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Polarizační nedokonalosti světla v interferometrii
Polarization imperfections of light in interferometry

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1 INTRODUCTION

1.1 MOTIVATION

This doctoral thesis is partly connected with a research project which was running at Pforzheim University and which was funded with financial support from an industrial partner and from the German Ministry of Research and Development in its FH3 program. The goal of this project was development of a laser vibrometer with a novel architecture: on the optical side based upon a polarization optical concept, and on the electronic side exploiting high-speed programmable electronic circuits (FPGAs). Background and main subject of the project is an optical laser vibrometer operating in a homodyne scheme. Homodyne schemes generally apply architectural concepts which generate a pair of quadrature signals which are then processed electronically to produce an output signal proportional to the speed of the measured target. Main emphasis of the dissertation is put on the optical part of the instrument, where a suitable architecture has to be defined, the properties of the required components have to be evaluated, and potential error sources resulting from non-ideal characteristics have to be determined.

1.2 CURRENT STATE OF THE ART

Interferometers are usually considered as belonging to either of two main families: heterodyne and homodyne interferometers [1].

Heterodyne interferometers have an architecture where the optical frequencies of the beams in measuring and reference path, respectively, are different. Superposition of these beams on the detector then produces, in the electrical domain, an IF signal with a frequency identical to the difference of both optical beams (so-called bias frequency). A movement of the target in the direction of the measuring beam then produces, through the well-known Doppler effect, a frequency shift on the measuring beam proportional to the target velocity. In case of a vibrating target the interferometer detector gives an output that is frequency modulated. The bias frequency mentioned above must be introduced in order to distinguish the sign of the target velocity. The preferred methods are to use an electro-optic device in one interferometer arm or to use a stabilized He-Ne laser whose output beam consists of two frequency components. The heterodyne technique is the most common approach in today’s interferometric laser vibrometry.

Contrary to the competing heterodyne approach with its light beams with differing optical frequencies, the homodyne scheme for generating signals from an interferometric arrangement is based on the use of two optical beams of the same frequency. Homodyne interferometers detect the phase difference between the measuring and the reference arms. The sign of the target velocity is, in this case, determined from two signals in quadrature generated at the output of the vibrometer.
Known methods for producing the required 90°-phase shift include the use of a beam splitter with an absorbing metal coating [2] and the use of specific polarization-optical arrangements [3]. The second method, although it requires additional components to be included in the setup, is preferred to the first one. It is because of the non-stable behavior of the metal coating in the beam splitter and due to the loss of the energy which was reported in the literature.

As mentioned, the heterodyne concept requires expensive optical components such as a Bragg cell or a Zeeman Laser. On the side of the electrical signal extraction, it requires RF circuitry which is also quite costly and does not offer a high flexibility. In contrast to this, the homodyne-based concept that we chose avoids all these drawbacks both on the optical and on the electrical part of the architecture. Thus, our strategy reduces the optical complexity for the prize of higher signal processing demand. Based on the fact that today highly integrated signal processing hardware such as DSPs (Digital Signal Processors) or FPGAs solutions are much less expensive than in the past, this so called HWSHD (Homodyne With Synthetic Heterodyne Demodulation) strategy is therefore competitive to the classical usage of expensive optical components in the heterodyne concept.

In our investigations of this concept we have to focus on two main fields of problems. The first occurs with any interferometrical setup using light from a noncooperative target rather than a mirror. The light returning from the investigated target will be far from an ideal laser field with plane wave fronts. Instead, it will possess a statistical nature generally known as speckles [4]. As was stated previously, in the class of interferometers treated in the work, the required directional information is acquired by appropriately making use of the polarization properties of the light beams brought to interference. Consequently, we must pay special attention to the polarization of the backscattered field, and we cannot limit ourselves to the case of fully polarized speckle patterns (so called fully developed speckles [4]).

The influence of a fully developed speckle field on an interferometric signal was investigated in [5], [6] and [7]. There was assumed, however, that the phase of the backscattered field is correlated only within a single speckle and that the correlation between speckles is zero. In the mentioned publications was clearly demonstrating the spoiling effect of speckles on the visibility, i.e. on the quality of the interferometric signal.

The second difficulty arises due to polarization imperfection of components used in the optical part of interferometer. The errors due to these imperfections are called periodic deviations and were thoroughly studied in the dissertation [8] for the case of a heterodyne vibrometer. In [8] one can find analytical formulations of these errors. These errors, however, are in general difficult to analyze not for their mathematical complexity but for the finding the origin of these errors. Periodic deviations result not only from the inherent imperfections of components (non-ideal retardations, non-ideal transmission and reflection coefficients...) but also from the rotational misalignment of these components which is in practice hard to measure and control. Apart from the polarization-optical components, it must be kept in mind that the
adjustment of all components (mostly mirrors and beamsplitters) has, above all, to satisfy several goals at once: measuring and reference beam must be brought to a good lateral and angular overlap in order to guarantee a good interference contrast (and to optimally exploit the available light power).

Periodic deviations also play an important role in another kind of measuring instrument, the so-called polarimeter. This instrument belongs to one of the oldest forms of interferometric measurements for determination of stress-induced birefringence in transparent materials. The recent technologies offer to produce micropolarizers arrays [9] and [10]. This brings a possibility of using these arrays in imaging [11] and in polarimetry. However, as can be found in [9], [10] these arrays have quite low extinction coefficients (between 100 and 300). Another difficulty is the exact orientation of transmission axes of micropolarizers. These two problems result again in the degradation of measuring performance due to the polarization imperfections of used micropolarizer arrays, and commonly used phase shift algorithms [12], [13] need to be refined.

The final part of the dissertation refers to polarization imperfections in optical communication with the emphasis on quantum optical communication. The part briefly summarizes published results in that field. Although this topic seems to be different from the main contents of the dissertation, some common features can be found. Namely, the function of the detector in communication schema is to determine which state was transmitted with the minimal probability of misdiagnosis. When polarization properties of light are used for encoding the information then a Wollaston prism fills the function of the detector and its imperfections increase the probability of misdiagnose. Some achieved results will be compared with papers from other authors [14], [15]. However a certain contradiction was found in [15].

1.3 DISSERTATION’S GOALS

The main part of the dissertation is thus devoted to the problems that arise by using real optical components which possess non-ideal polarization properties.

Let us summarize the main goals of the dissertation:

- Describe the influence of partly polarized speckle field on the interferometric signals.
- Find a solution how to reduce speckle effects resulting from the usage of non-cooperative target as the surface which is investigated by a vibrometer.
- Find the influence of periodic deviations on interferometric signals generated by vibrometer working in the homodyne concept and find the way how this spoiling influence can be eliminated.
- Study the influence of analyzer with low extinction coefficient and angular misalignment on measured retardation in polarimetry. Find an algorithm...
how the effect of low extinction coefficient can be eliminated from the current retardation determination procedure.

- Investigation of the influence of polarization imperfections on probability of misdiagnose in quantum optical communication.

2 INFLUENCE OF NON-COOPERIVE TARGET

In this section, we discuss the problems occurring in the interferometrical vibrometers (arrangements for high-resolution measurement of vibrating targets as in Fig. 2-1) which arise when the interferometer uses a conventional, so-called “non-cooperative” target rather than a mirror. In such arrangements, it is not generally possible to fix a mirror on the surface under consideration and as a result, the light returning from the target will be far from an ideal laser field with plane wave fronts. Instead, it will possess a statistical nature generally known as speckles [4]. This speckle field is then superimposed with the reference beam in order to generate an interferometric signal from which the information about the movement of the target can be derived by suitable electronic processing.

In the class of interferometers treated here, the required directional information is acquired by making appropriate use of the polarization properties of the light beams brought to interference. Consequently, we must pay special attention to the polarization of the backscattered field, and we cannot limit ourselves to the case of fully polarized speckle patterns (so called fully developed speckles [4]) whose influence on an interferometric signal was investigated in [5], [6] and [7]. It was assumed, however, that the phase of the backscattered field is correlated only within a single speckle and that the correlation between speckles is zero. However, when suitable imaging optics is used, then the phase of the speckle field is fully deterministic as will be shown later in this chapter.

The main original author work in this chapter is the influence of a partly polarized speckle field on an interferometrical signal and a speckle reduction due to the using of a suitable imaging optics. The results were published in [16] and [17]. Next an idea of using a zoom objective in vibrometry is realized in the chapter. This enhances performances of the vibrometer, namely detected signal is independent of the target distance.

Fig. 2.1. Standard architecture of an interferometrical laser vibrometer.
2.1 DEPOLARIZATION BY THE TARGET

The influence of a partly polarized speckle field on an interferometric signal was investigated by the author in [16]. However, there was no distinction between the depolarization and so called pseudo-depolarization. The former deals with the familiar time average definition of the degree of polarization. The latter is related to the ensemble average over the surfaces with different microstructure. In this case, the light is in fact fully polarized at a particular point in the observer plane but the state of the polarization changes with the position. When this kind of light impinges on the polarizing sensitive detector of sufficiently large area, then this light appears partly polarized even though that there are no changes in time. This situation can be explained that the speckle field is viewed a superposition of large number of spatial modes. Each mode has a well defined polarization. The strength of the mode amplitudes varies with the position and hence the state of polarization is different from point to point.

A certain class of the targets can introduce pseudo-depolarization. When this kind of light is brought to interference with the reference beam, the interference signal is reduced due to the finite area of the detector. The overlap between the reference beam polarization and the scattered beam with degree of pseudo-polarization $P_s$ is $(1+P_s)/2$. Hence, even when the backscatter light is completely pseudo-depolarized, the interference fringes are visible. This is illustrated in Fig. 2.2 where normalized interferometric signal is depicted as a function of degree of polarization and pseudo-polarization, respectively. Experimental data for different surfaces are also shown in Fig. 2.2.

![Fig. 2.2. Normalized interferometric signal as a function of degree of polarization (dashed line) and pseudo-polarization (solid line).](image-url)
2.2 MEASUREMENTS OF THE TARGET’S PSEUDO-DEPOLARIZATION

In Fig. 2.3, a measurement setup suitable for investigation of polarization behavior of targets in interferometry is shown. This setup allows a sharp focusing of the illuminated beam on the target which can lead to eliminating of higher spatial modes in the backscattered field as will be shown later. The next figure 2.4 can be interpreted as the measurement of linear degree of pseudo-polarization. Moreover, Meuller matrices of measured surfaces showed negligible amount of optical activity. Hence, linear degree of pseudo-polarization corresponds in good approximation to the overall degree of pseudo-polarization. Measurement data points were obtained for two different surfaces. Smooth ceramic surface (black curve), which strongly scatters light in specular direction and white paper (blue) which in the first approximation behaves like Lambertian scatterer.

The red curve corresponds also to the white paper, but in this case, the illuminated beam was focused sharply in order to reduce higher spatial modes, i.e. speckles. The speckle reduction is treated in detail in section 2.5.

However, the speckle reduction was not perfect because we used slightly different imaging optics from that which was used in the final arrangement of the vibrometer. The optics used in this case were anti-reflection coated but the optics did not enable focusing sharp enough to eliminate all higher modes. When we used the same imaging optics like in the final arrangement of the vibrometer, then the reflected light from microscope objective exceeded the light of interest, the one scattered from target. This was not a problem in the vibrometer because reflected light from lenses was eliminated by polarization means. The irradiance pattern of the target field formed at the detector looked as it is depicted in the second-last figure in Fig. 2.14 on page 18 rather than in the last one.

![Fig. 2.3. Measurement setup for determination of linear pseudo-depolarization of tested surfaces.](image-url)
Fig. 2.4. Detected scattered power from a target illuminated by a linearly polarized beam (633 nm, 1.2 mW) as a function of analyzer angle.

The important thing is that degree of pseudo-polarization increase with decreasing number of spatial modes in the backscattered field. This confirms the analogy with optical fiber.

Indeed, when an illuminating beam is focused sharply on the target, the fundamental mode dominates in the backscattered field and has properties of the original beam (polarization, direction of the propagation only opposite in sign) which caused the disturbance. It is remarkable to note that the diameter of the illuminated target area in the speckle reduction mode is comparable with the diameter of the core of single-mode fiber.

2.3 FIRST ORDER STATISTICS OF PARTLY PSEUDO-POLARIZED SPECKLES

In Fig. 2.5, two speckle patterns (cycle averaged optical intensity) with degree of pseudo-polarization 0.2 and 1 are shown. The patterns were produced by a computer simulation but experimentally, the former can be observed by illuminating a matt white surface (white paper for instance) and the latter by illuminating a metal surface.

The probability density functions of intensity (expressed in the number of counts where a given parameter lies in a particular interval) are shown in Fig. 2.6. Also shown is the analytically obtained density function of the intensity based upon intensity basis rather than amplitude basis [4]. The remaining Stokes parameters are depicted in Fig. 2.7. The polarization of the illuminating beam was assumed to be circular.
Fig. 2.5. Speckle patterns produced by white paper and a metal surface.

Fig. 2.6. The first order statistics of the intensity (irradiance).

Fig. 2.7. The first order statistics of Stokes parameters.
2.4 INTEGRATED SPECKLE PATTERN

Figure 2.8 shows probability distribution functions for modulated power for two different values of \( n \) which denotes how many speckles are collected from the target and are superimposed with the reference beam. Figures were obtained by numerical calculation and the reference power is taken to be 370 µW and the speckle power 10 µW.

The curves in Fig. 2.8 for fully developed speckles can be compared with [7] where experimental verification was shown. Next, from Fig. 2.8 one can see that the mean value of the interferometric signal (also denoted like modulated power) behaves like in Fig. 2.2.

Fig. 2.8. Distribution functions of modulated power for two values of \( n \). Target pseudo-depolarized incident beam.
2.5 SPECKLE REDUCTION

In the previous section, it was shown that collecting more power (speckles) scattered by the target reduces the contrast of the interference signal (modulated power). This spoiling effect is due to the stochastic nature of the speckles. However, with suitable imaging optics and for small oscillation amplitude of the target (order of 50 microns), the stochastic nature of the speckles can be reduced even for rough surfaces.

Let us assume imaging optics which is depicted in Fig. 2.9. The optics serve both for focusing the laser beam on the target and for collecting the backscattered light. The position of the second lens can be positioned by parameter $\Delta$. The amount of the light that reaches the detector placed in the image plane is determined by the aperture stop which coincides with the exit pupil.

When the target distance from the object plane (denoted as $z$ in Fig. 2.9) is much larger than the illuminated area of the target, the phase of the backscattered field is deterministic. In fact, the phase can be approximated by a radius of curvature which is identical with the value of $z$.

![Fig. 2.9. Imaging optics of an interferometer.](image)

![Fig. 2.10. Irradiance and phase of the backscattered field in the image plane. Radius of illuminated area $w = 25$ µm.](image)
The two figures in Fig. 2.10 show the field in the image plane. It was assumed that the target does not absorb the incident light which was produced by He-Ne laser with the output power 1mW. The laser light was collimated on the target to produce the spot of radius 25 microns.

One can see from Fig. 2.10 that the phase of the field can be approximated with the radius of curvature equal to $z$. The extent of the phase distortion apparent in Fig. 2.10 is given by the ratio $z/w$. In other words, to remove stochastic nature of the phase, one needs to use the imaging optics with the object plane situated sufficiently far from the target surface in comparison with the width of the spot of the illuminating beam.

Next, a photograph of the speckle field in the detector plane is shown in Fig. 2.11 on the left. The interferometric setting was the same as used in the computer simulation with results shown in Fig. 2.10.

Finally, the interference fringes, obtained by superimposing the speckle field with the uniform reference beam, are shown in Fig. 2.11 on the right. This photograph confirms that the phase of the speckle field formed by rough surface can be described in the deterministic way when certain conditions are met. In the photograph, there is also apparent the phase distortion shown at the bottom of Fig. 2.10.

One can see that the irradiance pattern in Fig. 2.10 is highly overmoded and that the phase of the speckles is deterministic. The speckle effect in the irradiance pattern can be reduced considerably so that only the fundamental mode will survive. This can be achieved by focusing sharply the laser beam on the target. The field for this case is shown in Fig. 2.12.

**Fig. 2.11.** A photograph of backscattered field in the detector plane (left) and interference fringes formed after superimposing with the reference beam (right).
The difference in the irradiance patterns between Fig. 2.12 and 2.10 can be explained in the following way: The rough scattering surface in the case of Fig. 2.10 was simulated as a large number of radiating elements. The intensity pattern over the surface was assumed to be Gaussian, and the phases of the radiating elements were assumed uniformly distributed and uncorrelated. Hence, the statistical correlation function of the electric disturbance (ensemble-averaged quantity over surfaces with different microstructure) on the surface was approximated by Dirac’s delta function. The amplitude speckle reduction (Fig. 2.12) is due to the fact, that the size of the illuminated area is comparable with the wavelength of the illuminating source. Then, the statistical correlation function in the surface plane is partly correlated and the width of the correlation function is approximately one wavelength. This fact results in killing of higher spatial modes. Based on our simulation results, we estimated the limit value of the beam waist on the target where higher-mode suppression can be expected as 25 microns.

The advantage of an interferometer working with this kind of backscattered field is that this field is similar to the reference Gaussian beam. Hence, it is simple to achieve the amplitude and phase matching on the detector to produce a maximum interferometric signal.

Before concluding the section with experimental results, we present a mathematical approach how the speckle reduction can be understood. First we will limit ourselves to paraxial approximation of the backscattered field. The field on the target can be then decomposed into Hermite-Gaussian modes which form a basis set [22]. This decomposition is suitable because the intensity pattern of any given mode changes size but not shape as it propagates forward in z – direction. Thus there is no mode coupling as the field propagates to the detector through free space and lenses.

The modulus of coefficient $c_{00}$ (the amplitude of the fundamental mode in the backscattered field) is depicted as a function of beam waist of the illuminating beam in Fig. 2.13. The coherence factor needed to evaluate this coefficient was chosen to correspond to the metal surface, white paper and in the last case, coherence was approximately one wavelength.

**Fig. 2.12.** Irradiance and phase of the backscattered field in the image plane (radius of illuminated area $w = 5\mu$m).
The modulus of the fundamental Gaussian-Hermite mode of the backscattered field for different surfaces as a function of beam focusing.

The results described in the section were verified experimentally with the results shown in Fig. 2.14. The two figures on top right are background radiation and reference beam pattern on the detector respectively. The remaining pictures illustrate the varying signal irradiances obtained by step-wise reduction of the size of the illuminated area on the target; the third figure depicts the case of 100 microns and the last figure (bottom right) depicts the case of 25 microns.
Fig. 2.14. (Continuing) Experimental verification of spatial modes reduction. Two figures on the top correspond to background radiation and reference beam, respectively. Remaining figures represent irradiance patterns of the field backscattered from the target for different sizes of illuminated target area (from $2w = 100 \, \mu m$ to $2w = 25 \, \mu m$). The dimensions of single area are 3 and 4 mm.

2.6 ZOOM LENS IN VIBROMETRY

Zoom lenses are standard components in modern photographic cameras and they are also being used in a broad range of technical applications [23]. However, to our knowledge, commercially produced vibrometers operate with optical systems having a fixed focal length. We demonstrate here, for the first time, that the use of a Zoom system in the imaging part of the vibrometer provides a considerable improvement in signal quality.

In Fig. 2.15 electrical output signals from the vibrometer (before digital processing) are shown for different targets placed at distances 0.5 m and 1m, respectively. The beam width was kept constant at 25 microns for both situations. By comparing the corresponding pictures for the same targets, one can see that the signal strength is not affected by the distance of the target and that the amplitude of the signal depends on the properties of the target.
Fig. 2.15. Left part: output signals of the vibrometer analog front end (i.e., before AGC and ADC) for different types of targets (metal, ceramic, white paper) placed at a distance 0.5 m from the front lens, right part: output signals of the vibrometer for different types of targets (metal, ceramic, white paper) placed at a distance 1 m from the front lens.

We conclude the section with a photograph of the experimental arrangement of the vibrometer shown in Fig. 2.16.
3 PERIODIC DEVIATIONS IN VIBROMETRY

In this chapter, it is studied how polarization imperfections of components influence the output signals of an interferometer.

The mostly used interferometers produce interference signals which are in quadrature at the output of an interferometer. These quadrature signals are generated using polarization method. The main tasks, which are solved by the optical systems, are that the phase shift between these signals is $\pi/2$, the amplitudes of both signals are equal and as high as possible for increasing the accuracy of a measurement. Such optimization for a specific optical system can be found in [3].

The errors due to the polarization imperfection of real optical components are called periodic deviations and were studied in detail in [8] for the case of a heterodyne vibrometer. In [8], one can find the analytical formulations of these errors. These errors, however in general, are difficult to analyze not for the mathematical complexity but for finding the origin of these errors. Periodic deviations result not only from the inherent imperfections of components (non-ideal retardations, non-ideal transmission and reflection coefficients...) but also from the rotational misalignment of these components which in practice is hard to measure and control.
The most important result in the chapter is that it is shown that in the first approximation, periodic deviations can be corrected in the optical part of the vibrometer. That is, output signals are in real quadrature.

### 3.1 INFLUENCE OF PERIODIC DEVIATIONS ON QUADRATURE SIGNALS

In Fig. 3.1, there is shown a schema of the interferometer which we have manufactured. It is the schematic schema of the real setup shown in Fig. 2.16. The meaning of the kets appearing in the schema is to represent particular polarization states. The normalization was dropped in the schema. All components are assumed to possess no losses and ideal polarization properties and also all rotational settings are assumed ideal for the moment.

The symbol $P_l$ denotes the power of the laser, $d$ is the component of the target displacement which is parallel to the illuminating beam and $k$ is the magnitude of the wave vector.

The action of the two last (measuring) polarizing beam splitters denoted as PBS 1 and PBS 2 is interpreted in a slightly different way than the first two PBS. This is done because these beam splitters accompanied with photodiodes (the photodiodes are not explicitly shown in Fig. 3.1) represent projective measurements (or simply measurements).

![Fig. 3.1. Architecture of the interferometrical laser vibrometer.](image-url)
To create two signals in the quadrature, the first two and the last two signals are subtracted in the analog part of the vibrometer. The resulting quadrature signals are depicted in Fig. 3.2. The resultant deformed “quadrature signals” due to the periodic deviation are shown in Fig. 3.8 where HWP was assumed to be non-ideal.

### 3.2 REDUCTION OF PERIODIC DEVIATION

Mathematicaly it can be shown that all polarization imperfection of the components placed before measuring PBS can be, in the first approximation, compensated by an intentionally rotational misalignment of QWP 2. The phase imperfection of NBS can be corrected again by rotational misalignment of QWP 2. The angular misalignments of measuring PBS can be, in the first approximation, neglected. Finite value of extinction coefficients has a crucial effect on the quality of the quadrature signals. This spoiling effect cannot be compensated in the optical part of the interferometer. These results were expected because the measuring PBSs (accompanied by photodiodes) perform true measurements on the states and the
components which precede these PBS perform a pure rotation of the states in the Poincare sphere. Finally, we conclude that by an additional rotational misalignment of HWP output quadrature signals can have not only required phase shift 90° but also same amplitudes.

3.3 EXPERIMENTAL VERIFICATION

Direct experimental verification of the elimination of periodic deviation in the optical part of the vibrometer is not easy due to the plethora of parameters which need to be measured. This includes not only devices parameters itself (eigenvalues determination) but also angles which specify connections between devices frames and lab frame. For these reasons, we only present photos of quadrature signals which were obtained after adjusting all optical elements (Fig. 3.4 on the left) and signals which were obtained exactly at same conditions only with the difference that QWP 2 was intentionally rotationally misalignment in order to obtain real quadrature signals (Fig. 3.4 on the right). The effects of the changing of amplitudes of the signals due to the correction can be observed (illustrated signals are before applying of AGC).

Next we demonstrate rotational misalignment of measuring PBS. After bringing both beams in interference and readjusting QWP2 and HWP in order to obtain quadrature signals in real quadrature and with the same magnitude (see Fig. 3.5 on the left) we intentionally misalignment measuring beamsplitter PBS1, approximately by 10°. The resulting quadrature signals are depicted on the right part of the figure.

Fig. 3.4. Quadrature signals from the real vibrometer, before and after phase correction.
4 POLARIZATION IMPERFECTIONS IN POLARIMETRY

The photoelasticity is one of the oldest forms of interferometric measurement. It involves the observation of fringe patterns for determination of stress-induced birefringent. Photoelastic stress was first investigated by so-called plane polariscope (also called polarimeter). Plane polariscope consists of a light source, polarizer, measured model, analyzer and detector. Model to be investigated is formed from transparent material, is non-scattering, has a form of a plate which normally is parallel to the beam and is homogenous in the beam direction. The information gained from a photoelastic experiment is then related to the stress or strain in the prototype, which is of different size and different material.

In phase shifting methods stated so far, the required information was collected sequentially by changing the orientations of elements within the polariscope. This restricts the applications of the polariscope to the static events only. To eliminate this drawback, another two optical setups were introduced. In the first case, three beam splitters were used in the optical setup of the polariscope. The beam splitters were used to split the beam emerging from the measured model into fourth path in four different directions. Then different configurations of a quarter-wave plate and analyzer were placed in each path in order to produce required phase shifted images. The second and most recent method introduced by Asundi and Liu [13] uses so called MultiSpec Imager which splits the beam emerging from the measured model into fourth path along the same directions. This brings an advantage of using only one CCD camera as a detector.

Fig. 3.5. Experimental illustration of amplitude correction and rotational misalignment of the PBS 1.
The recent technologies offer to produce micropolarizers arrays [9] and [10]. This brings a possibility of using these arrays in imaging [11] and in polarimetry in order to avoid beam splitting. However, as can be found in [9], [10] these arrays have quite low extinctions coefficients (between 100 and 300). Another difficulty is the exact orientation of transmission axes of micropolarizers. These two problems are investigated in this chapter.

4.1 USING OF NON-IDEAL POLARIZERS AND DEPOLARIZATIONS 
EFFECTS

In the mathematical analysis of the problem, a polarization state was written in the most general way as a sum of fully polarized part and unpolarized part. This enables simultaneous treatment of coherent and incoherent light sources and depolarization effects (the origins for these effects will be discussed shortly).

The important result was then found. Namely, that unpolarized part of the state and non-ideal extinction coefficient of the analyzer influence measured irradiances is the same way. Hence, all effects due to the depolarization can be in simple incorporated to the mathematical algorithm used for retardation determination.

Now measurement results which verified our theoretical predictions will be presented. The measurement was performed using two kinds of analyzers which differed in extinction coefficients, namely 1000:1 and 25:1. In each case, the analyzer was then rotated using motorized high precision mount in order to obtain the four required irradiances. Then the phase of the device under test (Soleil-Banibet compensator) was determined using a current well know algorithm and using our modified version. From Fig. 4.2 can be seen that modified version of the algorithm gives much better retardation estimation. The difference between measured retardance and actual one is denoted as a deviation in the figure.

Fig. 4.1. Optical bench simulating polarimeter using LED as a light source. Components from left to right are: LED, collimating lens, polarizer, chopper head, QWP 1, compensator used as device under test, QW2, analyzer placed in motorized high precision rotation mount, field lens, photodiode.
When analyzers are well oriented, hence without errors in alignment, then the sum of measured irradiances obtained using two analyzers with orthogonal transmission axes orientations is constant. Hence errors in misalignment can be easily recognized. This is shown in Fig. 4.3 where on the left the set of four analyzers were perfectly aligned and on the right intentional misalignment errors were introduced.

![Fig. 4.2. Experimental illustration of depolarization effects.](image1)

![Fig. 4.3. Experimental verification of analyzers alignment using sums of irradiances for orthogonal orientations.](image2)
5 POLARIZATION PROPERTIES IN COMMUNICATION

Quantum communication provides qualitatively new concepts which are in some aspects more powerful than their classical counterparts [31]. The most known novel schemes due to quantum communication are the secure exchange of cryptographic keys, the increase of channel capacity and the transfer of quantum information between distant parties.

This section is a study of the feasibility for adopting the concepts of quantum physics to optical communication. The quantum view on optical communication is necessary to properly describe transmissions where a sender encodes information by preparing the communication channel into a non-classical state (for example single photon transmission). But even in the schemes, where the transmitted information can be represented in classical manner, the quantum description offers new possibilities. Namely, it gives a recipe in which way the receiver should perform a measurement on the channel to ascertain which state was transmitted by the sender with the minimal probability of misdiagnosis.

5.1 CLASSICAL ON-OFF KEYING

The mathematical results which we derived can be most easily illustrated on the classical On-Off keying. In this communication schema the bit 0 is represented by a quantum system in state $|0\rangle$ (no laser pulse was sent) and bit 1 is represented by a system in state $|\alpha\rangle$ (laser pulse was sent). Because we are here interested in signals with very low intensities we also need to take into account background radiation.

![Fig. 5.1. Probability of error for classical OOK as a function of mean number of photons in the coherent state and with the mean number of photons in the background radiation as the parameter.](image)
When the receiver works simply that it counts arrived photons (a photo tube) the predicted probability of misdiagnosis or error probability is then depicted on left part of Fig. 5.1. Symbol \( n \) with appropriate index denotes mean number of photon in the laser pulse and mean number of photons in the background radiation in the detection interval. Note that these curves are usually stated in the literature as the quantum limit for OOK communication. However, an actual minimal error probability (see Fig. 5.1 on the right) is achieved with another type of detector. How this detector should work can be described mathematically, however an experimental realization of such detector was not still found.

5.2 SINGLE PHOTON TRANSMISSION

A simple schema for single photon transmission is shown in Fig. 5.2. The information is encoded into polarization state of the photon. Hence, the main influence on the error probability is overlap between two states which represent 1 and 0 bit, and the extinction coefficient of the Wollaston prism used in the receiver part. It is more convenient relate the extinction coefficient to parameter \( E = 1/(1 + e) \) which is the probability of misdiagnose due to the non-ideal extinction. The black curves in Fig. 5.3 have meaning of the error probability when the polarization of two photons, used for 1 and 0 bit, has zero overlap and this probability is depicted as a function of the angular orientation of the Wollaston prism.

![Fig. 5.2. Single photon transmission – illustration of states of polarization.](image)

![Fig. 5.3. Quantum error probability as a function of position of the Wollaston prism.](image)
In this case, the measurement basis which produces minimal error probability simply corresponds to the optimal rotational arrangement of the prism. Blue curves in Fig. 5.3 correspond to the situation when non-zero overlap between photons polarization was assumed.

The influence of background radiation on single photon transmission is shown in Fig. 5.4. Note, that we assumed zero overlap between two photons which correspond 0 and 1 bit and that the background radiation was unpolarized.

![Figure 5.4](image)

**Fig. 5.4.** Schema of the detector for single photon transmission and evaluated error probability as a function of background radiation strength.
6 SUMMARY

The topic of the doctoral thesis was investigation of polarization imperfections of optical components which are used to control and transform polarization of light. The theoretical results of this investigation were then applied to different fields which exploit light polarization.

The first application, were the achieved results were applied to, were arrangements for high-resolution measurement of vibrating targets, i.e. interferometrical vibrometers.

We showed how depolarizing surfaces influence the interferometrical signal in the speckle regime. However, the main original contribution to the vibrometry which was made in the thesis, was eliminating of speckle field using a suitable imaging optics. In fact, we showed, that when illuminating beam is focused sharply on the target then the fundamental mode dominates in the backscattered field and has properties of the illuminating beam even for depolarizing targets. Our results were published in [16] and [17]. Next, we showed how periodic deviations, i.e. errors due to the polarization imperfection of retarders, beam splitters and linear polarizers, can be, in the first approximation, eliminated directly in the optical part of the vibrometer. Only measuring method of properties of these devices was published in [24]. However, the possibility of the direct elimination of periodic deviations was used in a research project at Pforzheim University which goal was development of a laser vibrometer with a novel architecture.

The achieved author results in the vibrometry gave motivation to investigate polarization imperfections in polarimetry, i.e. interferometric measurements for the determination of stress-induced birefringence in transparent materials. The main contribution of this investigation is an innovation of the current algorithm which is used in order to determine the retardation of the investigated material. This result will be used in the another project which is currently running at Pforzheim University.

Polarization imperfections play also an important role in optical communication, especially in quantum optical communication where the polarization is used to encode the transmitted information. The obtained results, namely a procedure of prescribing a measurement basis in which the minimal error probability is achieved and the structure of background radiation, were published in [32], [33] and [34]. Author wish also to note, that these results was discussed with Markus Aspelmeyer from the institute of quantum information and computation in Vienna.

And finally a quantum description of optical devices used in interferometry was given in the thesis and was published in [28].
REFERENCES


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ABSTRACT

The emphasis of the dissertation is put on the investigating of polarization imperfections of optical components which are used to control and transform polarization of light. The theoretical results of this investigation are then applied to different applications which exploit light polarization, namely to the arrangements for high-resolution measurement of vibrating targets, to interferometric measurements for the determination of stress-induced birefringence in transparent materials and to the selected topics in quantum optical communication.