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Compact FBG grating array structure for high spatial resolution distributed strain sensing

B.A.L. Gwandu, L. Zhang, K. Chisholm, Y. Liu and I. Bennion

Photonics Research Group, Electronics Engineering and Applied Science, Aston University
Aston Triangle, Birmingham, B4 7ET, UK.
Tel: +44 (0)121 3593611; Fax: +44 (0)121 3590156

ABSTRACT

We report here an implementation of high-spatial resolution distributed sensors employing compact-grating-array structure, offering advantages of free designing dynamic range and simple interrogation by utilising established wavelength-division-multiplexing technique.

1. INTRODUCTION

The past few years have seen intensive research and development of fibre Bragg grating (FBG) sensing technologies for smart structure applications. In comparison with conventional sensors, FBGs for optical sensing offers a number of advantages including sensing a wide range of measurands, immunity to EM interference and interruption, light weight and miniature size, embeddable to composite materials and most importantly, intrinsic multiplexing capability. FBG sensing systems based on wavelength- and spatial-multiplexing grating array interrogation have been developed for smart structure applications across a wide range of industrial engineering projects. However, grating sensor arrays in these systems are used for quasi-distributed strain sensing, offering spatial resolution of typical values from few centimeters to several meters. There are some applications requiring short-gauge but high-spatial-resolution distributed sensors. FBG based high spatial resolution distributed sensors have been reported by Volanthen and LeBlanc *et al* [1,2,3], however, the interrogation techniques which they use are cumbersome, and limiting to the practical implementation for real applications.

In this paper, we report an implementation of high spatial resolution distributed sensing utilising compact-grating-array structure. This configuration permits directly employing the well established wavelength-division-multiplexing (WDM) FBG sensor array interrogation technique, therefore, offers advantage of high practicability for real applications. The additional advantage is that the dynamic range and spatial resolution are independently designable to be application-specific. Furthermore, high spectral resolution can also be achieved by apodising the gratings.

2. CONCEPT OF COMPACT-GRATING-ARRAY FOR DISTRIBUTED SENSING

The concept of a compact-grating-array is illustrated in fig. 1. The element gratings with distributed wavelengths are concatenated along a fibre without any physical gaps. The spatial resolution and sensing dynamic range for distributed sensing from such a structure are simply determined by the physical length of the element grating and the spectral spacing between the adjacent gratings respectively. The spatial resolution can be as high as 1mm since now it is possible to produce fibre gratings of such short length but still with sufficiently high reflectivity. However, there are some difficulties in realisation of free-tailoring wavelengths, high spectral resolution and incorporating large number of element gratings.

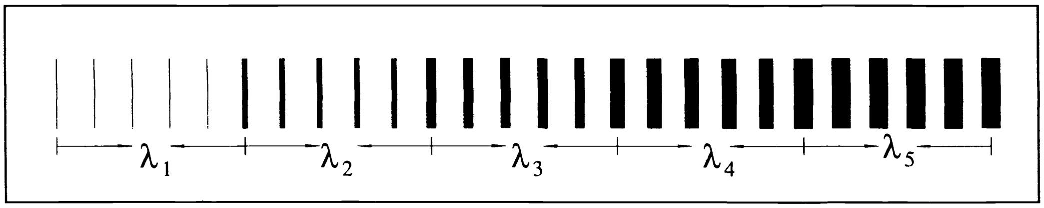

Figure. 1. Concept of a compact-grating-array

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At Aston University in UK, the sophisticatedly designed and fully programmable phase mask scanning fibre grating fabrication system is capable of arbitrarily positioning and scanning the UV beam of relative complex patterns. In addition, the system incorporates a computer-controllable fibre-straining unit which provides a method to free change grating wavelength even using one-period-pattern dedicated standard phase mask. Thus, the fabrication of compact-grating-arrays of arbitrary dynamic range and spatial resolution is realisable by this system.

3. COMPACT-GRATING-ARRAY FABRICATION

Two designs of compact-grating-arrays were fabricated using the above described grating fabrication system. The phase mask used in the fabrication contains a group of five 5mm-long concatenated pitch-patterns. A direct UV beam scan across this phase mask will allow produce a compact-grating-array consisting of five gratings of Bragg wavelengths from 1546nm to 1558nm with a ~3nm spectral spacing. Fig.2a shows a typical transmission spectrum of such a grating array structure. This structure can be used for distributed sensing offering an intrinsic spatial resolution of 5mm and a total sensing gauge of 2.5cm. In order to increase the spatial resolution, compact-grating-arrays comprising ten 2.5mm-long gratings have been fabricated using the same phase mask. This was achieved by a combination of straining fibre and programming UV beam position techniques. Prior to the UV exposure, the fibre was strained by an amount which would blue-shift Bragg wavelength by ~1.5nm. Then, the UV beam scan procedure was programmed in an on-and-off fashion along the phase mask with a 50% duty cycle. As a result, five 2.5mm-long gratings with 2.5mm physical gap and ~3nm spectral spacing between them were produced along the fibre. The fibre was then released from the strain and the UV beam start-position was off-set by 2.5mm in order to write the first grating from the first gap. The second scan was also followed the 50% duty cycle procedure and produced another five 2.5mm-long gratings situated exactly in the five gaps, resulting in a final compact-grating-array structure formed by ten 2.5mm-long gratings with ~1.5nm spectral spacing. In comparison with the five-grating-array structure, this sensor has improved the spatial resolution by a factor of two.

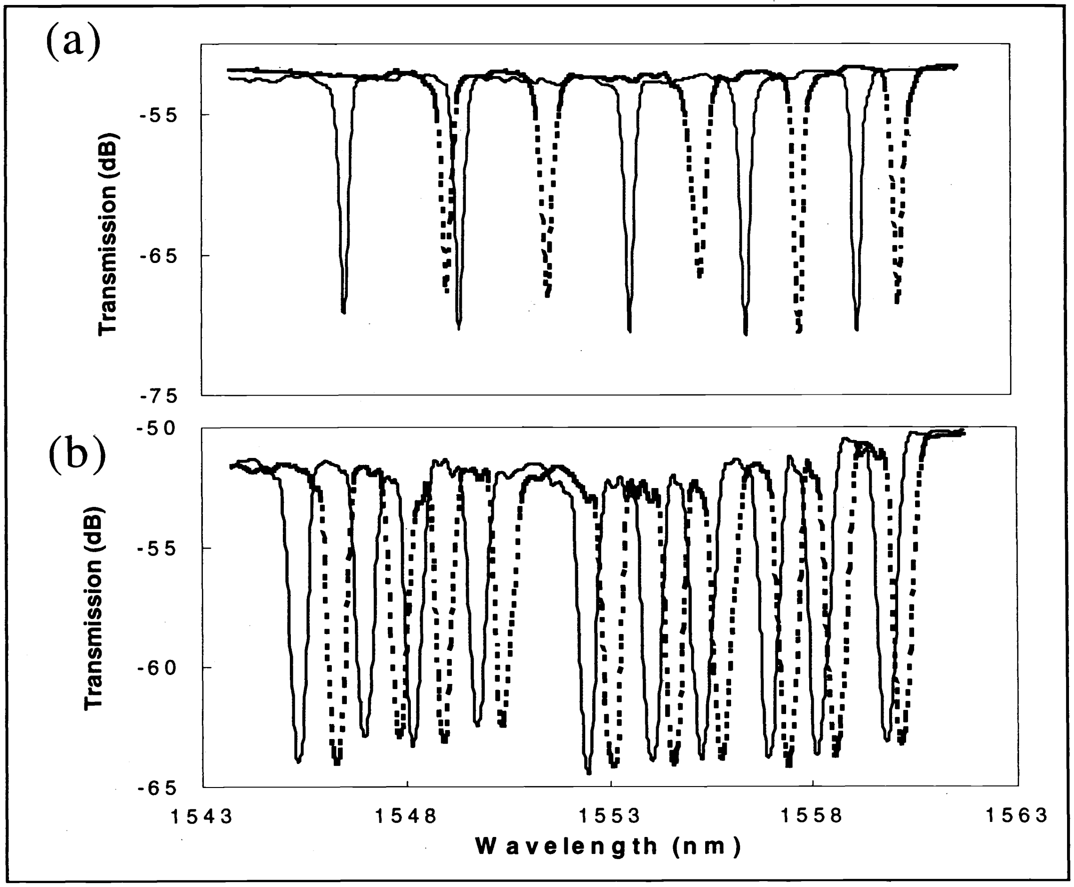

Figure. 2. (a) Transmission spectra of the (a) five-grating-array and the (b) ten-grating-array structures with (dotted-line) and without (continuous-line) distributed strain.

4. DISTRIBUTED SENSING

The distributed strain sensing experiment was carried out by applying linearly distributed strain to both the five- and ten-grating-array configurations. A four-point bend system was employed to create distributed strain. Fig. 3 shows the geometric configuration of this system. The fibre containing 2.5cm-long compact-grating-array was attached to the one side of a 0.5mm thick, 20mm wide and 150mm long metal bar. In order to eliminate the slippage effect, the fibre was glued onto the metal bar. The bar was bent by depressing the centre with a micrometer driver. According to the geometric configuration, the bend-induced strain distribution in the metal bar is approximately linear in the sections close to the ends of the bar.

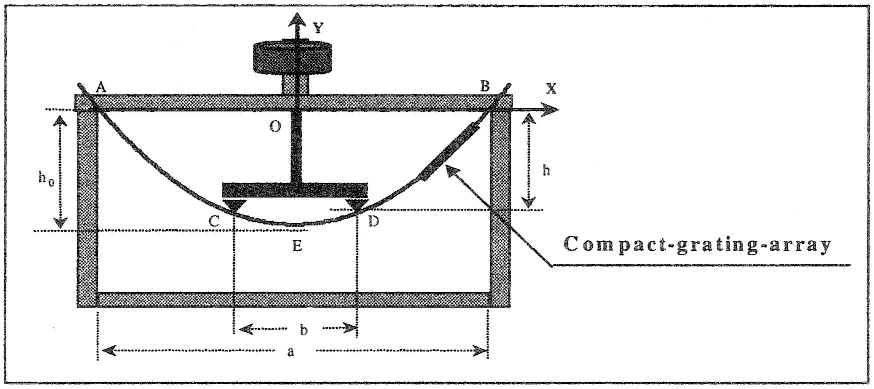

Figure. 3. Geometric configuration of a four-point bend system used for generate linear distributed strain.

When the grating-array was subjected to the distributed strain, the Bragg wavelength of each element grating shifts an amount according to its physical position along the bending metal bar. The transmission spectra of the two grating-arrays under distributed strain are also presented in fig.2 as dotted lines. It can be seen clearly from the figure that the transmission peaks in both structures shift accordingly so that the spectral spacings reflect the linear distribution of the strain. Fig. 4a and b plots the wavelength shift against the grating order for linear strains with increasing gradients. Both five- and ten-grating-array sensors exhibit a good linear response,

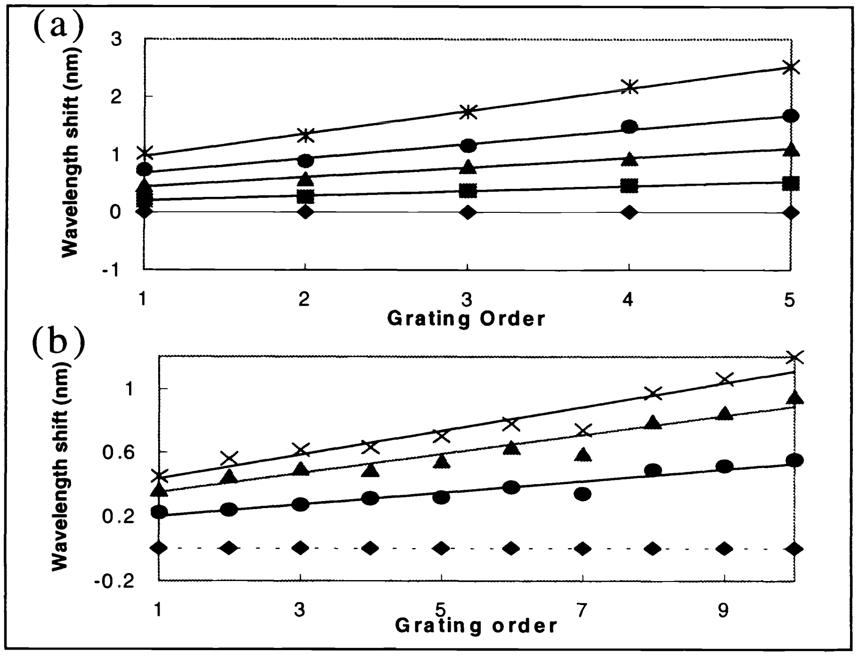

Figure.4. Wavelength shift against grating orders (a) for five-grating-array and (b) for ten-grating-array structures under increasingly linearly distributed strains.

demonstrating the effectiveness for distributed strain sensing. The slippage effect did occur to the seventh grating in the ten-grating-array sensor. As clearly shown in fig.4b, the strain response of this grating did not fit well with the rest of gratings possibly due to the loose glue effect.

Although the distributed strain sensing using compact-grating-array structures was implemented only for linearly distributed strain, the proposed structure should be capable of arbitrary local strain measurement within its defined dynamic range. It should be pointed out that for some applications where ~4-5mm spatial resolution is adequate, the grating apodisation technique can be employed in the grating-array fabrication to narrow the spectral response effectively increasing the spectral resolution.

5. CONCLUSIONS

To summarise, we have proposed and demonstrated a concept of high-spatial-resolution distributed optical sensing employing a compact-grating-array structure. Two configurations of five- and ten-grating-array have been fabricated and successfully used to implement distributed strain sensing. In comparison with other reported sensor structures and techniques, the compact-grating-array structure approach provides a simple and practicable solution for real applications as the WDM FBG sensing interrogation method can be directly applied. In addition, this structure also permits independent design for dynamic range and spatial resolution, adding more advantages for producing practical devices.

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