Heterodyne laser interferometry using a single polarisation-preserving optical fibre

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Abstract:
In displacement interferometry, beam delivery by optical fibres is an important issue as this enables to keep the laser source, which acts as a heating source, away from the path in which a displacement needs to be measured. A complication is the polarisation state of the laser beam, which needs to remain undisturbed as much as possible. We use a set-up in which a single polarisation-preserving fibre is used for both polarization directions which are used in heterodyne interferometry. To correct for strain- and temperature effects, a reference phase measurement is made after the fibre. Various types of polarisation-preserving fibres have been measured with regard to their polarisation-preserving properties. It is shown that with a good quality optical fibre and with proper alignment and phase-compensation methods, the remaining periodic non-linearities in a displacement measurement can be within a few nm.

Phase-shifts in fibres: need for a reference

For the delivery of a laser beam for heterodyne-laserinterferometry using one single optical fibre, it is necessary to use a polarisation-preserving single-mode fibre as with multimode-fibres the polarisation states are not defined. Using a polarisation-preserving fibre keeps the two orthogonal polarized frequencies which are emitted by the laser orthogonally polarized, however the birefringence in the fibre causes a phase-shift between the beams which is dependent on the temperature of - and the stress in - the fibre. This is illustrated in the figures below. Figure 1 gives schematically the set-up for a fed-fed laser interferometer. In normal operation, the interferometer uses its internal reference. Figure 2 gives the measured apparent displacement when the fibre is slowly cooling down after being heated up.

**Figure 1**: Set-up with internal and external reference detector

**Figure 2**: Temperature-dependent pathlength change
The figure shows that for a temperature change of 5 K, 5 µm apparent displacement is measured. This is not acceptable for precision dimensional measurements.

This can partly be solved by measuring the reference signal after the fibre, so the phase shift is measured by both the reference and the measuring interferometer. In this case, in figure 1 the external reference detector is used. The corresponding apparent displacement when the fibre temperature changes is depicted figure 3.

In this figure it can be observed that the initial linear drift of 4 µm has reduced to a periodic deviation of 11 nm peak-peak which is due to the receiver alignment and the fibre properties. This is a major improvement, however for further reduction it is necessary to characterise a fibre with respect to its polarisation-maintaining properties. How this is done is explained in the next section.

**Figure 3**: Pathlength change when using the external reference

**Fibre characterisation**

In order to predict the periodic errors as they are e.g. displayed in figure 3, it is necessary to characterise the fibre with respect to its polarising properties.

An ideal fibre would, when ideally aligned, transmit the two orthogonal linearly polarized laser beam without changing their polarisation state. When the fibre is less ideal, light will leak from the one state into the other, causing polarization mixing, and both beams might leave the fibre elliptically polarized and non-orthogonal. In order to measure these properties, a set-up as it is depicted in figure 4 has been built. Circular or non-polarised laser light is fed through a rotatable Glan-Thompson prism through the fibre, which polarizes the beam with an intensity ratio of 1:200 000.

The beam which is transmitted through the fibre is analysed with another Glan-Thompson prism after which the intensity is measured.

Where the prisms were oriented close to the main axes of the fibre, the intensity proved to vary, depending on the fibre temperature and the stress induced by bending the fibre.
Figure 5 gives an example of such variations: the fibre was bent, heated and cooled down respectively. It is observed that the intensity stays in-between a minimum and a maximum value. This minimum and maximum value are further taken as two measured values at one position of polariser and analyser.

Figure 6 gives the variation of both the minimum and maximum intensity where the polariser is optimally aligned with the fibre optical axis, and the analyser is near the 90° position, where the intensity would be zero for an ideal fibre. The observed variations in intensity can be explained by a simple model: it is assumed that in the beginning of the fibre a small amount of light leaks into the other polarization direction. At the end of the fibre this happens again: some of the leaked light leaks back into the original polarization axis. For the 90° analyser position this means that the light which leaks into this direction in the beginning of the fibre, interferes with the light leaking into it at the end. As we have already observed, the phase-shift between the polarisation direction depends on the stress and the temperature, so this explains the varying intensity, even with crossed polariser and analyser. Another peculiar observation is that the beam can be completely extinguished when the analyser is put at a small off-axis angle. In this case the leaked intensity interferes with a small fraction of the main beam of exactly the same intensity so the beams can interfere destructively.

Based on the assumption that in the beginning of the fibre a certain fraction leaks into the other polarisation direction, and the same happens at the end, a rather simple model could be made with this leakage fraction as the only parameter. In figure 7 the intensity as a function of analyser angle is plotted together with the model calculation as the smooth line. From the figure one can conclude that the model predicts all of the fibre behaviour, including the intensity and its variation at the orthogonal analyser position (here 115°) and the angles where complete destructive interference is achieved (113.2° and 116.8°). The fact that this fibre is better than the one of which measurements shown in figure 6 is observed from: (1) a lower intensity at the orthogonal position, (2) less variation in this intensity, and (3) the angles where destructive interference is achieved are closer to the orthogonal analyser position.
The measured intensity ratio can be used for model calculations [1], so periodic deviations in small displacement measurements can be predicted. However, figures 6 and 7 also illustrate that the fibre quality, in terms of extinction ratio, may vary, even when the laser, fibre and optics are optimally aligned. This means that also the non-linearity in a displacement may depend on the fibre temperature, especially when the fibre alignment is not optimal.

The fibres can be characterised by their extinction ratio which is the intensity transmitted through the axis which is illuminated divided by the average intensity at the orthogonal position. Figure 6 shows an extinction ratio of $(127\pm9):1$; figure 7 is the result for a specially selected fibre with an extinction ratio of $(844\pm17):1$.

**Optical displacement measurement result**

With the fibre as measured in figure 6 in a set-up as given in figure 1, a displacement measurement was carried out as would have been measured with an interferometer on the position as indicated in figure 1. In order to eliminate thermal drift and any influences of this optical system, this calibration was carried out with a Babinet-Soleil compensator in the interferometer position, which introduces a phase-shift by which a laser interferometer system can be calibrated [1]. In figure 8 the measurement results are given. The periodic non-linearities grossly correspond with model calculations and indicate that a fibres with an extinction ratio of about 1:100 give non-linearities of some 5 nm when used in a fibre-fed heterodyne laser interferometer. Better fibres, although hard to get, give better results.

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**Reference**