Picosecond bismuth-doped fiber MOPFA for frequency conversion

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Received August 10, 2011; accepted August 31, 2011;
posted September 7, 2011 (Doc. ID 152595); published September 22, 2011

We report the development of a bismuth-doped fiber master oscillator power fiber amplifier system. The system operates at 1177 nm, producing 28 ps pulses at 9.11 MHz repetition rate, with an output power of 150 mW and a peak pulse power of 580 W. We subsequently frequency double the output, resulting in a picosecond pulsed visible source operating at 588.5 nm, with a maximum average output power of 13.7 mW.

OCIS codes: 060.2320, 140.4050.

Bismuth- (Bi-) doped fiber continues to attract attention because of its broad gain bandwidth that covers the spectral region between ytterbium and erbium-doped fiber. While the nature of the active center responsible for laser behavior in Bi-doped fiber is still unclear, and the subject of ongoing study [1–3], Bi-doped fiber already shows promise as a platform for lasers and amplifiers for new applications. Continuous wave Bi-doped fiber laser systems operating around the 1.18 μm band have been reported [4,5] and passively mode-locked Bi fiber laser systems operating in this wavelength range have been demonstrated in systems employing carbon nanotubes [6] or semiconductor saturable absorber mirrors (SESAMs) [7,8]. This spectral region is of interest as frequency doubling gives access to the yellow/orange part of the visible spectrum.

In a recent publication [9], we demonstrated the amplification of picosecond pulses in a Bi-doped fiber amplifier (BiDFA). In this work we demonstrate the applicability of Bi-doped fiber for master oscillator power fiber amplifier (MOPFA) schemes, which are a proven route to the power scaling of mode-locked fiber lasers in the ytterbium and erbium gain bands, and have obvious applications, such as frequency conversion, where a high duty factor is desirable to take advantage of the peak-power dependence inherent to the second harmonic generation process.

Our MOPFA combines a SESAM-based mode-locked oscillator operating at 1177 nm with a two-stage amplification scheme, producing 28 ps pulses at a 9.1 MHz repetition rate and 150 mW output power. We also frequency doubled the output of the MOPFA to generate a picosecond pulsed output at 589 nm.

In this work we use only alumosilicate bismuth-doped active fiber as the gain medium, pumped at 1.065 μm. Full details of the fiber used are given in [10]. As reported in [3], achieving appreciable gain in bismuth fiber operating in the 1.18 μm band requires cryogenic cooling to force four-level laser behavior. As such, in this work our active fibers are cooled through submersion in liquid nitrogen. At room temperature the gain in the active fiber was insufficient for the mode-locked oscillator to operate.

An overall system schematic of the MOPFA is shown in Fig. 1(a). Figure 1(b) shows a schematic of the mode-locked laser (MLL) used in the MOPFA. The MLL employs a SESAM (details of which can be found in [7,8]) to initiate passive mode locking in a linear cavity geometry. This all-fiber configuration enables the realization of a monolithic integrated MOPFA design. A 5 m length of Bi-doped alumosilicate fiber was used as the active element, and a commercial ytterbium fiber laser was used as the pump source. The cavity was pumped through a chirped fiber Bragg grating (CFBG), which is highly reflective at 1177 nm and results in a net-anomalous dispersion cavity, allowing solitonic operation of the laser. The oscillator has two output ports, labeled OP1 and OP2, such that the oscillator could be monitored at OP2 while the output of OP1 was amplified. The oscillator operated at 9.3 MHz, corresponding to the fundamental repetition frequency of the cavity, with

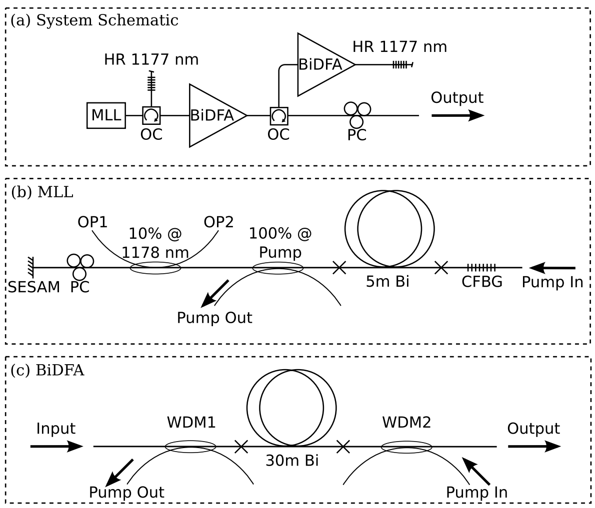

Fig. 1. (a) System schematic of all Bi-doped fiber MOPFA system incorporating a mode-locked laser [MLL, (b)] and two Bi-doped fiber amplifier [BiDFA, (c)]. Key to acronyms: OC, optical circulator; PC, polarization controller; SESAM, semiconductor saturable absorber mirror; OP1/2, output port 1/2; CFBG, chirped fiber Bragg grating; WDM1/2, wavelength division multiplexer 1/2.

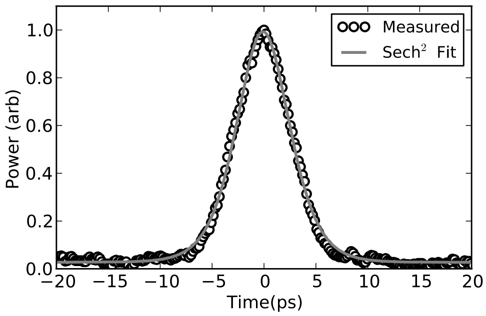

Fig. 2. Autocorrelation of mode-locked laser output. Sech^2 fit implies a deconvolved pulse duration of 3.9 ps.

a time averaged output power of −4 dBm from OP1. The autocorrelation of the laser output is shown in Fig. 2. A sech^2 fit implies a deconvolved full width half-maximum (FWHM) pulse duration of 3.9 ps. Figure 3 shows the output spectrum from the laser, where significant discrete spikes are evident on the long-wavelength side of the spectrum. We attribute these to third-order dispersion (TOD) introduced by the CFBG. Also evident are sidebands characteristic of average soliton regime operation. The radio frequency (RF) power spectrum of the MLL is shown in Fig. 4. A high peak-to-pedestal suppression ratio of 60 dB indicates good stability of the pulse train and the narrow linewidth of the beat signal at the fundamental repetition frequency of the cavity suggests low temporal jitter. The inset shows the higher cavity harmonics.

Before being amplified in the two-stage amplifier scheme, the MLL output was spectrally filtered so as to suppress the TOD lines. This also had the effect of restricting the pulse spectrum, leading to temporal broadening of the pulse, reducing the effect of self-phase modulation (SPM) in the amplifier chain. Filtering was achieved through use of an optical circulator (OC) and a fiber Bragg grating (FBG), highly reflective at the pulse wavelength, with a bandwidth of 0.2 nm. The spectrum after the OC is shown as the dashed curve in Fig. 3 and shows that the TOD features have been suppressed by over 30 dB.

A two-stage amplification scheme was employed. Each amplifier stage comprised a core-pumped BiDFA, as shown in Fig. 1(c). Each featured a 30 m length of Bi-doped alumosilicate fiber and was core-pumped using a commercial ytterbium fiber laser. Fused fiber WDMs were used for pump combination and extraction. The two stages differed in the optical pump power provided;

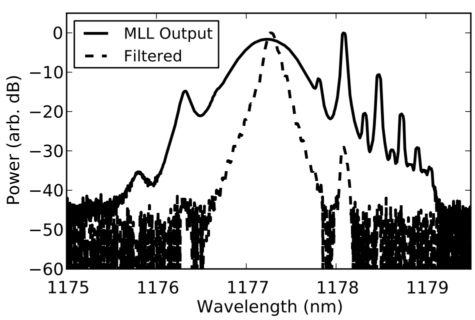

Fig. 3. Optical spectrum of the output directly from the mode-locked laser (solid curve) and after spectral filtering (dashed curve).

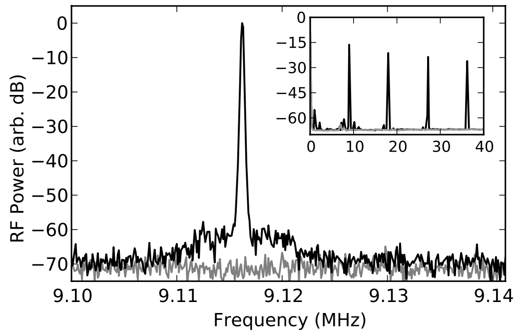

Fig. 4. RF power spectrum of mode-locked laser output. Gray curves indicate background level. Inset shows broad bandwidth scan.

the first stage was pumped at 2 W, while the second stage was pumped with up to 5 W. The second amplifier stage was double passed to maximize gain; one end of the amplifier was spliced to port 2 of an OC, the other end was spliced to a high reflector FBG (identical to that used between the MLL and first amplifier stage), which also acts a spectral filter to remove amplified spontaneous emission (ASE). The amplified output was returned to the OC and output from port 3. The circulators provided isolation between the stages of the MOPFA scheme, preventing backwards-propagating ASE being passed up the stages.

Figure 5 shows the spectrum of the output from the MOPFA system and shows 50 dB of isolation between the signal and the ASE. There was some broadening of the pulse spectrum through self-phase modulation. A total output power of 150 mW was recorded for a pump power of 5 W across the second stage amplifier.

The autocorrelation of the MOPFA output is shown in Fig. 6. The initial spectral filtering of the oscillator output resulted in temporal broadening of the pulse to a duration of 28 ps, corresponding to a peak pulse power of 580 W. Slight wings to the autocorrelation were attributed to the effect of the spectral filter between the mode-locked oscillator and the first amplifier stage.

A 20 mm long periodically poled lithium niobate crystal was then used to frequency double the output of the MOPFA system. The output was collimated using a 3.3 mm focal length lens and focused into the crystal using an 88 mm focal length lens, giving a focal beam waist of 44 μm and confocal length of 10 mm, shorter than the physical length of the crystal.

Both lenses and the input face of the crystal were antireflection coated at the fundamental wavelength of

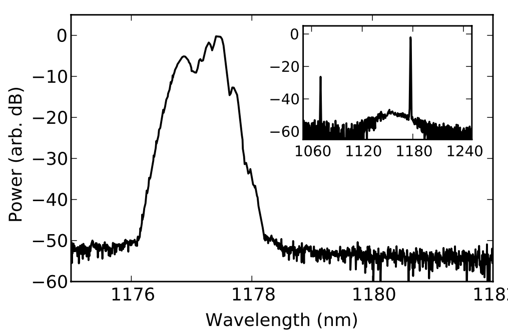

Fig. 5. Optical spectrum of MOPFA output at maximum output power. Inset: broad wavelength range spectrum.

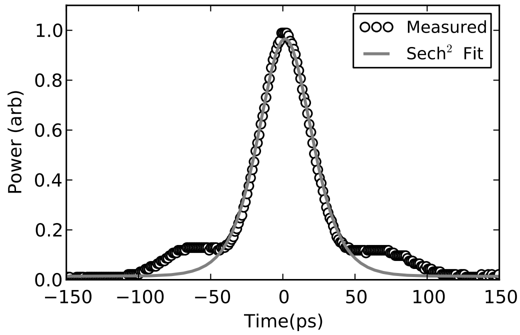

Fig. 6. Autocorrelation of MOPFA output at maximum output power. Sech^2 fitting implies a deconvolved pulse duration of 28 ps.

1177 nm. The output face of the crystal was uncoated. Phase matching was achieved through temperature control of the crystal (polling period 9.27 μm, phase-matched temperature 106.6 °C), and a fiber strainer polarization controller [as shown in Fig. 1(a)] was used to ensure that the MOPFA output was polarized along the Z axis of the crystal.

The MOPFA output power was tuned up to its maximum output of 150 mW by varying the optical pump power of the second amplifier stage. The frequency doubled power is shown as a function of the MOPFA output (fundamental) power in Fig. 7. The relation is seen to be initially quadratic with fundamental power, but above powers of 80 mW is seen to be linear. This is due to the increased spectral broadening of the MOPFA output through SPM with increasing output power, which reduces the proportion of the fundamental spectrum that is within the phase-matched bandwidth of the crystal.

The spectrum of the frequency doubled radiation (as recorded on an optical spectrum analyzer) is shown as an inset to Fig. 7. The peak of the spectrum is located at 588.75 nm, which agrees with the location of the peak of the MOPFA output spectrum at 1177.5 nm. The frequency doubled spectrum has a FWHM bandwidth of 0.16 nm, which implies a phase-matching bandwidth of 0.32 nm at the fundamental frequency. Also shown as an inset to Fig. 7 is a photograph of the far-field beam pattern. The frequency doubled output power was recorded as 13.7 mW—a conversion efficiency of 9% with respect to the total fundamental power or 20% with respect to the fundamental power within the phase-matched bandwidth of the crystal.

In conclusion, we have demonstrated an all-fiber integrated Bi-doped fiber based MOPFA system operating at 1177 nm capable of producing 28 ps pulses at 9.1 MHz repetition rate, with an output power of 150 mW,

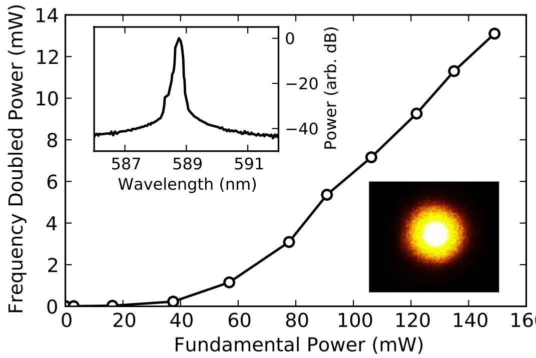

Fig. 7. (Color online) Conversion of MOPFA output (fundamental) power to frequency doubled radiation. Top left inset shows spectrum of frequency doubled output. Lower right inset shows photograph of far-field mode pattern.

corresponding to a peak pulse power of 580 W. We subsequently frequency doubled the MOPFA output, resulting in a picosecond pulsed visible source operating at 588.5 nm with a maximum average output power of 13.7 mW. This is, to the best of our knowledge, the first demonstration a MOPFA system based on Bi fiber amplifier technology and illustrates that Bi-doped fiber has promise as a platform for the development of laser systems with advanced configurations.

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