

Spatial Mode Demultiplexing of Femtosecond-Inscribed Fiber Bragg Grating in Multi-Mode Fibers for High Temperature Sensing

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Abstract: We report interrogation of one Fiber Bragg Grating sensor inscribed in Multi-Mode fiber with 45-mode spatial demultiplexer as well as monitoring of fifteen modes of nine different wavelength groups at temperatures steps up to 1000 °C.

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1. Introduction

Fiber Bragg Grating (FBG) sensor technology offers multiple advantages in comparison with traditional electronic sensors due to its high wavelength multiplexing capability and immunity to harsh environments such as irradiation or high temperature (HT) [1,2]. A conventional FBG sensor line consists of multiple FBGs inscribed in a single-mode (SM) fiber at specific wavelengths defined by their respective pitches, forming, for instance, temperature sensors at their location on the fiber [3]. Cailabs Proteus spatial demultiplexer (DEMUX) based on Multi-Plane Light Conversion (MPLC) offers additional multiplexing capabilities for fiber optic sensing in multi-mode (MM) fibers (MMF) [4,5]. A single FBG inscribed in MMF is able to excite multiple guided modes, generating FBG reflection peaks at Bragg wavelengths corresponding to phase match of those modes with the grating under test. Each reflected peak can then be monitored individually using Proteus, providing potential innovative solutions regarding optical fiber sensing using MMFs, including HT FBG sensing with dedicated fiber material [6,7], and protection coatings [8].

This paper presents results obtained with a 45-mode spatial DEMUX and a single FBG inscribed in MMF. First, we describe FBG inscription process and expose results corresponding to interrogation of the 45 channels of the Proteus module. Then, we describe the setup for interrogation of fifteen modes belonging to nine different wavelength groups while the FBG experiences temperature steps from room temperature to 1000 °C. Those results are finally described synthetically as well before conclusion.

2. Interrogation of one FBG with a 45-mode spatial DEMUX based on MPLC technology

CEA List femtosecond laser platform is dedicated to fiber optic sensor fabrication. In particular, point-by-point (PbP) FBGs able to sustain HT are fabricated by focusing input femtosecond laser pulses of tens to hundreds of nano-joules into the fiber core, producing an array of micro-voids at the desired pitch corresponding to the targeted FBG wavelength. Fig. 1(a) represents a photograph of FBG micro-voids inscribed in OM2 125/50 μm MMF, where pulse energy was intentionally raised in comparison with narrower-core standard SMF-28 FBGs.

Using this platform, we produced one FBG sensor around 1550 nm in this MMF and carefully spliced it to the identical MMF of a 45-mode Proteus. A standard erbium Broad Band Source (BBS) was used here in order to illuminate the FBGs, as well as a fiber optic circulator and an optical switch (Dicon GP750), allowing interrogation of this FBG with the 45 channels of the DEMUX. Fig. 1(b) depicts the 45 spectra obtained with an Optical Spectrum Analyzer (OSA, Anritsu MS9740A, 30 pm resolution) over 15 nm ranging from 1550 to 1565 nm. Each spectrum exhibit one dominant peak corresponding to FBG reflection, forming nine groups of reflection spectra according to the Hermit-Gaussian (HG) decomposition of the 45 channels.

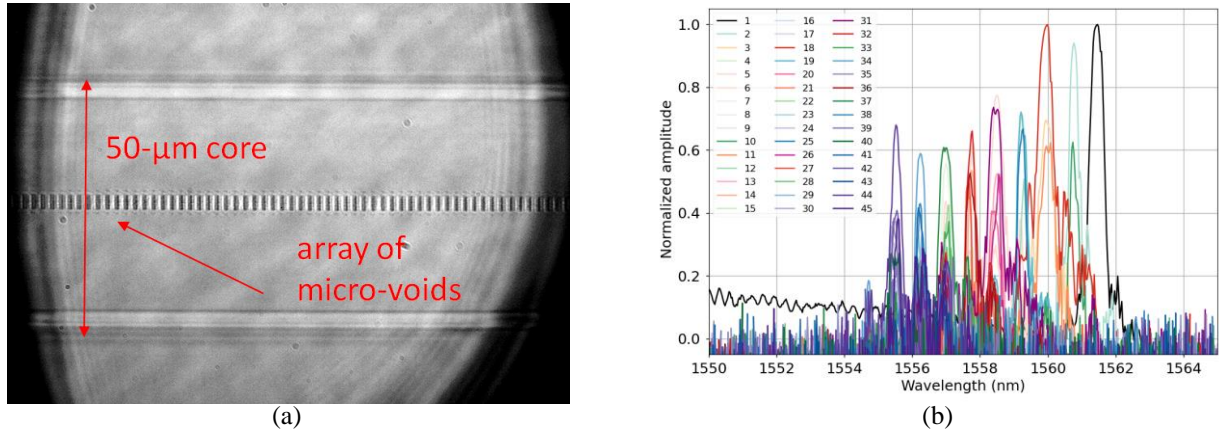


Fig. 1. (a) Photograph of typical PbP FBG micro-voids inscribed in MMF core. (b) Superimposed reflection spectra of one FBG interrogated with the 45 channels of a spatial DEMUX.

3. Interrogation of 15 channels during temperature steps of up to 1000 °C.

Femtosecond PbP gratings allow the FBGs to withstand temperatures from hundreds to more than 1000 °C. We insert the FBG mentioned in section 2 in a calibration oven (AMETEK-JOFRA) while 15 channels of the Proteus are interrogated using fiber optic switch. Fig. 2 depicts photographs of the instruments being used, including the optical source, spatial DEMUX, OSA, switch, and calibration oven. Only one of the two Proteus DEMUX located in the black rack-mounted package of Fig.2(a) (2 x 45 channels connected to 2 MMF) is studied in this paper. Channels are selected in order to cover the nine groups of wavelengths mentioned previously, with six additional channels corresponding to the two lowest wavelength groups. A computer program drives the switch and the OSA in order to record spectra of the 15 channels cyclically.

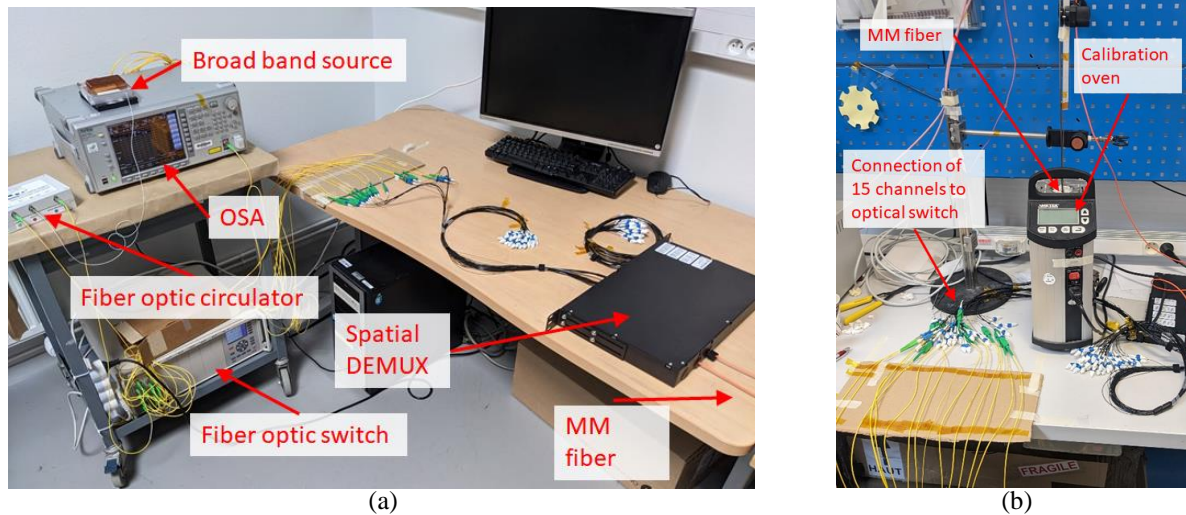


Fig. 2. Photographs of the setup. (a) Interrogation setup, (b) calibration oven, DEMUX channels and MMF.

The calibration oven is programmed to perform a single cycle consisting of five temperature steps (200, 400, 600, 800 and 1000 °C). After stabilization at 1000 °C, we switch the oven off while keeping recording the spectral blue shift of the different reflection spectra, as the FBG goes down to room temperature.

Fig. 3(a) depicts normalized spectra corresponding to three different channels of the DEMUX at different instants after reaching the steps. FBG resonant wavelengths corresponding to the selected groups (fundamental, two and eight) shift towards higher wavelengths as temperature goes up to the final temperature step. We also analyzed the spectra and performed FBG peak detection as well as Gaussian fit in order to compute FBG wavelengths of the

different channels, as shown on Fig. 3(b). This will further allow studying spectral shift of the different mode orders independently, along with optimization of detection algorithms as well as FBG inscription parameters, thermal treatment (TT) of several HT cycles, and fiber conditioning along the MM propagation path for modal content control. Indeed, we observed small fluctuations of this content during the test, taking the form of, for instance, varying peak amplitudes and crosstalks. Potential future investigations should take into account FBG spectral and modal response to its environment after stabilization with TT for better control of input MM signal of spatial DEMUX.

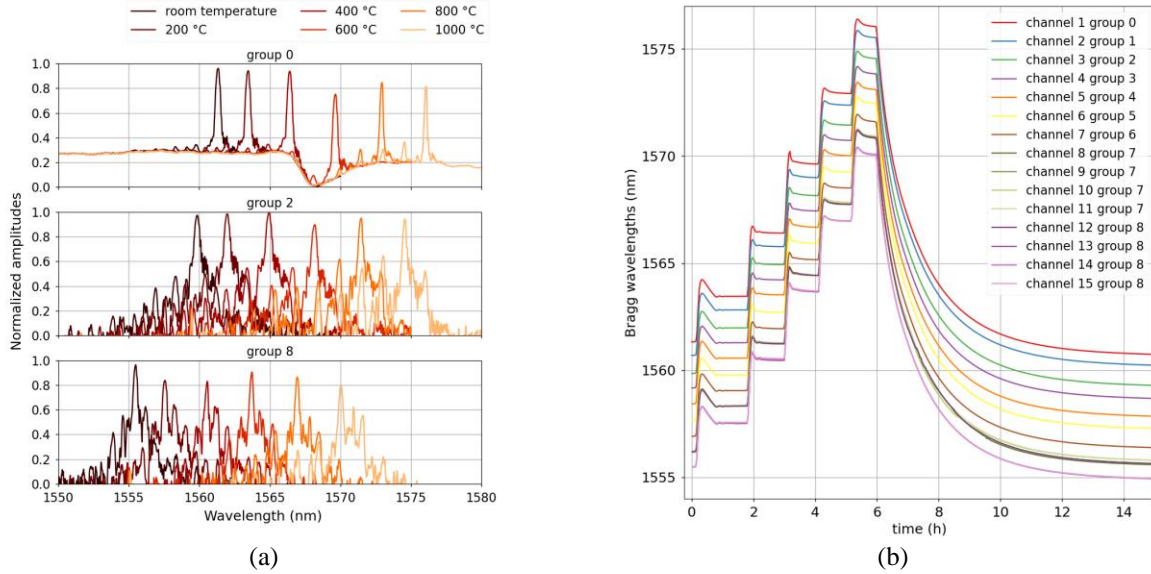


Fig. 3 (a) Normalized FBG spectra corresponding to three different channels of the spatial DEMUX after stabilization at the different temperature steps of the test cycle. Mode wavelength group of the selected channels is indicated as well. (b) FBG wavelengths recorded with 15 channels of spatial DEMUX during one temperature cycle including five temperature steps at 200, 400, 600, 800 and 1000 °C.

4. Conclusion

This paper presents the recent results obtained from a single FBG sensor inscribed in MMF using a spatial DEMUX in order to monitor various reflected FBG peaks corresponding to different modes. We describe the FBG spectra corresponding to 45 channels from HG decomposition with MPLC technology and perform spectral monitoring of fifteen channels while the FBG is exposed to five temperature steps ranging from room temperature to 1000 °C using calibration oven.

Research is being conducted in order to adapt FBG inscription to MM HT fibers and evaluate the benefits of spatial DEMUX interrogation. The ability of demultiplexing spatial modes in MMFs is of great potential interest for sensing applications since accurate filtering of the modal content of FBG reflected signals may allow for exploiting their different 2-D spatial profiles in core and cladding. Moreover, current development efforts taking advantage of specific materials for optical fiber and coating, as well as, adaptations of FBG inscription bench for HT MM sensor inscription, may also benefit from custom Proteus design adjusted to specific fibers, including adapted mode decomposition basis and number of channels.

5. References

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