Multicore optical fiber grating array fabrication for medical sensing applications

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ABSTRACT

In this work we report on a fiber grating fabrication platform suitable for parallel fabrication of Bragg grating arrays over arbitrary lengths of multicore optical fiber. Our system exploits UV transparent coatings and has precision fiber translation that allows for quasi-continuous grating fabrication. Our system is capable of both uniform and chirped fiber grating array spectra that can meet the demands of medical sensors including high speed, accuracy, robustness and small form factor.

Keywords: Shape Sensing, Fiber Gratings, Fiber Sensors, Optical Fiber

1. INTRODUCTION

As optical fiber sensors have become accepted in more industrial and medical applications, there has been increased interest in high performance fiber grating arrays that enable next generation sensing modalities requiring continuous or nearly continuous measurements along a given length. One example is shape sensing based on optical fiber [1,2]. A shape sensing fiber can be readily incorporated into various medical devices, including catheters used in surgery. In such applications, the shape sensing fiber can provide valuable information on the location and performance of medical instruments. It is possible to reconstruct the shape and position of an optical fiber from measurements of its local bend and twist [3]. Fiber shape measurements can be achieved by using a fiber with more than one core. Cores offset from the center of the fiber are sensitive to the local bend of the fiber because they experience tension and compression depending on the direction of the local fiber bend. In order to measure the local twist, it is also necessary for the offset cores to have a constant bias twist. Accurate measurements of bend and twist require spatially continuous or quasi-continuous, high resolution measurements of the strain state of each core along the entire fiber length. It has been shown that Optical Frequency Domain Reflectometry (OFDR) of Rayleigh scattering can provide such a continuous scattering signal [4]. However, signal to noise is poor in such systems due to the very low level of the Rayleigh scattered light. Moreover, the spectral signature of Rayleigh scattering, while stable in time, is random, thereby increasing the complexity of the processing algorithms. These requirements limit the speed with which shape can be reconstructed. For applications in which the fiber experiences relatively fast perturbations, Rayleigh scattering therefore has limited accuracy. One such area is shape sensing in medical procedures in which the shape and position of medical instruments must be updated in a rapid and accurate manner during the dynamic conditions of a surgical procedure.

In order to improve the shape sensing performance, it is therefore necessary to greatly increase the scattering signal received from the fiber cores. This can be achieved by inscribed fiber gratings in all of the cores of the optical fiber. Unlike Rayleigh scattering, fiber gratings back scatter light with high efficiency. Moreover, the gratings have a well-defined spectrum that is easily interpreted using OFDR. Reconstruction of shape using fiber gratings is therefore much more rapid and accurate, thereby enabling a new class of dynamic shape sensing applications as well as other dynamic sensing applications based on OFDR. A key challenge is a method of high volume fabrication of continuous or nearly continuous fiber gratings in the twisted multicore fibers relevant for shape sensing. For commercial viability, continuous grating fabrication cannot add significantly to the overall cost of the fiber and it cannot compromise other required properties of the fiber such as mechanical strength.

In this work we report on the capabilities of a flexible and scalable fiber grating array fabrication platform that addresses these requirements. Our system employs a reel to reel fiber handling system and inscribes gratings using a UV excimer laser. Our multicore fiber has a UV transparent coating that allows for rapid single pulse inscription of gratings in all cores without the requirements of stripping the coating, thus retaining high mechanical strength over the grating array. Precision positioning of the fiber enables quasi continuous gratings over arbitrary lengths of fiber. The system allows for a large range of spectral characteristics through the use of phase masks with uniform, chirped or other more complicated periodic structures, that may be chosen to suit the requirements of the grating array application.

2. FABRICATION SETUP

A schematic of our fabrication system is shown in Fig. 1. Optical fiber is mounted on a reel to reel spooling apparatus which includes a precision position encoder to measure the length of fiber removed from the payout spool. This position information is used to drive a pulsed excimer laser system which inscribes gratings in the fiber. Typically, the grating inscription uses a single pulse UV exposure at 248nm to inscribe the grating. Such single pulse inscription can produce gratings with sufficient strength for most applications that require nearly continuous grating reflection through the length of fiber. Typical grating refractive index modulations are in the range of 10^{-8}-10^{-6}. Note that, depending on the application, this refractive index modulation must be very low to prevent multiple reflections in the grating over lengths of many meters. Such multiple reflections can complicate the OFDR signal processing required to retrieve local strain in the fiber core. Single pulse grating fabrication is relatively insensitive to mechanical instabilities in the system. The laser pulses are typically 10-20nsec in duration, thus the fiber moves very little during a single pulse of UV light. This robust inscription loosens the requirements for fiber movements during exposure. Grating inscription is performed by projecting the UV inscription beam onto a phasemask with the desired grating period. Diffracted beams from the mask then produce a grating in the core of the optical fiber. For gratings that reflect in the telecom C band near 1550nm, where most OFDR sensor interrogators operate, the grating period is close to 500nm. The phase mask can impart various spectral characteristics to the gratings. For instance, each grating can have a chirped (or linearly varying) period, making the resulting gratings broaden in the spectral domain. The grating length is precisely controlled with an adjustable aperture that sits in front of the phase mask. Typical lengths for a single exposure are a few cm. The inscription beam is formed from a uniform portion of the UV excimer beam after expansion, and focused onto the fiber. The grating reflectivity may be changed by adjusting the UV beam power or by changing the focus of the writing beam. In order to produce continuous gratings in a given fiber with the aperture set to a certain length, a set of test gratings is first inscribed. These are used to adjust the position and reflectivity of each grating. Once these are set to the desired level, the system automatically inscribes nearly continuous gratings over arbitrary lengths without further operator interruption. Fiber used in our setup is protected by UV transparent coatings. These coatings are applied during the

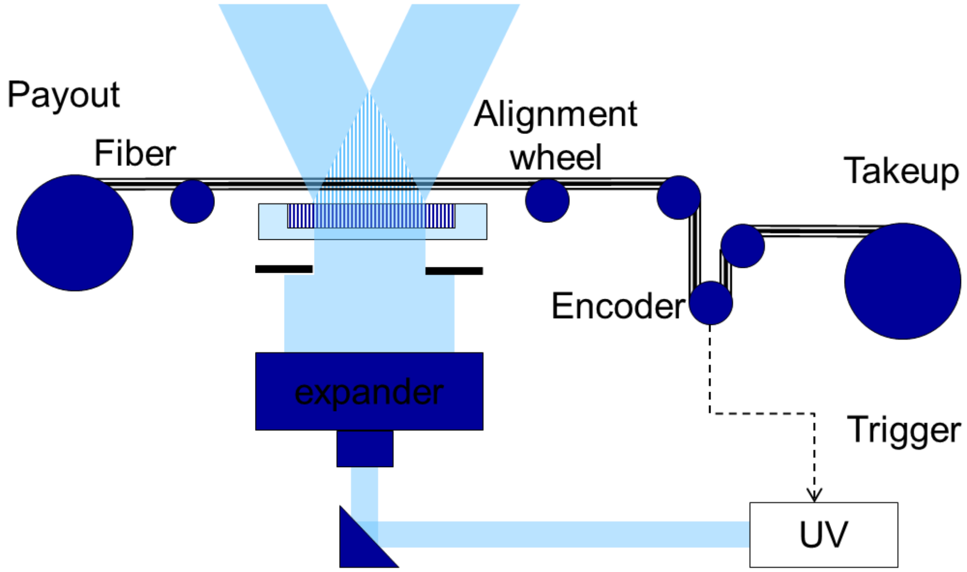

Figure 1. Schematic diagram of reel to reel grating array fabrication. To enable a 2D visualization, the plane in which the UV irradiation is propagating has been rotated by 90 degrees. UV inscription through a phase mask is accomplished with a single pulse of 248nm excimer laser radiation. Fast and accurate processing is enabled by the UV transparent coating on the fiber, which eliminates stripping steps and ensures minimal degradation of the fiber mechanical strength during the fabrication process.

fiber draw process using techniques similar to standard fiber coatings. However, a modification of chemical composition of the coating allows for transparency near the UV writing wavelength. Because the coating does not have to be removed and the UV fluence is low, mechanical strength degradation after UV exposure is minimal. Our system is capable of inscribing gratings in both single core and multiple core optical fibers. For multicore fibers, the gratings are inscribed in all cores at once with a single exposure eliminating the requirement of exposing a given length of fiber more than once. Such rapid parallel inscription is critical to achieving the goal of high volume fabrication of continuous gratings required for cost effective sensing applications.

3. GRATING ARRAY MEASUREMENTS

In Fig 2, we display data from a 25m length of uniform gratings inscribed in a single core fiber. Measurements were performed with a commercial LUNA OBR OFDR measurement system. The top plot shows the reflectivity and spatial derivative of the reflection phase, which is simply the local Bragg wavelength of the grating. Changes in the local Bragg period can be directly related to changes in the local strain in the fiber and therefore the phase derivative is the quantity of primary interest for sensing applications. We note that the reflectivity of the Bragg grating is ~23dB above the native Rayleigh scattering in the fiber (observed in the trace up to 9m), greatly increasing the signal to noise ratio. Moreover, the phase derivative shows far less noise than the Rayleigh scattering, allowing for much more rapid processing of the local Bragg wavelength information. The middle plot shows a close up of a short section of the grating. Gaps between gratings are indicated by the vertical dotted lines and are sufficiently small that the Rayleigh level is only partially visible between inscriptions. Moreover, the phase derivative shows only small deviations near each gap between gratings. In general, for useful shape reconstruction, the gaps between gratings must typically be less than 1mm. When the gaps are sufficiently small, it is possible to average over the small features observed in between each grating. The bottom plot of Fig. 2 shows the spectrum of a single grating. As expected for a uniform grating, a sharp spectral peak is observed at the Bragg resonance near 1547nm. Using the OFDR technique, the position of this peak can be tracked down to a spatial resolution that depends on the scan range used. For the scan range of 10nm, used in Fig. 2, the

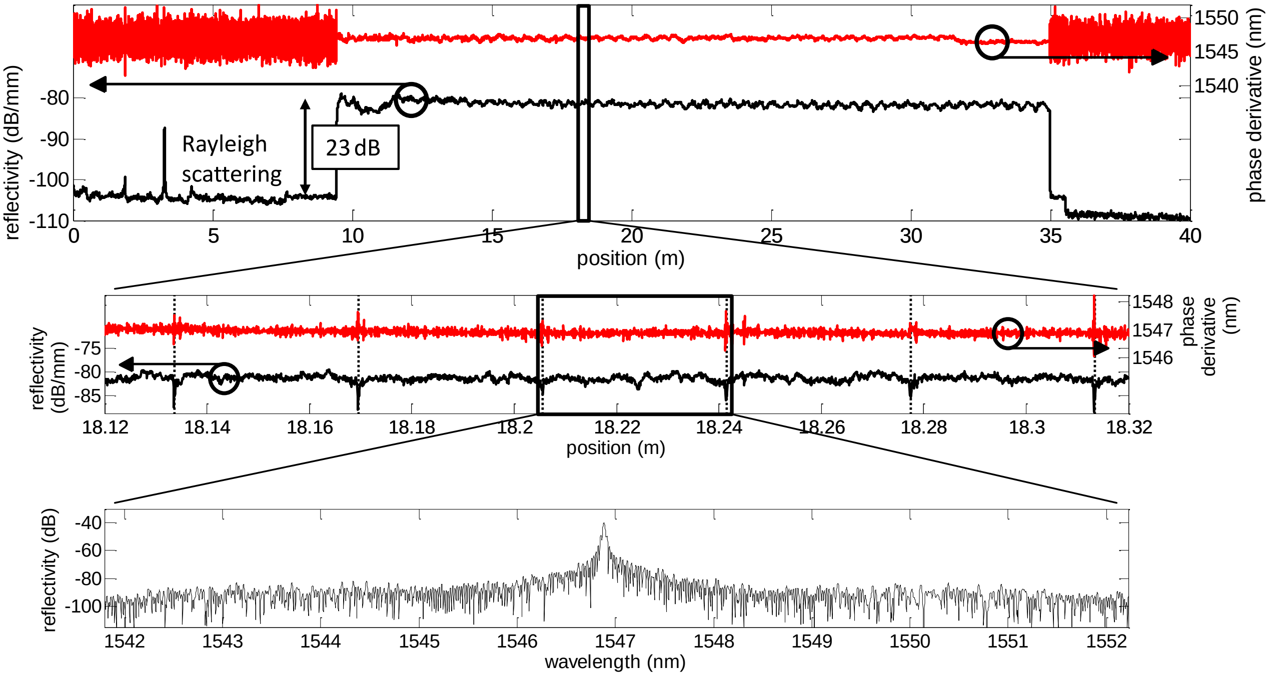

Figure 2. Top plot: Reflectivity (black, left axis) and spatial phase derivative (red, left axis) measured in a 25m long quasi-continuous grating array in single core fiber as measured using OFDR (LUNA OBR) with a 10nm scan range. Reflectivity 23dB above the Rayleigh scattering level is observed within the grating. Noise in the spatial derivative or local Bragg wavelength is also greatly decreased over that from the Rayleigh scattering. Middle plot: Enlarged section showing nearly continuous amplitude and phase derivative along the grating. Bottom plot: spectrum from a single 35mm grating exposure.

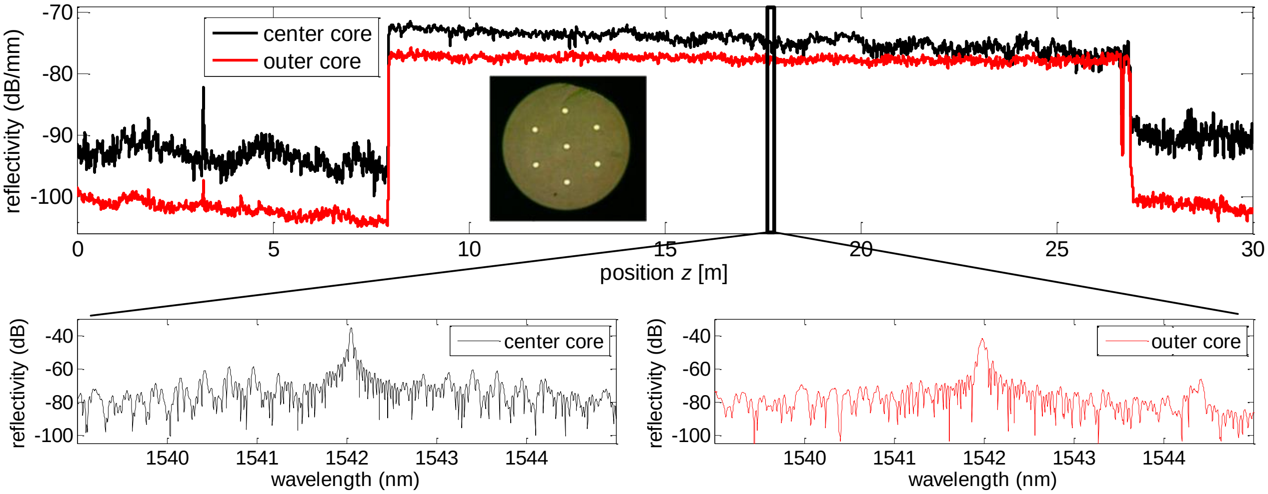

Figure 3. Top plot: OFDR trace from an 18m long quasi-continuous Bragg grating array in a twisted multicore fiber. The fiber profile is shown in the inset. Traces from the inner core and one of the outer cores are shown. Note that all six of the outer cores showed similar OFDR traces. Reflectivity is more than 23dB above the Rayleigh scattering from the fiber. Bottom plots: Spectra of a single 25mm grating in outer (right) and inner (left) core. Gratings were fabricated in all cores with a single UV exposure.

resolution is about 80 microns.

Fig. 3 demonstrates parallel fabrication in two cores of a twisted multicore fiber, shown in the inset. Gratings were fabricated in all cores at a given location with a single pulse of excimer radiation. The OFDR traces were measured for two cores of the twisted multicore fiber. Because the outer cores were twisted into a helix around the central core, they all show similar reflection and local Bragg wavelength along the fiber. The two bottom plots show reflection spectra from a 25mm section indicating a strong well defined Bragg resonance in both inner and outer cores.

4. CONCLUSION

We have reported on the capabilities of a continuous fiber Bragg grating array fabrication setup using reel to reel processing. Our setup is both scalable and flexible allowing grating inscription over arbitrary lengths of fiber from a given payout spool. The system has the flexibility to rapidly change the grating spectrum in different fabrication runs to accommodate a large range of requirements on the spectral properties of the grating array, including uniform and chirped grating periods. Precision translation allows our system to fabricate gratings that can meet the demands of various sensing applications that require continuous or nearly continuous measurements along the optical fiber. These include medical shape sensing, for which continuous, rapid monitoring of the position and shape of surgical instruments such as catheters shows the promise of improved outcomes for various medical procedures.

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