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# Q-switching and efficient harmonic generation from a single-mode LMA photonic bandgap rod fiber laser

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**Abstract:** We demonstrate a Single-Mode (SM) Large-Mode-Area (LMA) ytterbium-doped PCF rod fiber laser with stable and close to diffraction limited beam quality with 110W output power. Distributed-Mode-Filtering (DMF) elements integrated in the cladding of the rod fiber provide a robust spatial mode with a Mode-Field-Diameter (MFD) of 59 $\mu$ m. We further demonstrate high pulse energy Second-Harmonic-Generation (SHG) and Third Harmonic Generation (THG) using a simple Q-switched single-stage rod fiber laser cavity architecture reaching pulse energies up to 1mJ at 515nm and 0.5mJ at 343nm.

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## 1. Introduction

Fiber lasers and amplifiers are rapidly replacing conventional bulk solid-state lasers in various applications [1]. In particular, the development of LMA ytterbium-doped fiber systems have been extremely rapid in the last few years and record output powers from pulsed fiber amplifiers have been demonstrated [2,3]. The constant demand for higher pulse energies and peak powers have led to an increase of the effective area ( $A_{\text{eff}}$ ) of these fibers in order to mitigate nonlinear effect such as self-phase modulation, stimulated Raman scattering and four wave mixing. The damage threshold level of the fiber facet, which normally sets the limit to

the maximum possible extractable pulse energy, has also increased with the scaling of the  $A_{\text{eff}}$  [1], and further scaling typically requires expanding the beam size using pure silica endcaps, in order to avoid serious damage of the end-facet. A critical aspect of future power scaling of fiber lasers and amplifiers is beam quality degradation when the  $A_{\text{eff}}$  becomes larger and larger. State-of-the-art rare-earth-doped core manufacturing processes are difficult to apply to conventional Single-Mode (SM) step-index LMA fiber designs because of the required low NA and therefore extremely high index precision requirements. Better index control is achieved when the cladding index can be modified during draw to compensate the batch to batch index variations of the core manufacturing process. This can be accomplished with Photonic-Crystal-Fibers (PCFs) where the size of the air-holes can be adjusted in order to change the cladding index and therefore the fabrication of SM cores up to 100 $\mu\text{m}$  becomes possible [4,5].

The low nonlinearities of rod fibers allow generation of extremely high pulse energies even with short lengths [6]. Further power scaling can be achieved by using a Master-Oscillator-Fiber-Amplifier (MOPA) configuration [2,3]. In addition, rod fibers can be employed to achieve a robust, linearly polarized output for harmonic generation [7,8].

In this paper, we test a new SM DMF rod fiber design, demonstrated by Alkeskjold et al. [9], having a Mode-Field-Diameter (MFD) of 59 $\mu\text{m}$ , in different laser cavity architectures and demonstrate a stable and SM operation at 110W output power. The rod fiber design utilizes high-index ring-shaped elements as spatially Distributed-Mode-Filtering (DMF), which enables efficient suppression of Higher-Order-Modes (HOMs). The fiber is based on both Total-Internal-Reflection (TIR) and Photonic-Band-Gap (PBG) guiding principles and therefore guides light only in certain wavelength ranges. We demonstrate a high-energy Q-switched laser cavity generating pulses with pulse energy of 2.0mJ at 1030nm having high-brightness enabling efficient harmonic generation. Furthermore, by doubling and tripling the frequency, 1.0mJ pulse energy at 515nm and 0.5mJ at 343nm are achieved.

## 2. Distributed mode filtering rod fiber

In LMA PCF rod fiber designs, efficient suppression of HOMs is challenging due to the ultra low NA requirements, but also because the rod fibers are typically short (~1m) and kept straight, which complicates efficient HOMs suppression. The basic idea driving the development of the new DMF rod fiber design is more efficient HOMs suppression and manufacturability with acceptable yield. The high-index elements, called DMF elements, form cladding bands which HOMs are coupled to and therefore not guided in the core [9]. In this way, the core of the DMF rod fiber only guides in a certain wavelength range and exhibits non-guiding, SM and Multi-Mode (MM) behavior in different wavelength regions.

Figure 1 shows the transmission spectrum of a passive 85 $\mu\text{m}$  core DMF rod fiber. A halogen-tungsten source was coupled into the core of the DMF rod fiber, the output light was coupled into a SM LMA20 fiber and the spectrum was recorded with an optical spectrum analyzer. The oscillations in the spectrum originate from modal interference of the guided modes of the rod fiber as they are coupled to the SM LM20 fiber. The lack of oscillations indicates that only one spatial mode is guided in the core. The non-guided regime is found in the wavelength range 980-1030nm, which corresponds to the region where the Fundamental-Mode (FM) couples out to the cladding band. The inset of Fig. 1 illustrates the trends of the effective mode indices of the FM and HOM core mode together with the band of the cladding modes as a function of wavelength. In the same figure measured near field images are shown for different guiding regimes. At 1030nm the fundamental mode couples out to the cladding band and therefore the rod fiber operates in a leaky regime; at 1052nm the core supports only the fundamental mode and at 1085nm a combination of the fundamental and higher order modes is observed in the core of the rod fiber.

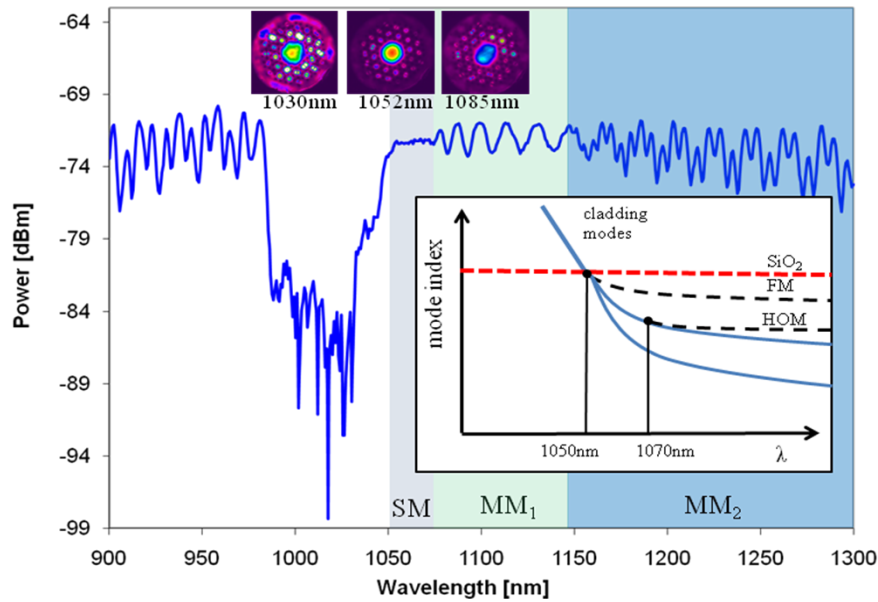


Fig. 1. Transmission measurement of a passive DMF rod fiber with 85 $\mu$ m core diameter. The measurement shows several interference patterns and indicates a SM region in the range 1050-1070nm. Sketched effective mode indices of the FM and HOM core mode together with the band of cladding modes as a function of wavelength are illustrated in the same figure. Measured near field images for different guiding regimes are also shown.

No oscillations are observed in the range 1050-1070nm which indicates that the HOMs are phase matched to the cladding modes and therefore only the FM is guided in the core, Oscillations are observed towards longer wavelengths (MM1 and MM2), which is a clear sign of interference between the FM mode and HOMs in the core region

Figure 2 shows a schematic and an optical micrograph of the manufactured DMF rod fiber having DMF elements arranged in a honeycomb-lattice, shown as cyan rings in the Fig. 2(a) and light colored rings in the Fig. 2(b).

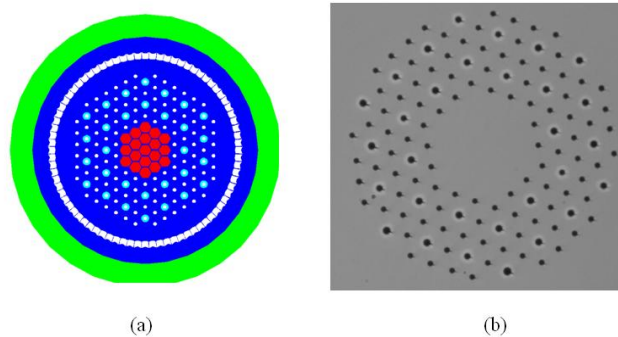


Fig. 2. The Distributed-Mode-Filtering rod fiber design. (a) Schematic of the rod fiber illustrating an Ytterbium-doped core and the high-index elements (Germanium) arranged in a honeycomb lattice. (b) Optical micrograph of a manufactured fiber, only showing the central region.

We manufactured an ytterbium-doped DMF rod fiber with a core diameter of 85 $\mu$ m having an estimated NA  $\sim$ 0.01. The size of the pitch was 15.0 $\mu$ m and the air-hole to pitch size ratio was 0.1. The fiber had a pump cladding diameter of 267 $\mu$ m with 0.6 NA, length of

120cm and pump absorption of  $\sim 27\text{dB/m}$  at 976nm. The rod fiber was SM in the range 1030-1045nm. Figure 3 shows the SM behavior of the SM DMF rod fiber, when the input beam at 1032nm is moved along the x- and y-direction. No HOMs are excited at 1032nm when the input was misaligned.

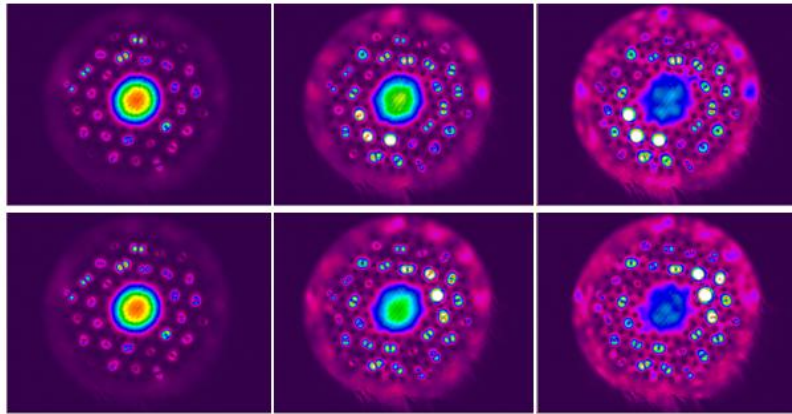


Fig. 3. Near-Field images of the Ytterbium-doped DMF rod fiber at 1032nm wavelength. The input beam is moved along the x (top row) and y (bottom row) direction and no HOMs are excited.

### 3. Measurement setup

For high power laser applications, the power conversion efficiency is an important parameter together with the beam quality and pointing stability. In the following experiments, a laser cavity setup was build in order to investigate the efficiency of the rod fibers and their beam quality.

We build a laser cavity setup to test the performance of the DMF rod fibers in a Continuous-Wave (CW) and Q-switched regime with high pulse energies. The experimental setup, shown in Fig. 4, consists of a CW 976nm pump diode with a 400 $\mu\text{m}$  core diameter delivering 200W output power, followed by a PCF DMF rod fiber, having polished end facets without end caps and angles of 5° and 0°. An Acoustic-Optical-Modulator (AOM) was employed when operating in a Q-switched regime. The laser cavity was formed by using either a Highly-Reflective (HR) mirror, flat response, or a Volume-Bragg-Grating (VBG) operating at 1030nm and the 4% end facet reflection. The length of the rod was  $\sim 75\text{cm}$  and the pump light was double passed through the rod fiber.

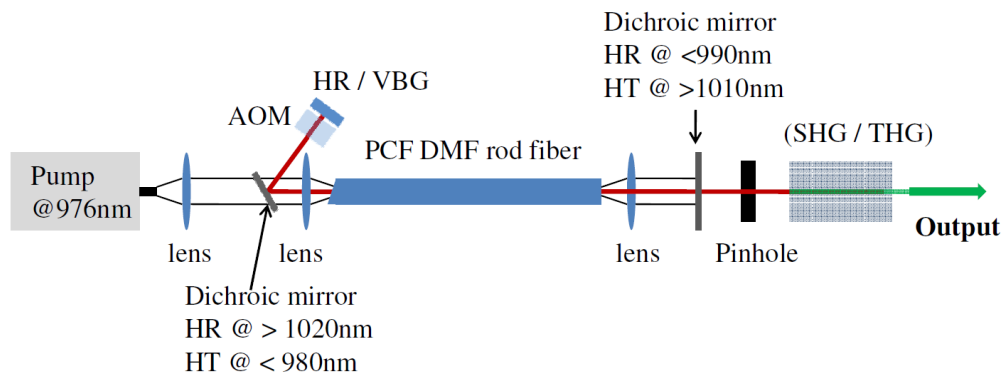


Fig. 4. Schematic of the laser cavity setup.

A pinhole positioned after the end facet of the rod fiber was used in order to quantify the ratio between the core light and the cladding light and to investigate the guiding regime of the core. In all the measurements, the pinhole was used and all the reported power values represent only the core signal power. LBO crystals were inserted after the rod fiber in order to evaluate Second-Harmonic-Generation (SHG) and Third-Harmonic-Generation (THG). In our experiments we used a commercial  $M^2$  measurement device (DataRay Inc, WinCamD + M2DU  $M^2$ ) with a standard 4 Sigma  $M^2$  calculation routine.

#### 4. Active measurements

##### 4.1 Continuous wave laser cavity measurements

No HOMs were observed when the rod fiber was operated in a CW laser cavity configuration using a flat HR mirror and the end facet as feedback. The output beam was very stable with close to diffraction limited beam quality, having  $M^2$  values less than 1.4. Any generated HOMs couple out from the core to the DMF elements. In this configuration, the lasing wavelength is not locked and lasing was observed in a wide wavelength range between 1024 – 1047nm, out off the SM region. This leads to degradation of the  $M^2$  number and spatial filtering is required to fully obtain a Gaussian limited beam with  $M^2$  approaching 1.

Figure 5 shows an optical slope efficiency measurement including a Near-Field (NF) and a Far-Field (FF) image recorded at 110W output power. The slope efficiency was measured to be 62% and was calculated using the measured core signal power versus the available pump power. The light intensity in the cladding region was low, increasing from 5% to 18% while the pump power was increased from 23W up to 210W.

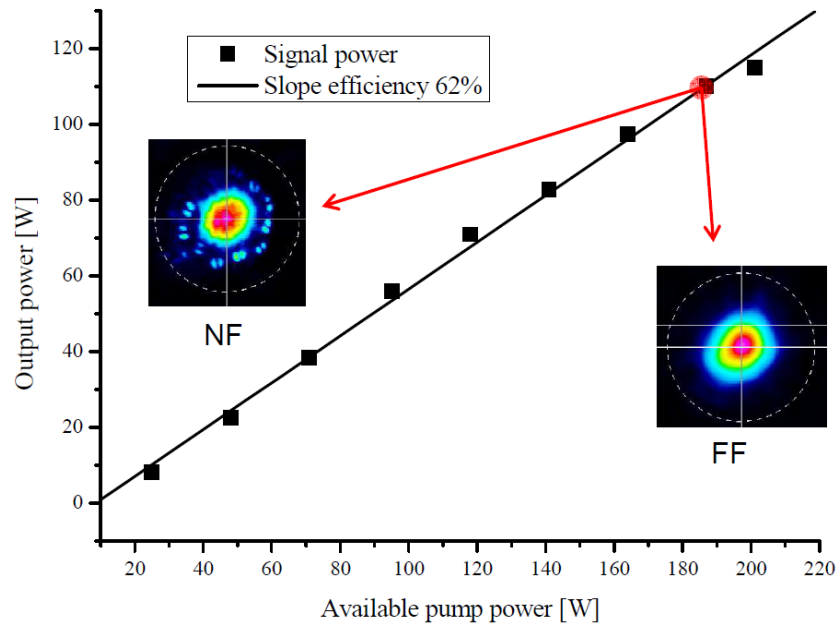


Fig. 5. Slope efficiency measurement of the DMF rod fiber, in a laser cavity (CW) configuration formed with a flat HR mirror. Insets show the NF and FF images at 110W output power.

##### 4.2 Q-switched laser cavity measurements

We inserted an AOM in the cavity and measured the beam quality using a flat HR mirror and the feedback from the end facet forming the cavity. We achieved again very stable and close to diffraction limited beam quality up to 104W of average output power with 100 kHz

repetition rate, corresponding to pulse energies of  $\sim 1\text{mJ}$ . With low repetition rates (10-30 kHz) we achieved pulse energies up to  $2.7\text{mJ}$ , giving a peak power of  $\sim 200\text{ kW}$ , close to the damage threshold level of the end facet. The slope efficiency was measured to be 57% with 100 kHz repetition rate, shown in Fig. 6 and the pulse width was measured to be 21 ns at the highest output power level. The beam quality was constant at all power levels and NF and FF images at 80W output power are shown in Fig. 6. The  $M^2$  were typically around 1.2 except at high output power, over 75W, where the light guided by the DMF elements caused an increase of the measured  $M^2$  value. If a smaller pinhole is used, a smaller  $M^2$  number can be achieved.

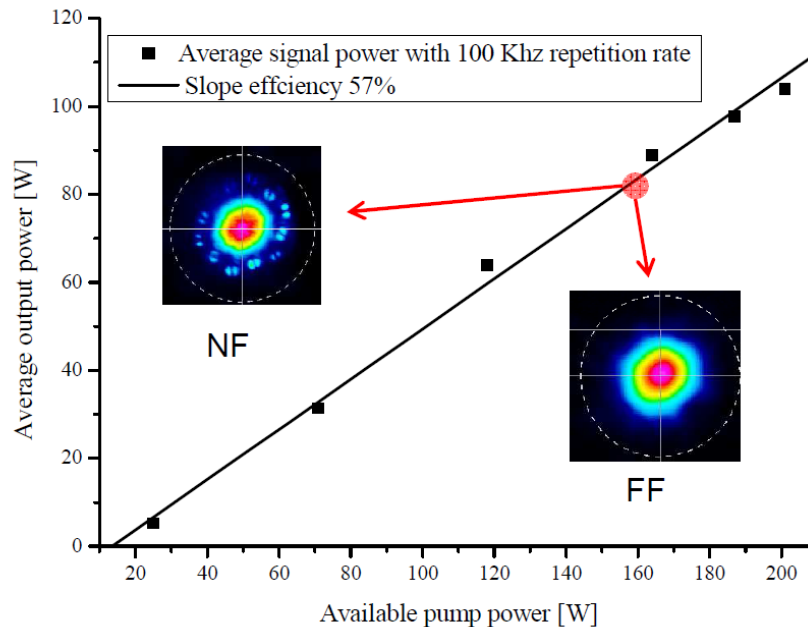


Fig. 6. Slope efficiency measurement of the DMF rod fiber, in a Q-switched laser cavity configuration formed with a flat HR mirror. Insets show the NF and FF images at 80W of average output power. The slope efficiency measurement was performed at 100 kHz repetition rate and the pulse width was measured to be 21ns at the highest power level.

#### 4.3 Wavelength locked Q-switched laser cavity measurements

We replaced the flat HR mirror with a 1030nm VBG exhibiting a 0.4nm band pass range. We tested the DMF rod fiber with various repetition rates up to 200kHz and up to pulse energies of 2.0mJ (10kHz), which we set as a limit in order to avoid damaging the end facet. We did not record any beam quality degradation with different repetition rates up to 47W of average output power and the  $M^2$  values were always  $< 1.1$ . We observed an abnormal behavior at high output powers. Above 47W, the output power started to decrease when the pump power was increased. The same behavior was observed with the CW configuration but this time above 69W of output power. The threshold level of this behavior seemed to depend on the applied laser cavity and shows that the spatial phase distortion introduced by the thermal load in the VBG cannot be perfectly filtered out by the short piece of rod fiber used in the cavity.

The measured slope efficiency was 51%, shown in the inset of Fig. 7. The same figure shows the recorded NF and FF images at 33W average output power. Improvement on the recorded NF images compared to the earlier experiments was observed due to the VBG locking the lasing wavelength to the SM region of the DMF rod fiber. The spectral width was measured to be  $\sim 0.4\text{nm}$  at 33W average output power with 20 kHz repetition rate and 14ns pulse width. The Q-switched laser cavity configuration provides high peak and average power



with a good spatial and spectral brightness and therefore efficient high power harmonic generation can be performed. The relation between spectral brightness of a source ( $B_{\text{spectral}}$ ) and spatial brightness ( $B_{\text{spatial}}$ ) is described by the following formula:

$$B_{\text{spectral}} = \frac{B_{\text{spatial}}}{\Delta\lambda} = \frac{\frac{P}{\Omega A}}{\Delta\lambda} \approx \frac{4P}{\pi^2 MFD^2 NA^2 \Delta\lambda}, \quad (1)$$

where  $\Delta\lambda$  is the linewidth,  $P$  is the output power,  $MFD$  is the mode-field diameter of the output beam,  $\Omega$  is the Far-field solid divergence angle of the output beam and  $NA$  is the numerical aperture of the core. We calculated the spectral brightness of our fiber laser to be  $125 \text{ W}/\mu\text{m}^2/\text{nm}$ .

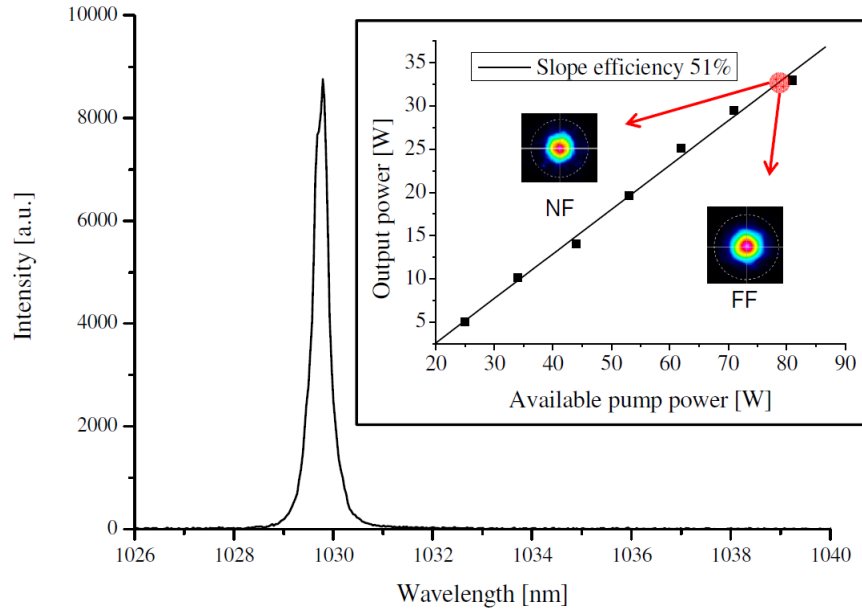


Fig. 7. Recorded output spectrum of the laser cavity at 33W of output power, with 20 kHz repetition rate, pulse width of 14ns and FWHM  $\sim 0.4\text{nm}$ . The inset shows a slope efficiency measurement together with NF and FF images at 33W of average output power. The slope efficiency measurement was performed with 20 kHz repetition rate and pulse length being 14ns at the highest power level.

#### 4.4 Second and third harmonic generation

We used a 20mm non critical phase matched temperature controlled LBO crystal for frequency doubling to green. We also performed third harmonic generation with two critically phase matched 15mm LBO crystals in a row [7,8]. All the crystals were antireflection coated. The output beam from the laser cavity was focused in the crystals with a  $\sim 200\mu\text{m}$  beam diameter.

We achieved a stable SHG up to 23W of average output power with 30 kHz repetition rate. We demonstrated a single-stage Q-switch rod fiber laser delivering record pulse energy of 1mJ at 515nm with 10 kHz repetition rate and 13ns pulse width, shown in Fig. 8. The same figure shows the maximum reached average power and pulse energy for the SHG.



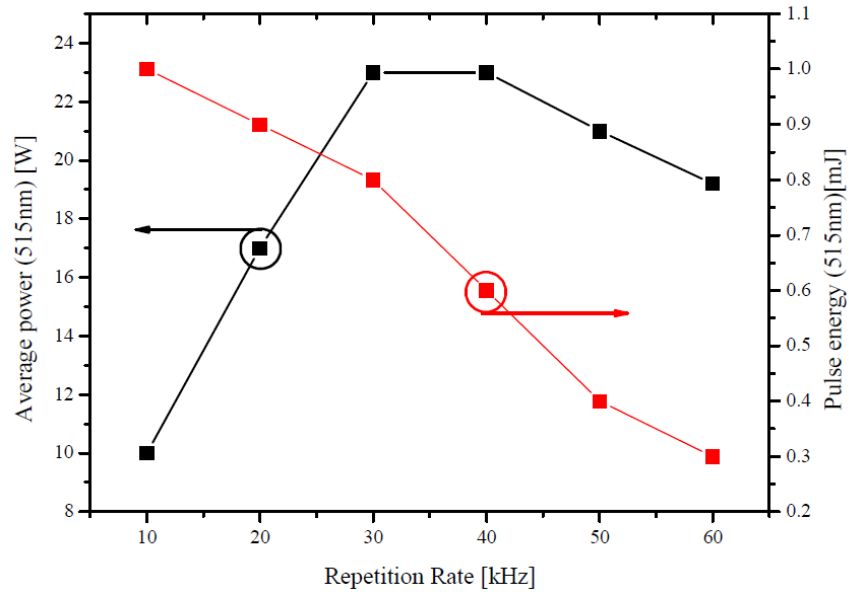


Fig. 8. Maximum reached average and pulse energy of the SM DMF rod fiber after SHG at 515nm as a function of repetition rate.

We operated the system at full power for about 10 minutes and we did not observe any power or beam quality degradation. The conversion efficiency from IR to green light was 48% and is shown in Fig. 9.

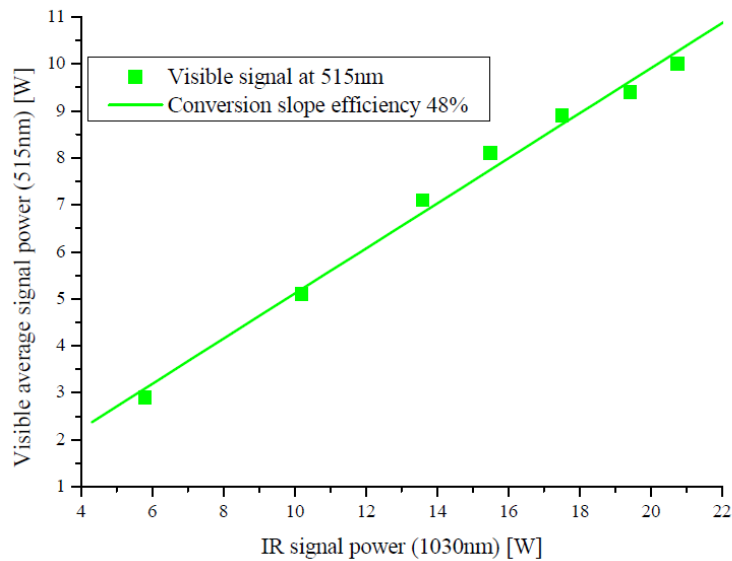


Fig. 9. Slope efficiency of the harmonic generations from IR to green light.

The beam quality was near diffraction limited with  $M^2 < 1.1$ , shown in Fig. 10. The  $M^2$  was recorded at 0.7mJ pulse energy with 10 kHz repetition rate and 14ns pulse width.

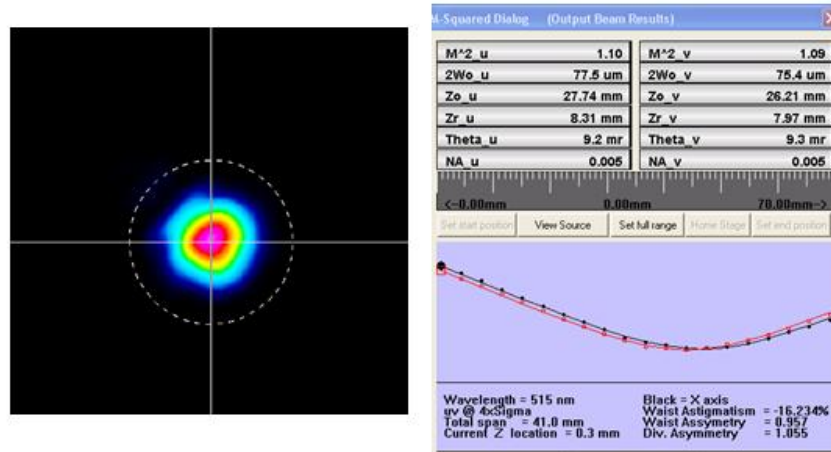


Fig. 10. Typical  $M^2$  measurement result from SHG, with 0.7mJ pulse energy, 10 kHz repetition rate and 14ns pulse width.

We also performed THG with the same system, inserting another LBO crystal. A record pulse energy of the generated UV light at 343nm was measured for the single-stage rod fiber laser cavity. We reached a stable output beam with near diffraction limited beam quality up to 500μJ, 400μJ and 300μJ with 10 kHz, 20 KHz and 30 kHz repetition rates, respectively, as shown in Fig. 11. The width of the pulse, at the maximum output power, increased from 11ns to 16ns when the repetition rate was increased from 10 kHz to 30 kHz.

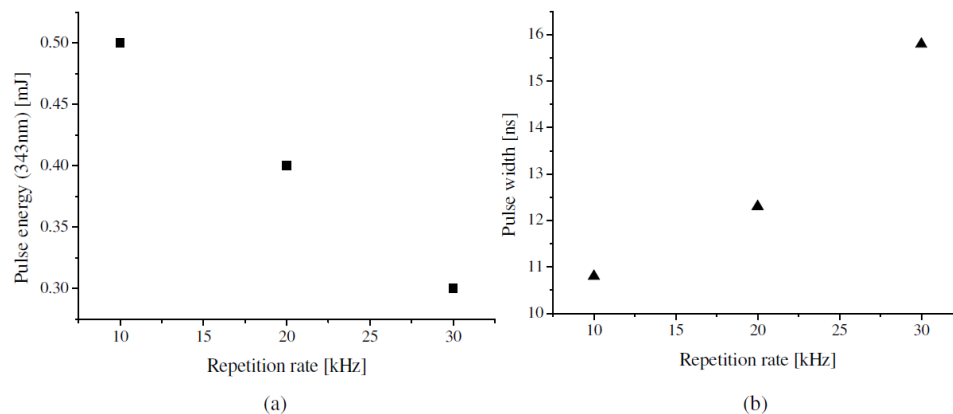


Fig. 11. Third harmonic generation at 343nm with different repetition rates. (a) Maximum reached pulse energy. (b) Measured pulse widths.

## 5. Conclusions

We have demonstrated the performance of a new ytterbium-doped rod fiber design operating in a laser cavity configuration exhibiting near diffraction limited beam quality and good power conversion efficiency. The rod fiber design utilizes Distributed-Mode-Filter (DMF) elements for HOM suppression and exhibits SM behavior having a MFD of 59μm. We demonstrate high peak and high average power from a Q-switched single-stage rod fiber laser cavity, with high spectral brightness (125 W/μm<sup>2</sup>/nm). We demonstrate efficient Second- and Third-Harmonic-Generation (SHG/THG) of pulse energies up to 1mJ at 515nm and 500uJ at

343nm with 10 kHz repetition rate and 13ns pulse width. To the best of our knowledge the achieved values are the highest reported for SHG/THG from a simple single-stage-Q-switch rod fiber laser.

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