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Compact fiber-coupled interferometric displacement sensors with strong suppression of parasitic reflections

Vitalii Shmagun[1], Thomas Fröhlich[1], Thomas Kissinger[1]

[1]*Institute of Process Measurement and Sensor Technology, Technical University of Ilmenau, Ehrenbergstraße 29, 98693 Ilmenau, Germany*

vitalii.shmagun@tu-ilmenau.de

Abstract

Fiber-coupled interferometric sensors utilizing the Range-Resolved Interferometry (RRI) technique have been developed to achieve high-precision phase measurements with low cyclic errors using laser diode wavelength modulation-based signal processing. A key feature of RRI is its ability to demodulate interference signals within a specific operational optical path difference (OPD) of an interferometer, making the system highly insensitive to parasitic interferences outside the working range. Here, a sensor with a compact, fiber-coupled Gradient Index (GRIN)-lens collimator, acting as a measurement head, is designed, which enables flexible integration into precision applications where space is limited.
A set of collimators was fabricated, and their performance was evaluated. The beam divergence was measured using the knife-edge technique, showing a consistent divergence angle of 0.32 degrees across multiple collimators. Additionally, to demonstrate the system's insensitivity to parasitic interferences, a "defective" collimator out of the set — affected by parasitic interferences as visible in the knife-edge experiment — was compared with a fully functional collimator. Both measurement heads were simultaneously tested in a nanomeasuring and positioning system (NPS6D-200), using a reference homodyne interferometer for benchmarking. The displacement signals from both collimators showed minimal discrepancy, indicating that both sensors performed similarly despite one being defective, confirming the sensor's ability to mitigate the effects of parasitic interferences. When compared to the reference homodyne interferometer, the deviation was less than 1 ppm for a 1 mm displacement, further confirming the sensor's high accuracy. These findings underscore the robustness and high performance of this fiber-coupled, compact measurement sensor concept for integration into advanced precision measurement and control applications.

Fiber-coupled interferometric sensors, range-resolved interferometry, GRIN-lens collimator

1. Introduction

High-precision interferometers are essential tools for displacement measurements in scientific and industrial applications. Conventional systems, such as homodyne and heterodyne interferometers, achieve exceptional accuracy with sub-nanometer resolution [1]. However, their intricate optical designs result in higher costs, bulkiness, and limited flexibility, which restricts their use in mass-market displacement and vibration sensors as well as in space-constrained application.

Alternative interferometric methods using modulated laser diodes have been developed to address these limitations [2, 3]. They enable the use of compact, fiber-coupled collimators as measurement heads, facilitating integration into smaller setups. The simplified optics reduce costs and enhance flexibility. However, these systems often encounter parasitic interferences from the Fabry-Perot cavity formed between the collimator and target surface [3]. These interferences, caused by multiple reflections within the cavity, can result in cyclic errors reaching several nanometers in amplitude, significantly reducing accuracy, especially in sub-wavelength range displacement measurements.

A recently developed technique, Range-Resolved Interferometry (RRI) [4], offers a robust solution to this challenge. RRI isolates and demodulates interference signals within a specific optical path difference range. By employing time-variant demodulation carrier and window functions, RRI effectively suppresses parasitic interferences outside the working range, allowing to demodulate interference phase even in the presence of multiple interferences signals.

An additional step to miniaturize interferometric measurement heads involves using Gradient Index (GRIN) lenses as collimators. GRIN lenses focus and collimate light by utilizing a radially varying refractive index, significantly reducing the size of the measurement head compared to traditional optical lens-based collimators. This makes GRIN lenses a promising choice for compact interferometric systems. Despite these advantages, only a few studies to date have explored the use of GRIN-lens collimators for interferometric measurements.

In this contribution, extending our previous work [5], RRI is combined with GRIN-lens-based collimators to develop a robust and compact displacement measurement sensor. GRIN-lens collimators were fabricated and evaluated for their optical and interferometric performance. Collimation quality was assessed through beam divergence measurements using the scanning knife-edge technique. The complete interferometric measurement system, incorporating two fabricated collimators, was integrated into a test bench and verified against a reference homodyne interferometer.

2. Measurement System and Design

The interferometric measurement principle employed in this work is based on the RRI technique [4, 6]. In the used RRI implementation, a narrow-linewidth (100kHz) laser diode (λ ≈

1548.19 nm) is sinusoidally modulated at a frequency of 2 kHz, with a resultant wavelength modulation amplitude of ±0.27 nm. The laser emission is directed through a fiber-optic circulator to the sensor collimator head, and the returning light is guided to an InGaAs photodetector. The resulting interferograms are demodulated during post-processing using the RRI technique.

The structure of the developed GRIN-lens collimator is shown in Figure 1. It consists of a single-mode pigtailed fiber ferrule with a polished, straight-cleaved end to maximize back reflection, housed within a glass ferrule adjacent to a quarter-pitch GRIN lens that collimates light. During assembly, the GRIN lens is glued into the glass ferrule, and the fiber ferrule is positioned as close as possible to the GRIN lens without reducing backreflection intensity. The glass ferrule is encased in an aluminum cylinder for protection, with a rubber strain relief added to minimize stress at the fiber connection. In this work, a set of collimators was fabricated, tested for collimation performance using the scanning knife-edge technique, and subsequently used as sensor heads in an RRI interferometric system.

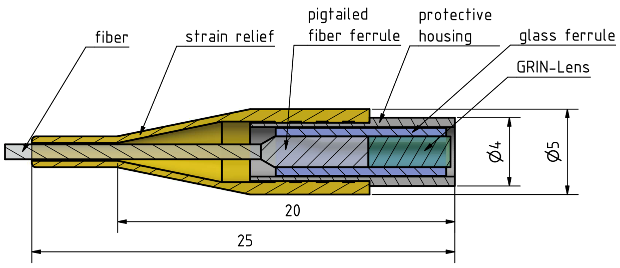

Figure 1. The drawing of a developed measurement head with a GRIN-Lens collimator, with key assembly dimensions marked.

3. Results and Discussion

Beam parameter estimation for the fabricated collimators was performed using the scanning knife-edge method. The results showed consistent parameters across the set: a beam waist radius of 186 $\pm$ 5 µm, divergence of 0.32 $\pm$ 0.01 degrees, and M^2 value of 1.05 $\pm$ 0.01. However, one "defective" collimator exhibited outlier results, with a significantly different beam radius profile, as shown in Figure 2. Analysis of these measurements revealed that this collimator produced additional beams due to multiple reflections between optical surfaces within its cavity.

Further investigation involved analyzing backreflection signals from the collimators without aiming them at any target. Figure 3 illustrates these signals. A typical collimator (Col. 1) displayed a sinusoidal backreflection signal, caused by intensity modulation that complements the laser diode's optical frequency modulation. In contrast, the defective collimator (Col. 2) demonstrated low-order interference fringes superimposed on the sinusoidal modulation, confirming the presence of parasitic reflections.

To demonstrate that, despite these defects, the defective collimator can still be used with the RRI system, both a normal collimator and the defective one were installed on a nanopositioning platform NPS6D-200 [7], that enables simultaneous tracking of mirror movement by the two RRI sensors heads and a reference homodyne interferometer.

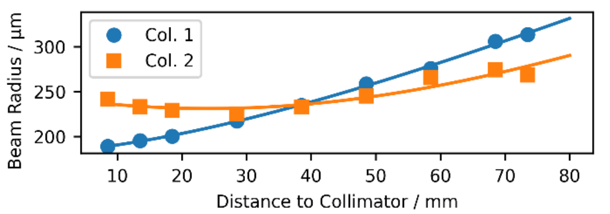

Figure 2. Measured and fitted beam radius as a function of distance from a collimator.

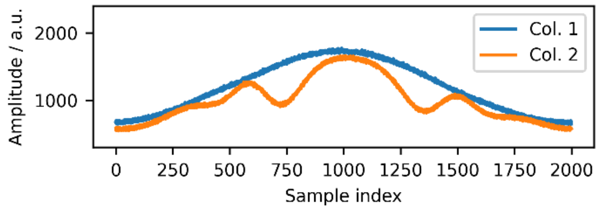

Figure 3. The backreflection signals from the first and second collimators. Low-order interference fringes are observed in the signal from the second collimator, indicating interference between the optical surfaces within the collimator.

Figure 4 illustrates verification measurements where the mirror was displaced by approximately 1 mm. Due to the GRIN lens collimators being positioned 82 mm outside the reference interferometer axis, the resulting Abbe offset was corrected in the signals presented in Figure 4. As depicted, the demodulated displacement signals from both collimators closely matched the mirror movement measured by the reference interferometer and demonstrated comparable noise levels. Deviations in the RRI signals from the reference interferometer were less than 1 ppm. An analysis of the Lissajous figures for both RRI signals revealed periodic nonlinearities at the order of 0.05 nm in both sensor heads, consistent with findings from previous research [5, 6].

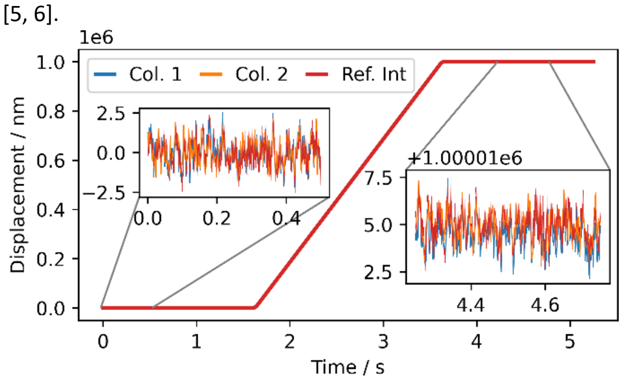

Figure 4. Demodulated displacement signals of 1mm mirror movement measured using two sensor heads.

4. Conclusion

This work demonstrated a compact fiber-coupled interferometric sensor based on the Range-Resolved Interferometry technique with GRIN-lens collimators. The fabricated collimators exhibited consistent beam parameters, with a divergence angle of 0.32 degrees. The interferometer system achieved high accuracy, with a deviation of less than 1 ppm compared to a reference homodyne interferometer over a 1 mm displacement. Tests with both fully functional and "defective" collimators demonstrated the system's resilience to parasitic interferences, confirming its robustness and precision.

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