THE USE OF DEFLECTING ELEMENTS IN INTERFEROMETRIC APPLICATIONS – ADVANTAGES AND CHALLENGES

John, K.; Theska, R.; Erbe, T.

Ilmenau University of Technology, Faculty of Mechanical Engineering, P.O. Box 100565, 98684 Ilmenau
Institute of Design and Precision Engineering, E-mail: Kerstin.john@tu-ilmenau.de

ABSTRACT

This contribution deals with the classification and characterisation of deflecting elements under the new aspect of their application in interferometric setups. Deflecting elements known from common imaging optics are generalised to basic mirror arrangements and evaluated with regard to their relevant transfer properties when used in interferometric measurements. A novel approach for the classification and systematisation of these elements is proposed, which focuses on the change in the optical path length and the lateral shift of the beam due to typically small displacements of the deflecting element. Insensitive and sensitive axes for these displacements are introduced as interesting approaches for novel metrological applications. The objective of this work is to show options for the use of those axes for the incorporation of deflecting elements in interferometric applications. The nature of the change of the polarisation of the measuring beam due to the deflection by a prism or mirror and its influence on the interferometric measurement is highlighted as well.

Index Terms - Interferometer, Deflecting Element, Prism, Mirror System, Metrology Frame

1. INTRODUCTION

Interferometric length measuring systems have become indispensable elements of positioning and measuring systems which have to meet highest requirements in repeatability and resolution in applications such as nanopositioning and metrology [1][2]. In these applications there is an increasing trend to arrange the interferometers in compliance with the *Abbe Alignment Principle* which – by skilful implementation – can be realised in all directions for two or three-dimensional measurement. The NMM-1, shown in Fig. 1A [3], was the first example of a nanomeasuring machine which realised the *Abbe Alignment Principle* in all three spatial axes and allowed a three-dimensional measurement of objects with reduced errors.

An important factor for the error reduction and the reduction of measurement uncertainty is the constancy of the position of the interferometers. The mechanical connection between the interferometers and the tool or probe is accomplished by a *metrology frame* which is a static machine structure particularly designed for thermal and mechanical stability. The need for increased working volumes of the devices demands larger measuring distances which results in increasing dimensions, reduced mechanical stability (static and dynamic stiffness) and significant thermal expansion lengths of the *metrology frame* – a potential error source in the measurement circuit [4]. This is a particular issue in three-dimensional applications.

A possible solution to reduce the size of the *metrology frame* is the use of deflecting elements (e.g. prisms and mirrors) detached from the *metrology frame* to fold the interferometric optical path and thus achieve a more flexible arrangement of the measuring systems. Fig. 1B shows a concept of a nanomeasuring machine with a small and symmetric metrology frame that connects the interferometers and the tool/probe while the deflecting elements are mounted to an independent frame with lower demands on stability.

However, the implementation of such elements into interferometric setups is a very challenging task, because they are likely to introduce additional errors into the system (e.g. through mechanically or thermally induced displacements of the deflecting element). By taking advantage of insensitivities of these elements to displacements, the mechanical structure of the system can be simplified and the access to the measurement object improved. The goal is to apply design principles [5] that aim for minimising the effects of external disturbances like:

- **Invariance**: realising a transfer function that is in wide ranges independent from external disturbances
- **Innocence**: realising a transfer function that depends on external disturbances only in 2nd or higher order
- **Error correction**: reckoning up the known influence of a disturbance during the measurement
- **Error compensation**: the disturbance evenly influences two oppositely changing structural parameters

as they are already known for conventional imaging optics.

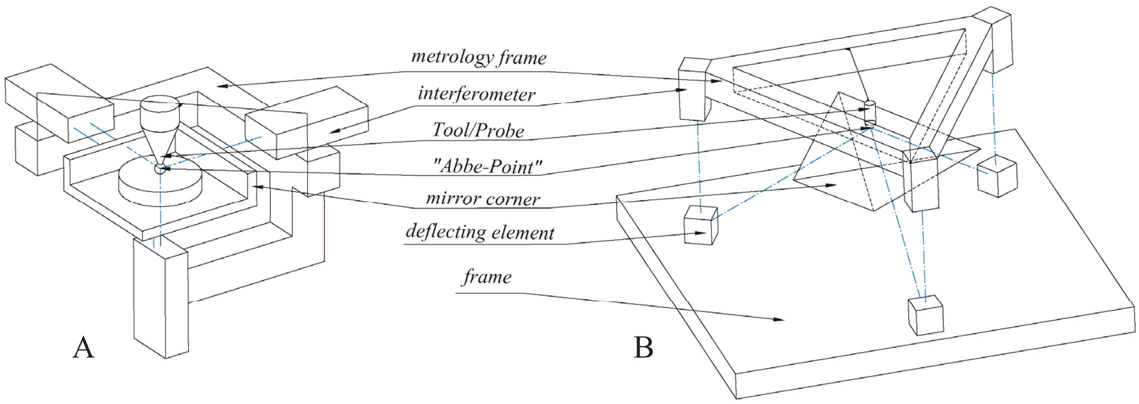


Fig. 1. A. Principle design of the NMM-1nanopositioning and measuring machine. For the three-dimensional measurement the interferometers are arranged in a Cartesian coordinate system in compliance with the Abbe Alignment Principle and coupled to the metrology frame.

B. An alternative design of a nanopositioning and nanomeasuring machine that makes use of deflecting elements for the interferometric measurement system. Thus, a much smaller, symmetrical and more stable metrology frame is achievable.

Prisms and mirrors are widely used as deflecting elements in the optical path of traditional imaging instruments, thus their image-deflection behaviour is well-investigated and documented [6][7][8]. However, many studies concern properties of optical deflection systems (e.g. image orientation) that are irrelevant for the deflection of interferometric laser beams [9] while interferometry specific properties (e.g. optical path difference and parallel beam displacement) have not been addressed so far.

In the context of nanopositioning and measuring applications the lateral displacement and the angular deviation of interferometer beams passing a deflecting element will be described. Both are essential for maintaining *Abbe Alignment Principle* compliance. The implications of changes in the polarisation of interferometer beams which usually are inevitable due to the effect of deflecting elements are briefly discussed.

2. APPROACH

In the case of interferometric setups the deflection of light is the deliberate change of the direction of light propagation which is mathematically described as the change of the wave vector [10].

In the following, all devices whose main function is to change the direction of light propagation are considered, referred to as deflecting elements. To achieve directional changes several physical effects can be used like reflection, refraction, diffraction or any combination of those three.

However, while changing the direction of propagation other properties of the beam like intensity, polarisation and wave front profile might be affected as well leading to undesirable changes in the regarded application.

In this contribution only deflecting elements that do not manipulate the wave front of the laser light shall be considered. The reason is that such deformations in any way would mean a distortion of phase information the wave is carrying and need to be corrected before the interferometric evaluation. This determination excludes most diffractive elements, since they would add a non-uniform phase to the wave front. The few exceptions to this rule will not be regarded here and are left to future research. Further, only planar optical surfaces are considered in this contribution, as curved surfaces would have a focusing effect on the beam. The current considerations shall be restricted to reflective systems like mirrors and reflective prisms. The investigation of refractive elements will also be part of future research.

Since prisms and mirror systems have long been used in optical systems there are several attempts to characterise and categorise them [11][12][13]. Prism applications are most prevalent in the field of conventional imaging optics. So, their effects on image orientation and angle transfer are well understood and documented.

However for use in interferometric applications other properties of deflecting elements are more important. If the deflecting element moves or tilts slightly (<10 µm or <1’) due to mechanical or thermal disturbances an occurring change in the optical path length will result in an immediate measurement error even if there is no change in the angle of deflection. Also a lateral shift of the beam will break the compliance with the *Abbe Alignment Principle* (Fig. 1) and thus indirectly increase the measurement uncertainty.

Among the several models commonly used to describe the properties of mirror systems and reflective prisms [6][14][15] there are none capable of covering the angle transfer properties as well as the lateral beam shift and the behaviour of the optical path difference. To characterise all these attributes of a deflecting element a three-dimensional vector approach is necessary.

Herein, all reflective surfaces are defined by their normal vectors while all beams are described by a vector originating from a point (cf. Fig. 2). The vector $\vec{b}$ of the incident light is assumed to be stationary in space.

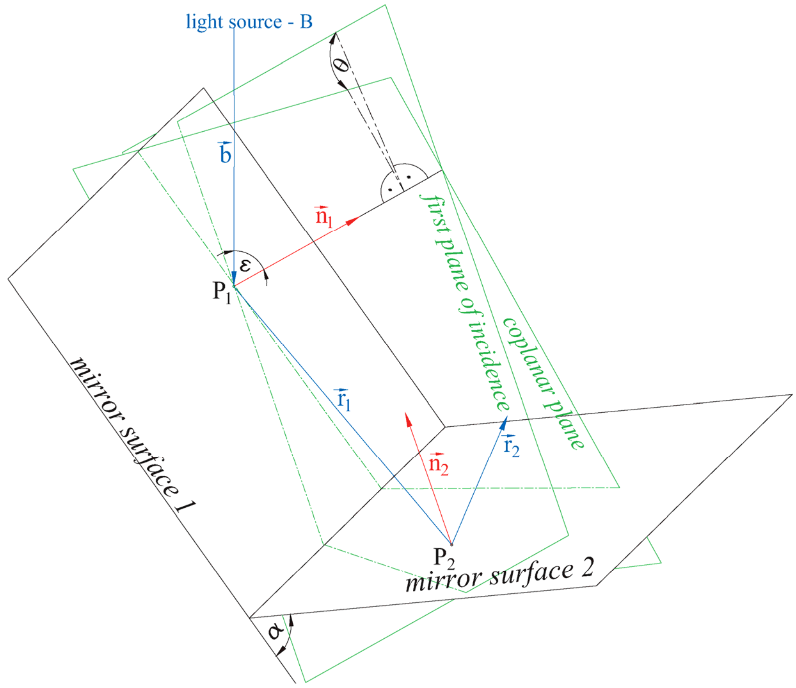


Fig. 2. Vector model for the characterisation of the properties of a mirror pair. The normal vectors of the reflective surfaces are labelled $\vec{n_1}$ and $\vec{n_2}$ for the first and second surface respectively. The vector $\vec{b}$ displays the direction of the incident beam originating from the light source in point B and is turned into $\vec{r_1}$ after the first and $\vec{r_2}$ after the second reflection. (All vectors are unit vectors.) The angle of incidence on the first surface is ε and α is the angle between the two mirror surface normal vectors $\vec{n_1}$ and $\vec{n_2}$. The angle between the first plane of incidence and the coplanar plane (formed by $\vec{n_1}$ and $\vec{n_2}$) is labelled θ.

3. PROPERTIES OF DEFLECTING ELEMENTS FROM THE VIEWPOINT OF INTERFEROMETRIC MEASUREMENT

To describe the transfer properties of deflecting elements it is useful to distinguish between errors caused by rotational and errors caused by translational movements of the deflecting element.

Any given arbitrary movement can be described, without loss of generality, as a combination of a pure rotation and a pure translation in linear superposition [16]. This allows for a separate evaluation of the consequences of a solely rotational and a solely translational displacement and their linear combination. For the centre of rotation a convenient point on the deflecting element is chosen that will give favourable results as demonstrated in subsection 3.2.

For mathematical purposes the laser beam is approximated by a perfect geometrical optical beam and the deflecting elements by prismatic bodies. Both are assumed to exhibit the following properties:

- infinitely thin beam
- ideally monochromatic light of constant power
- perfectly flat surfaces
- completely homogeneous and isotropic materials
- no deviation in the size and shape of the element (lengths and angles)
- “dispersion free” i.e. in the unfolded optical path the entrance and exit surfaces form a glass plate with parallel faces

Many classifications (e.g. [17]) divide deflecting elements into two main groups of odd and even numbers of reflections to clarify that the number of reflections determines most properties. In both groups there is a primary element which fulfils the task with a minimum number of reflections (Tab. 1). For odd numbers this is the single mirror and for even numbers the mirror pair which is two mirrors in fixed position relative to each other so that the pair can only be moved together. To describe prisms and mirror systems with higher numbers of reflections the primary element of the required group has added to it an arbitrary number of mirror pairs.

The next section considers the following beam deviations introduced by the displaced deflecting element that may cause measurement errors in an interferometric system:

- deviations in the angle of deflection
- lateral beam shifts
- optical path differences
- changes in the light polarisation

Therefore the primary elements of the two main groups of deflecting elements will be characterised: the single mirror and the mirror pair.

Since the influence of the prism material can be calculated separately and added linearly the remarks in sections 3.1 to 3.4 only refer to mirror systems in air. The effects of the prism material on beam deflection are described in section 3.5 allowing for full characterisation of prisms.

3.1 Angle of deflection

The characterisation of the behaviour of the angle of deflection is important for conventional imaging optics as well as for interferometric applications. It describes the relation between the incident and exiting beam.

In the case of interferometric applications, a slight change of this angle will lead to a measurement error because of a change in optical path length while a larger change can make interferometric evaluation impossible if the beam does not return to the right place (e.g. the optical detector). Since only flat optics are considered a change in the angle of deflection can only occur as a result of the rotation of the element.

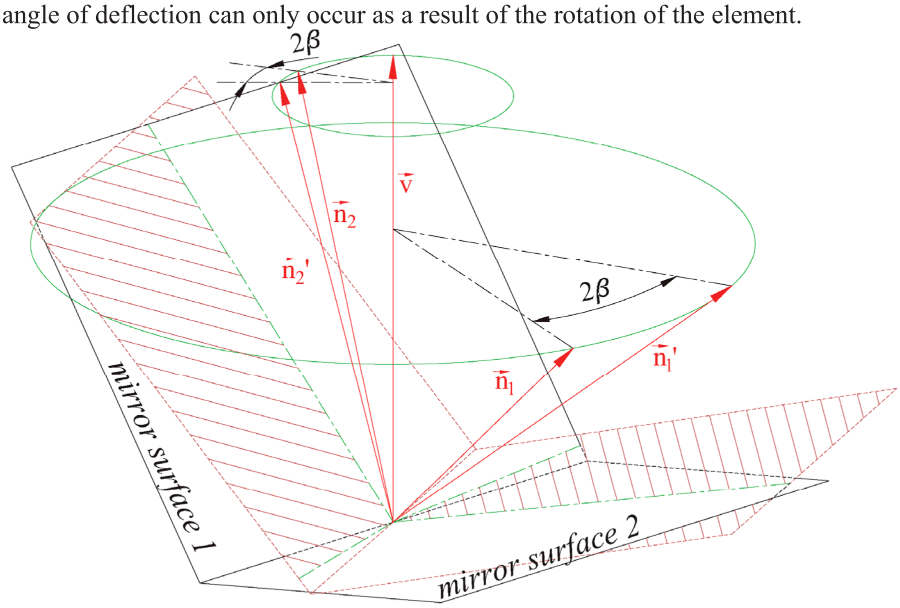


Fig. 3. Arbitrary rotational displacements of the deflecting element (exemplarily shown for the mirror pair) are described by a common tilt of all surface normal vectors ($\overrightarrow{n_1}$, $\overrightarrow{n_2}$) around the vector $\vec{v}$ by the angle 2β.

In this model, rotation of the deflecting element is described as a common tilt of all surfaces (and hence their normal vectors) around a unit vector $\vec{v}$ by the angle 2β (Fig. 3). The angle of deflection can then be calculated by deriving the dot product of incident and exiting beam. The angle of deflection is

$$\varphi_{\mathrm{sm}} = 180° - 2\varepsilon \qquad \textbf{(1)}$$

for the single mirror [13] and

$$\cos(\varphi_{\mathrm{mp}}) = 1 - 2 \cdot sin^2(\alpha)[cos^2(\theta) + cos^2(\varepsilon)sin^2(\theta)] \qquad \textbf{(2)}$$

for the mirror pair respectively. A tilt of the deflecting element will influence both ε and θ in a complex way. To describe this influence in detail is not necessary as it would not contribute to deeper understanding.

While the single mirror is always sensitive to rotational displacements the sensitivity of the mirror pair depends on the angle θ. In case that $\theta = 0°$ (Fig. 4), which represents the coplanar setup where $\vec{b}, \overrightarrow{n_1}$ *and* $\overrightarrow{n_2}$ are forming one plane, the expression **(2)** simplifies to

$$\varphi_{\mathrm{mp}} = 2\alpha \qquad \textbf{(3)}$$

which is independent from the angle of incidence and thus from the position of the deflecting element [15][18].

3.2 Lateral beam shift

If the beam retains its direction but is displaced laterally due to a movement of the deflecting element, it will hit the retroreflective mirror of the interferometer at a different position. In case of a three-dimensional interferometric measurement this shift will cause the beam to miss the common point where all laser beams (virtually) meet, called the “*Abbe-Point*”. This will break the compliance with the *Abbe Alignment Principle* and increase the measurement uncertainty.

The lateral beam shift describes the displacement of the beam parallel to itself when the deflecting element is moved. It is only feasible to define this quantity while a change of the angle of deflection is absent. Thus, in most cases only translations of the element can be the cause of this error.

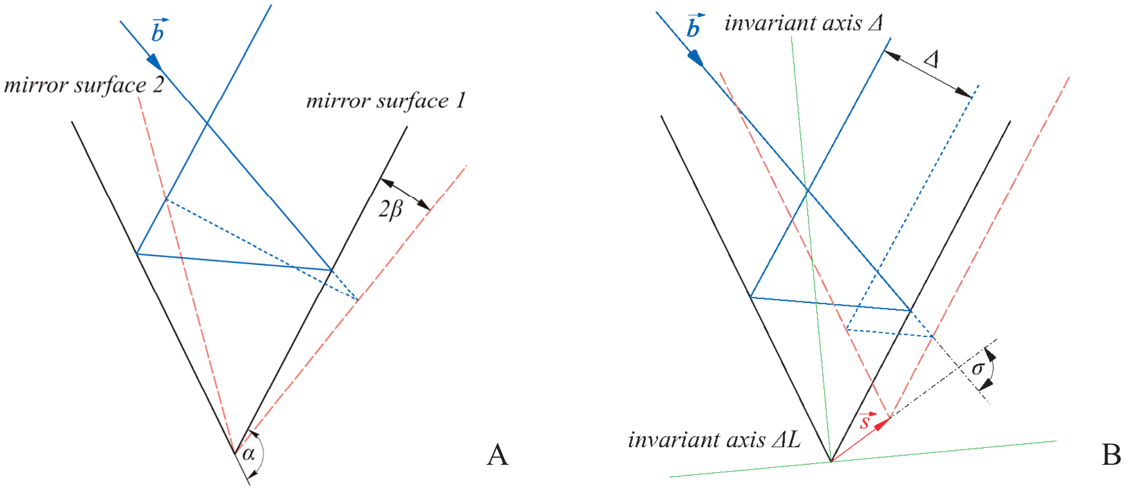


Fig. 4. A. Rotational displacement of the deflecting element for the coplanar mirror pair ($\theta = 0°$). In this special case no change in the angle of deflection is caused, nor does a lateral beam shift appear. Even the optical path length will remain unchanged in this case, if the centre of rotation is chosen to be in the intersection line of the two mirror surfaces.

B. Translational displacement of the deflecting element for the coplanar mirror pair ($\theta = 0°$). In this case the lateral beam shift and the optical path difference do not depend on the angle of incidence ε. Two perpendicular axes can be found where a translation of the element does not cause either a lateral beam shift or a change in the optical path length.

However, there are few exceptions where the angle of deflection is invariant to rotations of the deflecting element when rotations may cause a lateral beam shift as well. Such an example is the coplanar case of the mirror pair (as mentioned in subsection 3.1, Fig. 4A).

It can be shown that if the centre of rotation for this special case is chosen to be in the intersection line of the two mirror surfaces like in Fig. 4A no beam shift will occur for a rotation of the deflecting element (as long as θ remains 0). So the lateral beam shift is only reasonably described as a result of a translational movement of the deflecting element along the vector $\vec{s}$ (cf. Fig. 5).

$$\Delta_{sm} = 2|\vec{s}| \cdot \cos(\xi) \cdot \sin(\varepsilon) \qquad \textbf{(4)}$$

$$\Delta_{mp} = 2|\vec{s}|\sqrt{[\cos(\xi)\sin(\varepsilon) + (\cos(\theta)\cos(\varepsilon)\ \sin(\alpha) - \cos(\alpha)\sin(\varepsilon))\cos(\zeta)]^2 + \sin^2(\theta)\ sin^2(\alpha)\ cos^2(\zeta)} \qquad \textbf{(5)}$$

Equation **(4)** characterises the lateral beam shift for the single mirror and **(5)** for the mirror pair. In the coplanar case ($\theta = 0°$), instead of ζ and ξ, the angle σ is used to describe the position of the projection of $\vec{s}$ onto the coplanar plane in regard to the incident beam $\vec{b}$ (Fig. 4B). In this case **(5)** simplifies to

$$\Delta_{mp} = 2|\vec{s}| \cdot [\sin(2\alpha)\ \cos(\sigma) + 2\sin^2(\alpha)\ \sin(\sigma)] \qquad \textbf{(6)}$$

which is invariant to the angle of incidence ε.

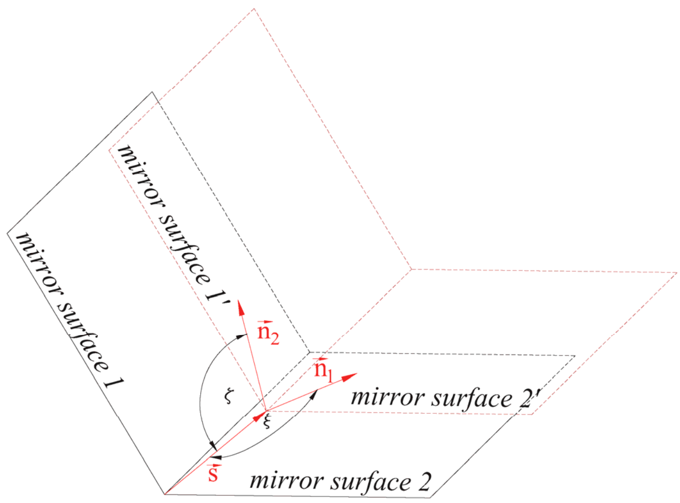


Fig. 5. Arbitrary translational displacement of a deflecting element (exemplarily shown for the mirror pair) by the vector $\vec{s}$. The orientation of $\vec{s}$ relative to the two reflective surfaces is described by the two angles ζ and ξ.

3.3 Optical path difference (OPD)

The optical path is the geometrical trajectory that the light needs to travel through the deflecting element weighted with the refractive index n_{medium} of the pervaded medium. A change in it causes variations in the phase of the beam which is the actual quantity measured by interferometers. Such a change can occur through rotation or translation of the deflecting element. In order to describe the value of this change for rotational displacements of the deflecting element, detailed information about the specific system is necessary e.g. the distance between the detector and the centre of rotation. This is why it is only useful to give the equations for translational displacements (**(7)** and **(8)**) and angle-invariant setups like described in subsection 3.1.

For the special angle-invariant case mentioned in subsection 3.2 and shown in Fig. 4A, the centre of rotation chosen to avoid the appearance of lateral beam shift, is appropriate to nullify OPD as well for all rotations of the deflecting element in the coplanar plane ($\theta = 0°$).

$$\Delta L_{sm} = -2 \cdot n_{medium} \cdot |\vec{s}| \cdot \cos(\xi) \cdot \cos(\varepsilon) \quad \textbf{(7)}$$

$$\Delta L_{mp} = 2 \cdot n_{medium} \cdot |s| \cdot [\cos(\zeta)\{\cos(\theta)\sin(\varepsilon)\sin(\alpha) + \cos(\varepsilon)\cos(\alpha)\} - \cos(\xi)\ \cos(\varepsilon)] \quad \textbf{(8)}$$

The OPD for the case when the single mirror or the mirror pair respectively is laterally moved by the vector $\vec{s}$ is described by **(7)** and **(8)**. In the coplanar case **(8)** simplifies to

$$\Delta L_{mp} = 2 \cdot n_{medium} \cdot |\vec{s}| \cdot [2\sin^2(\alpha)\ \cos(\sigma) - \sin(2\alpha)\ \sin(\sigma)] \quad \textbf{(9)}$$

which is invariant to the angle of incidence ε.

3.4 Polarisation

While beam polarisation is usually irrelevant for imaging optics, most interferometers types work with polarised laser light and rely on the polarisation to be unchanged for the measurement.

The beam polarisation can be affected by every boundary of two media of different refractive indices where the light is reflected and/or refracted. The *Fresnel equations* describe the changes that *s* and *p* polarised components undergo in amplitude and phase [10][19]. When total internal reflection is utilized (like in many reflective prisms) or the reflection occurs at a metal surface (like on many mirrors) a phase shift is added to the two amplitude components dependent on the angle of incidence. An error occurs if this phase shift changes during the measurement due to a rotation of the deflecting element.

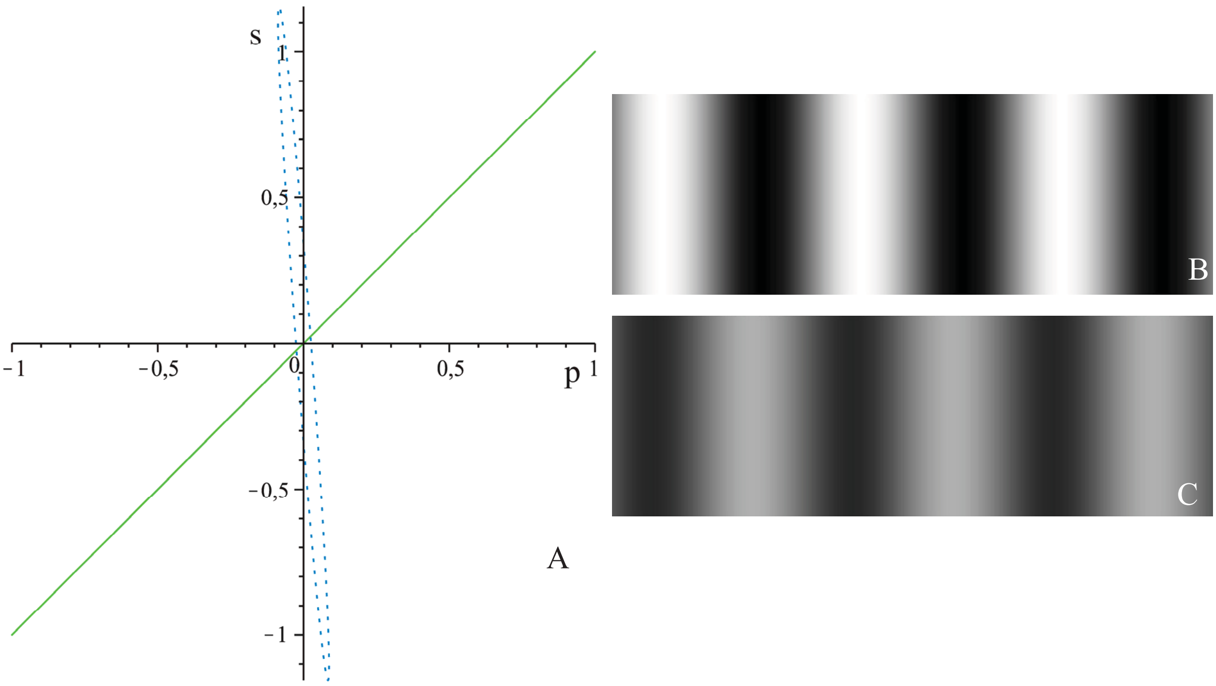


Fig. 6. A. Example for the polarisation of a beam that enters (solid) and leaves (dotted) a mirror pair after passing it twice and being retro-reflected on a flat mirror. The axes are aligned for the s and p components of the first reflection on mirror surface 1, the entering amplitudes have been normalised. ($\varepsilon = 28°$, $\theta = 10°$, $\alpha = 130°$, mirror coating materials: aluminium for the mirror pair and silver for the retro-reflective mirror with $n_{Al} = 1.44819 + 7.53669 \cdot i$ and $n_{Ag} = 0.13455 + 3.98651 \cdot i$ at $\lambda_{HeNe} = 632.8\,nm$ respectively)

B. and C. Simulation of the contrast deterioration in the interferometric evaluation of a beam with changed polarisation. B shows the interference pattern of two identical beams of the same polarisation. C illustrates the interference pattern of the incident and the exiting beam of the example from figure 6A. Compared to B the contrast has heavily decreased.

The result after several reflections usually is an arbitrarily polarised beam which means it has an elliptical polarisation (Fig. 6A). When the interference pattern is generated the s and p components interfere separately and their resulting intensity is added up incoherently. This will lead to a significant deterioration in contrast if the polarisations of the two beams differ.

Fig. 6A shows an example of the polarisation of a beam that passed a mirror pair, has been retro-reflected on a flat mirror and returned the same way through the deflecting element. It is obvious that the effects on the first and second passing do not cancel out but add up to a radically changed elliptical polarisation. As long as the deflecting element does not move no measurement error occurs, but the contrast greatly deteriorates as shown in Fig. 6B and C.

3.5 Influence of the prism material

While the prism material does not have any effect on the beam for lateral movements of the deflecting element, for rotational displacements it can influence the following parameters:

- the lateral beam shift,
- the optical path length and
- the polarisation of the light.

The prism material does not affect the angle of deflection because the prisms under consideration are assumed to be "dispersion free" which means that they have the effect of a planar glass plate in the unfolded optical path. Reflective prisms are usually designed this way to minimise the parasitic effects of refraction. As a planar glass plate – even if tilted – they only cause a lateral shift of the beam and a change in the optical path length (Fig. 7).

The lateral shift of the beam (Eq. **(10)**) depends on the angle of incidence on the entrance glass surface which is certainly related to the angle of incidence on the reflective surface(s) for any given prism but can be freely chosen when designing the prism.

The angles of incidence on the first medium boundary before (index A) and after (index B) the tilt are ε_A and ε_B. The corresponding angles of refraction are ε'_A and ε'_B which are related to ε_A and ε_B by the Snell's law of refraction [10]. The geometric length of the glass body of the prism in the unfolded optical path is labelled *d* (Fig. 7).

At the same time the optical path through the deflecting element changes because of the altered geometrical trajectory and the higher index of refraction:

$$\Delta_{material} = d\left[\frac{\sin(\varepsilon_B - \varepsilon'_B)}{\cos(\varepsilon'_B)} - \frac{\sin(\varepsilon_A - \varepsilon'_A)}{\cos(\varepsilon'_A)}\right] \quad \textbf{(10)}$$

$$\Delta L_{material} = n_{material} \cdot d\left[\frac{1}{\cos(\varepsilon'_B)} - \frac{1}{\cos(\varepsilon'_A)}\right] - n_{medium} \cdot d\frac{1}{\cos(\varepsilon'_A)} \cdot \left[\cos(\varepsilon_B - \varepsilon'_B)\left(\frac{\cos(\varepsilon'_A)}{\cos(\varepsilon'_B)} - \cos(\varepsilon_p)\right) - \sin(\varepsilon_B - \varepsilon'_B)\sin(\varepsilon_p)\right] \quad \textbf{(11)}$$

with

$$\varepsilon_p = (\varepsilon_B - \varepsilon_A) - (\varepsilon'_B - \varepsilon'_A) \quad \textbf{(12)}$$

and

$$2\beta = \varepsilon_B - \varepsilon_A \quad \textbf{(13)}$$

To describe the properties of a prism the lateral beam shift $\Delta_{material}$ and the OPD $\Delta L_{material}$ can be added signed and linearly to the effects of the displacement of the equivalent mirror system in air calculated according to subsections 3.2 and 3.3.

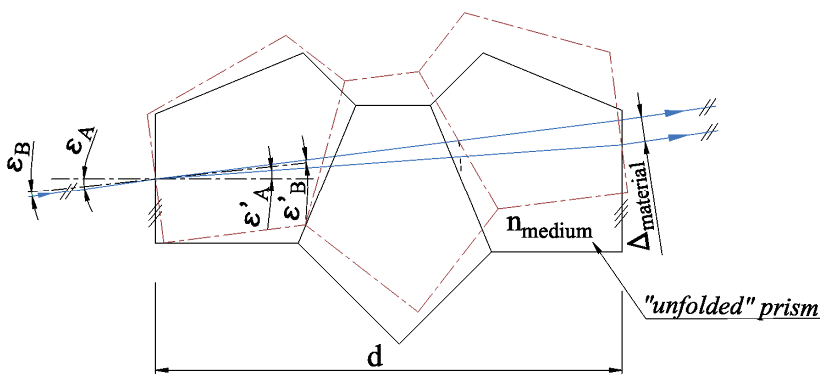


Fig. 7. The prism material influences the lateral beam shift $\Delta_{material}$ and the OPD $\Delta L_{material}$ like a planar glass plate of the thickness d if the deflecting prism is tilted (exemplified on an ideal 90° pent prism).

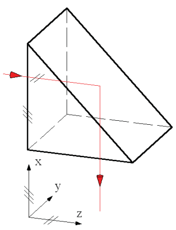
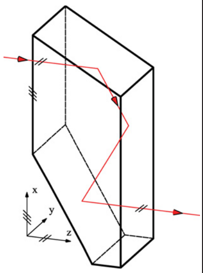
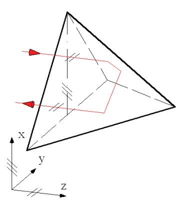
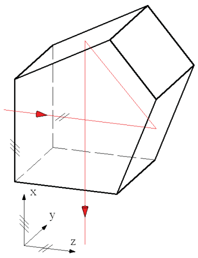
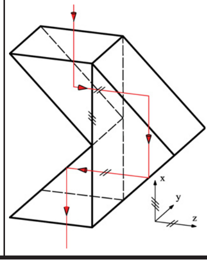
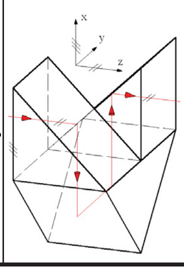
The polarisation of the beam is influenced on both boundary surfaces as described by the *Fresnel equations* for transmission (cf. section 3.4). The idea of the common plane of incidence of the two refractions in the unfolded prism suggests that their influence on the polarisation can be calculated simultaneously before regarding the reflective surfaces. The conventional way of calculation deals with every surface in the order of light passing. First simulations have shown a small difference between the results of these two approaches. Future investigation shall reveal whether this discrepancy is of numerical or analytical origin.

4. CONCLUSIONS-DISCUSSION

The properties of deflecting elements described in section 3 are the basis for understanding the errors introduced by the incorporation of such elements into an interferometric measurement system. This will allow a systematic approach to the robust design of such systems. The application of error compensation or error correction methods requires detailed knowledge about the errors that can occur in the system.

To simplify the mechanical structure and to design a more robust *metrology frame*, the deflecting elements are not attached to the frame but are allowed a slight movement due to mechanical and thermal disturbances. Direct errors are caused if this movement changes the OPD while indirect errors can increase the measurement uncertainty (e.g. if the *Abbe Alignment Principle* is infringed). Here it has to be taken into account that the light passes the deflecting element twice in opposite directions. Some effects might be cancelled out by this while others are augmented.

Tab. 1. Overview over reflective deflecting elements and their characterisation. The orientation of the coordinate system has been chosen according to the usual position of installation of the prism.

<table>
<tr><th colspan="6">reflective deflecting elements</th></tr>
<tr><th colspan="3">odd numbers of reflections</th><th colspan="3">even numbers of reflections</th></tr>
<tr><th>primary element: single mirror</th><th colspan="2">high-order elements</th><th>primary element: mirror pair</th><th colspan="2">high-order elements</th></tr>
<tr><td></td><td>coplanar arrangement</td><td>non-coplanar arrangement</td><td></td><td>coplanar arrangement</td><td>non-coplanar arrangement</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

To aid in the new implementation of these deflecting elements in interferometric applications and satisfy the changed requirements for these elements, a new approach for their categorisation is presented. The properties described in section 3 suggest that the division into the two main groups of odd and even numbers of reflections that has been chosen in previous categorisations is useful to retain. The highlighted special cases in sections 3.1 and 3.2 further suggest that another division into coplanar and non-coplanar arrangements is feasible for elements with higher numbers of reflections that are composed of several mirror pairs and the primary element of the respective group. A coplanar arrangement of two or more mirror pairs or a single mirror and a certain number of mirror pairs is given when the normal vectors of all reflective surfaces are in one plane. A coplanar plane can be defined in each mirror pair formed by the two normal vectors of both surfaces. In combination with other mirror pairs these planes do not necessarily coincide (Tab. 1).

For the coplanar use of the mirror pair (when the incident light lies in the coplanar plane, cf. Fig. 3B) there is an axis in which the deflecting element can be moved without affecting the lateral position of the exiting beam and another axis which does not cause a change in the optical path length. Unfortunately, these two axes are always perpendicular to each other which means that if one parameter is nullified the other becomes maximum. With the knowledge of these two axes the possible movement of the deflecting element can be constrained in such a way that undesired errors are kept to a minimum.

On the other side, the found sensitivities of the described elements can be utilized in a system to achieve an adjustable arrangement. Another application might be the highly sensitive measurement of angles through interferometric evaluation which is of special importance if the effects are augmented by the second passing of the light through the deflecting element. The viability of the transfer of this principle to other fields of application will be part of future work. With the knowledge of the properties of deflecting elements, design strategies can be developed that allow the implementation into interferometric applications.

5. FUTURE REASEARCH

The future research comprises a preliminary study of the viability of the extension of the model introduced in this contribution for the descriptions of more complex deflecting elements. These include systems with higher numbers of reflections, refractive elements and even a small group of special diffractive elements that retain the wave front profile. Along with the description of these elements, their invariant and sensitive behaviours are to be addressed. Making use of these properties, different design strategies for the use of deflecting elements in interferometric applications can be developed and methods for error compensation and error correction can be proposed. A generalised approach for the consideration of the polarisation changes caused by deflecting elements will be proposed as well.

6. ACKNOWLEDGEMENT

The authors want to thank the collaborative research center 622, "Nanopositioning and Nanomeasuring Machines" funded by the German Research Foundation (DFG) for the financial support of this work.

7. REFERENCES

[1] R. Donker, I. Widdershoven, H. Spaan, „Realization of Isara 400: a large measurement volume ultra-precision CMM", Asian Symposium for Precision Engineering and Nanotechnology, 2009
[2] E. Manske, R. Theska, W. Schott, "Nanopositionier- und Nanomessmaschinen - universelle skalenuebergreifende Werkzeuge für die Mikro-Nano-Integration", GMM-Workshop Mikro-Nano-Integration, Erfurt, 2010
[3] R. Theska, T. Frank, T. Hackel, G. Hoehne and M. Lotz, „DESIGN PRINCIPLES FOR HIGHEST PRECISION APPLICATIONS", ASPE Annual Meeting Proceedings, Orlando, 2004
[4] T. Frank, Konzeption und konstruktive Gestaltung der Messkreise von Nanomessmaschinen, Dissertationsschrift, TU Ilmenau, Muenster : Monsenstein und Vannerdat, 2010
[5] M. Schilling, Konstruktionsprinzipien der Geraetetechnik, Habilitationsschrift, TU Ilmenau, 1982
[6] H. Haferkorn, Optik: Physikalisch-Technische Grundlagen Und Anwendungen, Wiley-VCH, Weinheim., 2003
[7] H. Naumann, N. Schroeder, Bauelemente der Optik, Carl Hanser Verlag, Muenchen, 1992
[8] P. R. Yoder, Mounting Optics in Optical Instruments, SPIE PRESS, Bellingham, 2002
[9] W. Bischoff, "Der Drehlagenkreis für Bilder", Feingeraetetechnik, Wissenschaftliche Zeitschrift der Technischen Hochschule Ilmenau, Ilmenau, vol. 8, issue 3, pp. 257-266, 1962
[10] E. Hecht, Optics, Addison-Wesley, 2002
[11] DIN 58158, Optik-Prismen, Beuth Verlag GmbH, Berlin, 1971 (withdrawn)
[12] K. Mütze, Brockhaus ABC der Optik, VEB Brockhaus, Leipzig, 1961
[13] H. Naumann, Optik für Konstrukteure, Wilhelm Knapp Verlag, Duesseldorf, 1960
[14] W. Bischoff, "Die Ablenkung durch Spiegelprismen", Feingeraetetechnik, Wissenschaftliche Zeitschrift der Technischen Hochschule Ilmenau, Ilmenau, vol. 9, issue 4, pp. 597-604, 1963
[15] W. Bischoff, "Betrachtungen über Eigenschaften und Anwendungen ebener Spiegel", Feingeraetetechnik, Wissenschaftliche Zeitschrift der Technischen Hochschule Ilmenau, Ilmenau, vol. 12, issue 1, pp. 57-65, 1966
[16] J. Volmer (ed.), Getriebetechnik Lehrbuch, VEB Verlag Technik, Berlin, 1968
[17] A. Bochnia, Ein Beitrag zur Justierung optischer Geraete, Dissertationsschrift, TU Ilmenau, 1986
[18] W. Bischoff, "Das Spiegelpaar und seine Eigenschaften", Feingeraetetechnik, Wissenschaftliche Zeitschrift der Technischen Hochschule Ilmenau, Ilmenau, vol. 15, issue 1, pp. 105-110, 1969
[19] R. M. A. Azzam, N. M. Bashara, Ellipsometry and Polarized Light, North-Holland, Amsterdam,1977