polarising interferometer. For more clarity it is divided into two parts for interference generation (left) and signal evaluation (right). The first part is responsible for separating and recombining the measurement and reference beam to create the

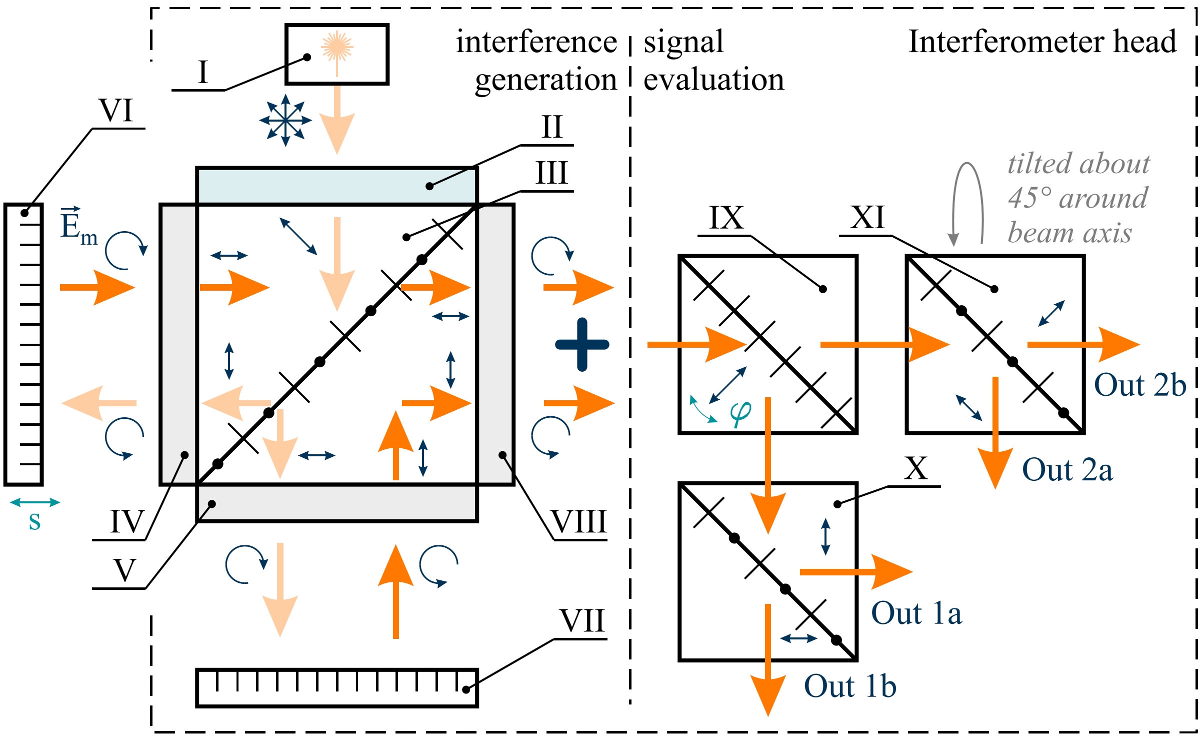

Figure 2. Basic structure of a polarising interferometer with the respective polarisation state; I laser light source; II linear polariser (45°); III, X and XI polarising beam splitters (XI tilted about 45°); IV, V and VIII quarter wave plates; VI movable measurement mirror; VII fix reference mirror; IX intensity beam splitter (50/50);

interference signal. The polarisations of the beam sections (orange arrows) are depicted by the small dark blue arrows. They describe the trajectory of the electrical field vector tip over time seen from a direction antiparallel to the beam's travelling direction.

The beam enters the interferometer head from the laser light source (I) at the top. It passes a linear polariser at 45° (II) to ensure the desired state of polarisation before entering the polarising beam splitter (III). The diagonal linear polarisation is decomposed by the beam splitter into two linear components of equal amplitude. The vertical one is reflected to form the measurement beam while the horizontal one is transmitted to create the reference beam.

Before leaving the interferometer head, both beams pass a quarter wave plate (QWP, IV and V) that transforms their linear polarisation into a left- or right-handed circular polarisation respectively. The handedness is inverted upon reflection at the plane mirrors (VI and VII).

When returning into the interferometer head, the beams have to pass the QWPs (IV and V) once again. The polarisation is reverted back to the linear state. The direction, however, is now perpendicular to the state before leaving the beam splitter (III). Therefore, no light is reflected back into the light source. The intensity that was reflected before is now completely being transmitted by the beam splitter (III) and vice versa.

The two resulting beam components are not able to interfere coherently due to their perpendicular polarisation (horizontal and vertical). Another QWP (VIII) is necessary to produce left- and right-handed circular polarisations that will add up to a linear polarisation at the exit. The azimuthal position of this linear polarisation changes according to the relative phase of the two circular components. This makes the line representing the direction of polarisation turn by the angle φ when the measurement mirror (VI) is being moved by the distance s.

For evaluation of a measurement value, four intensity signals with a relative phase difference of 90° to each other must be generated from this polarisation. These signals allow for counting and interpolation as well as detection of the movement's sense of direction as is common practice in incremental length measurement systems. This is done in the right part of the interferometer head (Figure 2).

An intensity beam splitter (IX) divides the beam into two equal parts without disturbing the polarisation. The linearly polarised beam of variable azimuth is then again decomposed into two components by another polarising beam splitter in each arm (X and XI). In output 1 the beam splitter (X) separates the light into a horizontal and a vertical linear polarisation state that form the intensity signals with a phase of 0° (Out 1a) and 180° (Out 1b). The beam splitter (XI) in output 2 is tilted about 45° and therefore generates two diagonal linear components that serve as the intensity signals with 90° (Out 2a) and 270° (Out 2b) phase shift respectively. Under ideal conditions all four outputs provide a sine signal of the same frequency, shape and amplitude, differing only in phase by 90°.

3.2 Polarisation interferometer with a deflecting element in the measurement arm

In the example in Figure 2, the expected signal $\vec{E}_m$ that is supposed to return from the measurement mirror is a right- handed circular polarisation. Although measurement and reference arm are interchangeable, in this contribution we will refer to them in this manner. We now consider a signal with an arbitrarily different polarisation that has been altered by a deflecting element inserted into the measurement arm of the interferometer between elements IV and VI.

The QWPs (IV and VIII) in combination with the encased polarising beam splitter (III) form a polariser for a circular polarisation of the expected handedness. We can decompose the returning signal $\vec{E}_m$ of the measurement beam into two components like we did before. In this case, however, we do not use two perpendicular linear polarisations as the basis, but two orthogonal circular polarisations, namely a left- and a right-circular polarisation. The component that corresponds to the expected polarisation (right-circular in this case) will pass the polariser (IV+III+VIII) without attenuation while the other will be extinguished completely. What passes this polariser is always a circular polarisation of the expected handedness. Only the amplitude will differ depending on the alteration of the returning beam.

We always consider the interference of a left- and a right-handed circular polarisation for the signal evaluation in the interferometer. Assuming that the reference beam has not been influenced, only the measurement beam component may vary in amplitude and phase. The addition of two orthogonal circular polarisations with different amplitudes and phases will always result in an ellipse (index r). Its ellipticity ε_r depends on the amplitude A_m and the ellipticity ε_m of the returning measurement beam (index m) while its azimuth θ_r depends on the phase δ_m and the azimuth θ_m of the measurement beam component.

3.3 Effects of polarisation changes on the interferometric measurement

The polarisation change that is introduced by any deflecting element can have two major effects on the interferometric measurement: 1) a decrease in signal contrast and 2) a change of the measurement value. We have to further distinguish between static effects and those changing during the measurement.

Static effects are introduced to the system due to the mere presence of a deflecting element. Their magnitude depends on the type of element and its position in the beam path. Besides that, they are constant making them systematic errors that can be corrected for. On the other hand a movement of the deflecting element may have a dynamic impact on the measurement. It can cause the signal contrast and the measurement value to change during the measurement. This effect will be indistinguishable from a movement of the measurement mirror.

3.3.1 Signal contrast

A drop in signal contrast does not present a direct measurement error. It does not lead to a wrong measurement value unless it falls below a certain threshold where a reliable evaluation is no longer possible. For a dependable measurement the signal contrast has to be kept high at all times.

The signal contrast C is identical at all outputs (Out 1a to Out 2b in Figure 2) under ideal conditions. It can range from 0 to 1 and is defined as [3]:

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} . \qquad (1)$$

I_{max} and I_{min} are the maximum and minimum intensities at the interferometer output over one cycle i.e. over a measurement range of half the wavelength. In the interferometer the ellipse resulting from the interference of measurement and reference beam is passed through polarisers to extract four different linear components from it. When this ellipse turns due to a movement of the measurement mirror, the extracted components will vary in amplitude/intensity. For a complete rotation of the ellipse I_{max} and I_{min} correspond to the squares of the longest and shortest ellipse radii. That makes

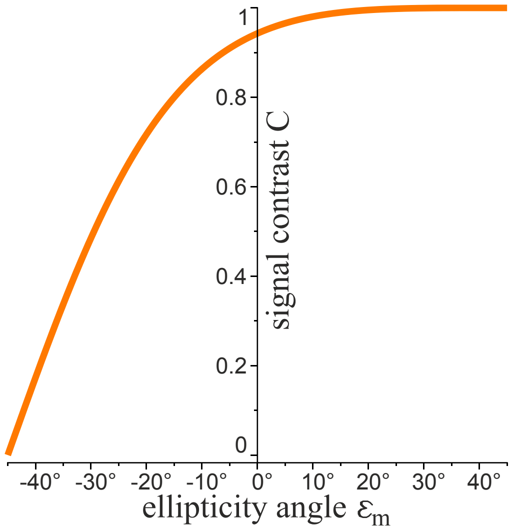

Figure 3. Dependence of the interferometric signal contrast C on the ellipticity ε_m of the measurement beam polarisation

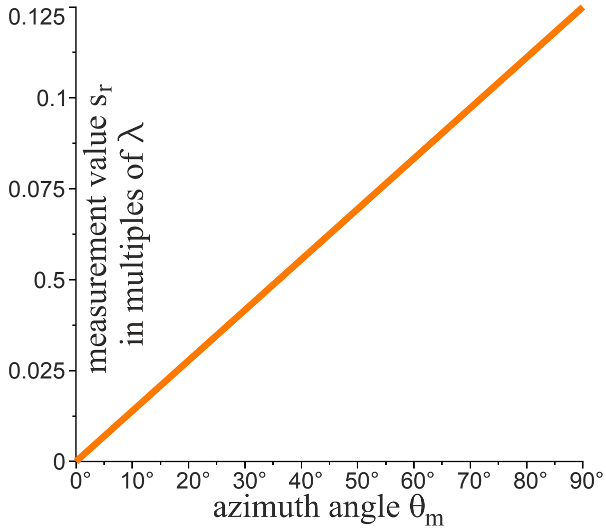

Figure 4. Dependence of the interferometric measurement value s_r on the azimuth angle θ_m of the measurement beam polarisation

$$\begin{matrix} I_{max} \propto \mathrm{a}^2 \\ I_{min} \propto \mathrm{b}^2 \end{matrix} . \tag{2}$$

With these relations the signal contrast only depends on the ellipticity ε_r of the interference ellipse which represents the ratio between the half axes a and b (cf. Figure 1). This in turn depends on the amplitude A_m and the ellipticity ε_m of the measurement beam. We get the highest contrast ($C = 1$) when the measurement beam's polarisation is exactly the expected circular polarisation. In this case the turning interference figure on which the evaluation is done has the shape of a line. The lowest contrast ($C = 0$) occurs when the orthogonal polarisation is returned, i.e. the circular polarisation of opposite handedness. The evaluated signal then degenerates into a turning circle. The relation is shown in Figure 3 and can be written as

$$C = \frac{\sqrt{2}A_m(\cos(\varepsilon_m) + \sin(\varepsilon_m))}{1 + \frac{A_m^2}{2}(1 + \sin(2\varepsilon_m))} . \tag{3}$$

It is notable that the contrast remains almost unabatedly high as long as the returning polarisation has the correct handedness. Even if distorted to a linear polarisation the signal contrast stays well above 90%. However, when the handedness is inverted, the contrast drops quickly. As threshold for a reliable signal a contrast of 70% is commonly used. This corresponds to an ellipticity of about -21° of the opposite handedness. Considering static effects only, no corrections have to be made until this value. Since the slope of the curve is quite small in said area, dynamic changes usually have a small impact and do not disturb the measurement.

3.3.2 Measurement value

The measurement value of the interferometer changes with the azimuth of the measurement beam polarisation. A static change due to the presence of a deflecting element in the beam path does not constitute a measurement error. It rather presents an offset which, if constant, will be cancelled out in difference measurements.

Dynamic changes, however, are critical. If the deflecting element moves during the measurement and therefore slightly changes the azimuth of the returning measurement beam polarisation, a direct measurement error is introduced. The resulting change in the measurement value will be indistinguishable from a movement of the measurement mirror. According to the signal generation described in section 3 the measurement value s_r will be derived from

$$s_r = \frac{\lambda}{4\pi n} \arctan\left(\frac{I_{1a} - I_{1b}}{I_{2a} - I_{2b}}\right). \tag{4}$$

Here, I_i is the intensity signals at the respective output and λ is the wavelength of the light in air whose refractive index is n. With a closer look at the intensity signals in the argument of the arctangent function we find that they do not solely depend on the phase of the measurement beam δ_m but also on the azimuth θ_m. Due to

$$\frac{I_{1a} - I_{1b}}{I_{2a} - I_{2b}} = \tan(\delta_m - \theta_m) \tag{5}$$

we are facing a linear dependence of the measurement value on the measurement beam's azimuth θ_m (Figure 4).

4. SIMULATIONS

The effects of a deflecting element on the interferometric measurement greatly depend on the type and shape of element as well as its position in the beam path. That means the type and arrangement of the surfaces determine the polarisation changes. As an example we want to show the effects introduced by a corner-cube prism to the interferometric system.

4.1 Static effects

We first compare the original interferometer setup (Figure 5a) with a test setup that comprises a corner-cube prism as deflecting element (Figure 5b). In both cases we consider an interferometer with a structure according to section 3.1. The measurement beam that leaves the interferometer head (light orange) has a left-circular polarisation of unit intensity (Figure 5c). Upon reflection on the retro-reflection mirror the handedness is inverted. Thus the beam returning to the interferometer head (dark orange) has a right-circular polarisation in case of the reference system.

In the test system the beam is refracted at the entrance and exit surface of the prism. Furthermore there are two surfaces where total internal reflection occurs. All of them have to be passed twice, resulting in eight additional surfaces. Since, for now, we want to assume ideal conditions the beam enters and exits the refractive surfaces orthogonally. Thus, the polarisation state is not altered here. The reflective surfaces, however, afflict changes to the parallel and perpendicular amplitude component according to Fresnel's equations [3]. These effects are not cancelled out on the way back, but add up. The result is a left-handed elliptical polarisation that returns to the interferometer (Figure 5 d).

In the reference system the returning polarisation has the expected shape and handedness and passes the circular polariser (cf. section 3.1) in the interferometer without attenuation. A small decrease in the amplitude is caused by losses due to the reflection on the retro-reflection mirror. As the reference beam experiences the same effect, both add up to an interference signal of contrast $C = 1$ (Figure 5e). The test beam, on the other hand, has a significantly different polarisation. It is greatly attenuated when passing the circular polariser. Mainly due to the inverted handedness the contrast of the interference signal drops to $C = 0.32$ (Figure 5f). In an experimental setup the signal would not be evaluable any more. One possible compensation method is discussed in chapter 5.

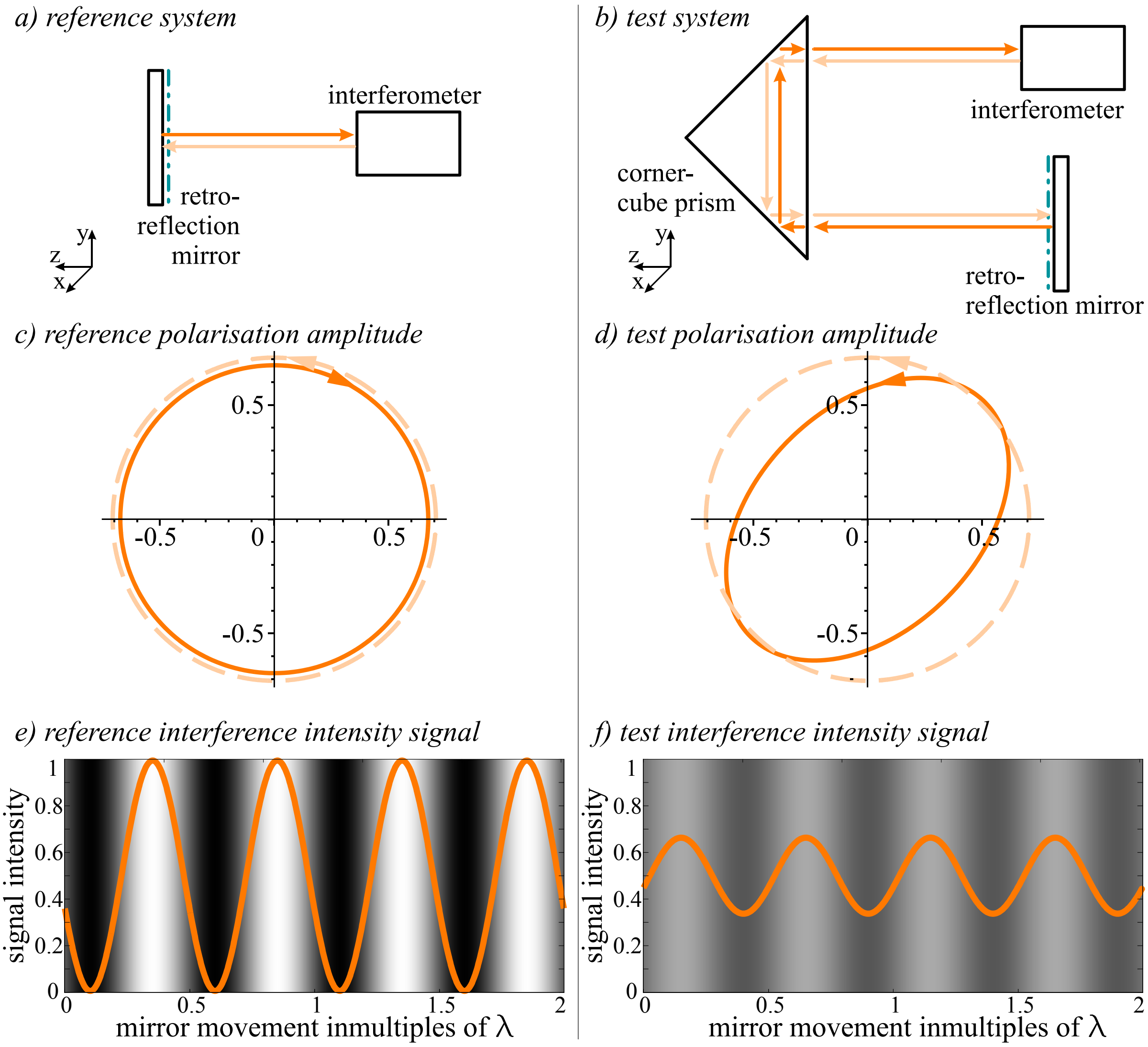

Figure 5. Contrast deterioration due to the presence of a deflecting element.
For the reference system (a) without a deflecting element the returning polarisation is a right-handed circle (c) and the interferometric intensity signal has a contrast of $C = 1$ (e). In the test system (b) the corner-cube prism as deflecting element changes the returning polarisation to a left-handed ellipse (d). The contrast drops to $C = 0.32$ (f). In both cases the interferometer is sending out a left-circular polarisation of unit intensity.

The measurement value of the test system will, of course, be different from the reference system. Even if the geometrical path lengths were identical, the higher refractive index of the prism material and the changed azimuth of the polarisation will lead to a deviating value. This deviation, however, is constant as long as the deflecting element maintains its position. It is merely an offset that will cancel out when doing difference measurements.

4.2 Dynamic effects

While in the previous example the position of the deflecting element was fixed we now want to consider the dynamic changes to signal contrast and measurement value when the element moves. When looking at turns of the prism about the x- and y-axis (cf. Figure 5b for the

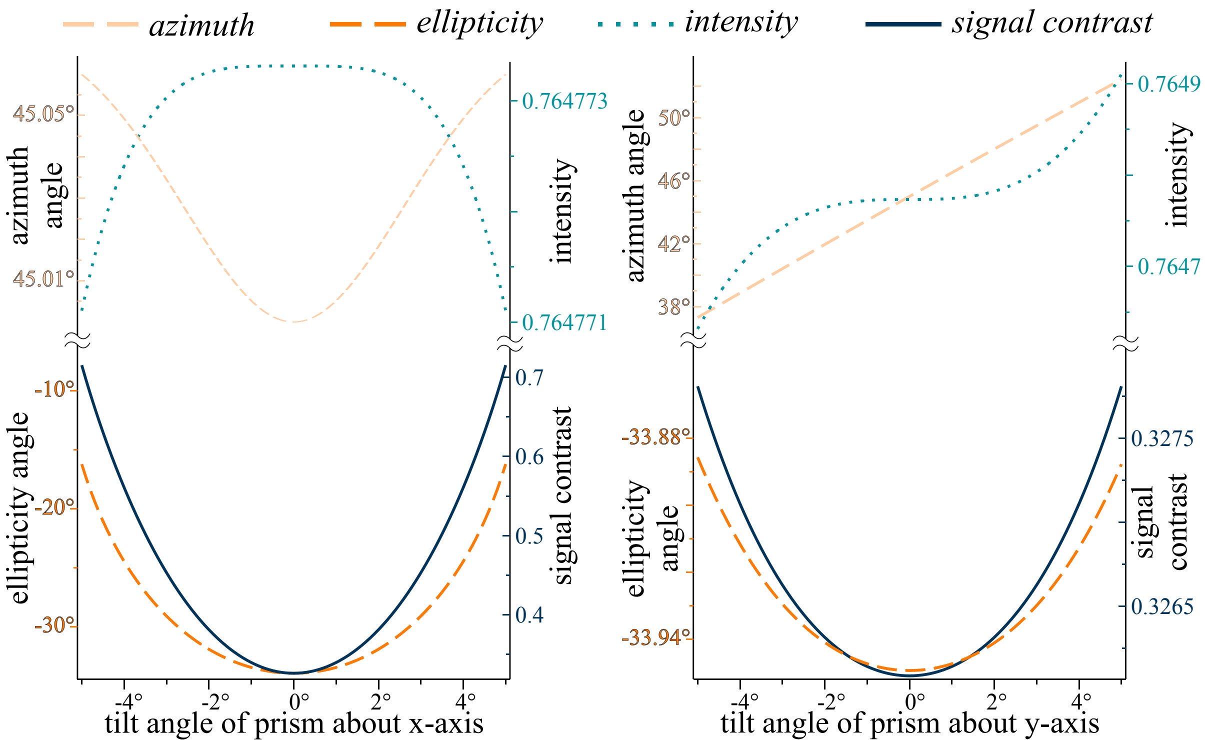

Figure 6. Influence of prism tilts about the x-axis on ellipticity, azimuth, intensity and signal contrast of the measurement beam polarisation

Figure 7. Influence of prism tilts about the y-axis on ellipticity, azimuth, intensity and signal contrast of the measurement beam polarisation

coordinate system) we find that changes of the azimuth and ellipticity are very well separable in this example (Figure 6 and Figure 7).

We first observe that the intensity (and therefore the amplitude) remains almost constant in both cases (turquois dotted curve). Please note the different scaling in the different parts of the axes. Thus, only the ellipticity (dark orange dashed curve) determines the signal contrast (dark blue solid curve). Both values are mainly unchanged when tilting the prism about the y-axis but vary greatly for tilts about the x-axis. Here we see that the ideal position of the prism at 0° is in fact the worst case concerning the signal contrast.

In contrast, the azimuth angle (light orange dashed curve) that determines the measurement value is almost constant for tilts about the x-axis but increases linearly when turning the prism about the y-axis. The measurement value goes along with the azimuth curve and therefore is omitted in the figures.

When the prism is turned about other axes that do not coincide with the coordinate axes, we receive a superposition of the described effects. Thus the ellipticity (i.e. the signal contrast) and the azimuth angle (i.e. the measurement value) are both changed at the same time. Exemplarily we show the tilts about the diagonals of the x-y-plane in Figure 8 and Figure 9.

The existence of such tilt axes where changes of azimuth and ellipticity angle are separable is a characteristic of this example. That does not necessarily apply to other prisms as well. Each deflecting element has to be treated separately to characterise its behaviour in terms of polarisation alteration.

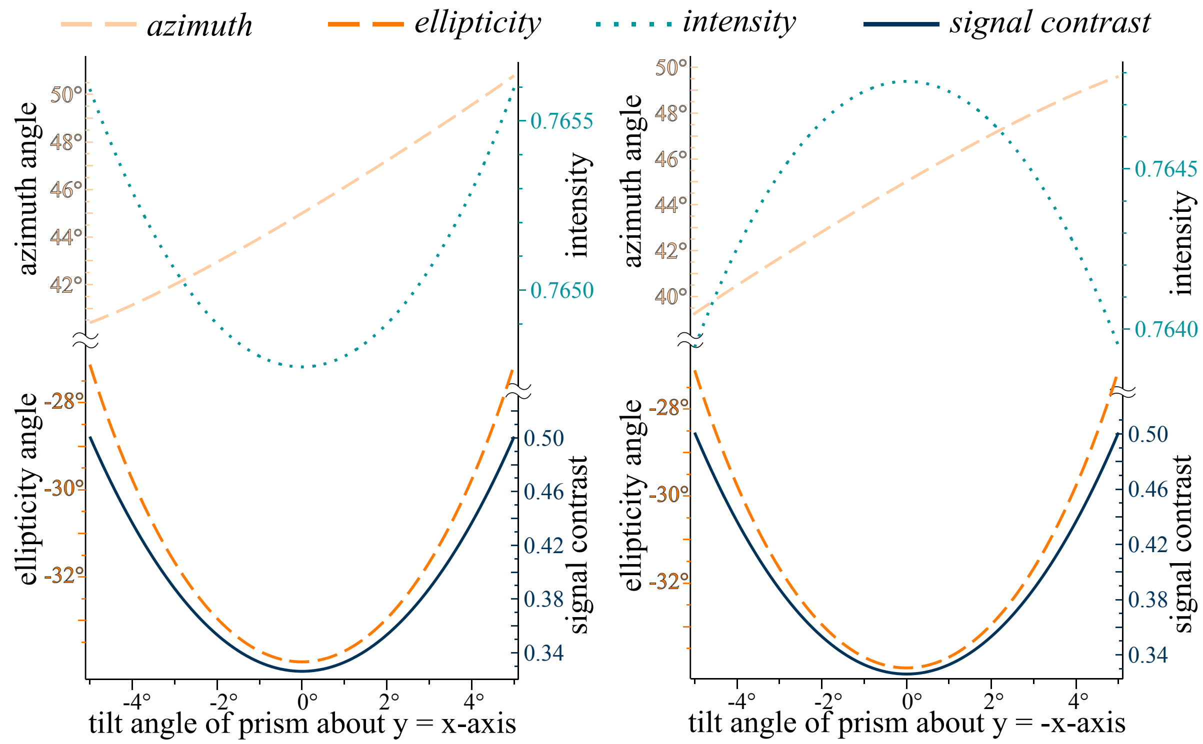

Figure 8. Influence of prism tilts about the y = x-axis on ellipticity, azimuth, intensity and signal contrast of the measurement beam polarisation

Figure 9. Influence of prism tilts about the y = -x-axis on ellipticity, azimuth, intensity and signal contrast of the measurement beam polarisation

5. COMPENSATION AND CORRECTION

5.1 Compensation of the signal contrast

In those cases when the effects described above falsify the measurement it is necessary to take actions of compensation or correction. The signal contrast can prevent the evaluation of the measurement completely when too low. Hence, there is no option for a correction. It needs to be compensated. On the other hand, when the contrast is sufficiently high there is no need for compensation since it does not compromise the measurement. The slope of the curve (Figure 3) is quite small in the range where the contrast is acceptably high. Thus small dynamic changes of the ellipticity do not influence the contrast as much and are therefore usually negligible.

If a static compensation of the ellipticity is required, one possibility is inserting a QWP into the beam path. We want to show this method for the example with the corner-cube prism where the contrast of 32% is too low for an evaluation of the signal. When travelling through a QWP the light is decomposed into two linear polarisation states along the two main axes of the crystal. Along the so called *fast* and *slow axis* the propagation speed differs for both components. Thus, a phase difference of $\pi/2$ or 90° is introduced between them before recombination at the exit. As a consequence the angular position of the QWP's axes has an important impact on how the polarisation is altered. A linear polarisation along either the fast or the slow axis, for example, will not be affected at all, while a linear polarisation diagonal to the axes will be altered to a circular polarisation.

Figure 10 shows the effects of a QWP introduced right between the interferometer head and the corner-cube prism in Figure 5b. For this graph the prism is not tilted, but kept in its original position at 0°. To show the dependence of the results from the angular position of the QWP the plot covers a turn of 180° about the axis of the light beam. We can easily see that the azimuth angle also varies over a total 180°. This dependence is not completely linear, though. Thus, an undesired rotation of the QWP during the measurement would introduce another error in terms of the measurement value. The compensating element can hence become an error source itself.

The compensation of the ellipticity angle and therefore the signal contrast is successful in this case. But we can also see that the ellipticity angle cannot be freely chosen through the angular position of the QWP. It varies in a very limited range. It is thinkable for other prisms that even by inserting a QWP we cannot correct the ellipticity to a desired angle. The intensity, as can be seen from Figure 10, is unaffected by the angular position of the QWP.

The location of the QWP in the setup also has a great impact on its behaviour. To proof this Figure 11 shows the very same graph as before for a QWP that is inserted between the corner-cube prism and the retro-reflection mirror (cf. Figure 5b). With the same elements just in a different arrangement, one can chose the ellipticity and therefore the signal contrast in a much wider range by rotating the QWP. The possible values for the signal contrast reach from almost 0 to just below 1. The azimuth angle in Figure 11 also covers 180° over the half turn of the QWP. But the dependence is much less linear.

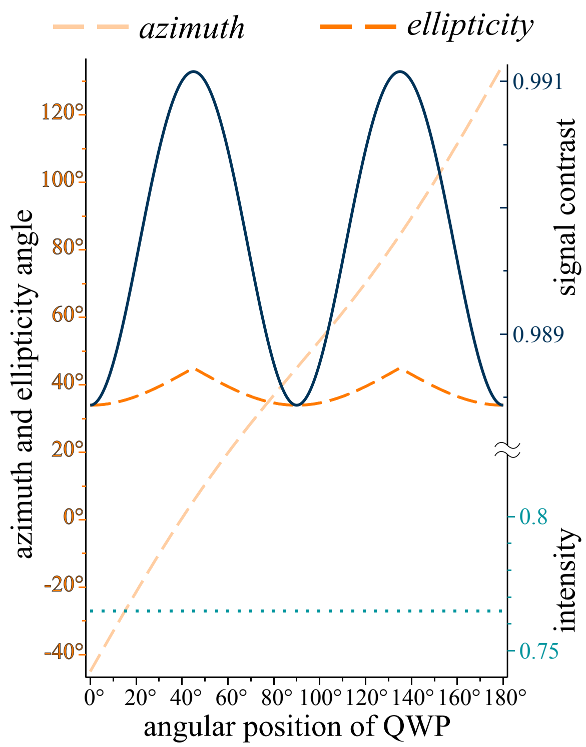

Figure 10. Influence of a QWP on ellipticity, azimuth, intensity and signal contrast of measurement beam polarisation; QWP between interferometer head and corner-cube prism

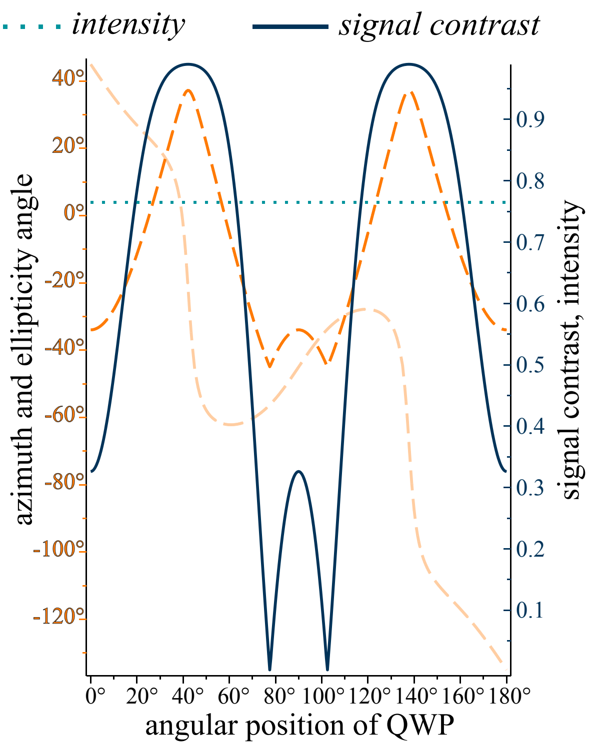

Figure 11. Influence of a QWP on ellipticity, azimuth, intensity and signal contrast of measurement beam polarisation; QWP between corner-cube prism and retro-reflection mirror

We can conclude that this compensation method is highly dependable on the given deflecting element and setup. When the deflecting element is constituted of several separate mirrors and/or prisms allowing us to place a QWP between them, the number of possibilities increases. So far there is no generalisation for the problem that applies to all deflecting elements.

5.2 Correction of the measurement value

The dynamic changes of the azimuth that falsify the measurement value have to be dealt with in a different manner. The suppression of the deflecting element's movement by mounting it together with the interferometer head on a large and complex metrology frame is one strategy of avoiding these errors. If we want to circumvent the elaborate design for such a frame, the errors need to be corrected.

This is best done by choosing the element and its position to make use of insensitive points. In such points the appearance of an external disturbance (i.e. a movement of the deflecting element) will cause no (*invariance*) or only marginal changes of 2nd or higher order (*innocence*) in the considered value (i.e. the beam polarisation). The remaining errors are then corrected numerically by detecting the movement and subtracting the calculated effects from the measurement value.

We have already found points of invariance and innocence in our example in chapter 4.2. We have been able to show that in this test setup the rotation of the prism about the x-axis does not affect the azimuth angle (cf. Figure 6). Additionally, rotations about the y-axis are insensitive with respect to the ellipticity (cf. Figure 7). Since there is a very small change in the respective numbers it is not appropriate to speak of true invariance here.

All curves in Figure 6 and Figure 7 (except for the azimuth angle in Figure 7) show a minimum at the point of origin where the slope is zero. We therefore have a point of innocence for both directions with regard to the ellipticity and for the x-direction with regard to the azimuth angle. Small changes around this point have a very small influence on the measurement. They can even be negligible depending on the required accuracy. Unfortunately this point is the one with the lowest signal contrast in our example. Besides this, it is beneficial to choose points with such favourable properties as operating points when designing the interferometric setup.

When looking at the azimuth angle in Figure 11 we can also find two points of innocence where a rotation of the QWP would have little effects on the azimuth. They are around 55° and 125° of the QWP's rotatory position. If one of these points is chosen for the implementation of the QWP, small displacements of it would be negligible in terms of the measurement value. These two points, however, are at a position where the contrast is not at its optimum. Thus, a trade-off is necessary.

6. SUMMARY AND PROSPECTS

In this contribution we have shown how the introduction of a deflecting element into an interferometric setup can affect the polarisation of the measurement beam. We investigated static changes that arise from the presence of the element in the beam path as well dynamic changes originating from the element's displacement during the measurement. The effects on the measurement comprise signal contrast deterioration and changes in the measurement value. Both are relatable to distinct parameters of the measurement beam polarisation.

For the example of a corner-cube prism we have demonstrated the existence of certain axes with special properties for movements of the deflecting element. Displacements around these axes change single polarisation parameters while leaving others (almost) undisturbed. Additionally, there are distinguished points of innocence around which the effects of displacements are very small due to a very small slope of the curve in that region. These characteristics, however, do not necessarily apply to all deflecting elements. They are dependent on the element's type and shape as well as its position in the beam path.

We have further discussed the use of birefringent components like a quarter wave plate to compensate the errors caused by the deflecting element. Again this method is highly dependent on the element. While it is efficient in the example of the corner-cube prism it might be ineffective for other deflecting elements. In the worst case the compensation element itself can even present an additional error source for the system.

On-going research is focussing on a generalisation of the found properties and investigating whether the specified characteristics can be transferred to other deflecting elements. In addition, we are looking into other compensation and correction methods and their applicability.

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