Environmentally stable high-power soliton fiber lasers that use chirped fiber Bragg gratings

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Environmentally stable high-power erbium fiber soliton lasers are constructed by Kerr or carrier-type mode locking. We obtain high-energy pulses by using relatively short fiber lengths and providing large amounts of negative dispersion with chirped fiber Bragg gratings. The pulse energies and widths generated with both types of soliton laser are found to scale with the square root of the cavity dispersion. Kerr mode locking requires pulses with an approximately three times higher nonlinear phase shift in the cavity than carrier mode locking, which leads to the generation of slightly shorter pulses with as much as seven times higher pulse energies at the mode-locking threshold. © 1995 Optical Society of America

With the development of highly chirped fiber Bragg gratings\(^1,2\) (CFBG's) a wide-ranging control of pulse widths in fiber laser systems by dispersive means has become possible. This is particularly valuable in all-fiber chirped-pulse amplification systems, which permit the construction of compact high-power sources of femtosecond pulses.\(^3\) CFBG's (providing large amounts of negative dispersion) have also found applications as intracavity elements in fiber oscillators and have permitted the construction of Kerr mode-locked erbium fiber soliton lasers that generate picosecond pulses with pulse energies as high as 10 nJ without the use of any amplifiers.\(^5\)

Such high pulse energies may be generated, since Kerr mode-locked soliton lasers follow simple scaling laws. Typically a certain minimum nonlinear phase shift is required in the cavity to provide a sufficient amount of amplitude modulation and soliton shaping to keep the pulses stable. In the absence of bandwidth limitations other than from the gain medium, i.e., when the pulse widths are limited by energy loss to the continuum, the minimum nonlinear phase shift is \(\approx \pi\) (Refs. 4–6) and nearly independent of cavity dispersion. The pulse width \(\tau\) then scales with \(\sqrt{|D_2|}\), whereas the pulse energy \(W\) scales with \(\sqrt{|D_2/\lambda|}\), where \(D_2\) is the total cavity dispersion and \(L\) is the fiber length.

Any practical applications of such lasers require that they be insensitive to temperature and pressure variations and that a reproducible procedure for the initiation of mode locking be found. By using polarization-maintaining erbium in part of the cavity and a compensation scheme for linear and nonlinear polarization evolution in the fibers, we demonstrate the feasibility of such environmentally stable high-power picosecond fiber soliton lasers for the first time to our knowledge, in which we show that reliable pulse start-up is obtained by a modulation of the fiber lengths.

We also investigate the performance of these laser systems in the presence of dominant carrier mode locking, since the pulses produced are in the picosecond regime and should also be reachable by this slower amplitude-modulation process. We show that at least in the picosecond regime both Kerr and carrier mode-locked soliton lasers can produce similar pulse widths and follow similar scaling laws, as soliton lasers based on carrier mode locking also require a minimum nonlinear phase shift in the cavity. For carrier mode locking the minimum nonlinear phase shift for pulse stability is only approximately \(0.4\pi\), which leads to a significant reduction in the generated continuum in the soliton lasers. Because the amount of amplitude modulation in a carrier mode-locked laser is only weakly affected by the nonlinear phase shift in the cavity, it appears that the nonlinear phase shift is required mainly to provide a sufficient amount of soliton shaping for pulse stability.\(^8\)

The experimental setup is shown in Fig. 1. The environmentally stable cavity design was based on polarization-maintaining erbium-doped fiber with a beat length at 1.55 \(\mu\)m of 7 mm, a doping level of 300 parts in \(10^6\) Er\(^{3+}\), a numerical aperture NA = 0.20, and a core radius of 2.8 \(\mu\)m. For Kerr mode locking a linear phase delay for waves propagating along the two erbium fiber axes could be incorporated by \(\lambda/2\) and \(\lambda/4\) wave plates, as shown. For carrier mode locking we removed the \(\lambda/4\) wave plate and launched linearly polarized light along one of the erbium fiber axes by appropriately rotating the \(\lambda/2\) wave plate. For the saturable absorber (SA) we used a design similar to the one suggested by DeSouza et al.\(^9\) The laser output was taken from the polarizer (P) as shown and was adjustable by rotation of the \(\lambda/4\) wave plate between the polarizer and the CFBG.

The complete cavity contained 5.5 m of erbium-doped fiber and 2.0 m of standard telecommunications fiber leads, giving rise to a total dispersion of \(-0.14\) \(\text{ps}^2\). The CFBG had a dispersion of \(-3.4\) \(\text{ps}^2\), i.e., \(\approx24\) times the fiber dispersion. The maximum reflectivity was >99%, and the FHWM bandwidth was 13 nm centered around 1.555 \(\mu\)m. The CFBG and the saturable absorber could be replaced with high-reflectivity mirrors (M) whenever required.

The fiber laser was pumped via a wavelength-division-multiplexing coupler (WDM) with a launched power of as much as 120 mW from a laser diode operating at 980 nm. To initiate Kerr mode locking we...
wound most of the fiber onto an electrically driven piezoelectric 4-cm-diameter drum, giving an intracavity fiber length modulation of 60 μm at a frequency of 23 kHz. With a beam diameter of 10 μm on the saturable absorber, carrier mode locking was self-starting. For both cases any mode-locking hysteresis could be nearly completely suppressed.

Typical autocorrelation traces and pulse spectra for pulses obtained with either Kerr or (dominant) carrier mode locking without a CFBG and with a CFBG are shown in Figs. 2 and 3, respectively. Note that the introduction of the saturable absorber led to a blue shift in both the cw and mode-locked emission wavelengths. This is simply a result of the quasi-four-level nature of the lasing erbium transition, which pushes the emission wavelength toward the peak of the gain cross section for an increase in intracavity loss.

Without the CFBG, Kerr mode locking produced 520-fs pulses (assuming a \( \text{sech}^2 \) pulse shape) with a time-bandwidth product of 0.39 and a pulse energy of 22 pJ, whereas carrier mode locking produced 750-fs pulses with a pulse energy of 8 pJ and a time-bandwidth product of 0.37. With measured maximum intracavity pulse energies of 120 and 80 pJ for Kerr and carrier mode locking, respectively (and the appropriate values for the measured intracavity loss), this gives rise to nonlinear phase shifts \( \Phi_{nl} \) of 1.5π and 0.45π for the two cases. Note that even in the presence of the saturable absorber some weak nonlinear polarization evolution was still effective, as the laser was still sensitive to polarization perturbations. However, since the saturable absorber does allow operation of the laser with a significantly lower nonlinear phase shift, it appears that the saturable absorber was dominantly responsible for the steady-state pulse shaping in the cavity.

With the CFBG, Kerr mode locking produced pulses with a FWHM of \( \Delta t = 3.4 \) ps (also assuming a \( \text{sech}^2 \) pulse shape) with an energy of as much as 440 pJ and a time-bandwidth product of \( \Delta \nu \Delta t = 0.48 \). On the other hand, carrier mode locking produced 4.0-ps pulses with an energy of 60 pJ and a time-bandwidth product of 0.38. For intracavity pulse energies of 700 and 640 pJ for Kerr and carrier mode locking, respectively, \( \Phi_{nl} \) was estimated to be 1.4π and 0.50π. As a lower limit for \( \Phi_{nl} \) for the two cases we measured 1.2π and 0.4π. Note that the discrepancy in output-versus-intracavity power is accounted for by the maximum allowable output coupling and the distribution of the intracavity loss elements. In the presence of the CFBG, the carrier mode-locking laser was insensitive to polarization changes, which demonstrates that nonlinear polarization can indeed be neglected in this case.

As may be seen, regardless of the presence of the CFBG a Kerr mode-locked erbium soliton laser

![Fig. 1. Environmentally stable Kerr or carrier mode-locked fiber laser incorporating a CFBG for pulse width control. FR's, Faraday rotators.](image)

![Fig. 2. Autocorrelation traces (top) and corresponding pulse spectra (bottom) of the Kerr mode-locked (solid curves) and carrier mode-locked (dashed curves) laser system in the absence of the CFBG.](image)

![Fig. 3. Autocorrelation traces (top) and corresponding pulse spectra (bottom) of the Kerr mode-locked (solid curves) and carrier mode-locked (dashed curves) laser system in the presence of the CFBG.](image)
requires an approximately three times larger intracavity nonlinear phase shift than does carrier mode locking. This difference in nonlinearity is also evident from the size of the small pedestal component on the autocorrelation traces and the size of the spectral sidebands, which nearly vanish for the carrier mode-locked laser. As a result, Kerr mode locking can produce slightly shorter pulses. Note, however, that these results hold only in the absence of bandwidth limitations other than from the gain medium itself; in the presence of additional bandwidth-limiting elements, Kerr mode locking can also operate with a lower nonlinearity. In both laser systems $W$ and $\tau$ scale approximately with $\sqrt{D_2}$.

It is interesting to note that we could obtain the higher intracavity powers in the presence of the CFBG’s only by raising the pump power to the oscillator by up to a factor of 5, i.e., the self-starting threshold was greatly increased by the presence of the CFBG’s. This shows clearly that the self-starting threshold in passively mode-locked lasers can be strongly dispersion dependent, a notion typically not covered by standard self-starting theories. However, self-starting theories deal only with necessary requirements for the initiation of passive mode locking. A necessary condition for the continuous operation of a passively mode-locked laser can be obtained only by selection of laser parameters that ensure pulse stability. Such conditions were derived by Haus et al., who showed that for large values of $|D_2|$, i.e., when any pulse chirp is negligible, $\tau W \approx D_2$, which also follows from the fact that the pulses are solitons and which is consistent with the current experiments. Note that, in contrast to the present observations, a (negative) dispersive limit on pulse stability was obtained for Kerr mode-locked solid-state lasers.

The scaling laws described here are particularly advantageous in the design of carrier mode-locked soliton fiber lasers compared with carrier mode-locked fiber lasers not operating in the soliton regime. These types of fiber laser can also easily be scaled up to produce pulse energies of 10 nJ or higher. However, a carrier mode-locked system will become more and more susceptible to damage to the saturable absorber with an increase in laser power, and therefore a change to an antiresonant Fabry–Perot saturable absorber design, relying on recent improvements in growth techniques for stacked dielectric mirrors at 1.55 $\mu$m, may then be required.

In conclusion, we have demonstrated an environmentally stable high-power picosecond erbium fiber soliton laser for the first time to our knowledge. We have shown that the pulse widths and energies scale with the square root of the cavity dispersion for both Kerr and carrier mode-locked soliton lasers, once the cavity dispersion is sufficiently large. We have also demonstrated that in the absence of bandwidth limitations other than from the gain medium carrier mode-locked soliton lasers can operate with an approximately three times lower intracavity nonlinear phase shift.

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References