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Monitoring of single-mode fiber laser heating using Rayleigh scattering and 1st order fs-PbP Fiber Bragg Grating

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Abstract: This paper presents the development of a CO₂ laser-based heating system to simulate fast thermal phenomena on high temperature resistant FBGs dedicated to high temperature profiles monitoring within components exposed to hot plasma inside Tokamak. We have demonstrated the reliability of two optical fiber based sensing techniques to control spatial and temporal annealing measurement during high and fast thermal process.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.3735) Fiber Bragg gratings; (230.1150) All-optical devices

1. Introduction

Studies on temperature-resistant Fiber Bragg Grating (FBG) sensors are currently conducted in order to study the behavior of Plasma Facing Components that will be operated the International Thermonuclear Experimental Reactor ITER based on the Tokamak concept of magnetic confinement. One typical objective is to instrument actively-cooled graphite and/or tungsten Plasma Facing Units and to monitor temperature profiles using multiplexed arrays of FBGs sensors. Exposed to high heat fluxes of 10 MW.cm⁻² and above, these divertor-related components have to withstand inhomogeneous temperature spatial distribution and fast and transient temperature increases up to 1000°C and even 2000°C at the surface exposed to the plasma.

In this paper we have designed a CO₂ laser-based heating system in order to simulate fast thermal increase and decrease in temperature along the core of a single-mode optical fiber. This setup will be used in order to characterize the reliability of high-temperature resistant Fiber Bragg Gratings sensors submitted to fast thermal phenomena reaching temperatures in excess of 1000°C. Advanced all-optical monitoring techniques are considered within this paper in order to spatially characterize the temperature profile of the laser-heated segment of the SMF fiber and thus improve the control and flatness of the temperature profile. Both Rayleigh-based optical frequency domain reflectometry and 1st order femtosecond point-by-point FBG (fs-PbP FBG) temperature sensing have been used to retrieve and optimize the temperature profile along the fiber.

2. Experimental setup

The experimental setup for CO₂ laser annealing is shown in Fig. 1. The CO₂ laser used is a ti60W from SYNRAD. It is water-cooled at 20°C, positioned on a stainless steel optical table coupled with pneumatic vibration isolator support and operating in an air-conditioned laboratory. It has a maximum output power of 60W and a 7% power stability. The laser power is controlled using Pulse Width Modulation (PWM) fixed to 20 kHz.

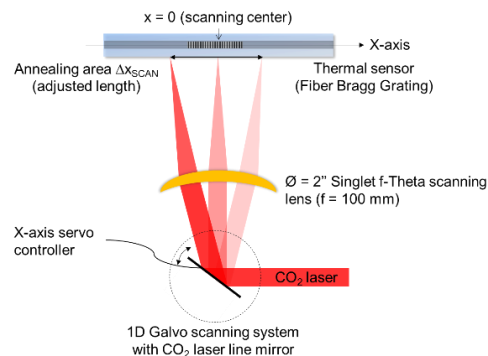


FIG. 1. CO₂ laser annealing setup

A PWM command-signal controls the laser output power by varying the duty cycle of the laser's RF amplifiers, which in turn controls the time-averaged RF power applied to the laser. The laser-based thermal heating process consists to use a 1D galvanometer scanning system coupled to a singlet f-Theta Scanning Lens (TSL). The galvo-optical system is controlled using a Labview program and a DAQ board generating the scanning function and the length (ΔX_{SCAN}) / frequency (f_{SCAN}) of the driving signal. To avoid inhomogeneous temperature along scanning area, we have used an externally-generated gating signal to control laser ON/OFF switch. During the command-signal of laser OFF, pre-ionize of the laser gas is maintained to just below the lasing threshold.

Two optical fiber based sensing techniques are used to monitor and thus optimize the control of the spatial temperature distribution along the SMF fiber scanned area. The first one is based on the Rayleigh-based Optical Frequency Domain Reflectometry (OFDR) using the ODISI A50 system from Lune Innovations and the second one is based on a 1mm-long 1st-order fs-PbP FBGs inscribed on a SMF-28 optical fiber uncoated on irradiated area. Fig. 2 shows the FBG sensor spectrum and temperature calibration curve.

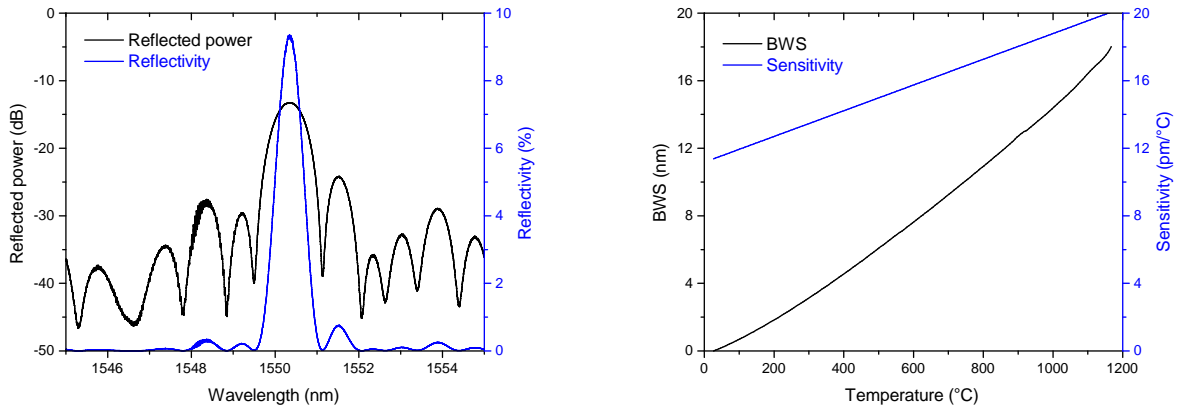


FIG. 2. Fs-PbP FBG reflectivity spectrum (a) acquired by a TUNICS T100S-HP and thermal calibration curves of the Bragg wavelength shift (BWS), black curve, and the sensibility, blue curve (b). The calibration curve of the Bragg wavelength could be fit by a second order polynomial function $\lambda_{BRAGG} = 3.808.10^{-6} T^2 + 1.117.10^{-2} T + 1.550.10^3$

At first time, a femtosecond point-by-point written FBG is positioned at the beam waist position and the scanning function is programmed to fully expose the grating's length. The fiber is fixed using adjustable fiber clamp, v-groove type, on 3-axis compact flexure stages. A metal load with a weight of approximately 50g is attached to one end of the grating to ensure that the fiber remains straight throughout the annealing process. The FBG is also connected to a wideband 3-port circulator, a C+L flattened ASE optical source and two different spectrum analyzers (a conventional Anritsu MS9740A) and also to a high speed spectrometer I-MON USB 512E from Ibsen Photonics operated at ~1 kHz developed at CEA List. The other end is fixed to a translation stage to move the fs-PbP FBG along the x-axis scanned by the CO₂ laser spot. The short length of the fs-PbP FBG enables us to retrieve accurately the temperature profile of the laser-heated fiber length. For steady state monitoring, we have also used an ODISI A-50 OFDR instrumentation in order to measure the temperature profile again with a 1mm spatial resolution.

The 1st-order fs-PbP FBG are written at CEA List using a setup specifically developed in order to develop arrays of multiplexed high-temperature resistant FBG sensors. This setup makes use of an 800 nm Legend Elite femtosecond laser from Coherent delivering fs-pulses at 1 kHz and with a pulse energy reaching 5 mJ. Two air-bearing stages from Aerotech and dedicated focusing and imaging optics are used in order to write 1st-order PbP FBG without requiring index-matching solutions. This free-space approach gives us a high degree of flexibility in this PbP photowriting scheme.

3. Results and discussion

3.1 Spatial annealing parameters

Figure 3 shows a homogeneous temperature along a single-mode fiber propagation axis applying a sinusoidal scanning function with a 14mm scanned length, at the first time, without gating signal (a) and at the second time, coupled with a gating signal to control laser ON/OFF (b). Results retrieved using both the fs-PbP FBG sensor (a+b)

and the ODISI A50 OFDR system (a) are given. The two measurement techniques show very similar results. Both techniques result in temporal and spatial integration of the temperature respectively over 1s and over 1mm typically). This explains that the temperature profiles are similar. The temperature spatial profile shows a high temperature on both edges, and decreases to the center. It is due to the sinusoidal driving signal sent to the galvo-optical system that converts the electrical signal into a scanning laser.

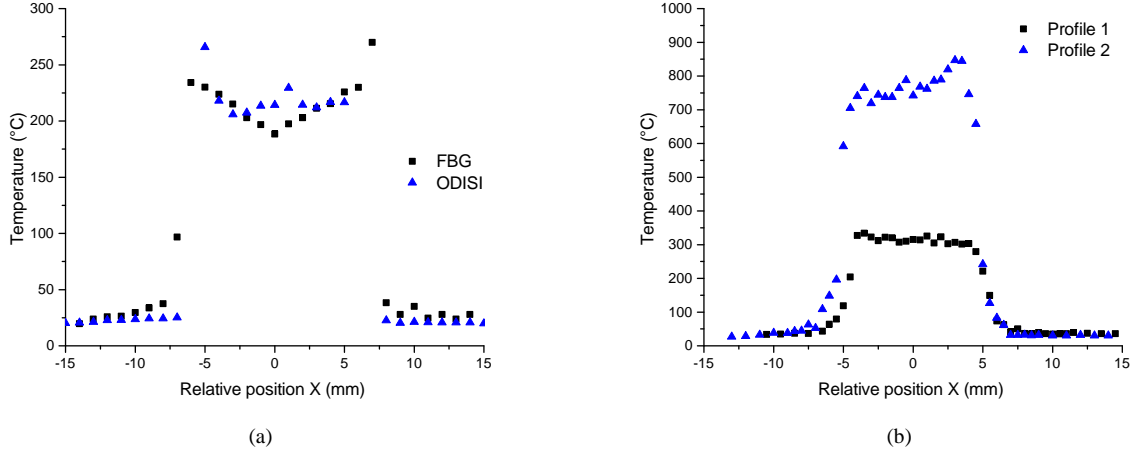


FIG. 3. Temperature according position along x-axis using CO₂ laser annealing, by means of the ODISI A50 and 1st-order fs-PbP FBG measurement without gating signal (a) and with gating signal (b).

Annealing parameters (a): scan movement: sinus, $f_{SCAN} = 100$ Hz, $\Delta X_{SCAN} = 14$ mm, PWM = 5 %, $f_{CO_2} = 5$ kHz.

Annealing parameters (b): scan movement: sinus + gating signal, $f_{SCAN} = 100$ Hz, $\Delta X_{SCAN} = 14$ mm, PWM = 10 %, $f_{CO_2} = 20$ kHz.

To avoid the thermal variation along X-axis, we have implemented a gating signal to cut the edge without diffraction effect as would be obtained using a simple slit. Using this gating approach we are able to get a temperature: $T_{measured} = 317.4 \pm 7.5$ °C i.e. < 3% for profile 1 and 769.4 ± 35.9 °C i.e. < 4.7% for profile 2 along a 6mm scanned length. The variation is due to power stability of CO₂ laser, accentuate at the activation of water-cooling.

3.2 Temporal annealing parameters

Figure 4 shows a temporal variation of the CO₂ laser heating at the center of the scanned length ($x = 0$) for different scanning frequencies using the 1st-order PbP FBG monitored using a 1 kHz spectrometer integrated at CEA List and based on the I-MON USB 512E platform proposed by Ibsen Photonics. Making use of advanced peak fitting algorithms, this monitoring system gives us insight into the thermal behavior between two consecutive scans by the laser spot. These measurements will be helpful to characterize high-temperature resistant FBGs during transient phenomena such as those expected during plasma heating in a Tokamak.

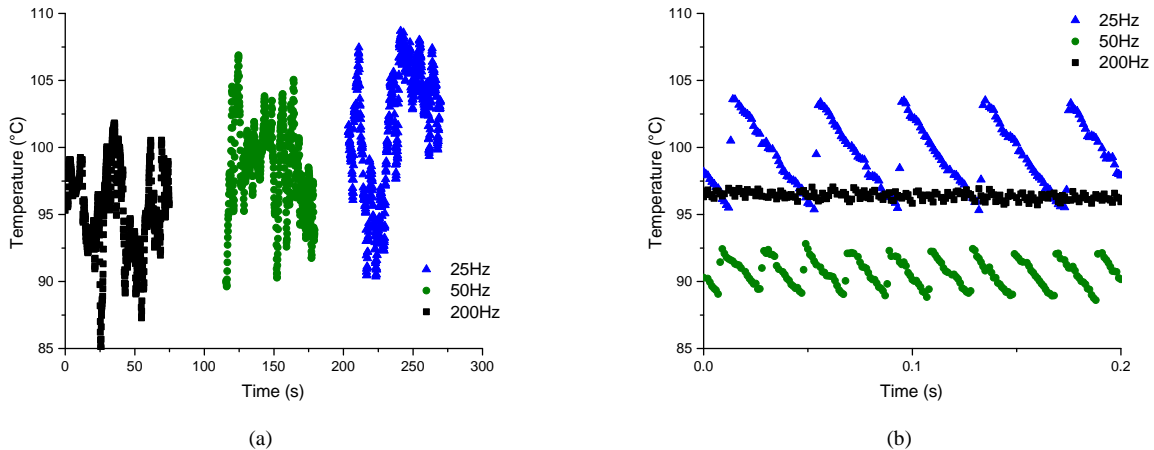


FIG. 4. High frequency measurements of temperature using CO₂ laser annealing with a 1st-order PbP FBG for different scanning frequency and for 10 Hz (a) and 1 kHz (b) frequency measurements. 10 Hz measurement consists to thermal average of 1 kHz measurements. Annealing parameters: scan movement: sinus + gating signal, $f_{SCAN} = 200, 50$ and 25 Hz, $\Delta X_{SCAN} = 14$ mm, PWM = 10 %, $f_{CO_2} = 20$ kHz.

Fig. 4a shows an annealing with a good stability of 95.2 ± 3.2 °C, 98.5 ± 3.3 °C and 101.4 ± 4.6 °C for 200 Hz, 50 Hz and 25 Hz respectively. We observe that the temperature increases as the scanning frequency decreases because the laser beam speed is less important so the time of annealing for a given Δx element is increased.

Fig. 4b highlights the decrease of temperature between two consecutive scanning of the fiber segment according to the scanning frequencies of the CO₂ laser. We observe a variation of temperature of 1.2, 2.5, 3.9 and 8.2 °C after the next beam scanning for scanning frequencies of 200, 100, 50 and 25 Hz respectively. For more stability, the highest possible frequency will be chosen.

3.3 Application: Regenerated Fiber Bragg grating (RFBG)

Multiplexed FBG arrays are considered for the Tokamak's divertor instrumentation. Sensing lines made of RFBGs and/or 1st-order fs-PbP FBGs will be used to map the temperature of the Plasma Facing Units especially within the WEST machine, and are expected to reach temperature in excess of 1000°C. The previous results show that the CO₂ laser annealing could be used not only to characterize temperature-resistant FBGs sensors (either regenerated or PbP gratings) with regard to fast phenomena but also to perform sophisticated annealing processes thanks to the accurate spatial control of the heating profile. One typical example of such a thermal process is the so-called regeneration of seed Fiber Bragg Gratings. Fig. 5 demonstrates the regeneration phenomena using the all-optical heating setup developed and exposed in this paper.

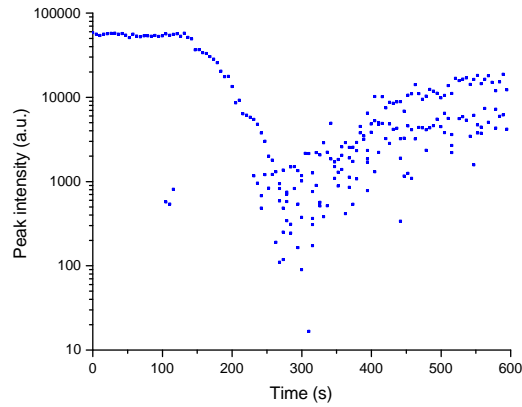


FIG. 5. Regeneration of FBG using CO₂ laser annealing

Annealing parameters: scan movement: sinus + gating signal, $f_{SCAN} = 100$ Hz, $\Delta X_{SCAN} = 14$ mm, PWM < 40 %, $f_{CO_2} = 20$ kHz.

The RFBG is obtained from a Type-I seed grating inscribed on a SM1500(9/125)P optical fiber from Fiber-core using a KrF laser and exposed to the writing beam until transmission saturation. FBG with a grating length of 5 mm and 99.986 % of reflectivity is used in this experiment.

4. Conclusions

In this work, we show the development of a CO₂ laser-based heating system to simulate fast thermal effect such as those expected from the hot plasma creation within a Tokamac. To monitor and optimize the spatial distribution along the scanned area, we use two processes based on optical fiber. One is based on Rayleigh scattering distributed sensing and the second one is based on a 1 mm-long 1st-order fs-PbP FBG. The second technique can be coupled to 1 kHz spectrometer to study temporal distribution. After optimization of this heating process, we demonstrate the use of this laser heating setup to regenerate a Fiber Bragg Grating. Such a setup will also give us insight into the impact of thermal shocks on the behavior and reliability of the transducer.