Performance characteristics of continuous multicore fiber optic sensor arrays

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ABSTRACT

We report on the optical and sensor performance characteristics of meter long continuous twisted multicore optical fiber gratings. We describe a method to analyze the optical performance of all the cores in the multicore array. We also report on the sensitivity of our arrays to local changes such as bend and twist. Our analysis provides guidance for the proper operating range of multicore fiber sensing arrays.

Keywords: Fiber optics sensors, Fiber Bragg gratings, Shape sensing, Optical fiber

1. INTRODUCTION

Fiber optic sensing has become a field of immense interest with a wide range of civil, energy and medical applications such as structural health monitoring, reservoir monitoring and shape sensing [1,2]. The extreme aspect ratio, mechanical flexibility and robustness of optical fibers allows for both very long and very thin sensor elements. These can monitor physical quantities such as strain, temperature and pressure either at certain discrete positions or continuously over lengths in excess of tens or even hundreds of meters. To measure the shape of an object, not only the strain, but also the local bend and twist need to measured. This can be achieved by adding multiple outer cores that form a twisted helix around the center core of the optical fiber. To accurately track the shape of the fiber, e.g., to provide a surgeon with real time information on the precise position of a catheter during minimally invasive surgery, all cores of the sensor fiber need to provide a sufficient signal level along the entire sensor length. In principle, the Rayleigh backscattering that any optical fiber inherently provides can be used and measured for this purpose [3]. However, the signal-to-noise ratio (SNR) that is achievable with Rayleigh scattering is relatively low, which increases the measurement time that is necessary to achieve the required spatial accuracy. A significantly higher SNR can be obtained by intracore fiber Bragg gratings (FBG).

FBG sensor arrays can be produced by various methods, including point by point [4], reel to reel setups [5], drum systems [6], and draw tower grating fabrication [7]. We have recently reported on a flexible method to achieve nearly continuous gratings of any length in both single core and multicore fibers using reel to reel fiber handling and a UV transparent coating [8,9]. Unlike the well known WDM sensor arrays that usually comprise a set of discrete gratings whose performance can be assessed with standard optical spectrum analyzers, the performance of the very large number of quasi-continuous shape sensing gratings is analyzed using optical frequency domain reflectometry (OFDR) techniques, as OFDR allows determination of the reflection spectrum and phase of individual gratings even if they spectrally overlap with a very large number of similar gratings along the fiber.

In this work, we report on an automated procedure that extracts detailed high resolution properties of long, nearly continuous FBG arrays in twisted multicore fiber. Our method provides a valuable tool for rapid assessment of the quality and performance of such ultra long grating arrays that can be used as the sensor fiber for shape sensing applications. We present an analysis of a long quasi-continuous multicore FBG array and compute its crucial performance characteristics such as amplitude, phase derivative and bandwidth for every single one of the roughly 10,000 gratings in a 50m long section, and we correlate these data values for all different cores. Finally, we demonstrate shape sensing using a 20cm section of our twisted multicore fiber.

2. SENSOR FIBER DESIGN, FABRICATION AND ANALYSIS

2.1 Sensor fiber design and fabrication

Shape sensing requires precise knowledge of the curvature and torsion along the entire sensor fiber. The curvature can be determined by comparing signals from cores at different positions in the cross section of the fiber, as reflections from a core on the elongated side appear at a longer wavelength than those from a core on the neutral axis or on the compressed side of the bent fiber. Torsion, in contrast, elongates all outer cores (in proportion to their radial distance from the center of the fiber). To determine the orientation of the torsion, i.e., to distinguish between left-handed and right-handed torsion, the cores are pre-twisted, either mechanically, or preferably during fabrication. Any additional torsion that has the same orientation as the existing twist further elongates the outer cores, which can be measured by an increased wavelength of the reflection, and it decreases if the mechanical torsion is counterdirectional to the existing twist in the fiber. A schematic of such a twisted multicore fiber is shown in Fig. 1(a) [10], with a center core being surrounded by six outer cores that form a hexagon in any cross section of the fiber, see Fig. 1(b) [8,9]. The period of the refractive index variation that forms the Bragg gratings in the cores of the fiber is indicated by green and black layers in Fig. 1(a) (not drawn to scale, as the refractive index period is only about 500 nm, while the outer diameter of the fiber is several hundred times larger, typically between 200 µm and 300 µm).

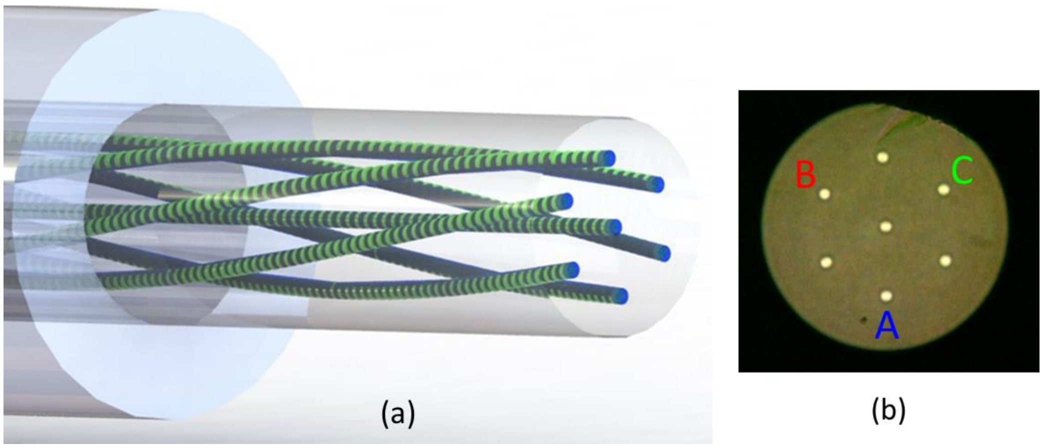


Figure 1. Twisted 7-core fiber. (a) Schematics of Bragg gratings inscribed in all cores. (b) Microscopic image of fiber cross section.

We fabricate this fiber with a UV transparent write-through coating that allows for simultaneous inscription of gratings in all its seven cores without any need for stripping and recoating. Near pristine fiber strength is maintained after grating writing, and the grating properties can be tailored according to customer specifications. For many continuous sensing applications that require long but weak gratings, a single shot of excimer laser radiation is sufficient to produce a grating of the desired strength. The grating inscription apparatus [8,9] that we use to generate quasi continuous grating arrays is depicted in Fig. 2.

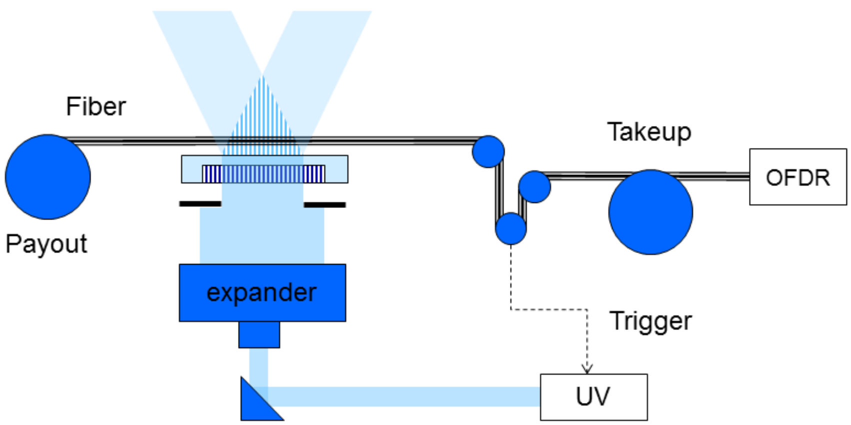


Figure 2. Reel to reel writing system for single core or multicore fiber gratings.

2.2 Automated analysis of very long grating arrays in twisted multicore fiber

For most of the conventional applications of fiber Bragg gratings such as laser module stabilizers, optical add-drop multiplexers and even highly complex dispersion compensating modules, the typical grating lengths are of the order of millimeters to tens of centimeters. In contrast, for sensing applications, the required grating array lengths can be of the order of tens to hundreds of meters. For any FBG inscription method, the probability of grating defects increases with the grating length. Hence, in particular the extremely long grating arrays that are used for sensing applications need to be thoroughly analyzed to guarantee that the sensor provides the full accuracy along its entire length. In the case of three-dimensional shape sensing for medical applications, this analysis must be performed with sub-millimeter resolution. This can be achieved with an OFDR measurement (e.g., Luna OBR), because it can accurately determine both amplitude and phase of the complex-valued reflection spectrum $r(\lambda)$. The properties of the Bragg grating in any given core are described by the mode coupling coefficient $q(z)$, which can be computed from the reflection spectrum by a time consuming inverse scattering transform, see, e.g, [11]. However, if the maximum reflectivity is sufficiently weak, multipath interference (MPI) from multiple reflections can be neglected, which dramatically speeds up the computation. In this case, the Fast Fourier transform (FFT) of the reflection spectrum (i.e., the impulse response at time t) is proportional to $q(z)$ and to the relative reflection per unit length at position $z = c_0 t/(2n_{\text{group}})$ along the fiber, where c_0/n_{group} is the group velocity of the propagation mode. This spatial trace needs to be sampled at a very high accuracy of the order of only tens of micrometers to guarantee a sufficient shape sensing accuracy for applications with tight bending radii of the order of millimeters to centimeters, e.g., to reliably compute the position of a catheter tip during surgery. For the 50.6 m long example array shown in Fig. 3, which consists of 1405 exposures of length 3.61 cm using the 7-core fiber from Fig. 1, we use a resolution of 39 µm, corresponding to an OFDR scan range of 20 nm. This array provides enough fiber for about 20 to 30 medical shape sensors elements. Due to the high complexity of these 450 MB of data shown in Fig. 3, an efficient automated analysis tool is indispensible to extract the performance characteristics of the gratings.

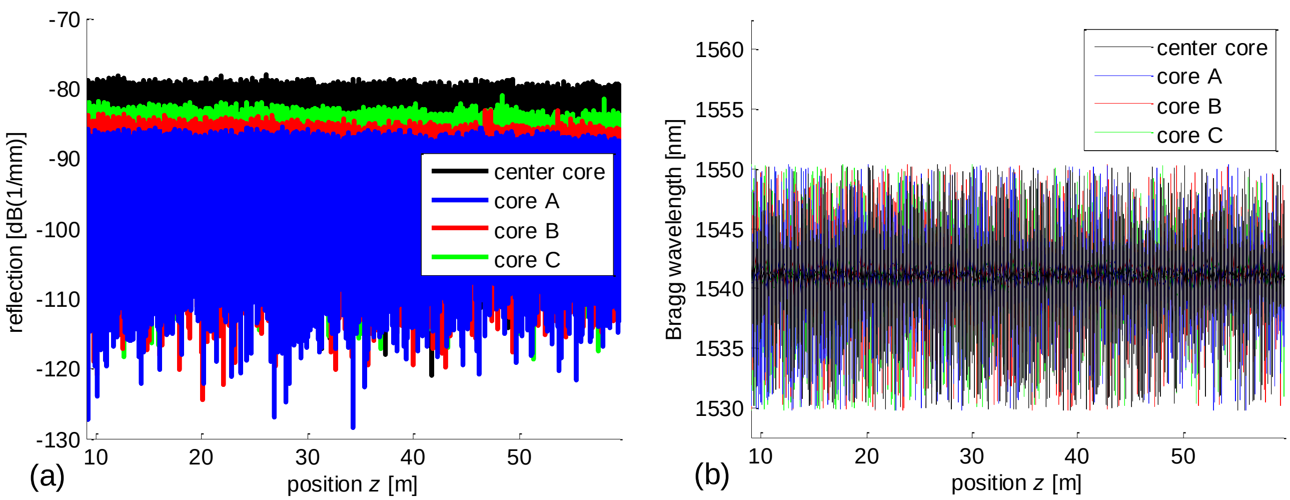


Figure 3. Raw OFDR data from a 50.6 m long FBG array in the 7-core fiber from Fig. 1 at a longitudinal resolution of 39 µm (OFDR scan range 20 nm). (a) Reflection amplitude. (b) Bragg wavelength (inverse spatial derivative of the reflection phase).

High performance distributed sensing applications impose tight limits on sensor parameters such as the local Bragg wavelength, which therefore must be accurately controlled over the entire length of the sensor. However, since gratings of such long lengths cannot be held straight during the measurement, there is unavoidable strain-induced chirp in the phase of the outer core signals, even if the fiber is wound in a single layer wind on a perfectly round and smooth spool. As a result, there is a periodic modulation in the local Bragg wavelength, see Fig. 3(b). The spatial period of this modulation is the inverse of the twist rate (roughly 50 twists per meter). In order to reveal the actual grating properties, we therefore numerically straighten [12] the fiber by applying a Fourier filter to the OFDR data. This procedure effectively eliminates the periodic modulation of the Bragg wavelength in the outer cores while preserving all the fine scale information that is required for a detailed assessment of the individual grating properties.

In addition to such spooling artifacts, the computed spatial traces of the different cores of a multicore fiber usually have longitudinal position offsets. This can result from different lengths of the single core fibers that connect the OFDR interrogator with the individual cores of the multicore fiber. For very long arrays, these position offsets can vary over the length of the array due to slightly different group indices n_{group} in the cores. However, longitudinal offsets are detrimental to the analysis process and make it very hard to distinguish between certain types of fine scale grating defects that might affect single or multiple cores. Therefore, our procedure precisely aligns all cores by analyzing the spectral peak of the Fourier transform of the local Bragg wavelength deviation, which is inversely proportional to the spatial phase derivative $\mathrm{d}\arg\big(q(z)\big)/\mathrm{d}z$.

After shifting and rescaling all cores to a common reference grid (e.g., the positions where the center core signal has been computed from the FFT of the OFDR signal), we can evaluate and compare quantities such as refractive index modulation, spectral peak reflectivity, wavelength and spectral FWHM. Some of the analysis results of this 50.6 m long array are shown in Fig. 4. With our automated procedure, a detailed analysis of these 7×1405 = 9835 gratings at a high resolution of 39 µm takes only about ten minutes. Our analysis can be scaled to arrays of any length and allows us to automatically assess each individual grating exposure.

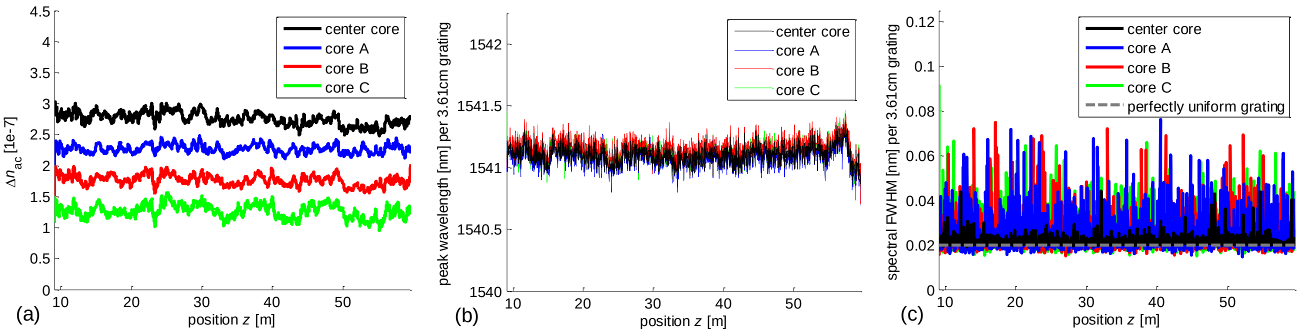
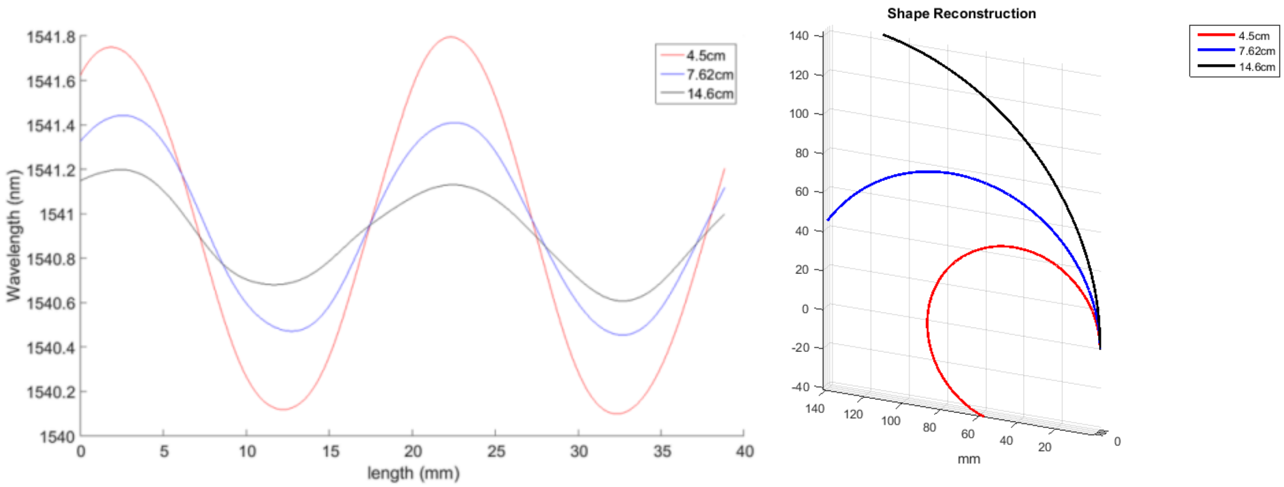


Figure 4. (a) Magnitude of the refractive index change (10 cm running average), plots of outer cores A/B/C were offset by $-0.5 \cdot 10^{-7}$, $-1 \cdot 10^{-7}$ and $-1.5 \cdot 10^{-7}$, respectively. (b) Spectral peak wavelength. (c) Spectral FWHM for each grating exposure (10cm running average) and for perfectly uniform gratings (- - -).

3. SHAPE SENSING APPLICATION

In order to characterize the sensing capabilities of the grating array, we use it to measure the bend radius for a set of known radii [13]. To find the fiber bend radius, we apply a shape reconstruction algorithm similar to that presented in [14,15]. A 20 cm long section of the 7-core FBG array is measured using a commercial OFDR system (LUNA OBR). As a first step, the fiber is held in a straight untwisted position to calibrate the sensor. The OFDR trace from this orientation is then used as a reference for the signal during the shape reconstruction algorithm. Subsequently, the fiber is wound around spools of different radii, and OFDR traces are recorded for the center core and three outer cores. Variations in the local Bragg wavelength of the inner and outer cores are related to the local bend in the fiber. These data are then used to reconstruct the shape of the fiber by solving the Frenet-Serret equations along the length of the fiber in a manner similar to that of [14,15]. Figure 5 shows the shape reconstruction of the fiber. The spatial variation of the local Bragg wavelength (which is the inverse spatial derivative of the reflection phase) of one of the outer cores of the fiber is shown in Fig. 5(a). The local Bragg period oscillates with a spatial period of about 2cm, which is the inverse of the twist rate. The amplitude of this oscillation is proportional to the inverse bend radius. Figure 5(b) shows the reconstructed shape of the fiber on spools with radii 4.5 cm, 7.62 cm, and 14.6 cm. The average radii obtained from the shape sensing algorithm are 4.44 cm, 7.73 cm, and 14.6 cm, showing good agreement over this range of fiber bend.



(a) (b)

Figure 5. (a) Oscillation of the period of Bragg wavelength in the outer cores of the twisted multicore fiber grating array for three different radii. (b) Shape reconstruction of a 20 cm long section of the grating array for three different bending radii.

4. SUMMARY

We demonstrated an automated analysis tool for very long Bragg grating based sensor arrays in twisted multicore fiber. These gratings were inscribed by single shot UV exposure in all cores of write-through coated fiber in a reel to reel setup that can write arbitrary lengths of these gratings. To reliably detect any grating defects that would deteriorate the sensing accuracy, the FFT-based analysis tool numerically straightens the fiber and precisely aligns the OFDR traces in all cores. As an example, we analyzed a 50.6 m long array that consists of totally 9835 gratings in 7-core fiber at a spatial resolution of 39 µm and showed the local grating strength, Bragg wavelength as well as the spectral FWHM of every single grating. As a demonstration of the shape sensing capability of this fiber, we showed how this sensor fiber can be used to reconstruct the shape of curved objects with varying radii.

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