Sensors and Actuators A 223 (2015) 141–150

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# Miniature silicon Michelson interferometer characterization for dimensional metrology

Hichem Nouira[a,*], Jean-Pierre Wallerand[a], Maurine Malak[b], Anne-Françoise Obaton[a], José Salgado[a], Tarik Bourouina[c]

[a] Laboratoire Commun de Métrologie (LNE-CNAM), Laboratoire National de Métrologie et d'Essais (LNE), 1 Rue Gaston Boissier, 75015 Paris, France
[b] Ecole Polytechnique Fédérale de Lausanne, Rue de la Maladière 71B, CH-2002 Neuchâtel, Switzerland
[c] Université Paris-Est, laboratoire ESYCOM, ESIEE-Paris, Cité Descartes, 2 Bd Blaise Pascal, 93162 Noisy-Le-Grand Cedex, France

ARTICLE INFO

*Article history:*
Received 20 May 2014
Received in revised form
24 December 2014
Accepted 29 December 2014
Available online 7 January 2015

*Keywords:*
MEMS (Micro Electro Mechanical Systems)
Optical micro-probe
Michelson micro-instrument
Dimensional metrology
Error sources
Uncertainty evaluation

ABSTRACT

Dimensional metrology applications require performing measurements of profile and form/shape of parts at a nanometer-level of accuracy. Therefore, the metrological characteristics of a miniature optical micro-probe based on a Michelson interferometer are evaluated. The optical micro-probe is designed to perform dimensional measurements with a target uncertainty in the order of few nanometers. Two micro-probe designs having reflection-transmission ratios of 75–25% and 25–75%, are characterized. Two optical setups have been implemented as well: firstly, using a single laser diode with a 1550.3 nm wavelength and secondly using a tunable laser source in the C-L bands. The characterization of the two micro-probes is performed using a new ultra-precise test bench, with respect to both dissociated metrology structure and Abbe principles. The experiments allow the evaluation of the error sources such as: stability, axial motion errors (residual errors), material dependence, tilt angle and roughness of the tested object. The experimental results revealed that dimensional measurements could be achieved with nanometer-scale errors, ranging from 2 nm to 15 nm, depending on the probe design and the reflectance of the device under test.

## 1. Introduction

Recent technological advancements led to an increasing demand for precise measurements of dimensions, topographic profiles and shapes of smaller components and tinier features. The components can vary from fuel injection nozzles, micro-lenses, fluidic channels and micro-piston-cylinders for pressure metrology to features and structures on MEMS chips. The progress in miniaturization puts stringent requirements on quality assurance in-line with manufacturing process. Therefore, numerous tactile single scanning micro-probes have been designed by National Metrology Institutes (NMIs), but most of them have quite similar designs, resolution and operation principle [1–6]. For instance, a white point optical stylus system has been developed by the Bosch Company and exclusively integrated on the Mar-Form-MFU100 apparatus [7]. It consists of a millimeter-sized optical stylus probe for form and shape measurements with less than 1 μm accuracy [8]. Its operation principle is based on a short coherence heterodyne interferometry divided into two subsystems: a modulation interferometer and a small robust optical probe connected through a single monomode optical fiber. The interferometer employs a broadband fiber-optic light source and works at the optical wavelength (λ) of 1550 nm and the synthetic wavelength of 36 μm.

This paper deals simultaneously with the characterization of two novel interferometric optical micro-probes and the investigation of their best deployment. A new high precision test bench is designed to ensure measurements with nanometer level of accuracy. The characterization of the micro-probes was carried out statically (in a stepwise operation mode) and compared to the data acquired from RENISHAW laser interferometer directly traceable to International System of Units (SI) meter definition [9].

The impact of different materials (aluminum, steel, silicon, copper, gold and ceramic) on the behavior of the optical micro-probes was evaluated. Those target surfaces are commonly used in dimensional metrology and in other sectors. Moreover, the effects of both angular misalignment and roughness of the artifact on the behavior of the micro-probes have been investigated. Optical tests have been performed with a first optical setup based on the use of a laser diode source working at the wavelength of 1550 nm.

---

* Corresponding author. Tel.: +33 1 40 43 37 63.
*E-mail address:* hichem.nouira@lne.fr (H. Nouira).

http://dx.doi.org/10.1016/j.sna.2014.12.031
0924-4247/© 2015 Elsevier B.V. All rights reserved.

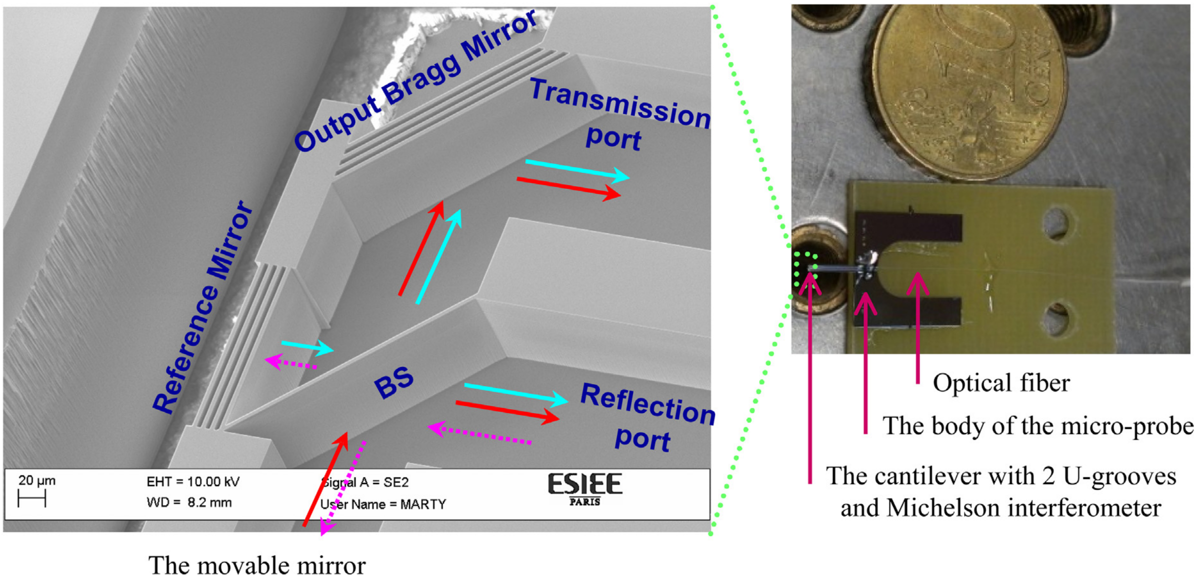

**Fig. 1.** Photograph of the micro-machined optical interferometer micro-probe together with SEM photography zooming on the Michelson interferometer integrated at its end. The different elements are described along with the transmission and the reflection ports. Magenta arrows designate the injected light, red arrows designate the path of the light beam reflected from the movable mirror (the movable mirror is not present in this figure) and cyan arrows designate the path of the light beam reflected from the reference mirror.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Following the obtained results, the most accurate micro-probe has been incorporated in a second optical setup where the laser diode source is replaced by a laser source tunable in the C–L bands. Similar tests were performed and the results reveal that the micro-probe can be used in the wavelength band from 1450 nm to 1600 nm.

## 2. Design of the interferometric micro-probe

The optical micro-probe consists of monolithic silicon block (Fig. 1) with a long cantilever beam acting as a probe whose dimensions are 390 µm thick, 550 µm width, 4 mm length; it involves a relatively large supporting area of nearly one square centimeter used for further handling and assembly to the measurement setup. A Michelson interferometer is integrated at the far end of the cantilever beam. In the interferometer design, the movable test mirror has been removed and it has been replaced by an external reflector (test object or artifact). The interferometer design involves a Beam-Splitter (BS) used to split light between the reference and movable mirrors. The reference mirror is a distributed Bragg reflector consisting of an alternation of four Silicon-Air layers to get a high-reflectance mirror.

Two different designs have been presented [10,11]: design “A” and design “B” corresponding to thicknesses of 3.58 µm and 3.62 µm for the BS, and, to reflectance–transmittance ratios of 75–25% and 25–75% for micro-probes “A” and “B”, respectively. For all Bragg mirrors, the silicon layer thickness is 3.67 µm while the air layer thickness is 3.49 µm. Photo of the micro-fabricated device is shown in Fig. 1 together with an annotated SEM photo that highlights the various components of the interferometric micro-probes. The micro-fabrication process [12] of the optical micro-probes is realized in ESIEE cleanroom facility.

## 3. Optical setup for characterization of the interferometric micro-probes

Two different optical setups have been proposed for characterizing the interferometric micro-probes described earlier. In both configurations, the Michelson interferometer is used in the reflection mode without need for any additional output fiber. A single lensed fiber coupled to a fiber circulator was used for both light injection and detection. The lensed fiber has a spot size of 50 µm and working distance of 1 mm. National Instruments acquisition card is used to control the movements and to acquire the data screened by the optical detector, connected to the reflection port of the circulator.

In the first optical setup, the light beam of the laser diode (ThoroLabs: LM14S2-1550.3 nm) passes successively through the circulator and the input optical fiber (AR-coated lensed fiber) packaged in the input U-groove of the silicon micro-probe. Then, it is reflected from the test object back towards the interferometer (Fig. 2). The reflected interferometric signal is transmitted again through the input U-groove and passes successively through the same input optical fiber (AR-coated lensed fiber), the circulator and

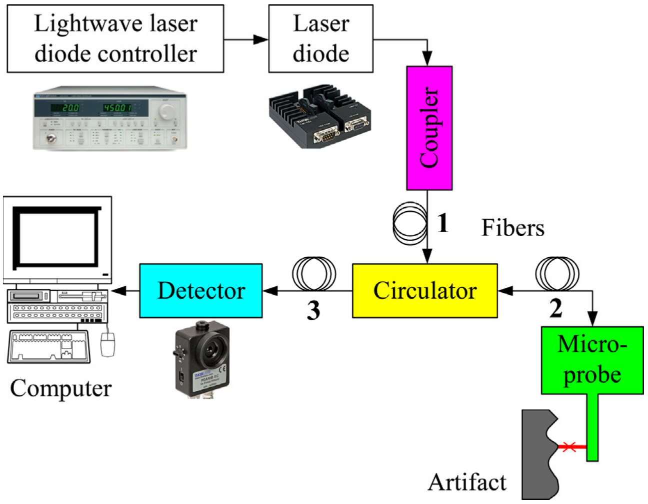

**Fig. 2.** Optical setup involving the miniature interferometer micro-probe, the laser diode source and the detector. The artifact can be a tiny bore hole or any flat surface.