A multicore optical fiber for distributed sensing

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ABSTRACT

With advancements in optical fiber technology, the incorporation of multiple sensing functionalities within a single fiber structure opens the possibility to deploy dielectric, fully distributed, long-length optical sensors in an extremely small cross section. To illustrate the concept, we designed and manufactured a multicore optical fiber with three graded-index (GI) multimode (MM) cores and one single mode (SM) core. The fiber was coated with both a silicone primary layer and an ETFE buffer for high temperature applications. The fiber properties such as geometry, crosstalk and attenuation are described. A method for coupling the signal from the individual cores into separate optical fibers is also presented.

Keywords: distributed sensing, optical fiber, multicore, Raman, DTS

1. INTRODUCTION

Optical fibers—small, lightweight, immune to electromagnetic interference, and having low loss over a wide wavelength range—are ideal for transmitting light signals over long distances. Furthermore, glass optical fibers have high mechanical strength and can work over a broad temperature range if coated with suitable protective layers. Rayleigh, Raman and Brillouin back-scattering in fibers can provide localized temperature, strain, polarization and vibration information along the fiber, creating very long, high-resolution sensor devices. As such, optical fibers are well-suited to distributed sensing in small cross-sectional spaces and have found successful use in a wide variety of applications including civil structures, transmission lines, and down-hole monitoring, among others [1].

To improve overall system performance, many of these distributed fiber sensing systems use multiple fibers. For example, systems use both single mode (SM) and multimode (MM) fibers to simultaneously measure several parameters such as temperature and strain. In many oil well monitoring systems, multiple fibers measure the temperature and pressure along with acoustic vibrations. Of particular interest to us is the use of multiple fibers in a bidirectional loop configuration, deployed in distributed temperature sensing (DTS) systems to achieve a reliable and high accuracy temperature measurement over long distance [2, 3]. DTS systems of this sort typically use graded index (GI) MM optical fibers as the sensing medium and measure the temperature along the fiber by the ratio of the back-scattered Raman Stokes to anti-Stokes (AS) intensities. The measured power of the Stokes and AS components is affected by the wavelength dependent loss (WDL) at the Stokes and AS wavelengths. Errors can be introduced into the measured temperatures if this WDL is not corrected. WDL can be caused by splices, stress on the optical fiber, fiber degradation in hydrogen environments and radiation; it can also vary over time. Various methods have been proposed to correct the WDL induced temperature error. One commonly used approach is a double-ended (or loop-back) system: two parallel fibers are connected at the distal end creating an elongated U-shaped optical pathway where light can be coupled into either leg at the proximal end of the system and where Raman Stokes can be acquired from either proximal end. The WDL can be then be corrected and the temperature error associated with it eliminated. This double-ended setup is also deployed in other sensing schemes to improve the signal-to-noise ratio.

When multiple fibers are bundled together within a space-limited installation cable, problems such as congestion of the conduit and error associated with fiber length mismatch will be created. This paper investigates multicore fiber (MCF), a single optical structure containing more than one core, as a small-diameter sensing element to provide a high-density waveguide count. This approach solves the problem of conduit and/or installation cable congestion and eliminates fiber-to-fiber positional error as each waveguide in the MCF is permanently fixed in its parallel configuration with respect to other waveguides in the MCF structure.

MCF has been proposed and demonstrated in communication applications. These MCFs include multi-SM cores for long haul communications [4, 5]—from seven cores in a 130 µm diameter cladding to 19 cores in a 200 µm diameter cladding. They also include multi-MM cores for short-reach optical links in data centers [6]. These MCFs are typically coated with acrylate materials that are unsuitable for applications with higher temperatures and harsh environments, such as may be encountered in many industrial sensing applications. Another important problem for MCF is how to connect the MCF to individual fibers for coupling the signals in and out of the MCF. This is typically accomplished by using either a tapered fiber bundle that is specifically designed to match the geometries of the MCF or bulk optics [7], both of which tend to be expensive. So, easily connecting to traditional single-core fibers is an important factor that must be considered when the MCF is designed.

In this paper we will report a low crosstalk MCF with three MM GI cores and one SM core. The properties of MCF including waveguide geometry, attenuation and crosstalk will be described. A practical mechanical interconnect between the MCF and single-core MM fiber commonly used in Raman DTS system is proposed and is demonstrated with reasonable insertion loss.

2. MULTICORE FIBER

2.1. MCF geometries

The MCF was drawn with a custom preform made using a rod-in-tube method, similar to that used in making commercially available polarization maintaining (PM) fiber.

The MCF has three GI MM cores and one SM core. An end-face image of the MCF is shown in Figure 1. The numerical aperture (NA) of the MM cores is 0.20 and the diameter is 50 µm. These MM cores are interoperable with single-core 50/125 GI fibers typically used in DTS systems. The SM fiber has a core size of ~9 µm, an NA of 0.12 and is designed for single-mode operation at wavelengths above 1300 nm.

The four cores are arranged in a square shape as shown in Figure 1 and located on a circle with a radius of 62.5 µm that is concentric to the cladding. The distance between the adjacent cores is 85 µm measured from the core centers. The outer glass cladding diameter is 250 µm to provide space between the cores, thus minimizing core-to-core crosstalk. The increased cladding diameter of 250 µm provides an additional reliability benefit by improving the fiber break strength to roughly four times that of a traditional 125 µm clad diameter optical fiber.

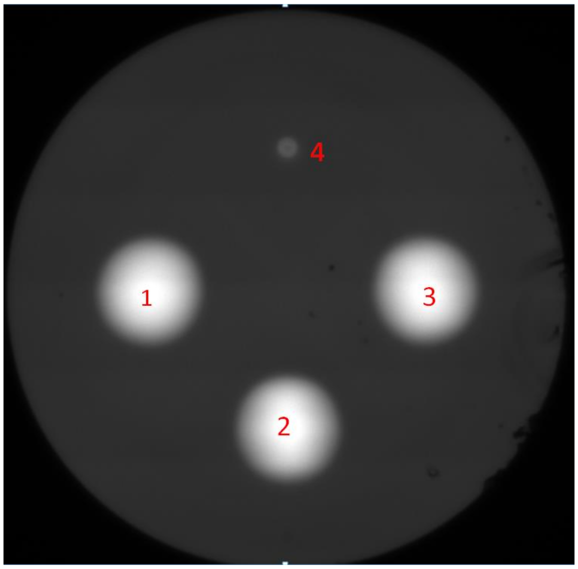

Figure 1. End-face image of the multicore fiber taken by an optical microscope with the fiber illuminated from both ends

The MCF cladding layer is further coated with a silicone primary coating and an ETFE buffer for high temperature applications (up to 125˚C) and with good chemical and abrasion resistance. The diameter of the ETFE buffer is 600 µm, small enough to fit into very small spaces such as the 1/8" metal tubes often used for delivery in high temperature oil well sensing.

The measured fiber geometries are shown in Table 1. The numerical aperture (NA) and core diameter are measured by launching light into the individual cores with a GI launching fiber (62.5 µm core diameter, 0.275 NA) to achieve the overfilled launch conditions required with industry-accepted testing methods. The locations of the cores are calculated in the polar coordinate system, with the cladding center as the coordinate center.

Table 1. Measured geometries of the MCF fiber

	Diameter (µm)	Core locations		Numerical aperture at 850 nm
		Radial distance (µm)	**Angle (degree)**	
Core-1	49.6	59.9	178.5	0.200
Core-2	49.2	61.3	272.8	0.202
Core-3	49.4	60.4	0	0.202
Core-4	8.9	62.8	87.7	-
Cladding	249.5	-		-

2.2. Fiber properties

The spectral attenuation of the MCF was measured by the cutback method using a PK2500 optical bench with a short segment of 50/125 fiber to launch light into the MM cores. The spectral loss of one of the MM cores is shown in Figure 2. It is similar to that of a commercially available single-core 50/125 µm GI fiber. The loss is 1.3 to 0.95 dB/km in the wavelength range of 970 to 1150 nm. The ripples in the spectral attenuation curve are most likely caused by the cladding modes, since this particular silicone has a lower refractive index than that of silica. The SM core attenuation was measured by an optical time-domain reflectometer (OTDR), displaying optical loss of 0.54 dB/km at 1310 nm and 0.7 dB/km at 1550 nm. The designed cutoff of the SM core is about 1200 nm, and the mode field diameters (MFDs) at 1300 and 1550 nm are 9.0 and 10.3 µm respectively.

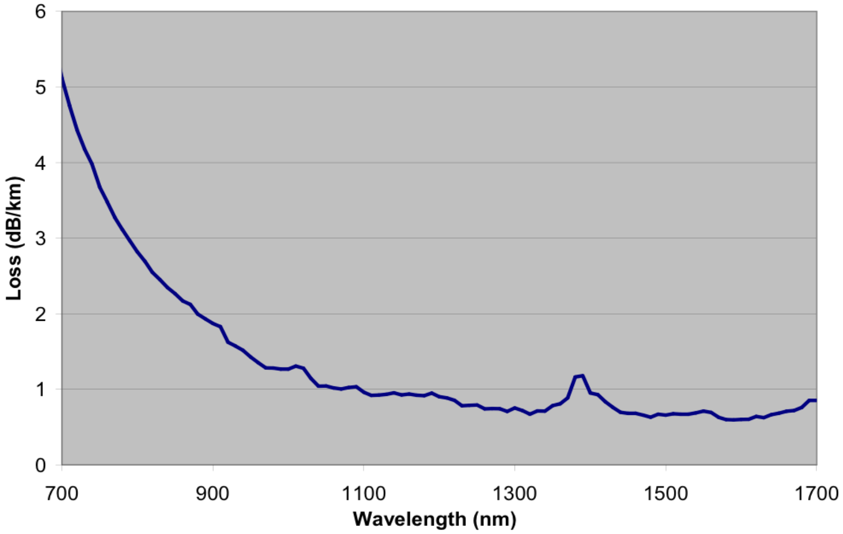

Figure 2. Spectral attenuation of one of the MM cores as measured by the cutback method.

Optical crosstalk between cores is an important factor for MCF to be used in distributed sensing applications. High crosstalk creates an undesirable condition where it is possible for light from one core to be coupled into adjacent cores if proximity is not well controlled. In addition, bend-induced core-to-core crosstalk must be considered in the spacing pattern for the final waveguide geometry.

Crosstalk was measured by launching light from a 50/125 fiber into core 2 and scanning the optical power at the output end face of the MCF with another section of 50/125 fiber. The crosstalk is the ratio of the optical power from core 2 to the optical power from core 1 or core 3. The measured crosstalk from core 2 to core 1 or core 3 is less than 40 dB with 400 meters of MCF coiled onto a 10-inch spool at a wavelength of 1064 nm. 1064 nm was used in this assessment as it is the wavelength of greatest interest with many commercially available DTS measurement systems. Assessment of crosstalk at alternative wavelengths is also possible but falls outside of the scope for this paper.

3. MULTIFIBER CONNECTOR

Connecting single-core fibers to the MCF and accessing each core is one of the difficult challenges for practical use of MCF. The MCF we produced was designed for easy mating to commercially available single-core optical fibers: the core-to-core spacing is large and the core sizes match standard fibers, simplifying the task of mechanical connection. To accomplish coupling, a connector was made with three single-core GI MM fibers and one single-core SM fiber as shown in the connector end-face image in Figure 3.

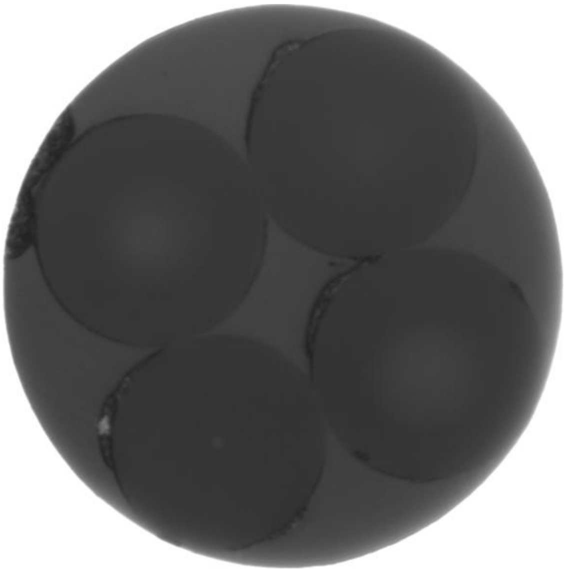

Figure 3. End-face image of the connector with three single-core GI MM fibers and one single-core SM fiber.

The three MM fibers each have a cladding diameter of 85 μm and core diameter of 50 μm. The SM fiber has a cladding diameter of 80 μm. The locations of the four fibers inside the ferrule were measured and the distances from the center of the ferrule are shown in Table 2. We can see that the offsets of the four fibers in the connector closely match those of the MCF, though the discrepancy of core 3 is large. To measure the insertion loss, the multi-fiber connector was butt-coupled to the MCF connector in a mating adaptor, and the connectors were rotated until the lowest insert loss was achieved. The insertion loss of the three MM cores were measured at 1064 nm and the SM was measured at 1550 nm. The insertion loss of the individual cores is listed below.

Table 2. Measured insertion loss of the multi-fiber to MCF connection

	Offset from ferrule hole center (μm)	**Insertion loss (dB)**
Core 1	60.1	0.6
Core 2	59.6	0.7
Core 3	55.4	1.0
Core 4	63.3	3.1

4. CONCLUSION

In summary we manufactured a MCF with low loss that is suitable for distributed sensing in harsh environments. The MCF includes four separate cores in a very small cross-section, with low cross-talk between cores. Furthermore, through this experimentation, we demonstrated the practicality of using mechanical interconnects to achieve reasonable insertion loss between MCF cores and traditional, commercially available optical fibers.

5. ACKNOWLEDGEMENT

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