# Integrated optical fiber shape senor modules based on twisted multicore fiber grating arrays

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## ABSTRACT

In this paper we report on the development of a complete integrated optical fiber assembly suitable for shape sensing. Our shape sensor module consists of a length (>1m) of twisted multicore optical fiber with fiber Bragg gratings inscribed along its length. Our fiber has a compact 180 micron coated diameter, a twist of 50 turns per meter and grating reflectivities greater than 0.01% per cm of array, suitable for high efficiency scatter measurements over many meters of fiber. Single core to multicore fanouts and low reflectivity fiber termination are used to terminate the end of the array.

**Keywords:** Optical fiber, Shape sensor, Fiber grating

## 1. INTRODUCTION

Shape sensing using optical fibers has the potential to impact various medical, industrial and defense related applications. Optical fiber shape sensing is a form of distributed sensing that uses scattered signals from optical fibers to ascertain local curvature and twist and thus the shape of a given structure. A key component of this system is a compact, integrated optical fiber assembly that allows sufficient sensitivity, accuracy and collection efficiency of the scattered signals. While shape sensing using many single core fibers bonded to a substrate can be effective in some applications, a single multicore fiber allows for a more compact and stable shape sensor suitable for demanding applications that require small footprint and immunity to temperature variations.

In this paper we report on the development of a complete integrated optical fiber assembly suitable for shape sensing. Our shape sensor module consists of a length (>1m) of twisted multicore optical fiber with discrete or quasi continuous fiber Bragg gratings inscribed along its length. Our fiber has a 180 to 200 micron coated diameter, a twist of 50 turns per meter, and grating reflectivities greater than 0.01% per cm of array, suitable for high efficiency scatter measurements over many meters of fiber. A tapered fiber bundle single core to multicore fanout can be either spliced or connectorized to this shape sensor array. Termination of the fiber grating array ensures low back reflection from the distal endface of the fiber array and thus minimal interference with sensor interrogation.

Our shape sensor modules can be combined with many different interrogator schemes and represent a complete optical sensor head solution for medical, industrial and defense applications.

Our report is organized as follows: To provide background on the optical requirements for shape sensing, we first review the principals of optical fiber shape sensing. We discuss optical interrogator units used to characterize sensor performance and also used in the final shape sensing application. We then describe the different components of our optical fiber shape sensor, including the twisted optical fiber, multicore fiber splicing, grating arrays, connectorization, fanouts, and fiber end termination.

## 2. SHAPE SENSING BACKGROUND

Shape sensing using optical fibers exploits the strain sensitivity of light propagating in an optical fiber waveguide core. [1,2]. When such a core is offset from the center of a fiber it experiences a strain that depends on the curvature of the fiber. With more than one offset core, the direction of the bend may also be determined. A center core may also be added to sense thermal and longitudinal strain variations. Finally, it is essential to ascertain the rate of twist of the fiber in order to determine its shape. Sensitivity to fiber twist can be introduced by adding a permanent twist to the outer fiber cores. In this way, when the fiber is twisted, the outer cores will all be strained in the same way, while the center remains unstrained. Several fiber designs can be used to satisfy this set of sensing requirements. The most straightforward design has offset cores at equal radius surrounding a central core.

Accurate shape sensing requires knowledge of the state of strain with very high spatial resolution. Therefore, the strain must be measured continuously, or nearly continuously along the entire fiber length. Two different types of sensing signals may be used to achieve this: Light scattering from the inherent Rayleigh scattering of the fiber cores or fiber Bragg gratings that are written into the optical fiber cores. Both types of light scattering have characteristic spectral features that can be used to determine the strain state at a given point along the optical fiber. In the case of fiber gratings, the refractive index in each core is quasi-periodically modulated. When the fiber is strained, the Bragg resonance of the grating is shifted by an amount given by

$$\frac{\delta\lambda_{Bragg}}{\lambda_{Bragg}} = k\varepsilon,$$

where $k \approx 0.78$ is determined by the fiber strain and photoelastic response. Thus, measurements of the local Bragg period of gratings in each core can be related to the local state of strain in each core. If the cores are transversely located at known offset positions, then the strain state of the fiber may be related to the local fiber bend magnitude and direction as well as the twist. Similarly, Rayleigh scattering measured over a finite bandwidth gives a certain spectral characteristic that is unique to each length of fiber. As the strain in each core is changed, this spectral characteristic will shift much like a Bragg grating spectrum shifts [3].

Once the local strain and twist are known, the shape of the fiber may be computed using geometric formulations such as the Frenet-Serrret equations that relate local curvature and twist to the evolution of a local coordinate system that tracks the fiber tangent [4]. These equations may be written as

$$\frac{\boldsymbol{d}}{\boldsymbol{ds}}\begin{bmatrix}\boldsymbol{T}\\ \boldsymbol{N}\\ \boldsymbol{B}\end{bmatrix} = \begin{bmatrix}\boldsymbol{0} & \boldsymbol{\kappa} & \boldsymbol{0}\\ -\boldsymbol{\kappa} & \boldsymbol{0} & \boldsymbol{\tau}\\ \boldsymbol{0} & -\boldsymbol{\tau} & \boldsymbol{0}\end{bmatrix}\begin{bmatrix}\boldsymbol{T}\\ \boldsymbol{N}\\ \boldsymbol{B}\end{bmatrix},$$

where $\boldsymbol{T}, \boldsymbol{N},$ and $\boldsymbol{B}$ are the tangent, normal, and binormal vectors at a given point $s$ along the optical fiber. The quantities $\kappa$ and $\tau$ are the local curvature and twist, respectively that are derived from the Bragg wavelength shifts observed along the fiber in each core.

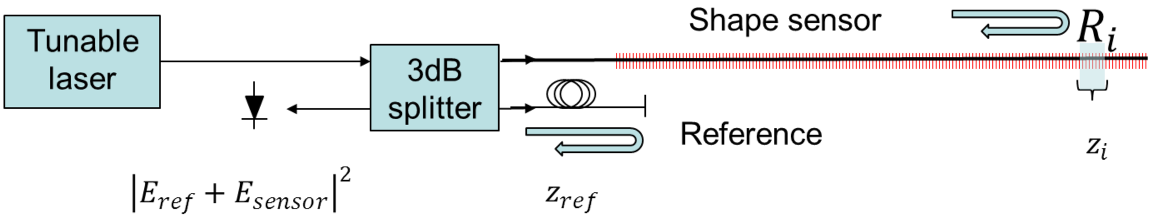


**Figure 1** Schematic of OFDR measurement system used for interrogation of optical shape sensors.

In practice, the local spectral characteristics of fiber gratings or Rayleigh scattering may be determined using techniques such as optical frequency domain reflectometry (OFDR). Such spectral interferometry may be performed with commercial instruments such as the LUNA OBR. Throughout this work, we use OBR measurements to characterize the phase and amplitude of light reflected from our fiber sensors. Since a modified multichannel version of the OBR may also be used for shape sensing interrogation, we describe this OFDR technique here in more detail. Fig. 1 shows a schematic of such a system. In OFDR, a narrow band laser signal is introduced into the fiber and the reflected light is collected and interfered with a reference signal that experiences a single back reflection. The laser is scanned over a given frequency range (or equivalently vacuum wavelength $\lambda$) to yield a spectrum in which the reflected light is represented by a term that oscillates as a function of the wavelength $\lambda$:

$$P(\lambda) = \left|E_{ref} + E_{sensor}\right|^2 \sim Re \sum_{z_i} E_{ref} R_i(\lambda) \exp\{j2k(z_i - z_{ref})\} + DC\ terms$$

Where the sum is over all points $z_i$ along the fiber, $R_i(\lambda)$ is the wavelength dependence of the reflection of the increment at $z_i$ and $k = 2\pi/\lambda$. Essentially, each point along the sensor contributes a term to the OFDR frequency trace that oscillates vs frequency with a period that is proportional to its position along the fiber. Thus, a Fourier transform of this spectrum will give the spatial dependence of the amplitude and phase of the light scattered from each point in the fiber:

$$R(z_i) \sim FT\{P(\lambda)\}$$

The intensity of the reflection is then simply $|R(z_i)|^2$. If a Bragg grating is present, the spatial phase of the light may be related to the local Bragg wavelength of the light through

$$k_{Bragg} = \frac{2\pi}{\lambda_{Bragg}} = \frac{\mathrm{d}Arg\{R(z_i)\}}{\mathrm{d}z},$$

where $Arg\{R(z_i)\}$ is simply the spatial phase of the reflected light. Thus, when a given core experiences a change in strain, the value of the spatial phase derivative at that point will change. The spatial resolution of the OFDR technique depends on the wavelength scan range. The larger the wavelength scan range, the finer the spatial resolution. A typical value would be a 20nm scan near 1550nm and this would give a spatial resolution of $40\mu$m. Such fine resolution is a significant driver for the use of OFDR in shape sensing where positional resolution is very important to ensure accurate shape reconstruction. Such accuracy cannot be obtained using discrete Bragg gratings in schemes that use spectroscopic or wavelength division multiplexed (WDM) or time domain (TDM) interrogators. Moreover, OFDR can also be used to measure fiber strain with Rayleigh scattering, making this approach quite versatile. The primary disadvantages of the technique are the stability and data handling requirements since it is an interferometric technique, and the large quantity of data limits the speed of the method and increases the cost of the interrogator. It also has less effectiveness with strong back reflectors due to multipath interference. However, as a diagnostic technique using weak Bragg gratings and Rayleigh scattering, OFDR is superior to other methods. Therefore we present OFDR traces of our devices in the work shown below.

## 3. SHAPE SENSING OPTICAL COMPONENTS

In order to satisfy the demand for accuracy, small size, and cost we have developed a set of components based on multicore technology. A schematic of our shape sensor optical assembly is shown in Fig. 2. Below we describe these parts in greater detail.

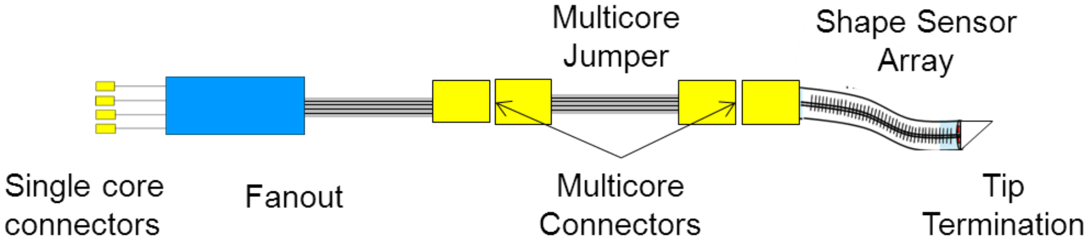
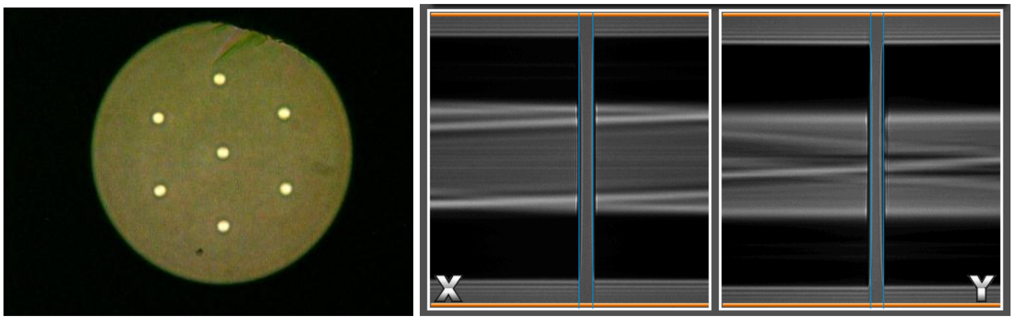


**Figure 2** Multicore optical fiber shape sensor assembly, including single core to multicore fanout, multicore connectors and jumpers, and the twisted continuous fiber Bragg grating sensor array with low reflection termination

Fig. 3 shows a cross section of a multicore optical fiber used for the sensor, fanout and jumpers. Six cores surround a center core at the neutral axis of the fiber. Only three of the outer cores are necessary for shape sensing. The other three give added flexibility and redundancy in manufacturing and improved sensing. The fiber glass dimensions are 125µm outer diameter with a 35µm core-to-core spacing. The fiber is coated with a UV transparent coating that ensures fiber strength while allowing grating inscription using standard methods as described below. The cores have a typical

NA = 0.21. This NA is chosen for increased photosensitivity, Rayleigh backscattering intensity, and bend loss immunity, while maintaining acceptable connector and splice losses. Importantly, the core positions are accurate to below 0.5 µm and the effective indices of the cores are matched to within 0.04%. These tolerances improve the accuracy of the resulting shape sensor and make the Bragg resonance of the gratings highly repeatable between cores. A permanent twist is imposed on the fiber during the draw process by spinning the preform at a high rate. Typical twist rates can be as high as 50 turns per meter or a twist pitch of 2.5cm.



(a) (b)

**Figure 3** (a) Cross section of a twisted multicore fiber (MCF) used throughout the optical fiber shape sensor assembly of Fig. 2. (b) Side view of a twisted fiber as seen from two orthogonal directions (x,y) in the Fitel S183 PM II fusion splicer. Twist of the fiber cores has been automatically aligned across the gap between the two fibers before performing the splice. Dark regions result from fiber lensing.

Another important component needed for testing the MCF is an effective MCF splicer that can align multiple cores as well as twist phase during the splicing alignment. We have adapted the splicing routines on the Fitel S183 PM II Fusion Splicer to obtain optimized splices for both twisted and untwisted MCF with seven cores. Fig. 3(b) shows orthogonal side views of two twisted multicore fibers that have been aligned with respect to each other.

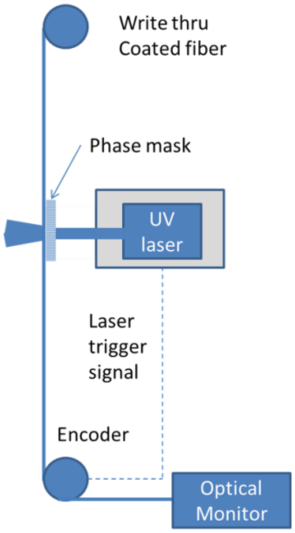


**Figure 4** Continuous fiber grating fabrication apparatus employing UV transparent coated fiber and precision encoders to achieve effectively continuous gratings along lengths in excess of 1m of fiber.

Fig. 4 shows the grating inscription apparatus used to write the quasi-continuous Bragg gratings that make up the sensor array. This process exploits a UV transparent fiber coating that protects the optical fiber to maintain its mechanical strength at near pristine levels while at the same time allowing for UV inscription of gratings using well known inscription methods. A precision encoder allows control of gaps between gratings to a level that is of the order of the shape sensor spatial resolution, making them effectively continuous for shape sensing applications. The inscription allows for parallel fabrication of gratings in all cores with a single shot exposure at each location along the fiber. An example of a 2m long grating is shown in Fig. 5. For clarity, only the center core signal is shown. The grating exhibits a reflection level 25dB above the Rayleigh scattering background. This enhancement in signal is one of the key benefits of using Bragg gratings for shape sensing. The inset shows the local spectrum from 1cm of grating. A sharply peaked spectrum is observed indicating a well defined Bragg resonance. The sharply peaked spectrum of the grating is also evident in the phase derivative (red line). This shows a well defined Bragg resonance near 1542nm that is maintained over the 2m length. The clearly defined spectral feature and phase derivative is also highly desirable for shape sensing since the algorithms used to track the phase simply rely on changes in local Bragg period. The plot also shows a 3dB increase in signal at the splice between the input standard single mode fiber (SSMF) and the multicore fiber (MCF). This increase is consistent with the core design which was intended to have a larger Rayleigh scattering signal than SSMF. Note that in the Rayleigh scattering region, the phase derivative is quite noisy compared to the FBG. This is expected since Rayleigh scattering results from random perturbations of the refractive index. Despite this noise, the Rayleigh scattering can also be used to obtain the shape of the fiber, however at the cost of processing speed and complexity. The 3dB increase in scattering resulting from our fiber design then improves the performance of our fiber for Rayleigh based sensing as well. Note that while the example in Fig. 5 shows a weak, fixed FBG period meant for OFDR interrogation, the flexibility of our writing apparatus would allow for a more conventional set of stronger discrete Bragg gratings at a range of wavelengths that would be suitable for wavelength division multiplexed (WDM) interrogation of our sensor array.

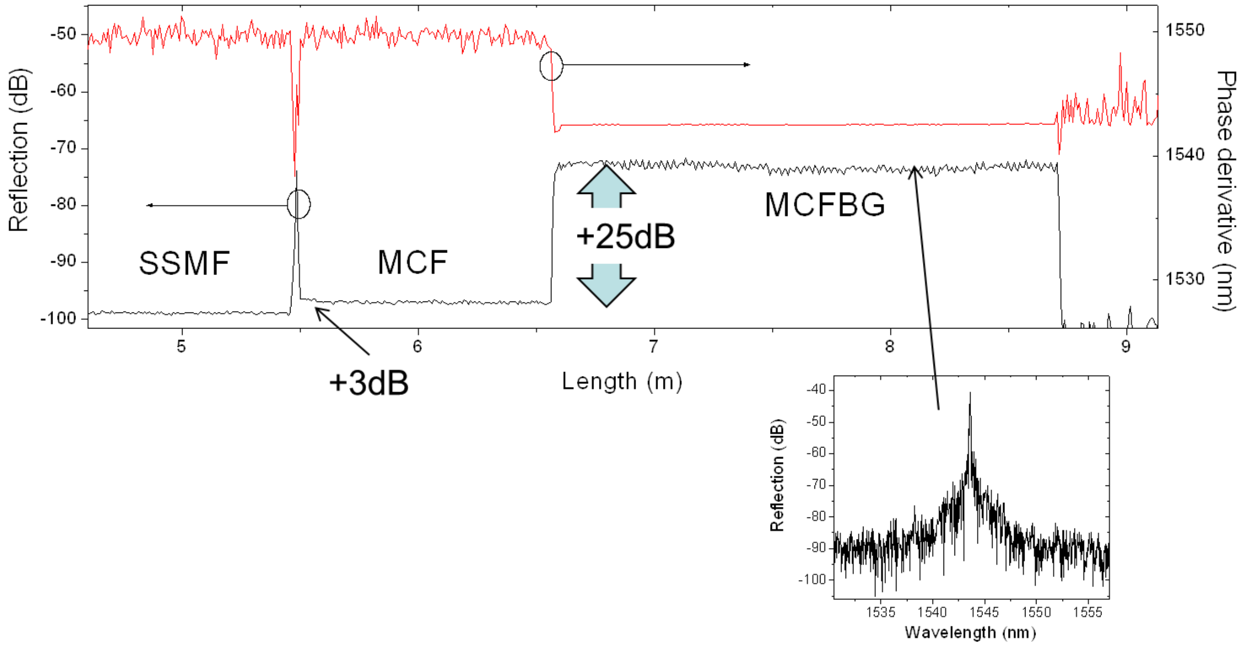


**Figure 5** OFDR (LUNA OBR) trace of a 2m long continuous FBG array. The black curve shows the reflected intensity as a function of position. A clear jump in the Rayleigh scattering intensity is observed at the splice from standard single mode fiber (SSMF) to the multicore fiber (MCF) near 5.5m. A 25dB increase in signal is observed near 6.6m where the multicore FBG (MCFBG) begins. The red curve shows the local Bragg wavelength, which is inversely proportional to the spatial phase derivative. In the Rayleigh scattering region, the phase derivative is very noisy, while within the Bragg grating very little noise is observed. The inset shows the spectrum extracted from a 1cm section within the grating.

Because the backreflection giving rise to the sensor signal is very low, it is important for the distal end of the fiber to be terminated so that there is minimal reflection. High return loss at the distal fiber end can result in reduced accuracy near the end of the sensor While a conventional angle cleave is the most efficient termination and can often achieve the required termination efficiency, the yield for this process is not sufficient for a manufacturable shape sensor. Moreover, such a cleaved endface is not protected sufficiently to maintain a specified return loss during normal handling of the sensor. We have developed a more robust termination based on polished and coated optical fiber. Such a termination is both effective, compact and robust to external effects such as liquids, dirt and other contaminants. Moreover, there is no thermal treatment of the fiber, meaning that the fiber mechanical strength is maintained near the termination.

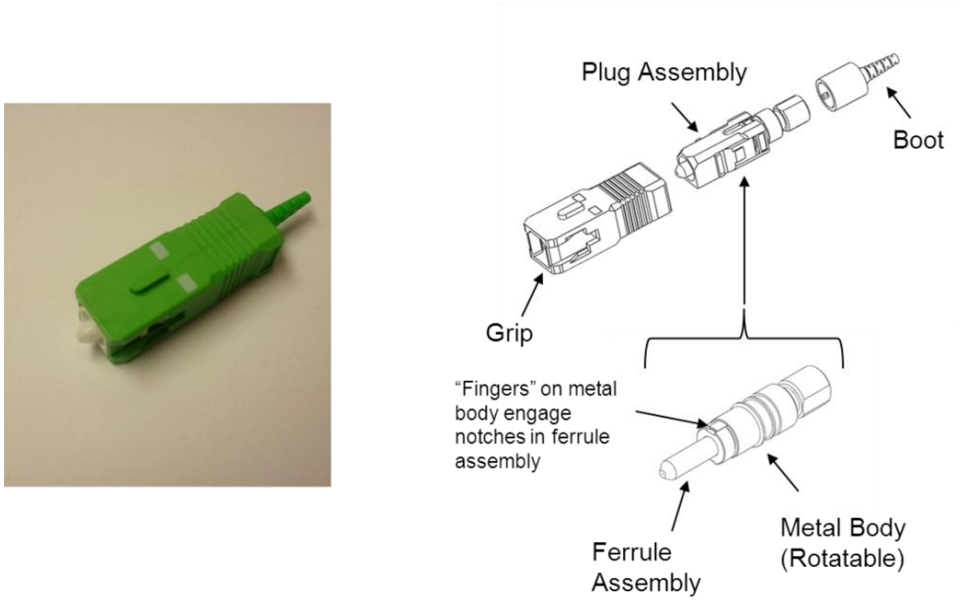


**Figure 6** Continuously rotatable SC APC multicore connector used to terminate the sensor array, jumpers and fanout.

One of the main constraints for shape sensing is that the sensor is modular. Because the interrogator is very expensive, its cost models require that it be used on many sensor arrays and that these arrays are, in some cases, consumable items. As a result, it is essential that the sensor array have a multicore connector that allows it to function with any interrogator. Multicore jumpers are also required in this scheme to increase the flexibility of the system setup. In many cases, it is important that the connectors and jumpers are made from the same twisted fiber that makes up the sensor. Thus, both twisted and untwisted connector varieties are required. Fig. 6 shows a picture and schematic of the multicore connector.

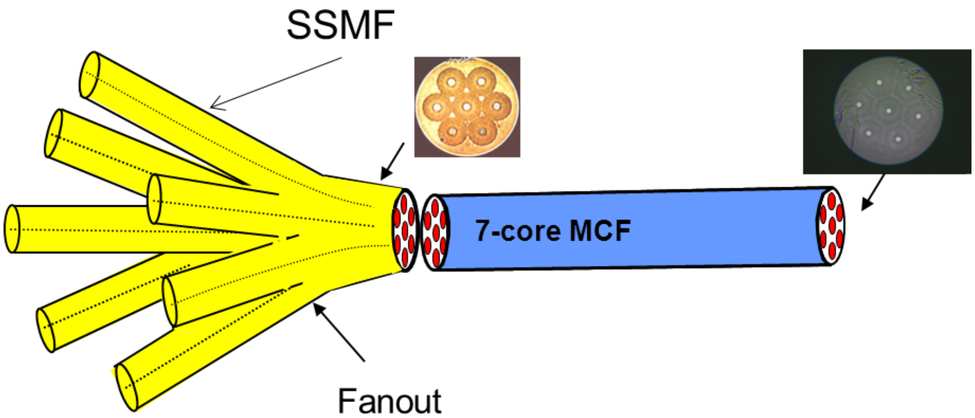


**Figure 7** Tapered fiber bundle fanout connecting seven single core standard single mode fibers (SSMF) to a single multicore fiber.

A critical fiber component when using any multicore optical fiber is a fanout that allows efficient, low loss connection between SSMF interrogator components and the multicore shape sensor assembly. OFS has developed a fanout based on its extensive product line of tapered fiber bundles used in fiber laser modules. Fig. 7 shows a schematic of this tapered fiber bundle device. A bundle of specialized single mode fibers is fused and tapered into an multicore fiber assembly whose spacing matches that of the MCF. Precision splicing allows a stable connection to both twisted and untwisted multicore fibers.

## 4. CONCLUSION

We have discussed a complete set of optical components suitable for optical fiber shape sensing applications in medical, industrial, and other applications. These include twisted optical fiber with multiple cores, multicore fiber splicing, fiber gratings for increased scattering efficiency, multicore connectors and jumpers, fiber termination, and single core to multicore fanouts. Our components are aimed particularly at medical applications that require robust, compact, high speed and highly accurate measurements. Connectorized parts allow end users the flexibility to configure the sensor for many applications in the medical market and beyond. In this work we demonstrate weak quasi-continuous Bragg gratings suitable for shape sensing based on optical frequency domain reflectometry (OFDR). However, our fiber also shows enhanced Rayleigh scattering over standard single mode fiber, making it attractive for Rayleigh scattering based shape schemes as well. Moreover, our sensors can be fabricated with grating arrays suitable for interrogation schemes beyond OFDR, including wavelength and time division multiplexed systems.

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