# Continuous Multicore Optical Fiber Grating Arrays for Distributed Sensing Applications

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*(Invited Paper)*

***Abstract*—We describe the fabrication and distributed sensing capabilities of very long continuous fiber grating sensor arrays in a twisted multicore fiber. The continuous gratings are fabricated in fibers with UV transparent coating using a flexible and scalable reel-to-reel processing system. Single-frequency continuous gratings are characterized using optical frequency-domain reflectometry and a shape reconstruction algorithm to measure fiber bend radius. Broadband reflection gratings are shown to act as enhanced quasi-Rayleigh scattering elements allowing for distributed temperature measurements in the presence of 10-dB transmission loss.**

***Index Terms*—Fiber gratings, optical fiber sensors, shape sensing.**

## I. Introduction

FIBER grating sensor arrays are lengths of fiber with intra-core Bragg gratings that can act as sensors of temperature and strain along a given length of fiber. They were first proposed in the late 1980s [1] and have been the subject of intensive research and commercialization since that time (e.g., [2], [3]). These sensors typically comprise short individual gratings at several distinct wavelengths and are interrogated using optical spectrum analysis and wavelength division multiplexing (WDM). Because of their unique advantages of compact, in-fiber design, multiplexing capabilities, and resistance to harsh conditions and electromagnetic interference, they have found application in various industries that benefit from distributed sensing, such as the oil and gas industry and structural health monitoring.

As this first generation of WDM-based localized sensors has gained commercial acceptance, there has been increased interest in next generation fiber sensors with enhanced capabilities that exploit advances in multicore fibers and continuous array fabrication. These include distributed temperature [4], strain [5] and acoustic sensing [6], as well as sensing of bend and shape [7], [8]. Such applications often require continuous or nearly continuous sensing along the length of the fiber. While Rayleigh scattering can provide a spatially continuous sensing signal [4], [5], it has limitations due to low signal intensity and the inherent randomness of the Rayleigh scattering spectrum. Distributed sensing applications can thus benefit from the increased elastic scattering and well controlled optical spectra of continuous intra-core Bragg gratings. In addition to the requirements of continuous sensing, some applications, such as shape sensing, also require multicore fibers. Offset cores in such fibers provide information about the state of bend and twist of the fiber such that sensing signals from these cores can be used to reconstruct the shape of an optical fiber. Accurate shape reconstruction over meters of fiber can require continuous, high speed measurements with a spatial resolution less than 1 mm.

A critical requirement for these applications is a cost effective method to fabricate continuous arrays of gratings over many meters in all of the cores of a multicore fiber. Many techniques to produce long arrays of continuous and nearly continuous single core gratings have been demonstrated, including point by point [9], [10], reel to reel setups [11], drum systems [12], and draw tower grating fabrication [13], [14]. We have recently reported on a fabrication system suitable for long continuous multicore sensor arrays [15], [16]. Our method uses reel to reel fiber handling and UV transparent coating [17], and is both flexible, allowing control over local grating spectrum, as well as scalable, allowing for arbitrary lengths of nearly continuous arrays to be inscribed in all cores of a fiber. Without removal of the fiber coating, near pristine fiber mechanical strength is maintained.

In this work we present our fabrication scheme and the properties of continuous grating arrays. We then describe nearly continuous single frequency grating arrays in twisted multicore fiber suitable for fiber shape reconstruction in medical instruments. We also demonstrate the bend sensing capability of the fiber by performing shape reconstruction of a fiber length bent around different fiber spools. We then show that a broadband enhanced scattering spectrum may be imprinted in all of the cores simultaneously. Finally, we compare the performance of the grating based scatter fiber to Rayleigh scattering in standard single mode fiber by using both fibers in OFDR based distributed temperature sensing in the presence of large signal attenuation.

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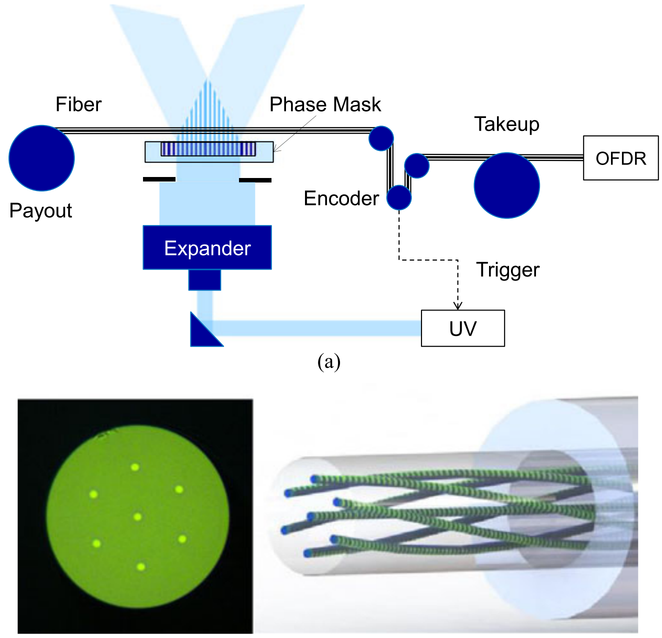


Fig. 1. (a) Reel-to-reel array inscription apparatus allowing continuous fabrication of gratings in all cores through UV transparent coating. (b) End-view image of a seven-core fiber with coating removed. (c) Twisted multicore fiber schematic showing UV transparent coating (right). Bare glass region (left) shown to highlight twisted multicore continuous gratings.

## II. Distributed Sensor Fabrication

Fig. 1 shows a schematic of our twisted multicore fiber and the inscription system used to imprint the grating arrays. The fiber is drawn with a permanent twist at a pitch of 2 cm by rotating the preform during draw. The germanosilicate cores have a numerical aperture of 0.21, a diameter of 6 microns, and are offset by 35 microns from each other. The glass diameter is 125 microns. The fiber is jacketed with a UV transparent acrylate coating and has a coated diameter of 200 microns. The fiber gratings are fabricated using the reel to reel apparatus shown in Fig. 1(a). The reel to reel spooling system sends the fiber past a phase mask where the fiber is exposed to a UV interference pattern that gives rise to the desired grating spectrum in the fiber cores. The UV source is a pulsed excimer laser operating at 248 nm. Our fiber is highly photosensitive only in the Ge doped core regions. Therefore, the gratings are written into all of the cores with a single flood exposure over a given length of the fiber. For many continuous sensing applications that require long but weak gratings, a single pulse of excimer laser radiation is sufficient to produce a grating of the desired strength. Such exposures produce refractive index modulations in the range of 1 to $4 \times 10^{-7}$. The exposure length is typically a few centimeters. The UV pulse fluence is typically a few 10 s of mJ/cm$^2$. The fiber is then translated by a fixed amount using a precision encoder. The result is a nearly continuous grating array that can extend over many meters. The optical spectrum of each grating is controlled by the phase mask. In this work we describe continuous arrays with both uniform gratings and broadband reflectors.

## III. Twisted Multicore Arrays for Shape Sensing

Our twisted multicore fiber is described in Fig. 1. Fig. 1(b) shows an end view of our twisted multicore fiber. The schematic in Fig. 1(c) shows how the outer cores twist around the central core, forming six helices. All of the cores have gratings inscribed continuously along their length. Such twisted multicore fiber gratings are required for demanding applications such as shape sensing. In this application, gratings in the outer cores are sensitive to the local bend in the fiber, while the helical twist makes the gratings sensitive to the local twist as well. It has been shown that knowledge of the local bend and twist at all points along the fiber can be used to reconstruct the shape of the fiber [8], [18], [19]. Shape reconstruction can improve the performance of various medical procedures that require precise knowledge of the shape and location of surgical instruments such as catheters. Because the shape reconstruction must be very precise, the strain distribution arising from bend and twist must be measured with very high spatial resolution, typically less than 1 mm. For this reason, a nearly continuous length of gratings is required. The gratings also greatly increase the signal available for the interrogation schemes. Increased signal to noise ratio is critical to improved performance.

Because the gratings are very weak and continuous, they are best interrogated using optical frequency domain reflectometry (OFDR) [20]. In this technique a narrow linewidth interrogation source is scanned over a range of wavelengths and the signal reflected from the grating is interfered with a reference signal. A Fourier transform of these spectral oscillations yields the phase and amplitude of the grating reflection vs position, $|r(z)|e^{i\phi_{\mathrm{FBG}}(z)}$. The spatial derivative of this phase gives a measure of the local Bragg wavelength at position $z$ along the fiber, $\lambda_{\mathrm{Bragg}}(z)$, through the definition:

$$\frac{2\pi n_{\mathrm{eff}}}{\lambda_{\mathrm{Bragg}}(z)} = \frac{d\phi_{\mathrm{FBG}}(z)}{dz} \tag{1}$$

where $n_{\mathrm{eff}}$ is the effective index of the guided mode and $\phi_{\mathrm{FBG}}(z)$ is the spatial phase of the grating. The local Bragg wavelength is sensitive to variations in strain and temperature and is a primary signal enabling optical fiber sensors. Fig. 2(a) shows an OFDR trace recorded for the center core and one of the outer cores of a 25 m long twisted multicore continuous fiber grating array made up of concatenated 3.5 cm exposures. We used a LUNA OBR, and each core required a few seconds of acquisition time. The reflected signal is 18 dB above the bare Rayleigh scattering of the fiber without gratings. Fig. 2(b) shows a zoomed plot of the local Bragg wavelength (inversely proportional to the spatial derivative of the reflection phase) at the start of the grating array. The noisy Rayleigh scattering of the bare fiber gives way to the much lower noise phase derivatives of the grating arrays in the two cores. The Bragg wavelength of the outer core oscillates with a pitch equal to the 2 cm twist period because this is the period at which the strain and Bragg wavelength in the outer cores are modulated along a bend, e.g., on a spool. Small peaks near 8.665 m and 8.702 m arise from the gap between the successive grating inscription exposures that

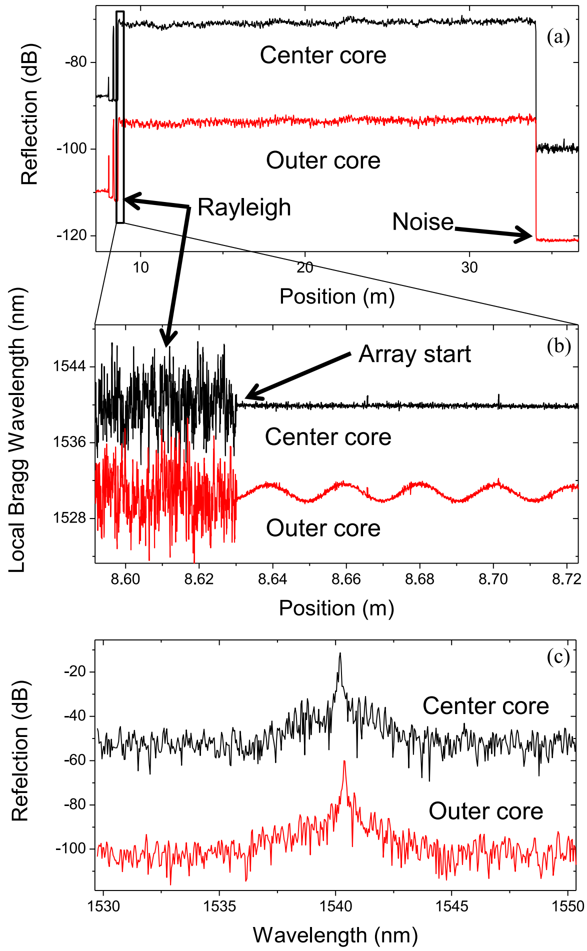


Fig. 2. (a) OFDR traces (smoothed and offset for clarity) observed for 25-m-long single-frequency grating array in the multicore fiber of Fig. 1; center core (black) and one outer core (red). Rayleigh scattering level in the sensor fiber and the OFDR noise floor are indicated with arrows. (b) Zoom of local Bragg wavelength versus position at the start of the grating array. At the array start (8.63 m), the noisy phase derivative of the bare fiber Rayleigh scattering gives way to the low-noise FBG signals. The oscillation in the outer core arises from fiber coiling. (c) Spectra extracted from the OFDR trace over 1 cm of a straight portion of the array; center core (black) and an outer core (red).

form the continuous grating. Finally, Fig. 2(c) shows spectra observed in the inner and outer cores over 1 cm of straight array.

In order to characterize the sensing capabilities of our fiber grating arrays, we used an array to measure bend radius for a set of known radii. To find the fiber bend radius, we use a shape reconstruction algorithm similar to that presented in [18], [19]. A 20 cm section of fiber was held in a straight untwisted position and an OFDR trace was recorded. The OFDR trace from this orientation was used as a reference for the fiber during the shape reconstruction algorithm. Subsequently, the fiber was wound around spools of different diameters and OFDR traces were recorded for the center core and three outer cores. Variations in the local Bragg wavelength of the center and outer cores were related to the local bend in the fiber. These data were then used to reconstruct the shape of the fiber using the Frenet-Serret equations applied along the length of the fiber in a manner similar to that of refs [18], [19]. Fig. 3 shows the shape reconstruction of a 20 cm length of the fiber. Fig. 3(a) shows the spatial variation of the local Bragg wavelength of one of the outer cores of the fiber. The local Bragg period oscillates with a spatial period equal to the twist rate. The amplitude of the oscillation is proportional to the inverse bend diameter. Fig. 3(b) shows the reconstructed shape of the fiber on three different spools of radii of 4.5 cm, 7.62 cm, and 14.6 cm (see Fig. 3(c)). The average radii for the reconstructions are 4.44 cm, 7.73 cm, and 14.6 cm, showing good agreement over this range of fiber bend.

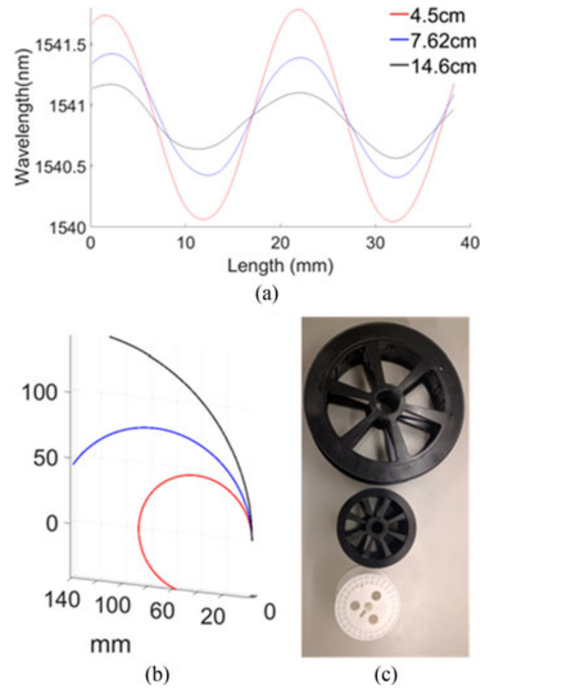


Fig. 3. (a) Local Bragg wavelength versus position for different bend radii. (b) Shape reconstruction for fiber bends of three different radii. (c) Spools used in the bend measurements.

## IV. Broadband Enhanced Scattering Fiber

As discussed in Section II, our grating fabrication system can imprint gratings with a variety of spectral properties. The UV transparent coating does not need to be removed, nor must the fiber design be modified. Only the phase mask and some parameters of the inscription process are changed to achieve a different spectrum, leading to rapid turnaround time of the system. One possibility is a broadband grating reflection spectrum. Such gratings can be useful in applications that require enhanced scattering over a larger bandwidth. These include applications that employ various forms of OTDR and OFDR to perform distributed temperature, strain and acoustic sensing. Such applications typically employ Rayleigh scattering, which is typically quite weak and thus limits the effectiveness of these sensors. A broadband, continuous grating can be used to enhance the signal for such applications.

Fig. 4 shows the result of the inscription of such broadband reflectors into our twisted multicore fiber using our fabrication system. A broad bandwidth was achieved by using a chirped phase mask for each exposure. The resulting grating had a

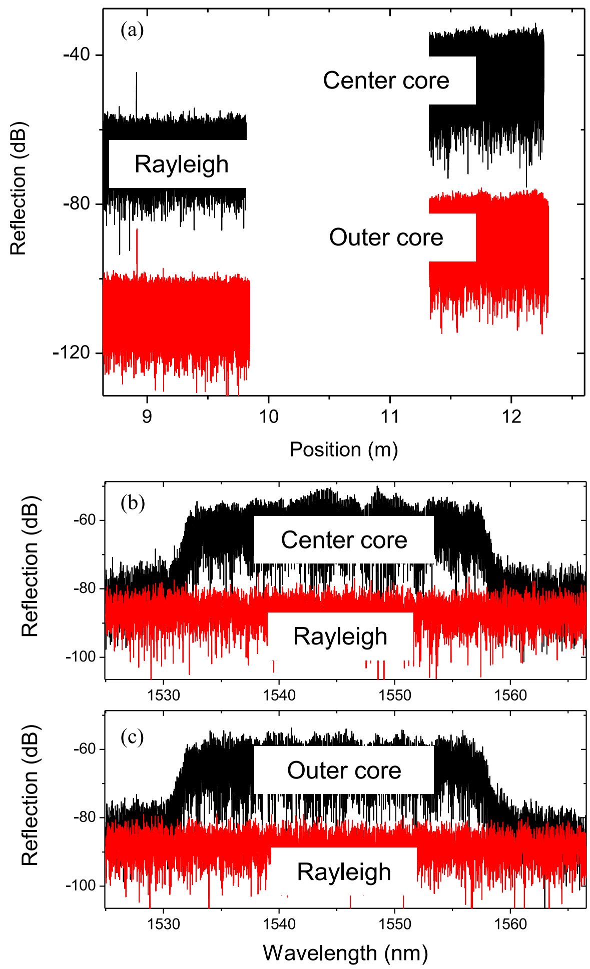


Fig. 4. (a) OFDR trace of continuous array with broadband reflection in the center and one outer core of the fiber shown in Fig. 1. Grating and bare fiber Rayleigh spectrum observed in the center core (b) and one of the outer cores (c).

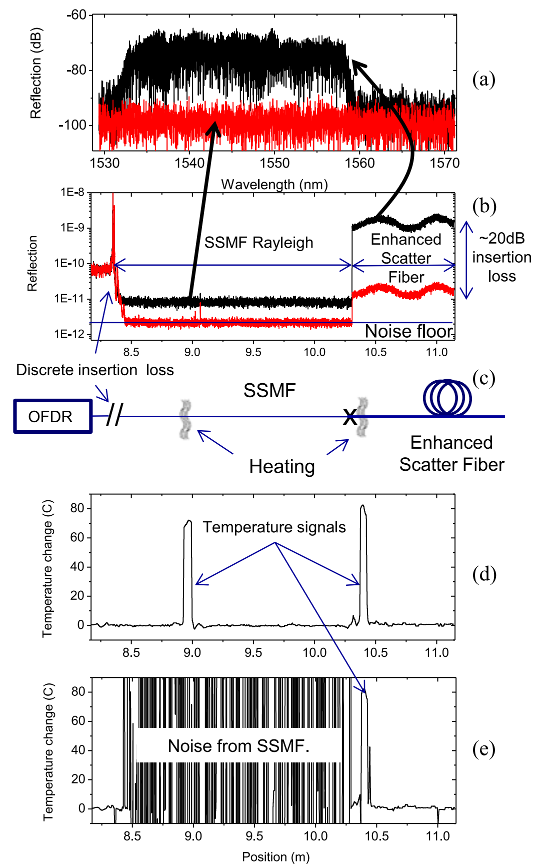


Fig. 5. (a) Optical spectrum of 5 cm of broadband enhanced scattering fiber and Rayleigh scattering from bare standard single-mode fiber (SSMF). (b) OFDR traces of SSMF and enhanced scatter fiber with high (black) and low (red) input loss. (c) Experimental setup showing location of 5-cm heaters applied to the fibers. (d) Temperature sensing signals with low input loss. (e) Temperature signals with high input loss showing only noise in the SSMF fiber and an intact signal in the enhanced scattering fiber.

bandwidth of roughly 25 nm. Unlike the continuous single frequency gratings, the broadband scattering gratings were overlapped in order to achieve a more continuous scattering spectrum along the fiber. Fig. 4(a) shows an OFDR trace from both the center and one outer core of a 2 m section of such a broadband twisted multicore fiber array. Fig. 4(b) and (c) show the spectrum of the grating over 10 cm extracted from the OFDR data at position 11 m in each array. They also show the bare fiber Rayleigh scattering spectrum obtained from 10 cm of fiber at position 9.5 m before the start of the grating. The other five outer cores showed similar spectra. These plots illustrate how a quasi-Rayleigh signal roughly 20 dB above the bare fiber Rayleigh scattering may be obtained in all of the cores of a multicore fiber with a single exposure.

Fig. 5 shows a demonstration of the sensing capability of the broadband enhanced scattering fiber. The enhanced scatter fiber grating sensor array was spliced to a length of standard single mode fiber (SSMF). Fig. 5(a) compares the Rayleigh scattering spectrum of SSMF with the broadband spectrum from the enhanced scattering fiber. The scattering is roughly 20 dB above the SSMF Rayleigh scattering over a 25 nm bandwidth. An OFDR measurement of both lengths of fiber was performed and taken as a reference. To generate a clear temperature signal, both fibers were heated over 5cm regions indicated in Fig. 5(c) using the splice protector curing heater on a fiber fusion splicer. A second OFDR measurement was performed, and temperature measurements were computed using the correlation algorithm built into the LUNA OBR [4], [5]. As we only required a clear temperature change to track as the signal loss increased, these measurements were not calibrated using the LUNA software. The attenuation at the input to the two lengths of fiber was then increased to 20 dB round trip loss and a second OFDR trace was recorded to obtain a second temperature measurement. When the input loss was low, both the Rayleigh scattering from the SSMF and the enhanced scattering fiber gave temperature signals as shown in Fig. 5(d). Fig. 5(e) shows how the SSMF failed to give a signal when the roundtrip transmission loss was increased to 20 dB. The enhanced scatter fiber was still able to provide a temperature response.

## V. Conclusion

We have shown how continuous grating arrays may be fabricated over many meters of multicore optical fiber. A reel to reel processing system allows for flexibility in the fiber length and optical spectrum, and also ensures inscription into all cores of a multicore fiber. In two examples we showed how such fibers can sense bend and temperature with increased signal to noise and precision when compared to the bare Rayleigh scattering of the optical fiber without gratings. The distributed sensing applications for these fibers show promise in various industries, including medical devices, oil and gas, security and structural health monitoring.

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