Single frequency fiber laser with external volume Bragg resonator

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ABSTRACT

We are reporting on a single frequency pulsed fiber laser based on extremely narrow band volume Bragg gratings (VBGs) recorded in photo-thermo-refractive (PTR) glass. The performance of Yb-doped fiber laser was studied in both passive and active Q-switch schemes. It is shown stable operation in both single TEM_{00} transverse mode and single longitudinal mode regimes. It generates pulses of 40 – 200 ns duration at a repetition rate of 10 – 100 Hz in active and 17-250 KHz in passive Q-switch configurations with a pulse energy of ~50 μJ, limited by the onset of stimulated Brillouin scattering that leads to fiber fracture.

Keywords: fiber laser, single frequency, active Q-switching, volume Bragg grating, holography

1. INTRODUCTION

Rare earth ions doped fiber laser systems attract more and more attention due to variety of applications such as laser sensing, LIDARs, coherent communications, optical fiber sensors and high-resolution spectroscopy. Fiber lasers have proved to be highly attractive coherent light sources due to their high-power capability, compact and portable design, robustness, output stability, cost effectiveness, and power scalability. The applicability of such laser systems, for example as long-range spectroscopic probes of atmosphere, highly depends on the linewidth, thus single frequency operation is highly desirable in order to keep the high coherent length.

Traditionally based on Distributed Feedback- or Distributed Bragg- Reflectors, single frequency fiber lasers provide high stability and narrow spectral linewidth. However, with a cavity length of less than 5 cm, their CW output power is limited to a few hundred mW and in Q-switched operation their pulse energy is typically < 1 μJ[1]. Subsequent fiber amplifiers is to be used to increase the pulse energy to the hundred μJ level and a record 126 μJ pulse energy has been reported from a three stage amplifier with specialty fiber and large core end stage[2]. An order of magnitude higher energy can be achieved in large mode area (LMA) fibers in the case of multi-frequency mode generation. Thus, 2.3 mJ was achieved in Yb-doped LMA fiber laser at the wavelength of 1090 nm with a repetition rate of 500 Hz[3]. Using Nd:YAG single crystal fiber 2.5 mJ sub-nanosecond pulses have been obtained in achieved in a kHz MOPA system[4].

Here we report on a master oscillator operating in a single transverse and longitudinal mode regime with 50 μJ of pulse energy.

2. VBG FABRICATION

Recent development in the use of PTR glass for recording volume holographic elements has led to the production of high efficiency volume Bragg gratings VBG[5]. The main advantage of such elements is that they allow for narrowband filters in both spectral and angular spaces and are suitable for high power laser applications. This allows high efficiency reflecting Bragg gratings to be recorded in several millimeter thick plates of glass with losses below 1%.

In this paper we present the results of preparation of matched VBGs serving as an output coupler (OC) and a highly reflective mirror (HRM) for Yb-doped fiber lasers. Thus, Fig. 1a presents a transmission spectrum of a 15 mm thick OC (VBG1) with diffraction efficiency of 45%. Spectral bandwidth of this grating is equal to 28 pm that corresponds to the theoretical value. The uniformity of the grating parameters has been tested to ensure effective spectral bandwidth. It was found that a gradient of a resonance wavelength across the aperture does not exceed 2 pm. It secures stable operation of

Sensors and Systems for Space Applications V, edited by Khanh D. Pham, Joseph L. Cox,
Richard T. Howard, Henry Zmuda, Proc. of SPIE Vol. 8385, 838503 · © 2012 SPIE
CCC code: 0277-786X/12/$18 · doi: 10.1117/12.923686

the grating across the whole aperture. A high efficiency grating (VBG2) was design with such a period that the resonant wavelength matches the one for OC. Diffraction efficiency of VBG2 has been tuned to just below 99% to avoid excessive broadening of a spectral profile. The measured spectral shape of the VBG2 is shown in Fig. 1b. It has a spectral bandwidth about 70 pm at FWHM. This value is just by 8 pm wider compare a theoretical value based on coupled wave theory. The achieved spectral bandwidth for the high efficiency RBG is the narrowest reported spectral bandwidth for high efficiency volume Bragg gratings. The achieved selectivity corresponds to 20 GHz in frequency domain. Additionally those gratings have a narrow angular acceptance that can be used to select not only longitudinal but transverse modes as well. Angular acceptance of those gratings is below 5 mrad. This angular selectivity would suppress high order modes with divergence exceeding this value.

3. EXPERIMENTAL RESULTS

Choosing the optimum Yb-doped fiber for operation in the 1 μm range is a compromise between a large mode volume and a number of active ions for high energy storage and, on the other hand, a fiber length that is short enough for robust single frequency discrimination and stabilization.

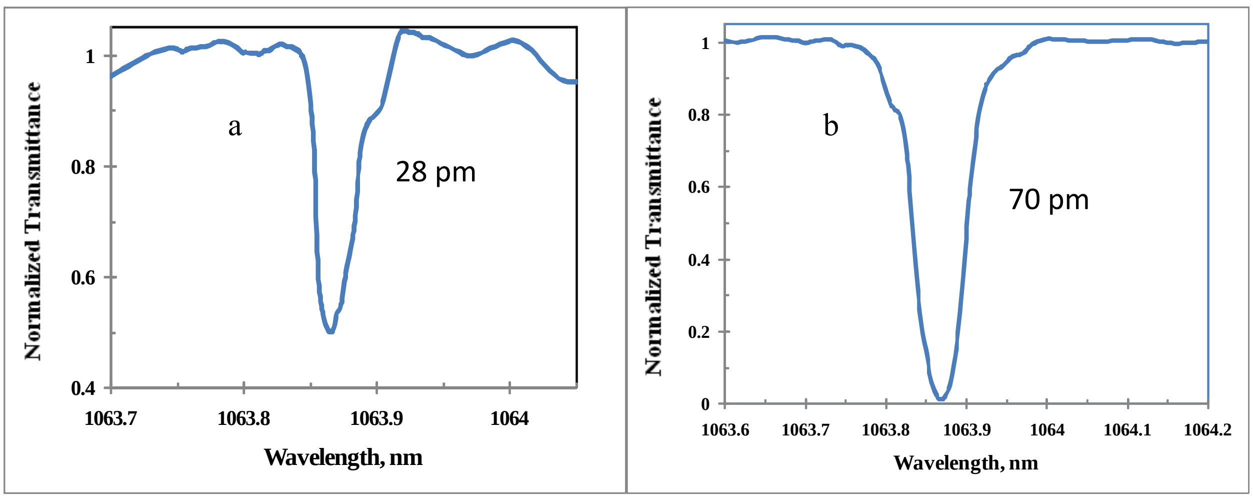

Figure 1. Transmission spectra of VBG1 (a) and VBG2 (b)

Our recently developed narrow band volume Bragg gratings (VBGs) which are used as selective elements in Yb-doped fiber laser have a spectral width between 28 and 100 pm. To have only a few tens of longitudinal modes inside the bandwidth of the mode selector, the overall cavity length has to be kept well below 1 m. This requires a fiber with exceptionally high pump absorption coefficient on the order of 15-30 dB/m for cladding pumping as well as pump diodes with a high brightness.

The major drawback of the fiber laser systems is that it can be damaged by high optical powers with smaller threshold than that in the bulk silica. The most susceptible parts of the fiber are end facets and the splicing points. Moreover, working in a single frequency pulse regime results another limiting mechanism as Stimulated Brillouin scattering (SBS) becomes important with lower threshold than that for end facet damage. In order to increase the SBS threshold the fibers with large mode area have to be used.

For this purpose we used commercially available Yb-doped fibers (Liekki/nLight) with relatively large mode fields, high Yb concentration, and high pump cladding absorption ~ 30 dB/m at 976 nm. Thus the fiber with 20 μm core diameter and 125 μm outer cladding diameter was used. The broad absorption band of ytterbium doped glass allows ytterbium doped fiber to be pumped by diode lasers operating at 915, 940, and 976 nm. In order to achieve the highest absorption in a short length of fiber, we have decided to use pump laser that operate at the maximum of the spectrally narrow 976 nm band. We have therefore used a high-brightness 25W fiber coupled laser bar from DILAS with a fiber core diameter of 200 μm and NA of 0.22. The laser diode was VBG stabilized and therefore the output radiation has a spectral width ~ 500 pm around 976 nm central peak.

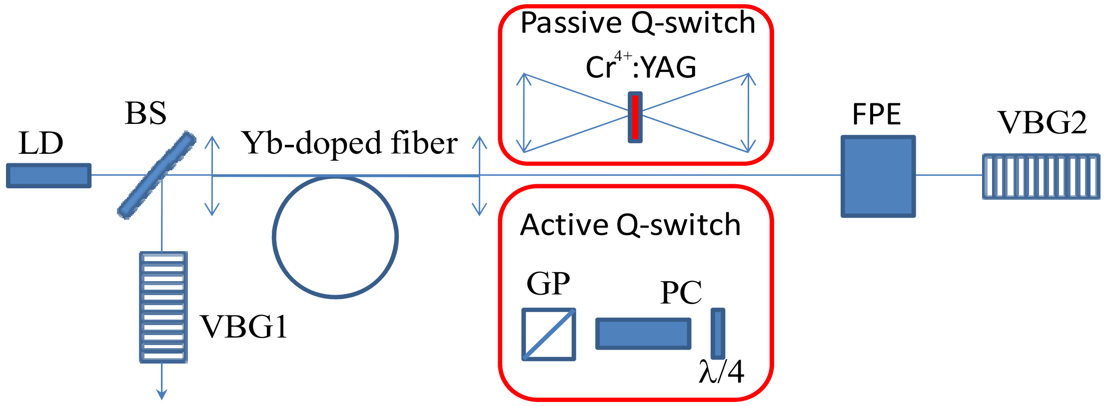

Figure 2. Experimental set-up. LD – laser diode; BS – beam splitter; GP – Glan prism, PC – Pockels cell; VBG1 and VBG2 – volume Bragg gratings, FPE – Fabry-Perot Etalon

The experimental set-up is presented in the Fig. 2. Pump radiation was coupled in to 75-cm Yb-doped fiber with coupling efficiency of 70%. In order to prevent parasitic lasing on the fiber facets, both fiber ends were angle cleaved. The cavity was formed by two matched VBGs with a central wavelength of ~1063.9 nm with characteristics described in a previous section. Dichroic beam splitters (BS) had a high transmission for pump wavelength and high reflection for the wavelength range of 1020-1100 nm. Matched VBGs was used in order to achieve laser radiation with a narrow linewidth and in order to suppress a feedback for ASE and therefore prevent parasitic lasing around 1030 nm.

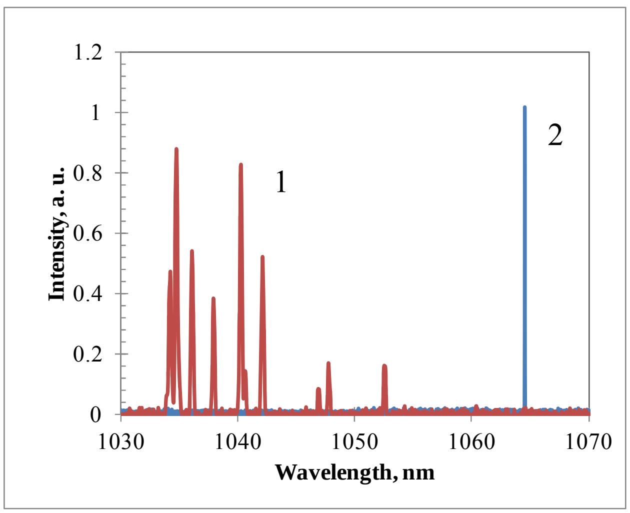

Figure 3. Emission spectra of a fiber laser consisting of wide band dielectric mirrors (1) and matched VBGs (2)

Thus, the application of reflecting VBGs in the laser cavity allowed drastic narrowing the emission spectrum down to ≤ 30 pm. In order to demonstrate the effectiveness of VBG's application we present comparative results for two types of the cavities (Fig. 3): with matched VBGs (curve 1) and the cavity formed by two mirrors (curve 2).
In order to get information about the number of longitudinal modes we used a scanning Fabry-Perot interferometer with free spectral range (FSR) of 1.5 GHz. The result showed that depending on the pump power we have up to 5-6 longitudinal modes. In order to reduce the number of longitudinal modes we introduced 15 mm solid state Fabry-Perot etalon (FPE) with R1 = R2 = 90% and FSR of 6.9 GHz. It allowed getting stable single frequency regime with a pump power of 10-20% above the threshold. Fig. 4a shows a scan over one FSR of scanning Fabry-Perot interferometer and

confirms that the only one longitudinal mode is present in the laser. For the pump level well above the threshold we observed appearance of the second longitudinal mode as it is shown in Fig. 4b.

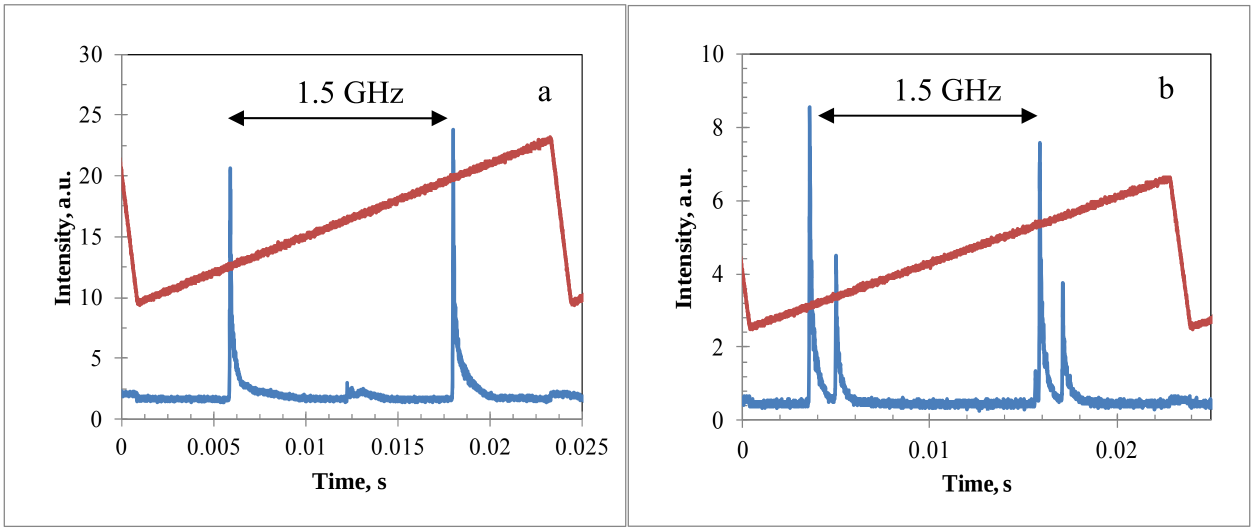

Figure 4. Transmitted signal from scanning Fabry-Perot Interferometer (blue curves) and a ramp voltage trace (red curves). a – single frequency regime, b – double frequency regime.

3.1. PASSIVE AND ACTIVE Q-SWITCHING.

Nanosecond operation of the laser was achieved by using both passive and active Q-switching technique. For passive Q-switching we used Cr^{4+}: YAG saturable absorber with 50% initial transmittance. The crystal was wrapped with indium foil and kept in copper housing for thermal load reduction. The insertion of the passive Q-switch element led to the generation of nanosecond pulses and depending on the pump power the repetition rate was varying from 10 kHz up to 250 kHz. As an example the part of the pulse train is presented in Fig. 5.

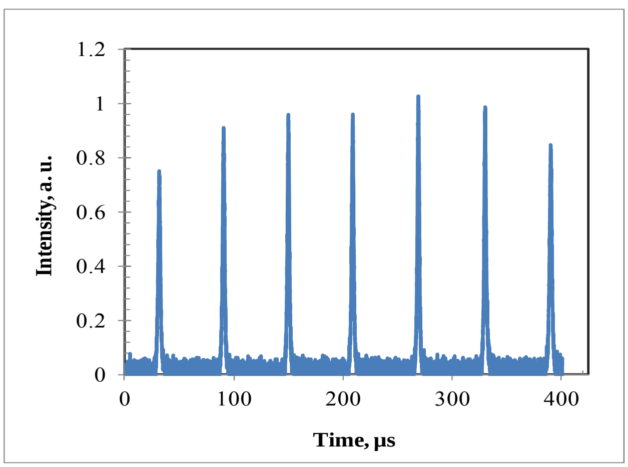

Figure 5. Train of nanosecond pulses with a repetition rate of 17 kHz.

The maximum energy of the pulses was measured to be ~ 70 μJ at pump power on 10% higher threshold. Further increasing the pump power did not increase the pulse energy. An increase in average power was accompanied by an increase of the pulse repetition rate and decrease of the pulse duration (120 ns to 40 ns). Consequently the pulse energy of the passive Q-switched laser was almost constant at all pump power levels. Figure 6 demonstrates two temporal profiles of the generated ns-pulses at high (a) and low, near threshold level (b) pump power. A Fourier transformation of time trace (a) showed that only two longitudinal modes were generated what is in a good agreement with the results presented in the fig. 4b. A typical oscillatory behavior in the temporal trace (Fig. 6a) of these ns-pulses can be explained by beating between several frequency components or longitudinal modes of the laser whereas for the case (Fig. 6a) the absence of beating confirms single frequency operation.

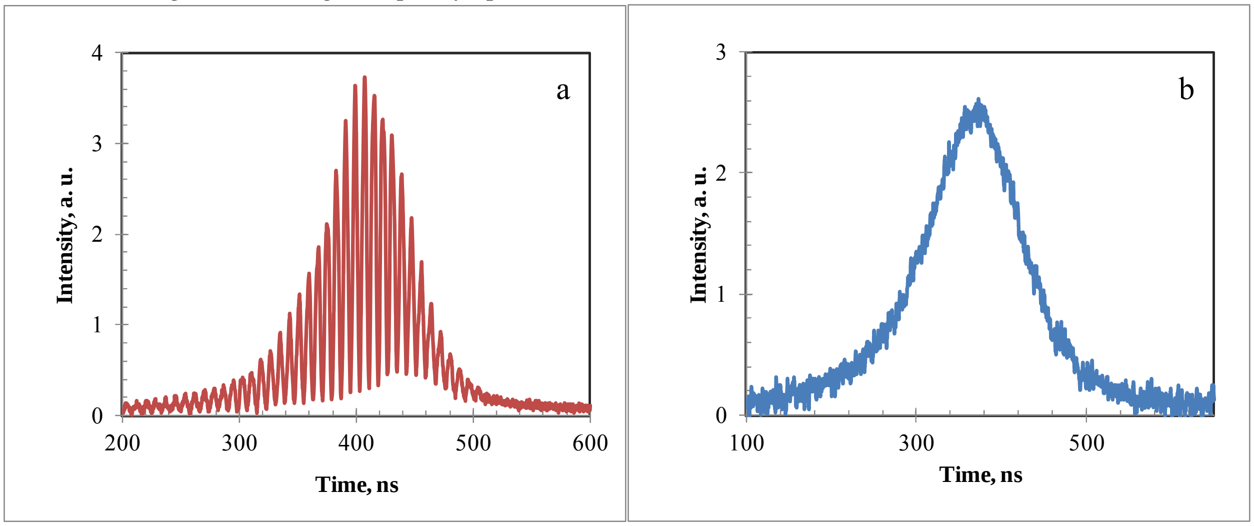

Figure 6. Temporal pulse profiles in a double (a) and single (b) frequency generation regimes

In order to be able to control the repetition rate of Yb-doped fiber laser in the range 10 – 100 Hz we replaced the passive Q-switcher by an electro-optical modulator (EOM) based on a BBO crystal. The EOM consisted of a polarizer (Glan prism), nonlinear BBO crystal (Quantum Technology Inc., Pockel's cell QS-4) and quarter wave plate (Fig. 2). In the absence of the etalon we observed maximum pulse energy of 300 µJ, albeit in a few longitudinal mode operation (Fig. 7, curve 1). In this case the laser was running at twice the lasing threshold and the pulse duration was 10 – 20 ns. Further increase of the pump power led to optical breakdown at the fiber facets. Implementation of an etalon into the cavity allowed working in stable conditions of single frequency operation with a pump level of 10 % above the threshold. At these conditions we were able to get pulse energy of about 50 µJ with a repetition rate of 10-100 Hz. The smooth shape of temporal pulse trace indicated on single frequency regime (Fig. 7, curve 2).
While increasing pump power we observed shortening of the pulses down to 10 – 20 ns together with the appearance of occasional 2 ns long spikes indicating the onset of stimulated Brillouin scattering (Fig. 7, curve 3). Unfortunately, these Brillouin pulses lead to unrecoverable optical breakdown inside the fiber.

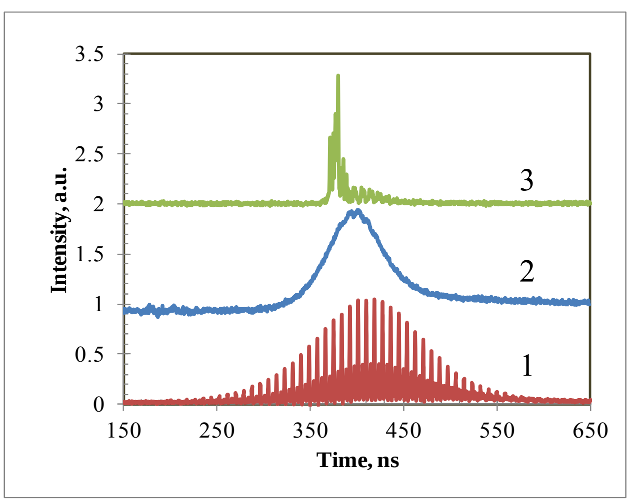

Figure 7. Temporal pulse profiles for different generation regimes. 1 – multi-frequency operation, 2 – single frequency operation, 3 – Brillouin pulse generation.

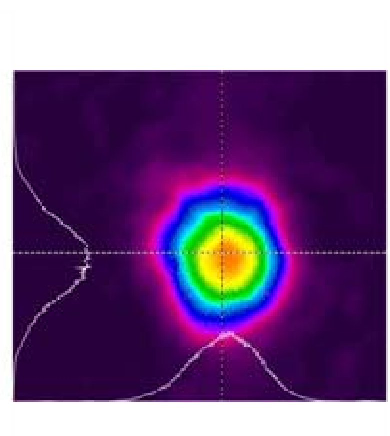

Figure 8. Far-field profile of the laser output

Our measurements of far field profile of the output radiation have shown that the laser generates almost TEM00 mode (Fig. 8.) despite the fact that the 20 μm Yb-doped fiber can support up to 9 modes at 1064 nm. We associate the single transverse mode operation with angular selectivity of the VBGs which quenches the highest-order laser modes.

4. CONCLUSIONS

Single transverse and longitudinal mode operation of nanosecond Yb-doped fiber laser was obtained. Both passive and active Q-switching techniques providing the same order of pulse energy (~50 μJ) were obtained. Control of the laser repetition rate and operation below 1 kHz (fluorescence lifetime in the Yb-doped fiber is ~ 1 ms) was achieved in an active Q-switching scheme. In a few modes regime we achieved maximum pulse energy of 300 μJ with pulse duration of 10 – 20 ns. The limiting factor was optical damage of the fiber facets. In the single frequency regime the increasing of the pump power led to shortening of the pulse duration which was affected by stimulated Brillouin scattering.

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