Real-Time Monitoring of the Modal Content of Monolithic Large-Mode-Area Fiber Lasers

F. Stutzki[1], C. Jauregui[1], C. Voigtländer[1], J. Thomas[1], S. Nolte[1], J. Limpert[1], A. Tünnermann[1,2]

1. Friedrich Schiller University Jena, Institute of Applied Physics, Albert-Einstein-Str. 15, D-07745 Jena, Germany
2. Fraunhofer IOF - Institute for Applied Optics and Precision Engineering, Albert-Einstein Str. 7,D-07745 Jena, Germany
**Author e-mail address: cesar.jauregui-misas@uni-jena.de*

Abstract: A method for the real-time monitoring of the modal content of a monolithic LMA fiber laser is reported for the first time. It allows for the direct observation of the dynamics of transversal mode competition.

OCIS codes: (060.2270) Fiber characterization; (140.3510) Lasers, fiber; (060.3735) Fiber Bragg gratings; (050.2230) Fabry-Perot

1. Introduction

Optical fiber lasers have received a great deal of attention in recent years due to their very attractive features, such as diffraction limited beam quality, high output powers or low maintenance costs [1]. However, as the output powers steadily increase, the tight confinement of the light in the small cores of the optical fibers along long lengths gives rise to the onset of detrimental nonlinear effects. In order to reduce the impact of non-linearity in high power fiber lasers, Large Mode Area (LMA) fibers were introduced [2]. These fibers, widely used nowadays, have core diameters in the tens of micrometers range, which considerably increase the threshold of nonlinear effects and fiber damage. However, these fibers are not strictly single-mode but support the guidance of a few transversal modes. The presence of higher order modes affects the performance of fiber lasers because it leads, for example, to a reduced beam quality and, in some cases, even to unstable operation. Therefore, it is becoming more and more important to be able to characterize the modal content at the output of fiber lasers. Several methods have been proposed during the years such as the S^2 imaging technique [3], the use of ring-resonators [4], computer-generated holograms as correlation filters [5], or low-coherence interferometry [6]. While these methods are useful for passively characterizing the modal characteristics of a fiber and can provide very detailed information, they are not really appropriate for analysing the output of real-world lasers. This is because all of them require the injection of probe light of known characteristics into the fiber. Furthermore, most of these methods do not allow real-time monitoring of the modal content of the fibers or, in order to do so, require, beforehand, detailed information of the modes propagating through the fiber.

In this paper we present, for the first time to our knowledge, a simple method for the real time monitoring of the modal content of monolithic fiber lasers. This method exploits the modal spectral separation induced by Fiber Bragg Gratings (FBGs) written in multimode or few-mode fibers. The real-time, direct observation of the modes present at the output of a fiber laser provides a useful insight into the dynamics of transversal mode competition and its relation with the stability of the laser output.

2. Measurement principle and setup

Fiber Bragg Gratings are the reflective elements of choice when building monolithic fiber lasers. FBGs provide, in singlemode fibers, a well-defined narrowband reflectivity spectrum localized around the Bragg wavelength $\lambda_B=2n_{eff}\Lambda$, where n_{eff} is the effective index of the fundamental mode and Λ is the period of the FBG. However, FBGs written in multimode fibers possess a different spectrum. Since in a multimode fiber each of the transversal modes allowed to propagate has a slightly different n_{eff}, the reflectivity spectrum of a FBG will exhibit multiple peaks at different wavelengths [7] (one per transversal mode). If the bandwidth of the reflectivity peaks is narrow enough, it is possible to achieve that only one transversal mode will be reflected at each wavelength. This provides a natural mechanism to spectrally separate the transversal modes. Additionally, exactly at the middle point between two reflectivity peaks corresponding to two adjacent transversal modes, there can be another peak corresponding to mode conversion carried out by the FBG between these two transversal modes. The inset of Fig.1 shows the measured reflectivity spectrum of a FBG written in a 20µm core LMA fiber. This fiber can only guide two modes (LP_{01} and LP_{11}) which gives rise to the rightmost and leftmost reflectivity peaks. The central peak corresponds to the mode conversion between the two transversal modes.

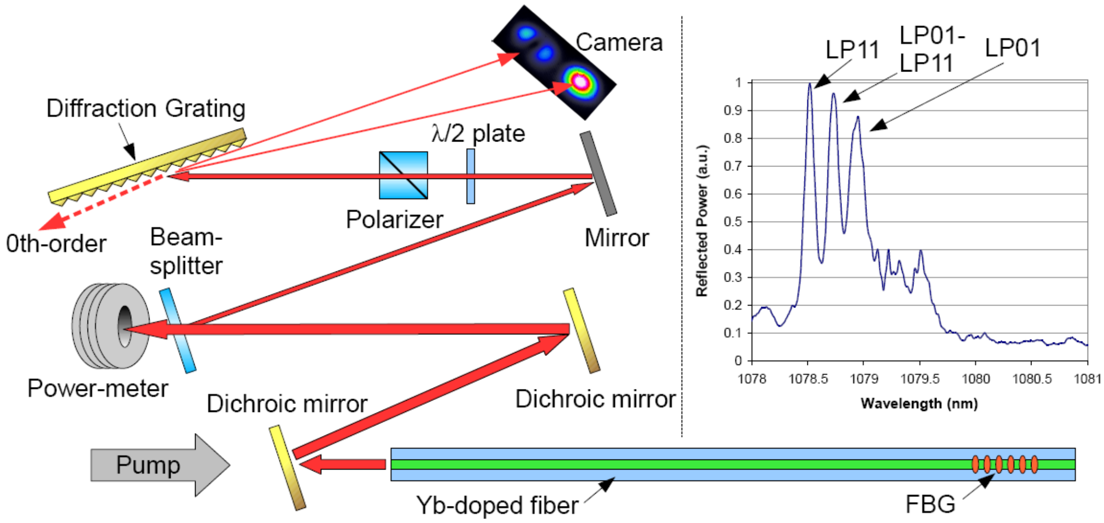

Fig.1. Experimental setup for the real-time monitoring of the modal content of a monolithic LMA fiber laser. The inset shows the reflectivity spectrum of the high reflectivity FBG. This spectrum exhibits three peaks: one for the LP_{01} mode (right), one for the LP_{11} (left) and one corresponding to the mode conversion between LP_{01} and LP_{11} (center).

Considering that the amount of mode-mixing taking place in the fiber core is negligible, at the output of the fiber (fiber end opposite to the FBG) the different transversal modes will be spectrally separated. Therefore, they can be spatially separated using a highly-dispersive diffraction Bragg grating (DBG) as illustrated in the setup shown in Fig.1. Thus, the different wavelengths present at the output of the fiber (transversal modes) will be diffracted in slightly different angles by the DBG, which means that, after a certain propagation distance, they will be completely separated in space. At this point a camera can be placed to monitor the mode profiles. Additionally an optical spectrum analyser can be used to simultaneously measure the spectrum of the reflected 0^{th} diffraction order (dashed red line).

This setup has the additional advantage that DBG are polarization sensitive elements. Thus, placing a polarizer and a λ/2 plate before it offers the possibility of independently monitoring the two orthogonal polarizations of each transversal mode. Furthermore, analyzing the image of the modes obtained by the camera can provide a good estimate of the relative powers carried by each mode in each polarization.

Even though this simple method can be used to characterize the modal content of passive fibers, in our opinion it really shines when characterizing LMA fiber lasers because its real time monitoring capabilities allows a direct observation of the dynamics of transversal mode competition.

3. Characterization of a LMA fiber laser

In order to illustrate the performance of this mode characterization method, a monolithic fiber laser in a 18m long, 20µm core diameter Yb-doped LMA fiber was built. The FBG was written with a fs-laser using the phase mask technique. The reflexion spectrum of the FBG is shown in the inset of Fig.1. This laser was able to provide up to 130Watt output power (only pump limited).

The first experiment consisted on the proof of principle of the characterization technique, in which we simply monitored the modal content of the output laser beam at a power of ~30Watt. As can be seen in Fig.2, and as expected from the simulations of this fiber, the output beam contains only two transversal modes: the LP_{01} (right) and the LP_{11} (left). Moreover, Fig.2 illustrates the capability of this mode characterization technique to discriminate between the different orthogonal polarizations of the modes. In order to take these two modal pictures we only rotated the λ/2 plate by 45°. It can be observed that the lower mode image is slightly shifted towards the left with respect to the upper picture. This is due to the birefringence of our FBG reflector.

Even more interesting than the quasi-static measurements presented in Fig.2 are the real-time capabilities of this technique. This allows, for the first time to our knowledge, for a direct correlation between the modal content of the output beam and some laser instabilities. This is exemplified in Fig.3. In this measurement the laser was operated at 40Watts output power. As can be seen, at this power level the laser had periods of stable operation followed by sudden periods of unstable operation. Even in the stable periods it can be seen that the output beam contains three modes (lower inset of Fig.3). The rightmost mode corresponds to the same LP_{01} shown in Fig.2, whereas the

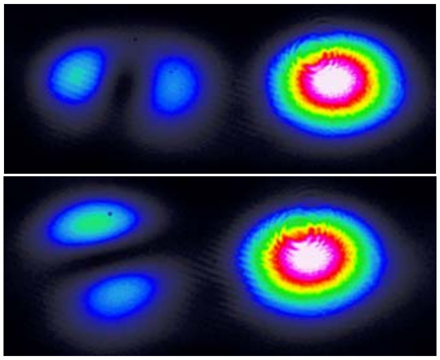

Fig.2. Mode content of a LMA-20 fiber for two orthogonal polarizations

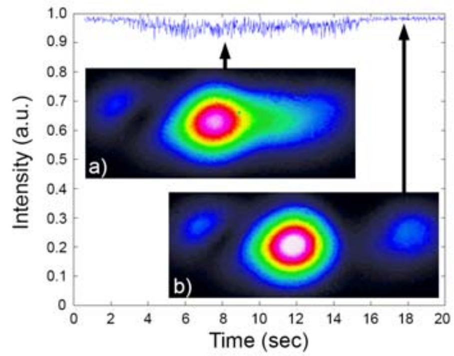

Fig.3. Stable and unstable regimes of the fiber laser output that correspond to changes in the modal content of the beam: a) modes in the unstable output, b) modes in the stable output

leftmost mode is the LP_{11} (only a lobe visible). Interestingly enough, the dominant mode is the middle LP_{01} that corresponds to the central reflexion peak of the FBG (see inset of Fig.1.), i.e. this mode comes from a mode conversion process. However, as revealed by our measurements, this mode configuration is not very stable and it undergoes periods of instability. These periods correspond to a substantial growth in power of the rightmost LP_{01}, which leads to a strong mode competition (upper inset of Fig.3) that can clearly be seen in our real time measurements.

We carried out an additional experiment in which we monitored the modal content of the output beam as we swept the laser output power from 5Watt to 100Watt. The results show that the mode content of the beam changes drastically with different output powers leading, additionally, to stable and unstable power levels.

4. Conclusions

In this paper a simple method for the mode characterization of monolithic LMA fiber lasers is presented. This method allows, for the first time to our knowledge, a direct monitoring in real-time of the different modes contained in the laser output. This characterization technique offers a very useful insight into the dynamics of fiber lasers.

The authors want to thank the German BMBF for financial support through the 13N9100 “FaBri” project.

5. References

[1] J. Limpert, F. Röser, S. Klingebiel, T. Schreiber, C. Wirth, T. Peschel, R. Eberhardt, and A. Tünnermann, “The rising power of fiber lasers and amplifiers,” IEEE J. Sel. Topics in Quantum Electronics **13**, 537-545 (2007).

[2] M. E. Fermann, “Single-mode excitation of multimode fibers with ultrashort pulses,” Opt. Lett. **23**, 52–54 (1998).

[3] J. W. Nicholson, A. D. Yablon, S. Ramachandran, and S. Ghalmi, “Spatially and spectrally resolved imaging of modal content in large-mode-area fibers“, Optics Express **16**, 7233-7243 (2008).

[4] N. Andermahr, T. Theeg, and C. Fallnich, “Novel approach for polarization-sensitive measurements of transverse modes in few-mode optical fibers,“ Applied Physics B **91**, 353-357 (2008).

[5] T. Kaiser, D. Flamm, S. Schröter, and M. Duparré, “Complete modal decomposition for optical fibers using CGH-based correlation filters,“ Optics Express **17**, 9347-9356 (2009).

[6] Y.Z. Ma, Y. Sychm, G. Onishchukov, S. Ramachandran, U. Peschel, B. Schmauss, and G. Leuchs, “Fiber-modes and fiber-anisotropy characterization using low-coherence interferometry“, Applied Physics B DOI 10.1007/s00340-009-3517-9 (2009).

[7] T. Mizunami, T.V. Djambova, T. Niiho, and S. Gupta, “Bragg gratings in multimode and few-mode optical fibers“, J. Lightwave Techn. **18**, 230-235 (2000).