Amplification of picosecond pulses and gigahertz signals in bismuth-doped fiber amplifiers

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We demonstrate the capability for amplification of picosecond pulses in two bismuth-doped alumosilicate fibers. A spectrally filtered supercontinuum source is used to provide a train of picosecond pulses at discrete wavelengths within the gain bandwidth of bismuth fiber amplifiers. With a 30 m length of active fiber, a small signal gain at 1160 nm of over 20 dB is observed. In addition, we assess the viability of amplification of high repetition rate signals in such amplifiers, applying a 10 GHz modulation to a continuous wave Raman fiber laser operating at 1178 nm, finding that such signals are amplified without noticeable distortion. © 2011 Optical Society of America

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There has been continuing recent interest in the use of bismuth (Bi)-doped fiber as a laser gain material [1–4] and a platform for broadband amplifiers with potential telecommunications applications [5,6] due to their large IR fluorescence band, covering the region between Yb- and Er-doped silica fiber. Currently no rare-earth-doped silica fiber amplifiers, apart from low-power soft glass praseodymium devices, cover this spectral band, which coincides with the region of low material group velocity dispersion in silica. Amplification of continuous wave (CW) signals in Bi-doped silica has been demonstrated in both bulk glass [7,8] and fiber [9,6] formats. In this Letter, we demonstrate the amplification of picosecond (ps) pulses and of high frequency modulated signals in single-mode Bi-doped fiber amplifiers core pumped with an ytterbium (Yb) fiber laser. This study confirms the potential for application of this technology in future telecommunication networks, and is, to the best of our knowledge, the first experimental demonstration of single-pass pulsed amplification in this emerging gain medium.

Two gain fibers were examined, both fabricated using a surface-plasma chemical vapor deposition process. Both are Bi-doped alumosilicate fibers, whose core glass is composed of 97 mol.% SiO_2 and 3 mol.% Al_2O_3, with a core diameter of $8\,\mu$m and a core/cladding refractive index contrast of 5×10^{-3}. The fibers differ in their core Bi center content. The first (hereafter referred to as fiber 1) has a core Bi center content of 0.002 mol.%, and the second (hereafter referred to as fiber 2) has a content of 0.004 mol.%. Fiber 2 also has a significantly reduced OH content.

The attenuation spectra for both fibers are shown in Fig. 1, and specifics of the fabrication technology, absorption spectra, and near-IR luminescence of fiber 1 and fiber 2 can be found in [10,11], respectively.

Measurements of the gain were conducted by counter-pumping the active fiber using a commercial CW Yb fiber laser operating at $1.06\,\mu$m with a maximum output power of 6.5 W. Our experimental setup is shown in Fig. 2; the amplifier was constructed from a 30 m length of active fiber, fusion spliced at either end to wavelength division multiplexers (WDMs) for pump combination/extraction.

A spectrally filtered pulsed supercontinuum (SC) source was used to provide a train of ps pulses selectable within the gain bandwidth of both fiber amplifiers. The SC source was constructed from a commercial ps mode-locked laser, the output of which was amplified in a Yb-doped fiber amplifier (YDFA) and directly fusion spliced to a 60 m length of photonic crystal fiber (PCF) with a zero dispersion wavelength (ZDW) of 1038 nm. The SC output from the PCF was spectrally filtered using a band-pass filter, centered at either 1160 or 1180 nm providing signal levels of −4 and −7 dBm, respectively. The spectra for the ps source using either filter are shown in Fig. 3. Autocorrelations of both selected wavelength ranges were taken (shown in Fig. 4) indicating an average FWHM pulse duration of 2.5 ps for the 1160 nm band and 1.6 ps for the 1180 nm band.

We measured the gain with increasing optical pump power for both wavelengths in both fibers by recording the spectrum and total output power for each pump level, so that the output power could be integrated within the −3 dB width of the input spectrum. As previously noted in [12] and subsequently in [13], the performance of Bi-doped fiber amplifiers are heavily influenced by fiber temperature. Accordingly, the optical gain was measured with the fibers cryogenically cooled to 77 K in liquid nitrogen, and also at room temperature.

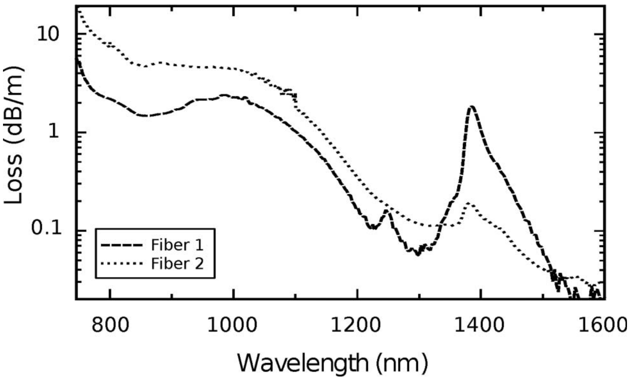

Fig. 1. Attenuation spectra for the two Bi-doped alumosilicate fibers examined.

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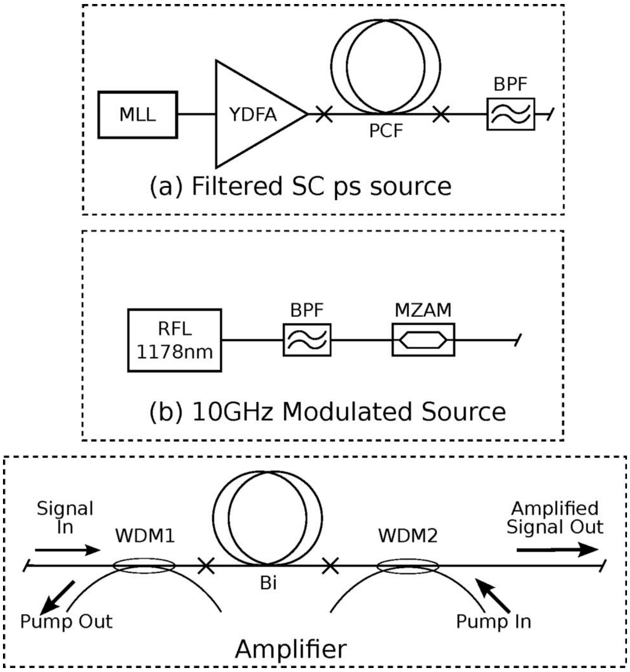

Fig. 2. Experimental setup. MLL, mode-locked laser; YDFA, Yb-doped fiber amplifier; PCF, photonic crystal fiber; RFL, Raman fiber laser, MZAM, Mach–Zehnder amplitude modulator; BPF, bandpass filter; WDM1/2, pump extractor/combiner.

The small signal gain saturation curves are plotted in Fig. 5. In the case of fiber 1, the gain saturated above ~2.5 W pump power for both signal wavelengths, giving a maximum gain of 21.2 and 15.7 dB for 1160 and 1180 nm, respectively, when cryogenically cooled. In the room temperature case, the corresponding maximum gain measurements were 6.3 and 5.5 dB. Even at the maximum pump power, gain in fiber 2 under cryogenic cooling was not fully saturated, but maximum gains of 21.8 and 16.1 dB were measured for 1160 and 1180 nm, respectively. At room temperature, the gain in fiber 2 was found to saturate before the amplifier reached transparency.

Autocorrelations were taken of the amplified outputs for maximum gain with cryogenic cooling and are shown, along with the autocorrelations of the inputs, in Fig. 4. Also shown are the FWHM pulse durations inferred from a sech^2 fit.

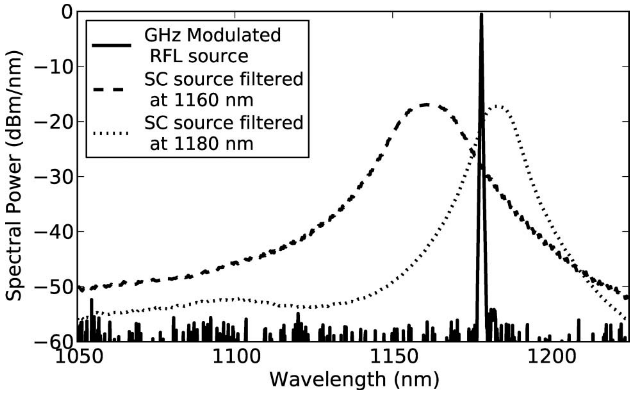

Fig. 3. Spectra for the various inputs, the modulated RFL source, and the SC source bandpass filtered at 1160 or 1180 nm.

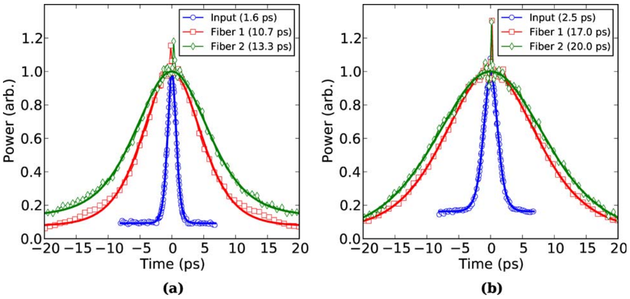

Fig. 4. (Color online) Autocorrelations of filtered supercontinuum input and amplifier output at maximum optical pump power in both gain fibers for (a) 1180 nm and (b) 1160 nm.

In both fibers, the pulses were subject to normal dispersion and were broadened to over 10 ps duration. A significant spike is apparent on the output autocorrelations. We associate this with the amplification of nonsolitonic radiation in the supercontinuum, which has acquired an anomalous chirp in the PCF, and was subsequently compressed as it was amplified in the normally dispersive Bi-doped fiber.

The gain provided by the amplifier for a high repetition rate modulated signal was characterized using a Raman fiber laser operating at 1178 nm, also shown in Fig. 2. The Raman cascade-based fiber laser was used to provide a CW signal at 1178 nm. A bandpass filter was employed to suppress residual pump lines in the laser output. This CW signal was then modulated using a Mach–Zehnder amplitude modulator (MZAM) to produce a 10 GHz sinusoidal signal with an average power of −6 dBm. The gain was measured, as described above, with increasing pump power, and the results are shown in Fig. 6. The gain in fiber 1 was found to saturate above ~2 W at 14.4 dB, while the gain was not saturated in the case of fiber 2, which exhibited a maximum gain of 17.7 dB. The amplified signals are shown as insets to Fig. 6 and show that the sinusoidal signal has been amplified with no noticeable distortion.

In conclusion, we have demonstrated the amplification of ps pulses at 1160 and 1180 nm in a Bi-doped

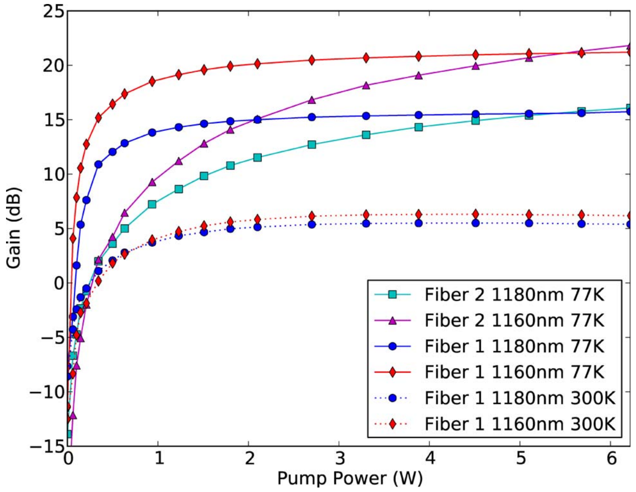

Fig. 5. (Color online) Gain in 30 m of doped fiber with increasing pump power in both gain fibers at 1160 nm and 1180 nm, employing cryogenic cooling (77 K) and also, in the case of fiber 1, at room temperature (300 K).

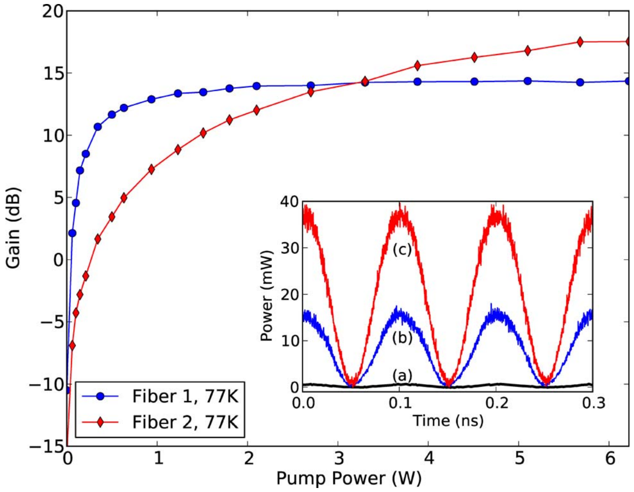

Fig. 6. (Color online) Gain in 30 m of doped fiber with increasing pump power in both fibers, cryogenically cooled to 77 K. Inset: optical signal at (a) input, and output from Bi-doped amplifier incorporating (b) fiber 1 or (c) fiber 2.

alumosilicate fiber amplifier using a Yb pump laser in a core-pump configuration. We measured the gain in 30 m lengths of Bi-doped alumosilicate fibers and, with cryogenic cooling, over 20 dB of gain was achieved in both fibers for input pulses at 1160 nm. We also demonstrated the amplification of a high repetition rate (10 GHz) modulated signal at 1178 nm, with gain of over 15 dB. This is, to the best of our knowledge, the first demonstration of amplification of ps pulses and high frequency modulated signals in a Bi-doped fiber amplifier.

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