Analysis of Ytterbium Doped Seven-core Fiber Laser for Materials Processing and Particle Image Velocimetry Applications

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Abstract: In this work, we have developed a theoretical model of a new type of pulsed fiber laser used a new generation of fiber used as an amplifying medium. This latter is called seven-core fiber. After performing a parametric study of this kind of fiber, we have successfully modeled our fiber laser cavity. Based on the simulations of the theoretical model, we have successfully demonstrated that the modelled laser can be generating two genres of nanoseconds pulses. The first one is to generate a large pulse with high energy applicate to materials processing (cutting, drilling and deep engraving of materials…). The second is to generate a pair of nanosecond pulses identical in energy for Particle Imagery Velocimetry (PIV) application. This seven-core cavity laser modelled is a good candidate to replace the other classical lasers for these applications.

1 INTRODUCTION

Over the past decade, rare earth fiber laser sources have become one of the most popular and fast developing laser technologies. Q-switched laser pulses with nanosecond durations are required for applications such as range finding, laser surgical, materials processing, high peak- power pulses, OTDR, Lidar and for pumping of nonlinear devices such as optical parametric oscillators (Majumdar, 2013), (Adachi, 2002), (Pan, 2009). This is mainly because fiber lasers possess several advantages including high conversion efficiency, high beam quality, maintenance, beam delivery and therefore are poised for a great leap in their popularity and reduction in their cost of mass production (Majumdar, 2013), (Limpert, 2007), (Wang, 2007). The conventional double clad fibers suffer from the limitations of nonlinear phenomena like Stimulated Brillouin Scattering (SBS) and mode quality degradation at high power levels. To have high power and high energy fiber laser, a new fiber generation has been achieved like seven-core fiber laser (Michaille, 2009), (Huo, 2004), (Shirakawa, 2011). A pumped multicore cladding is important, because the cores can be pumped by a common pump source (Abedin, 2012), (Huo, 2004). These lasers also have an advantage of being a large area what leads to a high doping concentration and a good beam quality (Kochanowicz, 2011). Due to the nature of the distributed cores, the thermal effects of the mechanical laser of multicore fiber (MCF) are attenuated compared to fiber laser (Huo, 2005).

In the one hand, several applications of materials processing need a large nanosecond pulse laser with pulse duration of 150 ns to 1000 ns with a high peak power. For example, the process of the texturing surface (Jouvard, 2007) and the process of surface coloring (Jouvard, 2007). These applications require long pulse laser varying from 200 to 500 ns, with pulse energy between 3 and 6 mJ (Jouvard, 2007). A large pulse laser with energy varying between 5 to 10 mJ is required to apply it to coherent anti-Stokes Raman spectroscopy (CARS) (Beyrau, 2004). Large nanosecond pulse with energy of 7 mJ and peak power about 25 kW is also recommended for metal drilling as Aluminum and Titanium and deep engraving applications (Kremser, 2014). Several efforts have been made to obtain this genre of pulse by using different types of fiber lasers cavity. (Mgharaz, 2009) report an Yb-doped fiber laser using a ring cavity actively Q-switched fiber laser by using an Acousto-optic modulator. They demonstrated an Ytterbium doped Q-switched fiber laser with which generated 4.8 mJ and 150 ns width pulses (Mgharaz, 2009). Their research clearly demonstrated the feasibility of achieving long Q-switched pulses in all-fiber configuration. However these lasers, so far, produced only relatively small pulse energy and peak power and far from the requirements for all laser material processing. Also, a large mode area fiber with a 30 mm core diameter is

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used and this large core enhances the number of modes guiding in a laser cavity and the constraints of choosing a small numerical aperture.

In the other hand, several research items were studied using the Q-switched fiber laser for emission of millijoules and microjoules nanosecond pulses used for several applications. The Particle Image Velocimetry (PIV) is one of these applications. The basic principle involves photographic recording of the motion of microscopic particles that follow the fluid or gas flow. Image processing methods are then used to determine the particle motion, and hence the flow velocity, from the photographic recordings. Provided there are enough particles within the area of flow under investigation, the entire velocity field of the flow can be determined (Http, 2017). This application requires a pair of nanosecond pulses separated by more than 500 ns. A seven-core fiber laser offers this alternative and is one of the best lasers for these applications such as their high efficiency, compactness size low cost, and good beam quality.

In this paper, after studying the characteristics of the multicore fiber, we are going to describe the numerical modeling the seven-core fiber laser. From the simulated results of the analytical model, we confirm that the modeled laser is a good candidate to emit two genres of pulses. The first is to generate a two identical nanosecond pulses for PIV application. The second is to product a large pulse width with pulse duration of 200 ns to 1000 ns and high peak power possible used for some materials processing.

2 SIMULATED RESULTS AND MODEL VALIDATION

The fiber cavity laser that we are considering is based on the typical linear Fabry-Perot cavity presented schematically in Figure 1. It consists mainly of two mirrors M_1 and M_2 an acousto-optic modulator (AOM) which is operating at the first diffraction order and the laser diode for pumping the cavity. The pump and the power and the output power are separated at the left end by a beam splitter. The ytterbium doped fiber has seven identical cores that are arranged in a hexagonal array.

After studying the characteristics of our seven-core fiber used in our simulation, we have validate the simulation that we carry out, using the same parameters as considered by (Huo, 2004). We have calculated the pulses predicted with our simulator.

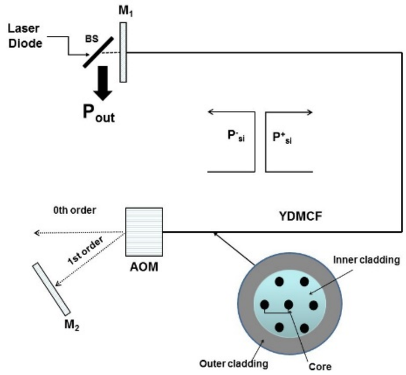

Figure 1: Fabry-Perot seven-core fiber laser cavity design.

We could then compare them to those observed experimentally and predicted with the simulator of the corresponding reference (Huo, 2004). The two output pulses calculated by our model and those obtained experimentally by Huo et al (Huo, 2004). are in good agreement: the same pulse shape, the same peak power of about 3.47 kW, the same pulse duration nearly 47 ns and even the energy which is equal to 0.22 mJ (Nassiri, 2017). Therefore, the output pulse energy obtained by simulated results of Huo et al. are is about 0.24 mJ (Huo, 2004). Consequently, it shows that our model is well validated to describe this type of multicore Q-switched fiber laser (Nassiri, 2017). This case corresponds to a 3m fiber length doped ytterbium with a concentration of 8.10^{25} m^{-3}. The acousto-optic modulator has a repetition rate equal to 5 kHz. The M1 mirror has low reflectivity of 4% and M_2 mirror has high reflectivity of 40%. The pump power is 15W. The pump and signal wavelengths of 940 µm. The other parameters are described in Table 1.

Table 1: Parameters used in our simulation (Huo, 2004).

Parameter	Value
$\sigma_a(\lambda_s)$	$1,4.10^{-27}$ m^{-3}
$\sigma_e(\lambda_s)$	$2,25.10^{-25}$ m^{-3}
$\sigma_a(\lambda_p)$	$3.\ 10^{-25}$ m^{-3}
$\sigma_e(\lambda_p)$	$5.\ 10^{-26}$ m^{-3}
$\Delta(\lambda_s)$	20 nm
h	$6.626068.10^{-27}$ m/s
τ_{ba}	1ms
α_s	5.10^{-3} m^{-1}
α_p	3.10^{-3} m^{-1}
n	1.45
c	3.10^{8} m/s

3 SEVEN-CORE FIBER LASER FOR MATERIALS PROCESSING AND PIV APPLICATIONS

In this section, we will study the two pulses obtained by our simulated model. The first is for PIV application and the second is for materials processing application.

3.1 Seven-core Fiber Laser for Materials Processing Application

The laser configuration proposed in fig.1 with the following modification has been used and already studied (Nassiri, 2017). The output power is extracted in the right hand of the cavity and the reflectivity of the two mirrors M_1 and M_2 are respectively 0.99 and 0.4. The pump power is 10 W, and the length of fiber is limited to 4m, and the Yb concentration is equal to 4.10^{25} cm^{-3}. The core radius of each one is limited only a 6µm. The laser provides 7 mJ pulse energy with estimated peak power of 26 KW and the full width at half maximum (FWHM) is 165 ns. This fiber laser configuration is a good candidate to replace Q-switched thin disc laser used to drilling and deep engraving of Aluminum and titanium in a laser wavelength emission equal to 1030 nm (Kremser, 2014). Therefore, in this paper, an enhanced pulse with 200 ns FWHM, 23 mJ and 58.24 kW at 1 kHz can be emitted by this nanosecond fiber configuration at 1064 nm by enlarging core radius to 8 µm only and reduced rise time to 280 ns is obtained as described in fig.2. The pulse produced in this wavelength can be used to process of texturing and coloring surface of titanium in place of Nd-Yag laser.

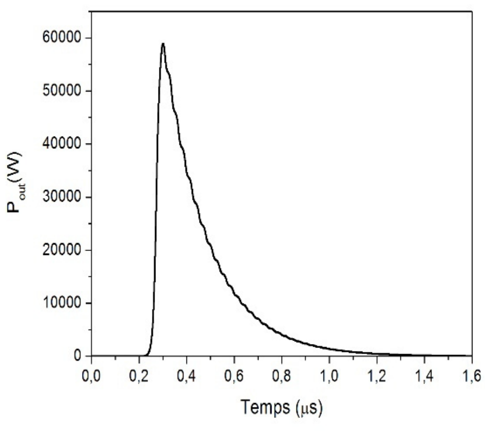

Figure 2: Large nanosecond pulse produced by a seven-core fiber laser cavity for drilling and deep engraving of aluminium and titanium.

3.2 Seven-core Fiber Laser for Partical Image Velocimetry Application

The laser classically used for PIV application is the Nd-Yag laser based on the two identical cavities. The first cavity emits the first pulse after sometimes the second cavity emits the second pulse and the pulses are finally superposed at the output of the two cavities. This genre of cavities suffer in several limitations such as the alignment of the two cavities and the problem of synchronization, moreover, the less beam quality. The fiber laser is an alternative key to avoid these limitations in terms of attributes including efficiency, reliability, beam quality, maintenance, and beam delivery.

Several research items were studied using the Q-switched fiber laser for emission of millijoules and microjoules nanosecond pulses. It is possible to emit a pair of nanoseconds pulses using only one fiber laser cavity with a good alignment of two pulses at the output of the system. (Mgharaz, 2009) report an Yb-doped fiber laser using a Fabry-Pérot Q-switched fiber laser cavity to produce two identical pulses for PIV. They demonstrate that fiber laser cavity that is able to emit a pair of nanosecond pulses separated by more than 626 ns for a 42 kHz repetition rate. The energy the two pulses are respectively 36.5µJ and 35 µJ while their pulse-durations at FWHM are 8.15 ns and 8.1 ns respectively. The same authors report an Yb-doped fiber laser using a ring cavity which generated two identical pulses separated by a temporal spacing exceeding 532 ns (Mgharaz, 2011). The FWHM and the energy of each pulse are (185 ps; 0.15 mJ) and (115 ps; 0.14 mJ), respectively. The two pulses are not rigorously identical. But the main parameter for PIV experiments is there concerning energy between both pulses (Mgharaz, 2011). These researchers have clearly demonstrated the feasibility of achieving two identical pulses for PIV in all double clad fiber laser configurations. However these lasers, so far, produced only relatively small pulse energy and peak power, far from the requirements for all laser applicate to PIV.

In this paper, we have successfully demonstrated an actively Q-switched seven-core fiber laser which produces two identical pulses of high energy with large nanosecond time duration to be used for PIV application. These pulses are obtained by used the parameters described previously. The reflectivity of the two mirrors M_1 and M_2 were respectively 0.95 and 0.99. The pump power was 10.75 W, and the length of fiber was 25m. The Ytterbium concentration was equal to 1, 19.10^{25} cm^{-3}. The core radius of each one is limited a 8 µm and the rise time of AOM is 8 ns. We insert also an undoped fiber with length of 40m to increase the temporal interval between the multiple peaks.

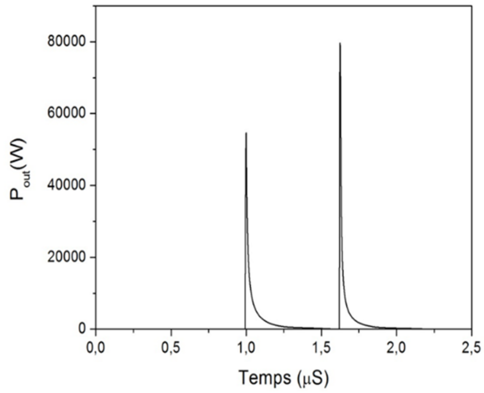

Figure 3: Pair of Nanoseconds Pulses Produced by a Seven-Core Fiber Laser Cavity for PIV Application.

The produced pulses energy and FWHM of the first pulse and the second pulse are respectively (1.71 mJ, 13.6 ns) and (1.70 mJ, 10.2ns) (Fig. 3). The separation of the neighboring peaks is actually equal to the round trip time for our 25 m doped fiber and 40m for undoped fiber. This multicore fiber laser configuration is a good candidate to replace the classical Nd-Yag laser and the one core fiber laser cavities for this application.

4 CONCLUSION

In this paper, we have presented the design of seven core fiber laser cavity that is able to emit a pair of nanoseconds pulses separated by more than 500 ns applied to PIV. The produced pulses energy and FWHM of the first pulse and the second pulse can be exceed the some millijoules and would satisfy PIV requirements. This seven-core fiber laser cavity is a very good candidate to replace the Nd-YAG laser used classically in term of compact, low cost, beam quality, and spatial alignment, and the one core fiber laser cavity in term of emitted energy.

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