Letter

Spectral filtering effect of fused fibre couplers in femtosecond fibre soliton lasers

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Abstract. A fused fibre coupler has been used as a spectral filter in a femtosecond fibre soliton laser to eliminate the spectral sideband structure associated with periodic amplification of solitons in the regime where the characteristic soliton period of the generated pulses approaches that of the overall fibre laser loop length.

Using various techniques and configurations, the passively mode-locked erbium fibre soliton laser has been widely investigated as a source of femtosecond pulses [1–5]. Through operating in a regime of negative group delay dispersion, self-formation of ultrashot pulse solitons, where sufficient power levels are achievable, considerably simplifies the laser systems. Stability of periodically amplified solitons can be maintained through operating in the guiding centre [6] or average soliton mode [7], which was first discussed by Mollenauer et al. [8]. The generated solitons are stable to any perturbing parameter of the system, i.e. gain, fibre dispersion etc., provided that the characteristic soliton period (length) is greater than the amplification (overall loop) length or any other perturbing length scale in the laser cavity. Stable propagation can then be understood in terms of an averaged nonlinearity and/or dispersion. However, for decreasing soliton pulsewidths, the soliton period (proportional to $t^2$) reduces considerably (for example, a 300 fs soliton at 1.55 µm in a fibre with an average dispersion of 2 ps nm$^{-1}$ km$^{-1}$ has a soliton period of ~18 m). Consequently, it becomes increasingly difficult to meet the requirement that the overall length (amplification period) is considerably greater than the soliton period. When these lengths become comparable, the perturbed soliton can effectively respond to the perturbation, shedding energy as a dispersive wave, which interacts with the soliton in a phase-matched interaction driven by the periodic amplification, giving rise to the now characteristic sidebands in the output spectrum [9]. This instability acts as a limit to the minimum pulsewidths achievable and in most rare-earth-doped soliton lasers the full gain bandwidth is not effectively utilized.

Methods have been demonstrated for the reduction or removal of the sideband spectral features, which can contain a significant fraction of the available energy. The shortest pulses have been obtained by avoiding soliton effects, using positively dispersive fibre, and extra-cavity compression [10]. In the soliton regime, one approach has been to use low-dispersion fibre and short-length cavities [5]. However, one of the simplest approaches is to spectrally filter, transmitting only the central soliton spectrum in the laser. We first demonstrated this using a
Figure 1. Schematic of the experimental femtosecond Er fibre laser (see text for captions). The additional modifying fused fibre coupler is indicated.

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fibre-pigtailed Fabry–Perot [11]; however, the (3.5 nm) transmission bandwidth of the device limited the pulsewidths to the picosecond regime. In this letter we demonstrate a similar application of a fused fibre coupler for the reduction of the sideband features in a simple femtosecond Er fibre laser configuration. One clear advantage of this is that the fused coupler is an essential component of the fibre lasers and through judicious choice of filtering, elimination of spectral sidebands can be automatically achieved in fibre soliton lasers.

Figure 1 shows a schematic of the passively mode-locked fibre soliton laser investigated. The pulse shaping and formation was based upon the ‘ultrafast saturable absorber’, intensity-dependent transmission characteristic of a nonlinear optical loop mirror NALM [12], as employed in figure-of-eight lasers [1, 2]. This was constructed from a 3 dB fused coupler using dispersion-shifted fibre, 10 m of Yb:Er fibre, 7.5 m of dispersion-shifted fibre F ($\lambda_0 = 1.55 \mu m$) to introduce asymmetry and a polarization controller PC2. The amplifier was pumped via a WDM fused coupler, and pumping was undertaken either using a CW Nd:YAG laser source (as indicated in the diagram) or by laser diodes. One end of the 3 dB coupler was optically terminated to eliminate back reflections, while the other was directly contacted to a 100% reflecting broadband mirror via a 10% fibre output coupler. In the initial cavity, the only other element incorporated was a polarization controller PC1 which was used to rotate (by $\pi/2$) the polarization of the return radiation to the NALM. The overall fibre length of this simple fibre laser was 28 m. Typically, for an incident pump power of 1.5 W at 1.06 µm, output powers of 5.4 mW were obtained in fundamental soliton pulses of ~380 fs (as shown in the insert of figure 2). It can also be seen from this autocorrelation that a slight pedestal component, associated with the sideband components, was present. In the time domain, for this pump geometry the output exhibited several random but periodic pulses per round trip. Spectrally, the output exhibited the characteristic sideband instability, as shown in figure 2, with the first order component ~9.5 nm from the central wavelength of the soliton spectrum. In addition to the soliton spectrum ($\Delta \lambda \sim 7$ nm), a strong CW component is present, centred around 1.56 µm, which is a result of the phase-dependent switching characteristic of the NALM. To the long wavelength side of the soliton spectrum, the sideband intensity was considerably reduced as a result of the low gain of this particular fibre at the longer wavelengths. From figure 2 it can be seen that the sideband orders exhibit spectral splitting. This arises due to the cross-coupling of the orthogonal modes in the birefringent fibre within the NALM.
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Fused fibre couplers exhibit an effectively sinusoidal transmission function, which in single pass provides a modest filtering effect, but in a fibre resonator provides adequate finesse for the suppression of the low level spectral features associated with the sideband instabilities. With the ~7 nm spectral bandwidth of the solitons generated in the basic fibre laser, a fused fibre coupler was constructed in-house using an IRE-Polus fibre fusion coupler workstation, with parameters optimized for the above fibre laser. Figure 3 shows the transmission function of the manufactured coupler, with a peak transmission at 1.562 µm (the peak of operation of the fibre laser) and a 3 dB bandwidth of 9.5 nm. When inserted into the original fibre laser cavity as shown by the dashed box in figure 1, complete suppression of the sidebands was observed (see figure 4). The CW component was still present, but this could be removed by utilizing intensity-dependent polarization rotation. Because of the slight operational spectral limiting effect of the coupler, the optimized pulsewidths were slightly longer than those generated by the unmodified laser. The insert in figure 4 shows a representative 425 fs pulse autocorrelation which also shows significant pedestal reduction.

In conclusion we have shown in a simple passively mode-locked erbium fibre laser, suppression of the sidebands which are associated with the periodic amplification of ultrashot pulse solitons, without significant increase in the generated femtosecond pulse durations and for no reduction in output powers. This was achieved in an all-fibre geometry, through the introduction of a fused fibre coupler. The technique could be widely applied through optimization and selection of the fused couplers which are essential to the operation of these lasers, and eliminates the need for additional cavity components for spectral selection and confinement. On the other hand, the spectral limiting effect of these elements in existing fibre laser
Figure 3. Transmission of the fused fibre coupler filter.

Figure 4. Spectral output from the fibre laser incorporating the fused fibre coupler. The insert shows the associated pulse autocorrelation.
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systems should be considered since they could and can act to limit achievable pulsewidths.

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References