We demonstrate an ytterbium gain band self-induced modulation instability laser. A highly nonlinear holey fiber is used to provide the anomalous dispersion required for bright soliton generation at 1 μm. The all-fiber integrated source yields a 40 GHz train of 4 ps pulses at a wavelength of 1064 nm. © 2006 Optical Society of America

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High repetition rate pulse sources find use in, for example, frequency metrology,1 time-resolved spectroscopy,2 and nonlinear microscopy.3 It has been demonstrated that simple fiber cavities containing only an erbium-doped fiber amplifier (EDFA), a bandpass filter, and polarization controllers can produce bright soliton trains with repetition rates as high as 260 GHz.4–6 provided that the average cavity dispersion is anomalous. The mode-locking process has been attributed to modulation instability4,7 of the cw field resonant in the cavity, which through feedback leads to the generation of a high-quality train of ultrashort solitons with a repetition rate determined by power and group velocity dispersion. The system is commonly referred to as the self-induced modulation instability laser (SIMIL) to differentiate it from systems in which externally introduced modulation instability carrier waves were used.8–10 Recently it has been numerically and experimentally shown that if the average cavity dispersion is normal, the SIMIL can produce dark soliton trains.11 Nonetheless, for the production of bright soliton trains with all-conventional fiber systems, the operating wavelength is restricted to above 1.28 μm, since below this wavelength, standard fiber is necessarily normally dispersive. Highly nonlinear holey fiber (HF), however, can provide anomalous dispersion below 1.28 μm, so that bright soliton SIMILs in this spectral region are now possible through operation in the so-called average soliton regime.12 Here, for the first time to our knowledge, we experimentally demonstrate a SIMIL that operates below 1.28 μm. The laser cavity contains a length of anomalously dispersive HF and an ytterbium-doped fiber amplifier (YDFA) with a relatively low normal dispersion due to its short (2 m) length. The laser cavity has an average anomalous dispersion, and a 4 ps bright soliton train at a repetition rate of 40 GHz is generated. The HF used is fusion spliced to conventional fiber, thus enabling an all-fiber integrated configuration.

The experimental configuration is shown in Fig. 1. The HF (Blaze Photonics SC-5.0-1040 nm) had a core diameter of 4.9 μm, a mode field diameter of 3.6 μm, and a loss at the zero dispersion wavelength (1038±5 nm) of 1.9 dB/km. It was fusion spliced to conventional fiber at the input and output ends with losses of 1.0 and 0.8 dB, respectively. Since modulation instability (MI) is polarization dependent, two fiber polarization controllers were used to optimize and stabilize the laser. A fiber pigtailed isolator was employed to ensure unidirectional operation and to suppress Brillouin scattering. Gain was provided by a double-clad, side-pumped ytterbium-doped fiber amplifier, which could provide up to 2 W of average output power. The pump light was counterpropagated through the short (~2 m) gain fiber and was extracted at the amplifier input. An optical bandpass filter (BPF) that was mounted in a fiber pigtailed air-gap was also employed. The BPF had a FWHM of 1 nm and a central wavelength around 1.06 μm. Fifty percent of the laser power was recirculated via a fiber coupler. In total, the cavity contained ~7 m of normally dispersive standard fiber and ~100 m of anomalously dispersive HF. Since a standard single-mode fiber typically has a dispersion of 30–50 ps nm−1 km−1 at 1.06 μm, and the HF had a dispersion of ~5 ps nm−1 km−1 at 1064 nm, the average cavity dispersion is expected to have an anomalous dispersion of 1.4–2.7 ps nm−1 km−1. For picosecond pulses, this leads to a soliton period on the kilometer scale, which is substantially greater than the cavity length, so we expect that the laser should operate in the average soliton regime (with a fundamental soliton power of ~20 mW) and without substantial shedding of nonsolitonic radiation. The system output was simultaneously analyzed in a second-harmonic generation (SHG) background-free autocorrelator and a spectrum analyzer by using a second coupler.

Fig. 1. Experimental configuration. BPF, bandpass filter. PC, polarization controller.
A typical output autocorrelation once the polarization controller settings are empirically optimized is shown in Fig. 2. Note that the laser has been observed to self start. From the autocorrelation we obtain a repetition rate of 41.0±0.5 GHz and a pulse duration of $\approx 4$ ps, assuming a sech² shape. The noise pedestal is $\approx 1\%$. By using a half-wave plate just before the autocorrelator, we found the output to be linearly polarized, although with a measurement resolution of less than 20 dB. Note that the linearly polarized output was a consequence of optimizing the polarization controllers to obtain the maximum SHG intensity after autocorrelation. The output spectrum, taken with 0.01 nm resolution, is shown in Fig. 3. The spectral peaks have a modulation depth of $\approx 39$ dB and are separated by 0.15 nm. The corresponding repetition rate is 40.1±0.3 GHz, which is in reasonable agreement with the repetition rate measurement from the autocorrelation trace. The FWHM of the individual spectral peaks is resolution limited. The total FWHM spectral width is estimated to be 0.35 nm, leading to a time-bandwidth product of $\approx 0.4$. This value correlates reasonably well with the theoretical value of 0.315 for solitons, given the uncertainties in the measurement of the temporal and spectral profiles. The laser output was also measured by using a 5 GHz photodetector and an analog oscilloscope and was found to be cw. Intensity fluctuations of $\approx 10\%$ of the cw intensity level were observed, and may be due to longitudinal mode beating, mechanical and thermal instabilities, and polarization instability. The output power was measured to be 50 mW, corresponding to a power just after the YDFA of 360 mW. Note that the threshold for MI occurred for an amplifier output power of 100 mW. Some long-term instability over time scales in excess of 10−15 min was observed as a result of polarization drift, requiring empirical optimization of the system to recover the state of operation described in Figs. 2 and 3. We observed a gradual reduction in the spectral modulation depth over this time scale, although the pulse duration was maintained. It is most likely that this was associated with mechanical instability in the laser, leading to depolarization and phase shifts of the pulses. Improved stability could be obtained through the use of polarization maintaining fiber. The use of an intracavity Fabry–Perot filter is also known to improve the stability and noise characteristics of the SIMIL. It should also be possible to obtain higher repetition rates and shorter pulse durations through the use of a broader bandwidth filter or an optimized HF.

In conclusion we have demonstrated a self-induced modulation instability laser that operates in the normally dispersive regime of conventional fiber. The anomalous dispersion of the incorporated holey fiber and the low dispersion of the short length ytterbium-doped fiber led to an average anomalous dispersion that permitted the generation of a bright soliton train at a wavelength of 1064 nm. A train of $\approx 4$ ps duration pulses with a repetition rate of 40 GHz was obtained, and shorter pulses and higher repetition rates should be possible by optimization of the system parameters.

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References