Video Article

Writing Bragg Gratings in Multicore Fibers

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URL: https://www.jove.com/video/53326
DOI: doi:10.3791/53326

Keywords: Engineering, Issue 110, Fiber optics, fiber Bragg gratings, multicore fiber, fiber Bragg grating fabrication, astrophotonics, beam propagation, atmospheric suppression

Date Published: 4/20/2016

Citation: Lindley, E.Y., Min, S.s., Leon-Saval, S.G., Cvetojevic, N., Lawrence, J., Ellis, S.C., Bland-Hawthorn, J. Writing Bragg Gratings in Multicore Fibers. *J. Vis. Exp.* (110), e53326, doi:10.3791/53326 (2016).

Abstract

Fiber Bragg gratings in multicore fibers can be used as compact and robust filters in astronomical and other research and commercial applications. Strong suppression at a single wavelength requires that all cores have matching transmission profiles. These gratings cannot be inscribed using the same method as for single-core fibers because the curved surface of the cladding acts as a lens, focusing the incoming UV laser beam and causing variations in exposure between cores. Therefore we use an additional optical element to ensure that the beam shape does not change while passing through the cross-section of the multicore fiber. This consists of a glass capillary tube which has been polished flat on one side, which is then placed over the section of the fiber to be inscribed. The laser beam enters the fiber through the flat surface of the capillary tube and hence maintains its original dimensions. This paper demonstrates the improvements in core-to-core uniformity for a 7-core fiber using this method. The technique can be generalized to larger multicore fibers.

Video Link

The video component of this article can be found at https://www.jove.com/video/53326/

Introduction

Fiber Bragg gratings (FBGs) are widely used as narrowband filters due to the fact they can be customized for a large number of applications[1]. They are not limited to suppressing single wavelengths; complex transmission spectra can be created by the use of aperiodic refractive index variations[2]. One limitation is that FBGs can only be inscribed in single-mode fibers (SMFs), as the wavelength that is suppressed for a given grating period depends on the propagation constant. In a multimode fiber (MMF), where each mode has a different propagation constant, the suppressed wavelength for each mode is different and hence the grating does not give strong suppression at any single wavelength.

The impetus for this experiment comes from astronomy. Under seeing-limited conditions, direct coupling into an SMF is difficult and inefficient; extreme adaptive optics are required to do so[3]. Because of this, MMFs are typically used when collecting light from the telescope focal plane[4]. Therefore in order to keep the functionality available only to SMFs, it is necessary to have efficient conversion between SMFs and MMFs. This is made possible with the photonic lantern, a device which consists of a multimode port connected to an array of SMFs via a taper transition[5]. Photonic lanterns were used in the GNOSIS instrument, in which the SMFs contained FBGs to remove atmospheric emission lines (caused by OH radicals and other molecules) from near-infrared observations[6]. The drawbacks of using individual, single-core SMFs for this task are that they must be written one by one and spliced individually into the optical train, requiring significant time and manual effort. The technique described in this article attempts to address these shortcomings using a more complex fiber format to provide the single-mode functionality.

The next generation OH suppression instrument PRAXIS[7] will make use of multi-core fibers (MCFs). These fibers contain any number of single-moded cores embedded in a single cladding. The advantage of this approach is that the MCF can be tapered into an MMF with the resulting photonic lantern being a compact and robust self-contained unit. In the completed instrument, light from the telescope will be coupled into the MMF port of the lantern; the taper transition will separate this light into the single-mode cores where it will pass through the FBGs. After the wavelength filtering the remaining light is dispersed onto a detector, the spectra collected.

Using MCFs also speeds up the process of writing gratings, as all cores can be inscribed in a single pass. However, the writing process must be modified in order to ensure that all cores have the same reflection characteristics. This is because the curved surface of the cladding acts as a lens during side-writing of the FBGs, resulting in a UV field which varies in power and direction at each core if the standard side-writing method is used. Hence each core will have a different transmission profile, and the fiber will not provide strong suppression at a single wavelength[8].

A group at the Naval Research Laboratory experimented with modifying the distribution and photosensitivity of cores to cancel the effects of this variation[9]. The downside of using such an approach is that the fiber must be redesigned for every combination of cladding size, core size, number of cores and chemical composition. In addition, the lack of axial symmetry in the resulting designs means that the MCF cannot be effectively tapered into an MMF with a circular core. This paper details a different approach to the problem: modifying the field within the fiber by having it pass through a flat surface instead of being directly incident on the curved cladding. Using this approach results in a technique which is transferable to a variety of MCF designs and sizes, particularly the axially symmetric fibers which we wish to incorporate into photonic lanterns.

To create the necessary flat surface, the MCF is placed inside a UV-transparent capillary tube which has been ground and polished on one side to give a flat outer wall. A small gap must be left between the fiber and capillary, since the latter may contain ±10 µm variations in diameter. See **Figure 1** for a representation. This paper will describe the experimental procedure to write FBGs in this manner and provide examples of the possible improvements. For more information see previously published simulations[10] and experimental results[11].

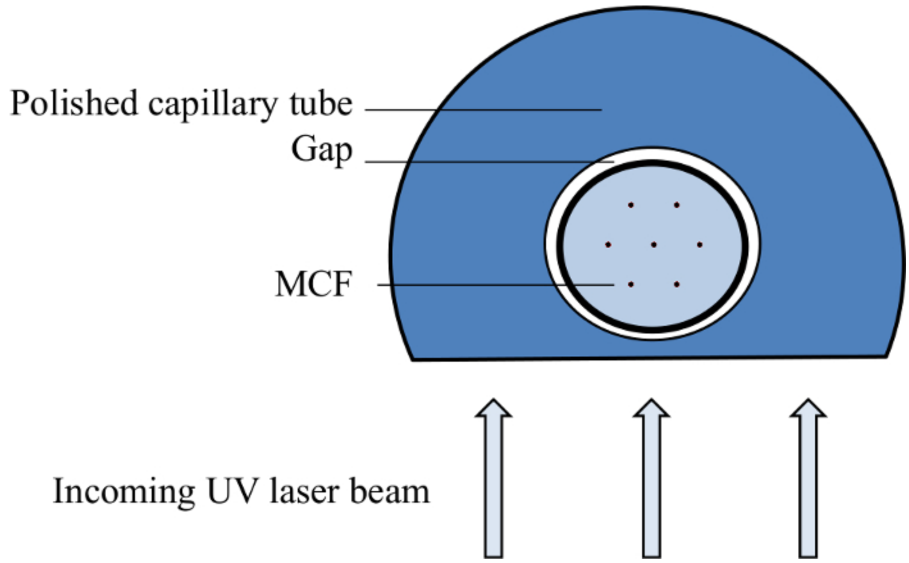

Figure 1. Diagram of polished capillary tube as used in FBG production. The MCF is placed inside the capillary tube. The gap between the two should be small but allow for small variations in diameter. The UV light which has passed through the phase mask then enters the system through the flat side of the capillary tube. Please click here to view a larger version of this figure.

Protocol

1. Preparation of Polished Capillary Tubes (ANFF OptoFab)

1. Obtain glass capillary tubes with inner diameter closely matched to fiber diameter. The closer in size, the better the performance, but ensure that a ±10 µm variation in capillary size is allowed for. Remove any protective coatings from the capillary tubes. Shave off coatings with a razor blade to remove them without damaging the tubes.
2. Taper the capillary tubes to a smaller diameter if required. Use a computer-controlled automatic tapering machine if available.
    1. Secure a length of tubing with clamps at either end.
    2. Heat the capillary to melting point evenly around its diameter using a hot filament located between the clamps.
    3. Draw the capillary through the heating element with a constant tension until the desired length has been tapered to the smaller diameter.
3. Cut the capillary tube into approximately equal lengths with a glass cutting tool. Ensure that these are at least 2 cm longer than the intended grating length but small enough to fit within the polishing equipment used. Note: For this experiment, a capillary length of 7 cm was used.
4. Attach 8-10 of the capillary lengths to a glass puck using UV-curable glue. Install the puck onto a jig compatible with the lapping/polishing machine.
5. Use the lapping/polishing machine to grind the exposed walls of the capillary tubes to a flat surface. CAUTION: Do not inhale loose grit. Note: The abrasive element is Al_2O_3 in a suspension of reverse-osmosis purified water.
    1. Use 25 µm grit until the remaining thickness of the capillary wall is approximately 70 µm. Use a micrometer to measure the displacement of the jig during grinding and hence the amount that has been removed.
    2. Switch to 5 µm grit and grind until the remaining thickness of the wall is approximately 50 µm.
6. Use the lapping/polishing machine to polish the flattened surface for at least 3 hr with high-purity colloidal silica in alkaline dispersion (NaOH). Note: This restores the surface to optical quality. The silica can be prevented from solidifying by adding 1 part 0.004 M NaOH to 3 parts polishing solution.
7. Separate the capillary tubes from the holding puck by soaking overnight in acetone.
8. Examine the capillary tubes at both ends under a microscope with 10X magnification to check the wall thickness. Note: A good quality capillary will have a uniform thin (~ 50 µm) wall along its length.

2. Creation of Gratings

1. Hydrogenate the MCF to increase photosensitivity.

1. Place the fibers to be hydrogenated into a sealed airtight chamber. CAUTION: Ensure the chamber is securely bolted due to the presence of pressurized gases.
2. Pump high purity H_2 into the chamber. Use N_2 gas as a booster to increase pressure.
3. Leave the fibers inside the chamber for an extended period: 2 weeks at 300 bar and room temperature, or 3 days at 380 bar and 80 °C.
4. Vent the gases from the chamber and remove the fibers. CAUTION: Ensure the room is well ventilated. Gases may act as asphyxiants, or fire risk in the case of H_2.
5. Keep the fibers in a freezer with temperature -70 °C or below until they are used. This slows the rate of hydrogen outgassing and preserves the increased photosensitivity.

2. Strip the protective coating from the MCF. Strip MCFs the same size as SMFs with a standard SMF fiber stripper; otherwise shave off the coating with a razor blade. Remove the coating from the region where the grating is to be written, all the way to the end of the fiber.
3. Insert the stripped end of the fiber into the capillary tube, and slide the tube along the fiber so that it covers the region to be inscribed.
4. Put on UV-protective eyewear. Mount the fiber on the moving stage which holds the phase mask, with the flat side of the capillary tube angled towards the phase mask. Ensure the fiber is positioned within the interference pattern created by the mask, but not touching the mask itself as this may cause damage.
5. Align the 244 nm laser so that the beam is perpendicular to the flat surface of the phase mask. Ensure that the fiber receives at least 90 mW of laser power.
6. Expose a 4 cm length of the fiber to the UV interference pattern by moving the fiber and phase mask together with respect to the incoming beam at a rate of 0.25 mm/min.
7. Remove the capillary tube from the fiber.
8. Anneal the grating at 110 °C for 20 hr to stabilize the wavelength response. Note: This step is optional as the grating will stabilize by itself over the course of approximately three days, but annealing makes the process faster.

3. Analysis of Spectra

1. Cleave both ends of the fiber. Use a fiber cleaver that allows the user to set both fiber diameter and tension to ensure a flat end surface.
2. Illuminate one end of the fiber using a tunable laser with a central wavelength approximately matched to the Bragg wavelength.
3. Connect a CCD camera to a PC with control software to display and record the fiber output. Image the fiber output with the CCD camera, using a microscope objective lens with 50X magnification in front of the camera to ensure that all cores cover multiple CCD pixels. Note: The following steps 3.4.1 – 3.5.5 are specific to the custom software used by the authors and represent only one method of capturing spectra.
    1. Select a circular region of pixels corresponding to each core by clicking on the centers of cores as they appear in the image in the control software. Enter the diameter of the cores in units of pixels in the 'Length or Diameter' field.
    2. Record the pixel values registered by the camera for the selected regions. Sum the values for all pixels covering a given core to quantify the total throughput at that wavelength.

4. Connect the tunable laser to the control PC so that observations and data collection can be automated.
    1. Enter a wavelength approximately 5 nm below the Bragg wavelength in the 'Start Wavelength' field.
    2. Set the wavelength increment of the laser to 0.01 nm in the 'Scan - Step' field. Note: Set the delay between steps to at least 300 msec so that lasing is stable at each wavelength before measurements are recorded and the next wavelength step occurs.
    3. Enter a wavelength approximately 5 nm greater than the Bragg wavelength in the 'End Wavelength' field.
    4. Click the 'Automatic Scan' button to set the laser to the defined Start Wavelength and increase the wavelength by the chosen increment at regular time intervals.
    5. Record the intensity transmitted through each core for each wavelength step. Export the calculated values to a text file by enabling the 'Text File Save' option.

5. Repeat the scan at least 3 times and average the data from all runs.
6. Plot transmitted power versus wavelength for each core to generate a set of spectra.
    1. Compare the spectra of all cores to confirm whether they have the same suppression characteristics. Check that the central wavelength, depth and bandwidth of each grating match.

Representative Results

The effectiveness of this technique is best demonstrated by comparing the multicore fiber Bragg gratings (MCFBGs) that result from exposure with and without the capillary. **Figure 2** shows the transmission characteristics of a 7-core MCF exposed using the standard method for SMFs, with individual core spectra represented by different colors. There is minimal overlap between the suppressed wavelengths, and core #5 has received weaker exposure resulting in a shallower notch. Both effects are due to variations in power within the fiber during the writing process. Note that the flat cutoff at -36 dB is due to the limited dynamic range of the camera; all transmission values are scaled relative to this minimum.

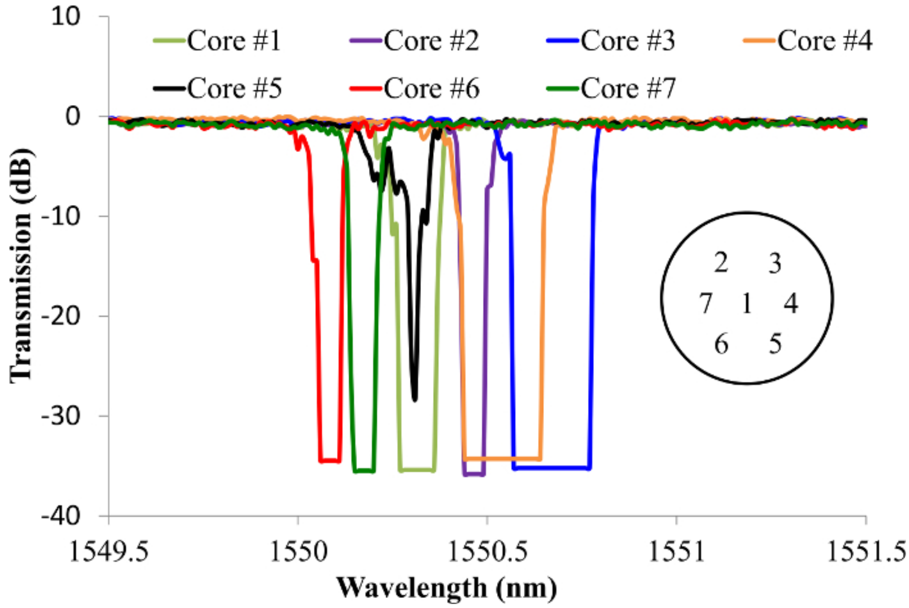

Figure 2. Performance of MCFBG cores with no compensation for lensing. This plot shows the transmission spectra of individual cores when the MCFBG is produced using the standard method for SMFs. There is minimal overlap between notches. (Inset) Diagram of core numbering. Adapted from previous publication[11]. Please click here to view a larger version of this figure.

In **Figure 3**, the same data is shown for an identical fiber which was exposed inside a capillary tube with inner diameter 140 µm. (Note that the Bragg wavelengths are approximately 2 nm lower than in the previous case as this grating was annealed before measurement. The variation between cores is maintained before and after annealing.) In this MCFBG, 6 out of 7 cores have well aligned notches, with an overlap centered at 1548.25 ± 0.01 nm. The misaligned core, which is located at the center of the fiber, has a Bragg wavelength 100 pm shorter than the others. The effect of having this mismatched core is to limit the fiber's total suppression to -8.5 dB; in other words, 1/7th of the light at 1548.25 nm can pass freely through the MCFBG. If only the outer cores are included in the calculation (*i.e.*, core #1 is blocked or otherwise not illuminated), a maximum suppression of >36 dB is possible. These results are represented graphically in **Figure 4**.

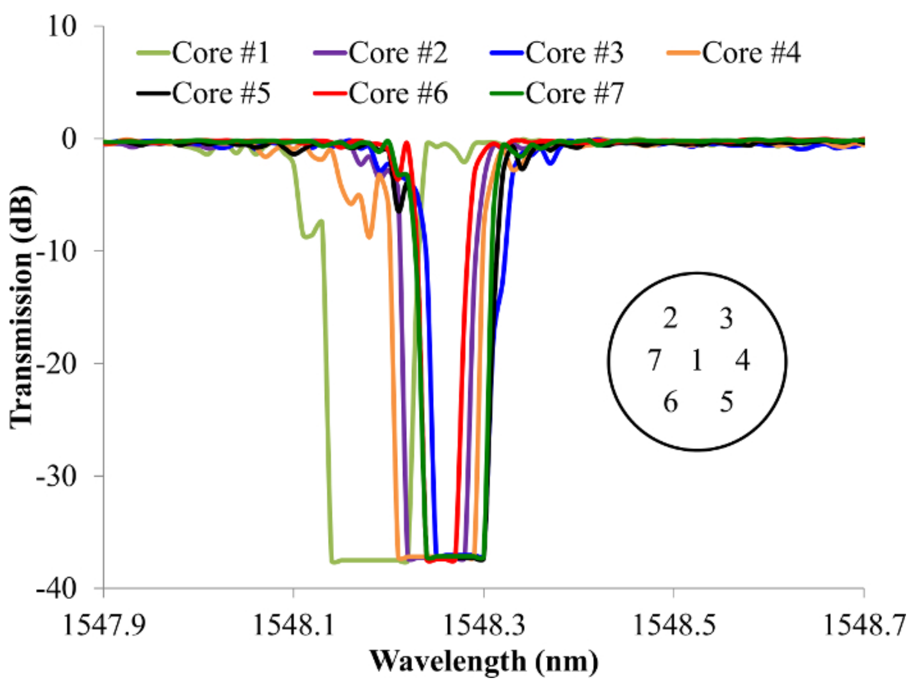

Figure 3. Performance of MCFBG cores with polished capillary tube. Transmission profiles of all gratings in the 7-core fiber with the capillary tube used to compensate for lensing. The wavelengths of reflection of the outer six cores overlap centered at 1548.25 ± 0 0.01 nm. The grating response of Core #1, which is located in the center of the fiber, is offset towards shorter wavelengths. (Inset) Diagram of core numbering. Adapted from previous publication[11]. Please click here to view a larger version of this figure.

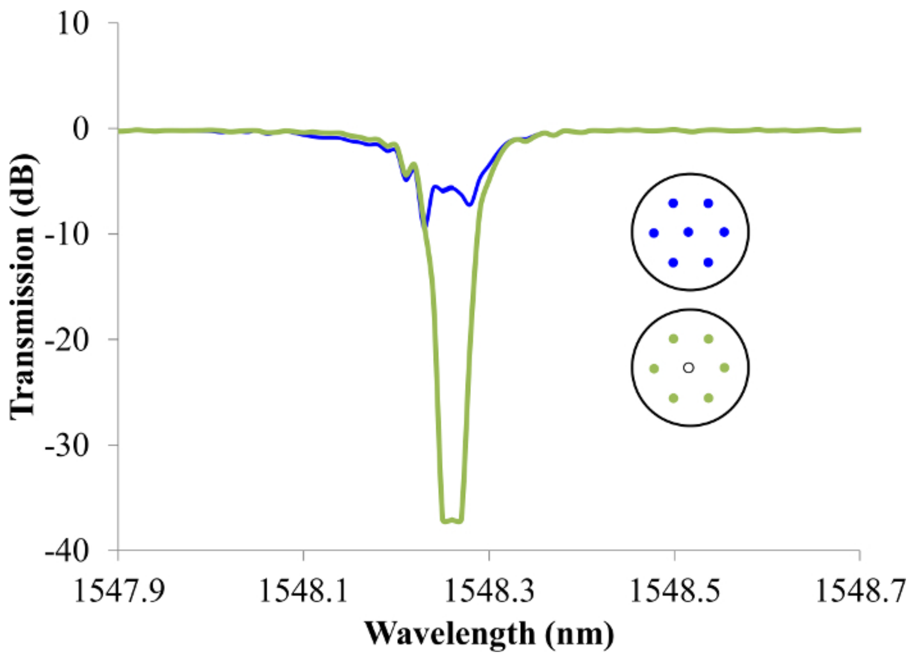

Figure 4. Overall performance of MCFBG. Comparison of overall fiber performance with (blue) and without (green) the center core included. Adapted from previous publication[11]. Please click here to view a larger version of this figure.

Discussion

Figures 2 and **3** together show that introducing the polished capillary tube (PCT) when writing gratings is sufficient to improve the uniformity of core spectra in the MCFBG. The rest of the inscription process is largely unchanged from established methods for creating SMF gratings and can be used with most existing FBG writing systems. Hence the preparation of PCTs as outlined in section 2 of the protocol is most critical for improving MCFBG uniformity. The best results are achieved with tubes where the polished wall has a consistent, small thickness; the 50 µm thickness chosen here gives a compromise between maintaining the strength of the glass and minimizing the distance between the fiber and phase mask.

However, even with the PCT there is an additional effect that causes the middle core of the MCF to have a different wavelength response to the other cores. We used a different hydrogenation regime as mentioned in Step 3.1 of the Protocol section to investigate whether the variation was caused by a lower hydrogen uptake in this core, but no improvement was observed. The variation also cannot be explained by cores casting shadows on each other during UV exposure, as this would result in the outer 6 cores also having poorly matched responses. Instead the behavior can be explained by the central core having different optical properties to the others, despite being identical when manufactured.

MCFBGs cannot be used as effective replacements for their SMF counterparts unless all cores within a single fiber have the same transmission spectrum. We intend to experiment with secondary corrections to existing MCFs made with the PCT, using the effects of thermal and mechanical strain to shift the Bragg wavelengths of the outer cores to match the center. The experiment described in this article will also be repeated for larger core numbers to determine the extent to which shadowing and radial Bragg wavelength variation effects scale with the number of 'rings' of cores.

The technique is currently limited in effectiveness for the case of very large fibers or high core numbers. In the former scenario, the cores in a large fiber which are furthest from the incoming beam are not exposed to the interference pattern. This is because we use a Mach-Zender interferometer in these experiments which limits the maximum write depth; this effect occurs because the interference pattern extends only a few hundred microns beyond the phase mask. We intend to address this in future experiments with a redesigned Sagnac interferometer, which will have a depth of field at least twice that of the current equipment. In the second situation where the total core number is large, some cores may be positioned within shadows cast by cores closer to the phase mask. The effect of this on MCFBG quality is not yet known; we will investigate this with 19-, 37-, and 55-core fibers using the method described above.

These experiments have shown that minimal, inexpensive changes to the grating writing procedure can extend its applicability beyond SMFs. Once MCFBGs can be created with filtering capabilities equal to existing SMF technology, they can be employed in any application of photonics, allowing construction of compact and robust devices without sacrificing performance. As outlined in the introduction, the authors' primary goal is to incorporate MCFBGs into new astronomical instruments; however, they can potentially be employed in any system that already makes use of single-mode optics and/or accurate wavelength filtering. Like their single-mode counterparts, MCFBGs can be used in transmission and reflection depending on the application.

Disclosures

The authors declare that they have no competing financial interests.

Acknowledgements

The SAIL labs are funded through JBH's Australian Laureate Fellowship from the Australian Research Council.

This research was supported by the Australian Research Council Centre of Excellence for Ultrahigh bandwidth Devices for Optical Systems (project number CE110001018).

Experimental work was performed in part at the OptoFab node of the Australian National Fabrication Facility, utilizing NCRIS and NSW state government funding. Fiber hydrogenation services were provided by TE Connectivity in Redfern. SLS would like to acknowledge the Optics and Electronics Laboratory, Fujikura Ltd, Japan for providing the 7-core fiber used in this experiment.

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