Optical Fiber Technology 27 (2016) 8–16

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

Precision 3-D microscopy with intensity modulated fibre optic scanners

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ARTICLE INFO

Article history:
Received 17 July 2015
Revised 30 September 2015
Available online 28 November 2015

Keywords:
Optical fibres
Scanning
Profile
Multiresolution analysis

ABSTRACT

Optical 3-D imagers constitute a family of precision and useful instruments, easily available on the market in a wide variety of configurations and performances. However, besides their cost they usually provide an *image* of the object (i.e. a more or less faithful representation of the reality) instead of a truly object's *reconstruction*. Depending on the detailed working principles of the equipment, this reconstruction may become a challenging task. Here a very simple yet reliable device is described; it is able to form images of opaque objects by illuminating them with an optical fibre and collecting the reflected light with another fibre. Its 3-D capability comes from the spatial filtering imposed by the fibres together with their movement (scanning) along the three directions: transversal (surface) and vertical. This unsophisticated approach allows one to model accurately the entire optical process and to perform the desired reconstruction, finding that information about the surface which is of interest: its profile and its reflectance, ultimately related to the type of material.

1. Introduction

The study of surface morphology is a field of extensive research from which a myriad of important practical applications are derived [1]. In particular, profile (height variations along the surface) and structure become crucial parameters in many important processes, also serving as an indication of the sample's quality. In consequence, a good number of suitable instruments have been developed and the market is nowadays able to offer high performance equipment whose response may be improved if customisation were incorporated.

Among the different methods to map the structure of a surface [2], optical based techniques are very popular due to a variety of reasons such as contact-less operation or high reliability [3]. In addition they offer some information about the material that helps to determine its composition. Confocal microscopes [4,5] or low coherence interferometers [6] constitute good examples of optical instruments that one can use to study surfaces in an accurate way. This last technique usually requires special care to yield precise results, also having some limitations [7]; it can also be implemented with optical fibres [8] what adds substantial operating advantages.

There is, however, another way of using optical fibres to determine the profile of a surface by light reflection, the so called intensity modulated fibre optic displacement sensors (FODS) [9]. They can employ communication grade fibres and simple electronics is enough to process the information because this is solely based on intensity modulations, so they become cheap and easy to build. Their working principle is simple: an object is illuminated through a fibre (or a bundle of fibres) and the reflected light, collected by another (or the same) fibre, is used to compute the distance between the tips of the fibres and the target, distance that can be determined with precisions reaching the submicron range.

FODS cover a wide range of practical applications [10] and are also suitable to make research on surfaces [11]. The spatial capability is simply achieved by scanning the fibres along the surface and recording the responses at each point. However, there exist some deficiencies inherent to this technique that need to be solved in order to make the FODS suitable for yielding accurate profiles of essentially opaque surfaces. Here these limitations will be considered, finding their main causes and showing some procedures to correct them, thus paving the way for FODS to reach the level of reliable and low-cost 3D-imagers. This will be done with the help of a simple experimental setup together with a model that allows explaining the results. It should be mentioned that, unlike other microscope approaches in which the image represents faithfully the object, this one needs further processing to interpret the primary pattern and reconstruct the target's surface.

2. Description of the instrument

The developed instrument, in its simplest configuration, is sketched in Fig. 1. It consists of a pair of optical fibres, I–R (for Illuminating and Receiving light), mounted on a three-axis stage.

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http://dx.doi.org/10.1016/j.yofte.2015.11.002
1068-5200/

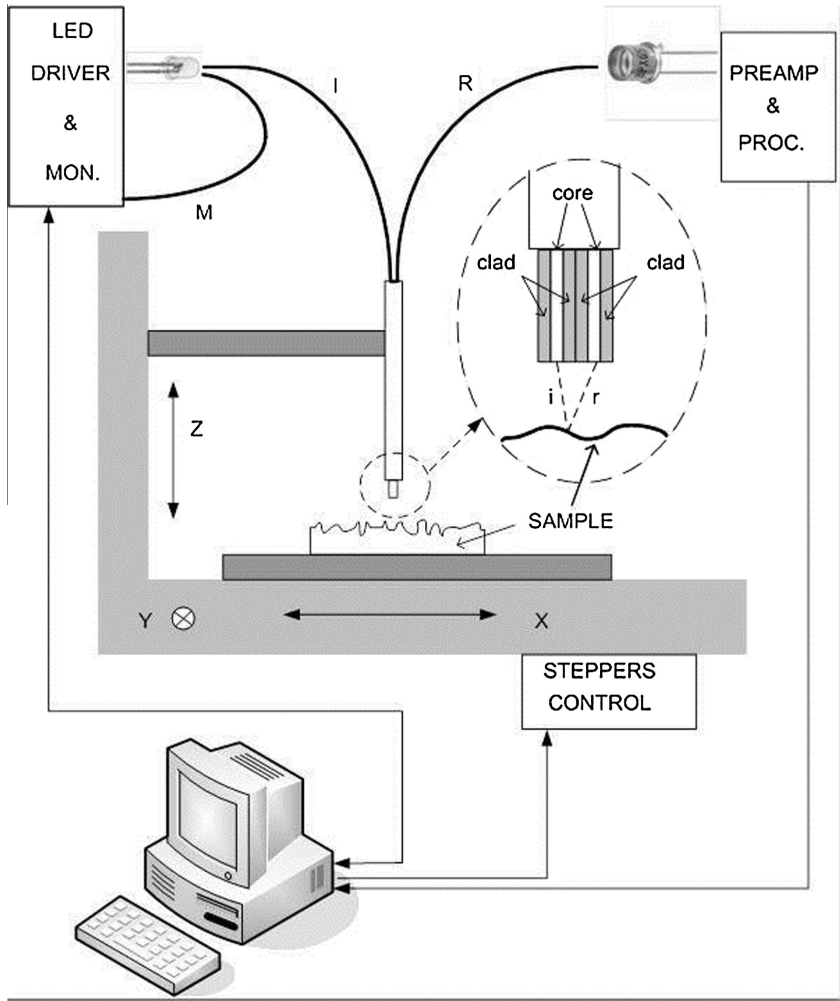

Fig. 1. Sketch of the instrument.

This stage is moved under the action of stepper motors that assure resolutions of 4 microns in the lateral (*X–Y*) plane and 1.25 microns in the vertical (*Z*) axis; the fibres are aligned with the *X*-axis. A computer controls these motors, as well as the electronic that drives the light source and processes the signal from the photo detector.

Common communication grade fibres have been used, single mode OS1 (9/125) for I-fibre and multi-mode OM2 (50/125) for R-fibre. The detection head has been formed simply by gluing together both uncoated tips (see the inset) after carefully polished. One obvious benefit from the small size of the detection head (0.25 mm diameter in our case) is its applicability in situations where other optical components are not able to fit, apart from the well known immunity of optical fibres to electromagnetic interferences or their tolerance to harsh environments [12].

Both the source, a LED, and the detector, a photodiode, have been directly coupled to each fibre. A common lighting white LED [13] has been used here to perform all the experimental tests. In order to be able to use the instrument with moderate ambient light, a pulsating driving schema has been adopted. In this way, each measurement comprises two steps. First, the LED is turned on and the photodiode response (reflected light plus background) is recorded; second, the device is turned off and so only the background contributes to the signal. The true value is the difference between both records. The amount of light illuminating the object can be precisely controlled by changing the amplitude of the pulsed current exciting the LED, light that is constantly monitored through the fibre plus photo detector labelled M in the drawing; this signal is used to normalise all the measurements.

The optical power that reaches the photo detector becomes actually low because the illumination cone is very small and the sample may not reflect a lot of light, what implies that a careful design of the readout electronics turns out to be a key point. A PIN photodiode [14] is preferred to other alternatives because of its handling simplicity and better SNR if a suitable preamplifier is used. A low noise charge amplifier [15] has been built that, together with suitable filters and ADC, provides 16 bits of dynamic range.

3. Intensity-position responses

3.1. Z axis

It is well known that separated emitter/receiver FODS yield an intensity–distance curve that looks like the shown in Fig. 4. This curve possesses three main characteristics. When the detection head touches the sample ($Z = 0$) no light is reflected and therefore the signal is null, situation that persists until a certain height is reached where some reflected light begins to enter the receiver tip. Starting at this point, the intensity increases rapidly with a somehow linear behaviour in good part of the interval close to the target; it is the high resolution zone (HRZ), because minor