Low-threshold self-induced modulational instability ring laser in highly nonlinear fiber yielding a continuous-wave 262-GHz soliton train

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Modulational instability (MI) is employed in a self-induced ring cavity configuration based on highly nonlinear dispersion-shifted fiber (HNL DSF) and an erbium-doped fiber amplifier to generate a continuous-wave 262-GHz train of 365-fs optical solitons. The laser operates around 1540 nm, with an average output power of 15 mW. MI is achieved at a low threshold as a result of low average cavity dispersion and high fiber nonlinearity. It is shown that, because of the normal dispersion of the HNL DSF, the solitons exist in the average soliton regime. © 2002 Optical Society of America

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Modulational instability (MI) is a passive physical process through which a high-repetition-rate train of solitons can be generated in an optical fiber. The term refers to the transition from continuous-wave (cw) light to short pulses when amplitude fluctuations on the cw light level are amplified and temporally compressed as a result of the interplay between self-phase modulation and anomalous dispersion in an optical fiber. MI can be viewed, in the frequency domain, as a parametric interaction between a carrier pump wave and sidebands that develop from fluctuations in the cw input light. The resultant light waves superimpose to generate the output pulse train. The parametric interaction is phase matched by self-phase modulation, although fiber nonuniformities and system fluctuations can result in variations in the phase-matching condition. The use of MI as a technique to generate high-repetition-rate pulse trains is advantageous, as it does not rely on expensive ultrafast modulators and it could, therefore, find application in research laboratories as a flexible means of testing high-bit-rate optical telecommunication devices.

Hasegawa and Brinkman first theoretically described the technique in optical fibers in 1980, and subsequently Tai et al. experimentally demonstrated MI in a single-pass configuration by using quasi-cw input pulses. The input light consisted of long, ~100-ps, pulses so the threshold power (5.5 W) for MI could be reached and undesired nonlinear effects, such as stimulated Brillouin scattering, avoided. MI was shown to develop from amplified spontaneous emission generated in an intracavity erbium-doped fiber amplifier (EDFA). Such configurations are self-induced in that no externally introduced MI carrier waves are used. In Ref. 6 it was shown that the combination of low cavity loss and high EDFA gain (from a 650-mW EDFA pump at 980 nm) resulted in a MI-generated 130-GHz train of 1.8-ps pulses. Yoshida and Nakazawa reported, in Ref. 7, a more stable variation of the self-induced MI ring laser in which an intracavity etalon with a free spectral range equal to the MI repetition rate lowered the MI threshold. In addition, most fibers used were polarization maintaining to stabilize the system, and a filter was incorporated to permit control over the MI spectrum. A 115-GHz train of 1.6-ps pulses was generated from a much lower EDFA pump power of 130 mW.

In this Letter we demonstrate a low-threshold self-induced MI laser that employs an intracavity EDFA in a ring cavity configuration based on highly nonlinear dispersion-shifted fiber (HNL DSF). HNL DSF has a core area that is typically 10× smaller than that of conventional fiber and, as a result, exhibits high nonlinearity. It has already been employed as the basis of several fiber devices, including Raman amplifiers and wavelength converters. Current HNL DSFs are typically constructed with low-sloped dispersion and a zero-dispersion wavelength near 1.55 μm for potential telecommunication applications. These fiber parameters are attractive as low and flat cavity dispersion aids in the MI process. We show here that a cw 262-GHz train of 365-fs solitons can be obtained at a low EDFA output power because
of the HNL DSF and low average cavity dispersion. Furthermore, as the HNL DSF exhibits normal dispersion at the lasing wavelength, it is shown that the resultant pulses exist in the average soliton regime.

Figure 1 depicts the experimental configuration of the MI fiber ring laser. The MI process was self-induced and initiated by cw amplified spontaneous emission from a commercial EDFA that provided up to 600 mW of output power. The majority of the cavity length constituted a 607-m HNL DSF that had a nonlinear coefficient of $21 \text{ W}^{-1} \text{ km}^{-1}$ and a low-shaped dispersion about a zero-dispersion wavelength of 1552 nm. It is noted that, in a single-pass configuration with 1 km of the same fiber, MI was observed with in-fiber cw powers of $\sim 40 \text{ mW}$. To optimize phase matching and stabilize the system a polarizer (POL.) and two polarization controllers (PCs) were employed. Furthermore, the MI process was assisted by use of a 12.8-nm tunable bandpass filter (TBPF) to restrict lasing to near the zero-dispersion wavelength of the cavity. It was found that, without the TBPF, lasing tended to occur at a longer wavelength and MI did not efficiently build up in the ring. Adding 4 m of dispersion-compensating fiber (DCF) yielded a low cavity dispersion at the laser wavelength that encouraged MI and reduced its threshold. An optical coupler was used to extract 20% of the laser power at each round trip. The output pulse train from a MI laser was simultaneously analyzed in an optical spectrum analyzer and in a second-harmonic generation autocorrelator at a ratio of 1:99 by use of a tap coupler. A length of dispersion-compensating fiber was included after the ring output coupler to compensate for the dispersion introduced by these external measurement fibers.

Figures 2 and 3 depict the spectrum and the autocorrelation of the optimized modulational instability laser, respectively, for an EDFA output power of 280 mW. From Fig. 2 it can be seen that the laser output resembles a typical MI spectrum consisting of equally spaced sidebands about a central wavelength of $\sim 1540 \text{ nm}$. The spectrum has a modulation depth of $\sim 20 \text{ dB}$ and is clearly shaped by the EDFA gain, extending from $\sim 1528 \text{ nm}$ to $\sim 1570 \text{ nm}$. It has an approximate 3-dB bandwidth of 8.5 nm and a sideband spacing of 2.1 nm. These parameters theoretically correspond to a sech$^2$ pulse duration of 293 fs and a repetition rate of 268 GHz. As the 3-dB bandwidth is comparable to the 12.8-nm bandpass of the TBPF, some spectral shaping by the TBPF is expected to have occurred.

Figure 3 shows autocorrelations of the pulse train over a long time period of $\sim 43 \text{ ps}$ and the autocorrelated and a cross-correlated pulse at a higher resolution (inset). From these traces the pulse train was observed to have a repetition rate of 262 GHz with pulse durations of 365 fs, similar to the values predicted by theory. Figure 3 shows a slight amplitude modulation in the pulse train that can be attributed to system instability. The pulse train was investigated over a larger time scale with a 5-GHz photodetector and an analog oscilloscope and was found to be cw. From the inset of Fig. 3 it can be seen that the pulses have a negligible background that is $\sim 1.5\%$ of the peak amplitude. The cross-correlated pulse was observed to have a smaller amplitude and a longer duration, $\sim 600 \text{ fs}$, than the autocorrelated pulse. This feature is indicative of timing jitter, which could be a result of instabilities in the system. The average power of the pulse train was measured to
be 15 mW, which corresponds to an approximate pulse peak power of 138 mW when a sech² pulse profile is assumed.

Pulse durations as short as 330 fs were obtainable by adjustment of experimental parameters such as the TBPF bandpass position, the EDFA output power, and polarization. However, a higher degree of timing jitter was observed with such pulses. Ultimately the largest spectral bandwidth and the minimum pulse duration were limited by the 12.8-nm bandpass of the TBPF. High-quality repetition rates of up to ~300 GHz were observed under various experimental conditions. Stable lasing was observed with EDFA output powers that ranged from 192 to 298 mW, corresponding to respective ring output powers from 10.2 to 15.9 mW. Note that this configuration has a low threshold as MI begins, with an EDFA output power of approximately 30 mW.

The average dispersion of the ring cavity was measured to be 0.10 ps nm⁻¹ km⁻¹ to within 0.04 ps nm⁻¹ km⁻¹. By use of this result, the soliton period for a 365-fs pulse was calculated to be 0.54 km, which is comparable to the 0.65-km length of the cavity. As a result, the soliton may react slightly to dispersion and optical intensity variations as it propagates around the ring. Some shedding of radiation may take place, but the associated spectral sidebands would be removed by the 12.8-nm TBPF. The experimental results yielded a 0.39-bandwidth-duration product that correlates fairly well with the 0.315 value that is characteristic of solitons. The discrepancy could be due to instabilities from the potential shedding of radiation and effects such as the soliton self-frequency shift.

An important consideration is that the HNL DSF, which constitutes the majority of the fiber length in the cavity, has a normal dispersion at 1540 nm of −0.34 ps nm⁻¹ km⁻¹. As a result, self-phase modulation can take place in the HNL DSF but temporal compression cannot occur. Temporal compression must take place in regions of the ring that exhibit anomalous dispersion. It is thus concluded that pulse formation is a result of the average characteristics of the cavity and that the pulse train exists in the average soliton regime.

We have presented a low-threshold self-induced modulational instability laser that incorporates an intracavity EDFA and normally dispersive highly nonlinear dispersion-shifted fiber. A continuous-wave 262-GHz train of 365-fs solitons was generated at 1540 nm with an average output power of 15 mW. Because of the normal dispersion of the HNL DSF, which constitutes the majority of the cavity fiber, it is concluded that the pulse train reacts to the average anomalous dispersion of the ring and exists in the average soliton regime. This simple configuration does not rely on expensive high-speed modulators and, as a result, could find application as a flexible and cheap means of generating high-repetition-rate ultrashort solitons to test optical telecommunication devices in research laboratories.

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