Highly birefringent 98-core fiber

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We report on the fabrication and characterization of a polarization-maintaining multicore fiber. The fiber has 98 aligned cores, each with a birefringence of $\approx 2.3 \times 10^{-4}$. The beat length, polarization extinction ratio, and polarization orientation are characterized. © 2014 Optical Society of America

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Multicore fibers or fiber bundles have been developed for clinical endoscopic applications since the 1950s and very little has changed in their intrinsic design [1]. Often the best fiber design for a specific endoscopic application, such as fluorescence endomicroscopy [2], requires fitting as many uncoupled cores as possible into a fiber of convenient size such that it may fit into a specific orifice or incision with minimal discomfort to a patient. This results in clinical endoscopic systems incorporating fibers with tens of thousands of dissimilar cores which are scanned proximally in order to build up an image. Dissimilar cores are used to reduce core-to-core coupling. Alternative approaches are to scan the distal end of a single mode fiber or scan the output light by means of mirrors. In these latter cases the probe size is limited by the physical size of this distal scanning mechanism, rather than the fiber size, typically to a few mm.

Recent developments in multicore fiber endomicroscopy (specifically for two photon excitation) suggest moving from the one-core-one pixel scanning approach to an imaging modality where each individual core is part of a phased array [3–5]. A spot can be formed and scanned at the output by adjusting the phases in each individual core. This allows for miniaturization of the fiber optic probe by eliminating the need for any distal optics. None of the fibers reported to date have been designed to preserve the polarization of the input light. Polarization preserving cores would be an obvious advantage to fibers used for multiphoton endoscopic imaging techniques as well as reducing cross polarized (and hence redundant) light in a phased array reconstruction.

Here, we present a simple highly birefringent (HiBi) multicore fiber designed to deliver polarized light. The fiber is based on the use of stress birefringence [6] and has significantly more cores than a previously reported multicore polarization preserving microstructured fiber [7]. It incorporates individual cores flanked by boron-doped silica inclusions designed to apply stresses and introduce anisotropy in the cores. We describe the fabrication and report on the characterization of the polarization properties of the fiber.

The multicore HiBi fiber was fabricated using the stack and draw technique commonly used for photonic crystal fiber fabrication [8]. Ninety-eight individual graded index germanium doped rods (Draka-Prysmian, NA = 0.21) were jacketed with pure silica and used to form the cores. To form the stress applying parts (SAPs), thin walled capillaries were stacked on either side of each core and, after the stack was complete, 18% boron doped silica rods (Draka–Prysmian) were inserted into the capillaries. Rows of cores and SAPs were alternated with rows of pure silica rods to reduce off-axis effects of the SAPs on the cores. The cores and SAPs were also positioned in the same location in each row, giving a rectangular array of cores from a hexagonal stack. The stack was drawn to preforms (each approximately 3.2 mm in diameter) and then to fiber with an outer diameter of 230 μm. An optical micrograph of the final fiber is shown in Fig. 1. The center-to-center separation of the cores is 16 μm on one axis and 14 μm on the other; the diameter of each core was 2 μm and the diameter of each SAP was 7 μm. The fiber was designed for single mode use at 800 nm and was measured to be single mode at wavelengths greater than 600 nm. Significant coupling between adjacent cores was not observed at a wavelength of 800 nm over short lengths appropriate for endomicroscopy. At longer wavelengths, coupling could be observed between adjacent cores with no low index inclusion between them. The loss, measured through a

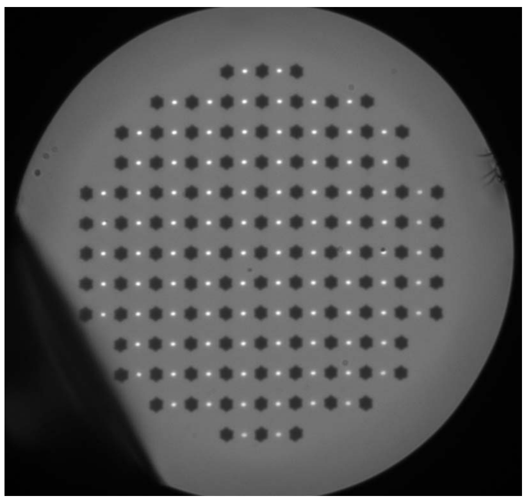

Fig. 1. Optical micrograph of the HiBi multicore fiber. The white regions are germanium doped silica cores and the black regions are boron doped silica SAPs. The outer diameter of the fiber is 230 μm, the cores are 2 μm in diameter and set on a 16 μm × 14 μm grid. The diameter of each stress applying region is 7 μm.

50 m cutback over all of the cores, was 26 dB/km at 800 nm.

The polarization beat length of several cores at various locations within the fiber was measured using the side scanning technique [9]. In this technique both polarization modes of a core are excited and can be observed beating against one another through the side of the fiber using a camera with an exposure time of several seconds. The light source used to excite the polarization modes was a 633 nm continuous wave helium neon laser. The polymer coating of the fiber was stripped off several centimeters, and the stripped section of fiber was placed under a microscope. The side of the fiber was observed with a silicon CCD camera through the microscope. The total length of four maxima for the beating polarization modes was measured for several cores in different locations around the fiber. In each measured core the beat length (L_b) was observed to be 2.8 mm giving a birefringence (B) of

$$B = \frac{\lambda}{L_b} = 2.3 \times 10^{-4}$$

comparable to that of commercial single core HiBi fibers [10].

The alignment of the polarization axes of the cores was investigated. Light from a polarized supercontinuum source [11] was passed through an 800 nm bandpass filter. The polarization of the light incident on the fiber endface was controlled with a half wave plate, and a rotating polarizer was placed at the fiber output. The fiber length was 3.6 m. The output beam could be either imaged onto a CCD camera to launch light into a certain core or, by means of a flip mirror, onto a power meter. A quarter of the cores were tested so all possible applied stresses were accounted for. A schematic representation of the fiber with the notation used is shown in Fig. 2. The minimum transmitted light was found in each core by rotating the half wave plate and the polarizer at the output. The orientation of the half wave plate was noted and the corresponding angle of the polarized light (twice that of the half wave plate) is recorded in Table 1. The angle of the half wave plate could be accurately determined to one degree corresponding to two degrees of polarization angle. The mean polarization orientation is taken to be 0° in Table 1. The polarization only deviates from the average by ±3° with the majority of values lying within ±1°.

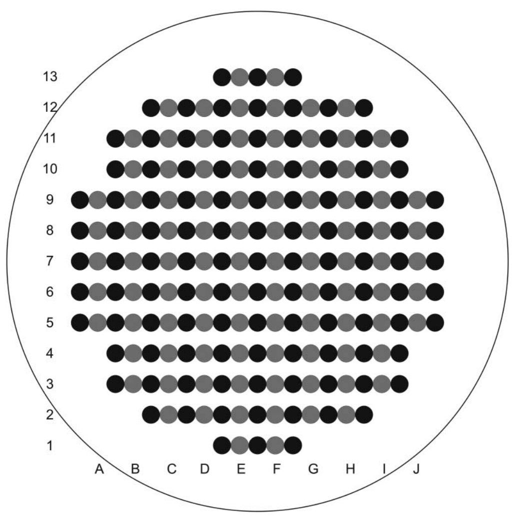

Fig. 2. Schematic diagram showing core notation for the ninety eight core fiber. The locations of germanium doped cores are shown in gray and identified by a letter and number, boron doped regions are indicated in black.

During the measurements of the polarization state alignment, the output polarizer was also rotated to allow the maximum transmittal of light. From this, the polarization extinction ratio (PER) over the 3.6 m length could be calculated (in dB) for each core

$$\mathrm{PER} = 10 \log(P_{\max}/P_{\min}),$$

where $P_{\max}$ and $P_{\min}$ are the maximum and minimum transmitted powers, respectively. The mean value of the PER for all the tested cores was 19 dB; individual values for each measured core are shown in Table 1.

In summary, we have presented a simple fiber which can propagate light through 98 cores while maintaining the polarization state in each individual core. The birefringence was measured to be 2.3×10^{-4}, and the polarization orientation of each core was found not to vary by more than ±3°. The birefringence compares well with single core HiBi fibers showing that the introduction of further stress inducing elements into a HiBi fiber does not result in a degraded performance. In future work we plan to change the positioning of the individual cores to optimize the fiber design for multiphoton microscopy and incorporate a low index outer jacket to improve the signal collection efficiency at the distal end of the fiber and return it to the proximal end.

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Table 1. Polarization Orientation and Extinction Ratio

Core					E13
Offset (deg)					1
PER (dB)					19
Core			C12	D12	E12
Offset (deg)			3	−3	1
PER (dB)			19	19	19
Core		B11	C11	D11	E11
Offset (deg)		−1	−1	−1	−1
PER (dB)		20	18	20	19
Core		B10	C10	D10	E10
Offset (deg)		1	−1	1	1
PER (dB)		20	19	19	19
Core	A9	B9	C9	D9	E9
Offset (deg)	1	−1	1	−1	−1
PER (dB)	18	18	19	19	19
Core	A8	B8	C8	D8	E8
Offset (deg)	−1	−3	−1	−1	−1
PER (dB)	20	18	19	19	19
Core	A7	B7	C7	D7	E7
Offset (deg)	−1	1	1	−1	1
PER (dB)	20	19	19	20	19

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