Narrow-line, 1178nm CW bismuth-doped fiber laser with 6.4W output for direct frequency doubling

A. B. Rulkov[1*], A. A. Ferin[1], S. V. Popov[1] and J. R. Taylor[1], I. Razdobreev[2], L. Bigot[2] and G. Bouwmans[2]

[1]*Femtosecond Optics Group, Imperial College London, SW7 2BW, England*
www.femto.ph.ic.ac.uk
[2]*IRCICA-CERLA, Université des Sciences et Technologies de Lille, 59655 Villeneuve d'Ascq, France*
**andrei.rulkov@ic.ac.uk*

Abstract: We achieved a 0.2nm linewidth output at 1178nm with powers up to 6.4W in a linear 80m Bismuth-doped fiber cavity pumped by a 55W Yb fibre laser. The potential of frequency doubling of the non-polarized output at 1178nm in MgO doped periodically poled lithium niobate was demonstrated and resulted in 125mW average power at 589nm. The approach can be extended to a linearly-polarized large mode area format with under 0.1nm linewidth capable of scaling to Watts level in the 560-620nm range.

OCIS codes: (060.2290) Fiber materials; (060.2320) Fiber optics amplifiers and oscillators; **(**190.2620) Frequency conversion.

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1. Introduction

With the rapid advances of diode-pumped fiber laser technology, there appeared a growing interest in extending the wavelength coverage range of continuous wave (CW) and pulsed fiber laser sources to 1100-1300nm [1-4] because of the demand for high power visible in the 550 to 650nm range. Apart from the wavelength coverage, the fundamental high power CW fiber sources need to be capable of producing either narrow-line linearly polarized radiation to enable efficient single-pass frequency doubling in highly nonlinear periodically poled crystals [1, 4] or operate in near single-longitudinal frequency mode that can allow the use of 80-90%

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efficient external resonant cavity frequency conversion with bulk crystals [5]. The use of the high power Ytterbium-doped, and particularly aluminum-oxide host glass, fiber lasers for generating wavelengths in the 1120nm-1180nm range faces the problem of low-gain and typically require high Q, long laser cavities resulting in relatively broad laser emission linewidths [2, 3] particularly in a linearly polarized format. In this respect, the use of Stimulated Raman Scattering (SRS) for downshifting the fundamental wavelength of an Ytterbium fiber laser in an optimized polarization maintaining cavity format proves to be more promising [4]. However this approach would have to involve cascaded linearly-polarized SRS fiber converters should narrow line operation be required above 1180nm.

The recent discovery of photoluminescence of Bismuth-doped silica glasses [6] led to the development and demonstration of a new class of fiber gain media doped with this poor-metal-type ion that provides broad gain in 1100-1250nm range [8]. The energy diagram of bismuth ions in a silica host is still unclear, and additional complications with building bismuth doped lasers relate to the strong variation of the excited state lifetime across different absorption bands [8] and the inability, so far, to initiate lasing in fibers with bismuth concentration in excess of 0.005 weight % [8, 9]. However the presence of multiple absorption bands of Bismuth from the visible through to the near infrared, and in particular around 1µm, make bismuth doped silica fiber a good candidate for covering the 1100-1300nm wavelength gap. The scheme is especially interesting since pumping at 1µm can be provided by the well-established rare-earth doped fiber laser technology where the power of single-stripe multi-mode diodes at 980nm can be efficiently converted into high brightness single-mode radiation around 1.07µm in Yb-doped fiber lasers whose CW output powers reliably scale into multi-kW range [10].

The first bismuth doped fiber laser demonstrated [9] had an output power up to 460mW at 1146 and 1215nm, with the power limit imposed by the bulk pump laser. The approach has been extended to an all-fiber configuration with the best efficiency of up to 24% achieved at 1200nm [8]. Here we report first results on development of a power-scalable narrow-linewidth Bi-doped fiber source that can also be used for direct frequency doubling into the visible. The increased pumping was provided in an all-fiber format by employing a 50W single-mode Ytterbium fiber laser directly spliced to the isotropic bismuth fiber laser cavity. A 6.4W output power emission at 1178nm with ~0.2nm (FWHM) linewidth was obtained. Despite the generally non-polarized output format, the use of quasi-phase-matched congruent periodically-poled lithium niobate crystal with MgO doping allowed generation of 125mW at 589nm.

2. Experimental setup and results

The Bismuth-doped fiber preform was fabricated using a conventional modified chemical vapor deposition (MCVD) process; the Bismuth ions were solution-doped into a porous silica layer in the AlGeP co-doped core in a concentration of 0.005 weight %. The manufacturing and the spectroscopic properties of the preform and fiber are identical to those described in Ref. [8]. The preform was drawn into a single-mode fiber, compatible with commercial Corning HI-1060 to facilitate direct fusion splicing with the pump laser and passive fibre cavity components. In order to maintain the trade off between efficiency of Ytterbium pump absorption in the low concentration bismuth fibre and to suppress unwanted nonlinearity we used 80m of the bismuth fiber with reduced Ge content. Up to 80% of the pump radiation was absorbed at 1070nm. A linear cavity at 1178nm was configured by incorporating a Highly-Reflective HR (99.9%) 0.36nm stop-band fiber Bragg grating (written in a Corning HI-1060 compatible fiber) between the pump source and the active fiber (Fig. 1) and an Output Coupler OC with narrow, 0.09nm stop band.

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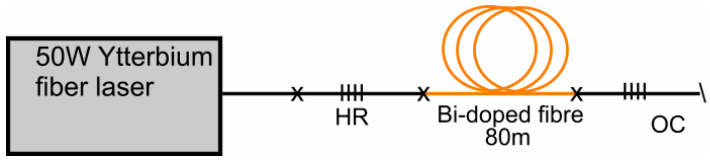

Fig. 1. The setup of the Bismuth doped fiber laser. HR is highly reflective FBG and OC is output coupling FBG

A procedure for arc-splicing of the gratings-fibre to the bismuth fiber splice loss was optimized by using an automated (Ericsson FSU 975-PM fusion splicer) built in incremental arc parameters variation procedure and resulted in losses as low as 0.2dB per splice. A combined loss of the active bismuth fibre with the spliced gratings of 0.4dB was measured in the transparency window of the bismuth fibre at 1550nm. Pumping a configuration with an angle-cleaved output fiber instead of the output coupler (in order to suppress the feedback) a maximum single-pass gain of 2.8dB at 1178nm was recorded.

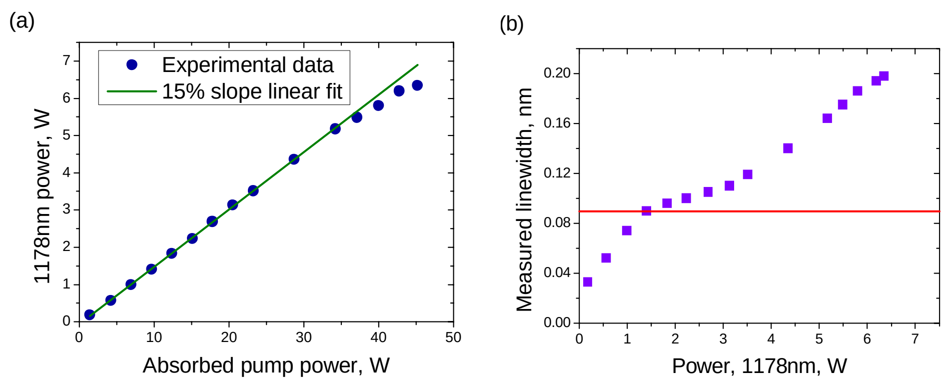

Fig. 2. (a). 1178nm laser output power vs absorbed pump power; (b) linewidth (FWHM) evolution of the 1178nm output. Horizontal line indicates the OC FBG linewidth

Core pumping of the 1178nm laser cavity was organized by using a commercial 1070nm non-polarized fiber laser (YLR-50, IPG Photonics) capable of producing 55W output, directly spliced to the 1178nm HR grating with a total measured transmission loss through the grating at the pump wavelength of less than 0.25dB. OC gratings with various reflectivities were assessed with the aim of maximizing the power of 1178nm output and a 50% output coupler was found to be optimum. To compensate for a slight mismatch in the HR and OC gratings central wavelengths the OC grating was slightly mechanically stretched to ensure spectral overlap.

Figure 2(a) illustrates the dependence of the 1178nm power on the absorbed pump power. The maximum output power recorded at 1178nm with the 50% OC was 6.4W and was limited by the available pump power. The lasing threshold was estimated to occur around 500mW of the absorbed pump power and a 15% slope efficiency was recorded. We observed no degradation of the output power in a series of experiments. The low Ge concentration (~0.6 weight % averaged over the core area) in the bismuth fibre allowed to minimize the SPM broadening of the linewidth, Fig. 2(b), to below 0.2nm and no Raman Stokes signal was observed. The slight roll-off at the highest output powers in Fig. 2(a) most probably relates to broadening of the lasing linewidth significantly beyond the linewidth the OC grating resulting in the reduced feedback, Fig. 2(b).

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3. Frequency doubling to 589nm

A test single-pass SHG of the 0.2nm linewidth 1178nm output of the bismuth laser was performed in a 8mm long (non-optimized length) periodically poled MgO-doped lithium niobate crystal (MgO:PPLN), available in house, with a poling period of 9.23μm and duty factor of 50:50. The crystal front facet had an AR coating at the fundamental wavelength and no AR coating on the output facet. The 1178nm fiber laser emission was re-collimated and focused into the crystal placed in a temperature stabilized oven. The focal spot size and confocal length were optimized with respect to the power at 589nm. The residual signals at 1070 and 1178nm were removed using dielectric beamsplitters.

We did not record a distinct polarization state of the 1178nm laser emission directly; however adjustment of a mechanical fiber polarization controller incorporated at the laser output resulted in a variation of the 589nm signal power below 20%. This indicated that approximately a half of the 1178nm power was used in the nonlinear frequency conversion in the MgO:PPLN.

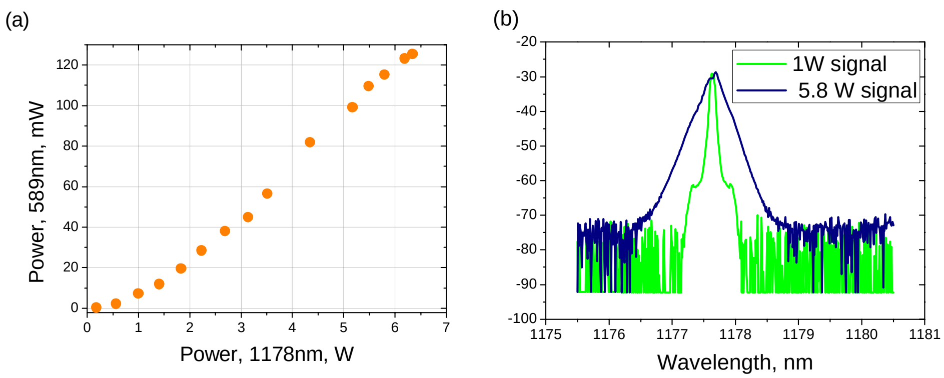

Fig. 3. (a). The 589nm power (in-crystal) vs 1178nm non-polarized pump.(b) Typical modification of the linewidth of the 1178nm fundamental with the output power .

Figure 3(a) illustrates the recorded dependence of the second harmonic signal on the input power. A maximum of 125mW in-crystal power (the value is recalculated taking into account the Fresnel reflection of the crystal) at 589nm was achieved. The conversion efficiency with respect to the total non-polarized fundamental power was close to 2%. The initial parabolic growth of the SH signal regressed to linear, as the pump power approached 3W which corresponds to the onset of further linewidth broadening of the fundamental, Fig. 2(b), Fig. 3(b). The broadening at these power levels is typically SPM-driven, similar to that observed in [4], and is due to the relatively long cavity length of the bismuth laser (80m).

4. Conclusion

In conclusion, we have demonstrated a 6.4W, 0.2nm linewidth bismuth fiber laser at the wavelength of 1178nm, with the potential of direct frequency doubling to 589nm in periodically-poled crystals. A 125mW average signal power at 589nm was obtained. With a polarization maintaining, large-mode area format bismuth doped fiber, as well as with a higher power Ytterbium single mode pump laser, the approach should allow scalability of the average powers in the visible beyond the watt-level.

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