euspen's 26th International Conference & Exhibition, Krakow, PL, June 2026

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An ultra-compact chromatic confocal sensing probe enabled by metasurfaces and micron resolution 3D printing

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Abstract

The ever-increasing demand for on-machine and in-situ metrology has driven substantial recent progress towards the reduction in size and weight of surface metrology instrumentation. Use of integrated metrology is vital to improve process performance in ultra-precision manufacturing, with chromatic confocal sensing (CCS) a popular choice for single-point surface topography and thickness measurement in volume restricted applications. These applications include, but are not limited to, single-point diamond turning and roll-to-roll manufacturing where early detection of non-conformant processes leads to significant improvements in productivity and energy efficiency.

Here we demonstrate a novel fibre-linked CCS sensor approaching the size of a grain of rice (8 mm long, 3 mm diameter), with a weight of less than 0.1 g while maintaining an axial measurement range of over 150 µm. We discuss metasurface design and assembly of high tolerance two-photon polymerisation (2PP) printed parts to ensure precise positioning of a single mode fibre behind a 2.6 mm diameter metasurface substrate. We establish the relationship between returned wavelength and the location of the measurand and then present an initial 2.5D surface topography measurement of a step height sample.

Keywords: Metasurface, Optical Sensors, Metrology, Confocal

1. Introduction

A significant effort is currently underway to change the way optical metrology is deployed in manufacturing to realise the vision of 'Industry 4.0'[1,2]. Measurements are trending towards on-machine and in-situ providing rapid feedback which unlocks real-time process correction and monitoring of manufacturing processes. To achieve this there is a requirement to produce sensors in an ultra-compact form suitable to deliver in-line, in-process measurements.

Optical sensors are ideal for this task due to their ability to provide non-contact, high speed, and high-resolution measurements of surfaces, however the large size and weight of current optical components limits their deployment in some cases. While efforts have been made to reduce the size of optical instrumentation, progress is incremental[3]. Optical metasurfaces, nanostructured surfaces that allow the precise manipulation of light and are capable of replicating and combining the function of conventional optical elements without the associated size and weight, offer a solution to provide a step-change in the development of ultra-compact optical instrumentation[4].

In the following we present our work on the development of an ultra-compact chromatic confocal sensing (CCS) probe constructed from a single metasurface lens and high precision two-photon polymerisation (2PP) 3D printed probe body. This development builds upon our previous proof-of-principle work showing how we have transitioned from a table top demonstrator using large kinematic mounts[5,6], into a 8 x 3 mm probe ready for deployment for on-machine measurements. The metasurface design is described, followed by the probe design and assembly. The range of the probe is evaluated, and measurement of a step height artefact is performed to demonstrate the functionality of the sensor.

2. Metasurface design

The metasurface presented here simply functions as a lens which takes light from an on-axis point source before the metasurface and focusses it to an on-axis point after, a set distance away at the design wavelength. Changes in the wavelength, and the wavelength dependence of the phase delay that the pillars impart, mean that the light is focussed to a different point in space along the optical axis for each wavelength. The metasurface design uses the truncated waveguide approach to control the phase delay of the incident light[7], and cylindrical nanopillars are chosen due to their polarisation insensitivity. The metasurface is constructed of gallium nitride (GaN) nanopillars etched from the surface of a 4.5 µm layer of GaN on a 430 µm thick sapphire (Al_2O_3) wafer. The nanopillars have a height of 750 nm and are arranged in a square lattice with a period of 450 nm. To achieve the required 2π phase delay needed to convert an arbitrary incoming wavefront into an arbitrary outgoing wavefront, modulo 2π, the nanopillar radii are varied from 70 nm to 180 nm in 10 nm steps, at an incident wavelength of 660 nm.

3. Probe design and assembly

Figure 1 shows the CCS probe body, manufactured using a 2-photon polymerisation printer (UpNano Nano One), which acts as a custom ferrule to precisely position a single mode fibre behind the metasurface substrate. The substrate is glued to the front of the body resulting in a probe which measures just 8 mm long and 3 mm diameter, as shown in figure 2.

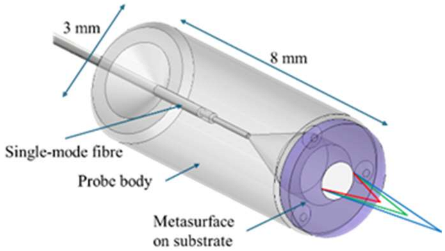

Figure 1. *Schematic showing how the fibre, probe body and substrate are located.*

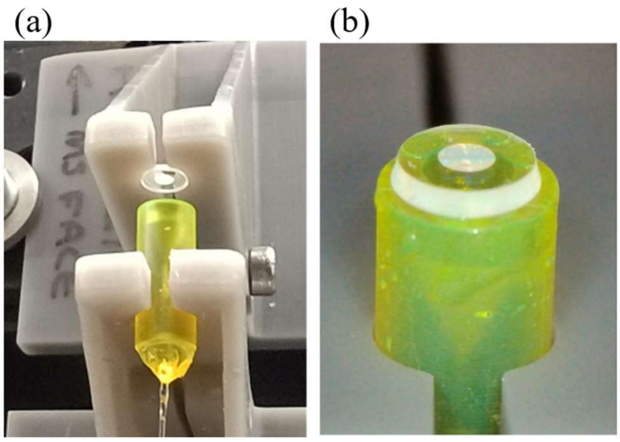

Figure 2 *(a) Left: Assembly of the metasurface probe. (b) Right: a completed probe with metasurface substrate glued to the probe body.*

5. Probe performance evaluation

To use the probe as a distance sensor, light from a broadband source is coupled to the probe with a 2x2 fibre optic coupler (FOC). The light returning from the probe then couples back though the FOC into a spectrometer.

Initial assessment of the CCS probe was carried out to determine the chromatic confocal response of the system by scanning a mirror along the optical axis and recording the measured signal over a range of 300 µm, as shown in figure 3.

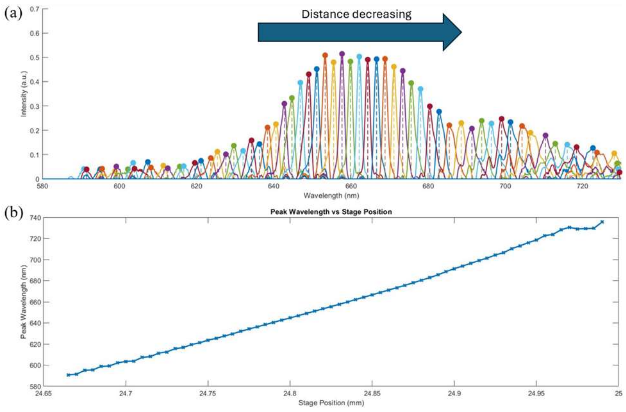

Figure 3. *(a) Intensity of the measured signal as a mirror is scanned along the optical axis. (b) Resulting measurement positions.*

A 2.5D surface topography measurement of a 30 µm step height artefact was carried out by scanning the probe with a motorised XY translation stage. The result of this surface topography measurement is shown in figure 4.

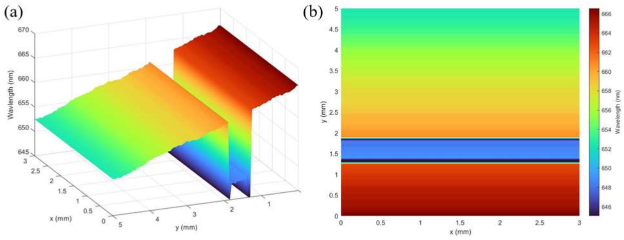

Figure 4. *A 2.5D surface topography measurement of a 30 µm step height artefact. (a) shows a 3D plot of the measurement result. (b) shows a top view.*

6. Summary and further work

We have developed an ultra-compact, robust, monolithic metasurface CCS probe suitable for deployment for on-machine measurements. We have characterised the chromatic confocal behaviour of the probe to determine its range and demonstrated 2.5D surface topography measurement of a 30 µm step height artefact.

Acknowledgements

The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funded programmes EP/T02643X/1, EP/Z53285X/1 and EP/W017032/1 along with the UK's Royal Academy of Engineering and Renishaw PLC who sponsor Xiangqian Jiang's REng/Renishaw Research Chair.

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