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Multiplexing interferometers to provide novel capabilities for nanometrology

Thomas Kissinger
Institute of Process Measurement and Sensor Technology, Technical University of Ilmenau, Germany
thomas.kissinger@tu-ilmenau.de

Summary:
Multiplexing interferometers within a single beam, based on their optical path difference, using laser wavelength-modulated signal processing techniques such as the range-resolved interferometry method, allows for interesting new capabilities in precision interferometry. For example, these include single-beam differential interferometry or position encoders with multiple degrees-of-freedoms using only a single fibre-coupled access port.

Keywords: optical interferometry, interferometer multiplexing, pseudo-heterodyne interferometry, range-resolved interferometry, nanometrology

Introduction

The ability to spatially resolve and synchronously demodulate the interferometric phase at multiple locations along a single beam, based on the optical path difference (OPD) of each individual interferometer, allows new, innovative uses in precision interferometry. This is possible using new variants of laser wavelength-modulated (pseudo-heterodyne) interferometric signal processing techniques, such as the range-resolved interferometry (RRI) [1] technique. Here, a sinusoidal modulation of the laser wavelength introduces a unique carrier signal for each interferometer dependent on the respective OPD that can be used for phase demodulation of that interferometer.

General advantages of pseudo-heterodyne signal processing techniques are that interferometric phase demodulation can be achieved, unlike in most homodyne or heterodyne techniques, without the need for polarization-optical components or other methods of beam separation. Furthermore, using diode lasers, wavelength modulation can be achieved by simple injection current modulation, minimizing component complexity. Numerous pseudo-heterodyne techniques have been proposed in the past. These include techniques with linear (sawtooth or triangular) modulation waveform, such as the original pseudo-heterodyne scheme [2]. While linear techniques are conceptually simple, they pose practical difficulties because of the difficulty in keeping a linear sweep waveform stable owing to the many harmonics present in the modulation waveform. A second class of pseudo-heterodyne schemes uses sinusoidal modulation waveforms. These include the phase generated carrier [3], and the deep frequency modulation [4] methods. Similar techniques are also widely used in commercially available Fabry-Perot interferometers [5].

Multiplexing Interferometers

Prior approaches, with the exception of some specialized schemes [6], generally only allow demodulation of the phase of a single interferometer at a single OPD. Therefore, no multiplexing is possible and furthermore, the presence of multiple interferometric signal components, which could also be unintentionally introduced by multiple or parasitic reflections, can cause nonlinearity problems. In contrast to most schemes, the RRI approach uses very strong wavelength modulation of the laser diode. This allows the separation of multiple signals in the recorded interferogram based on their OPD-dependent fringe rate. In contrast to prior art [6], this is not restricted to a specified OPD grid, but OPDs of constituent interferometers can be continuously variable once a minimum separation, dependent on the laser wavelength modulation excursion, is exceeded.

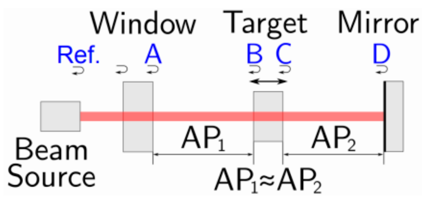

Fig. 1. Setup of the single-beam differential interferometry approach, with the movement of a semi-transparent target being measured by computing the difference between two nominally equal air path lengths AP1 and AP2 from four reflections A to D.

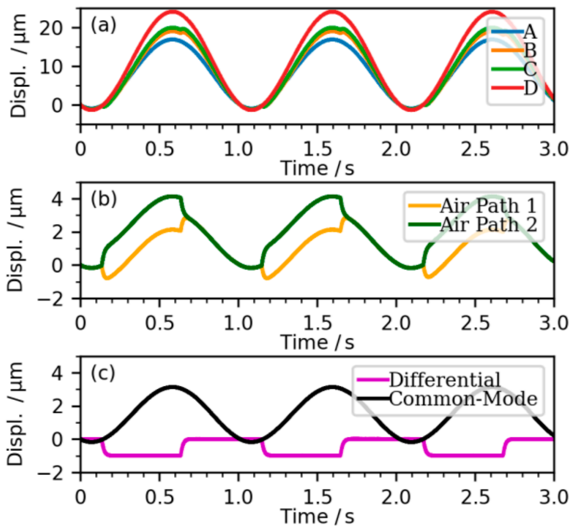

Fig. 2. Example measurement where the target step movement can be cleanly separated from an intentionally introduced sinusoidal wavelength disturbance.

One interesting example of the usefulness of multiplexing interferometers is single-beam differential interferometry [7]. The general principle of this approach is shown in Fig. 1. Here, four interferometers are spanned between the reference, obtained from the fibre tip reflection at the fibre collimator, interfering with the four respective window/mirror surfaces marked A to D. The aim of this approach is to measure the movement of a semitransparent target window. This is being measured by evaluating the difference between the phase signals corresponding to the two air paths AP1 (B-A) and AP2 (D-C). Because the two airpaths are nominally of similar length, calculating their difference reduces the effective dead path to near zero, strongly suppressing common-mode influences, such as air refractive index changes, laser wavelength drift or homogeneous thermal expansion. Fig. 2 shows an example measurement, where a 1 µm step movement is measured in the presence of an intentionally introduced sinusoidal disturbance of the laser wavelength of ±45 ppm amplitude. Here, Fig. 2(a) shows the phase signals that are directly measured for the four reflections A to D. Fig. 2(b) then plots the signals for the computed air paths, while Fig. 2(c) illustrates clean separation of the step movement from the common-mode disturbance.

A further example of multiplexing interferometers is described in detail in [8]. Using a single laser, a single photodetector and a single fibre coupled access port, a total of three interferometers are multiplexed, enabling use of this configuration as a 3D stage encoder. Multiplexing several interferometers onto only one access fibre is especially interesting for vacuum or cryogenic environments, where such an arrangement reduces the number of fibre feedthroughs required. For example, the multiplexing of interferometers using RRI has recently been demonstrated by Christiansen et al. [9] in a cryogenic environment, ultimately intended for space use.

Conclusion

The ability to multiplex interferometers has many potential applications, some of which are discussed above. In addition, these approaches also leverage on the availability of cost-effective yet highly coherent monolithic laser diodes and associated fibre components, originally developed for the telecoms industry. Therefore, range-resolved signal processing techniques open up novel solutions to existing measurement problems in precision engineering.

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