Dual-wavelength operation of a passively mode-locked
"figure-of-eight" ytterbium-erbium fibre soliton
laser

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Abstract

Stable, dual-wavelength operation of a diode-pumped, passively mode-locked, ytterbium-erbium "figure-of-eight" (FBL) fibre
laser has been achieved by including tunable filters and/or fibre gratings in the laser cavity. The centre wavelengths of the two
channels were independently tunable when gain compensation was provided in the cavity. Bandwidth-limited solitons could be
generated.

Rapid progress in the development of passively
mode-locked fibre lasers over the last three years has
produced a number of alternative sources of ultra-
short soliton pulses in the 1.53-1.56 μm wavelength
region. Mode-locking mechanisms have included the
nonlinear amplifying loop mirror [1] (NALM),
nonsaturable polarisation rotation [2] and
saturable absor-
sion in multiple quantum well (MQW)
structures [3]. These lasers typically generate solitons
whose optical spectra include a number of discrete
sidebands, whose origin is the well-documented soli-
tion resonant instability [4,5]. It is this instability
which frequently limits the pulse durations which may
be achieved by a given system, since it introduces a
pulse-duration dependent loss. Optimisation of cavity
designs to avoid the instability has permitted the
 generation of sub-100 fs pulses [6-8]. In this oper-
ating regime the gain-bandwidth of the amplifier
medium can limit the attainable pulse duration, hence
spectral sidebands may not be observed.

An alternative approach to generate pulses with no
accompanying cw components, if gain-bandwidth
limited pulses are not required, is to introduce a fil-
tering element into the cavity, which limits the pulse
duration before the onset of the resonant instability
[9]. This has recently been demonstrated to generate
transform-limited solitons with no sideband struc-
ture in the optical spectrum [10]. In this letter we
report the operation of a similar diode-pumped ytt-
erbium-erbium FBL, which includes two filtering ele-
ments, capable of generating two independent trains
of mode-locked pulses. Although spontaneous dual-
wavelength mode-locked operation has been re-
ported before [2], this is the first time that such be-
haviour has been controllable. Tuning elements may
consist of Fabry-Perot interference filters or Broad-
reflection fibre gratings written into the fibre core.
Three separate laser cavity configurations have been
demonstrated. The cavity design is based on the spectrally sta-
bilised ytterbium-erbium FBL described in Ref. [10].

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Fig. 1 shows the schematic of this cavity with two tunable Fabry–Pérot filters inserted into the feedback loop of the laser. The signal leaving the output port of the NALM passes through a Faraday isolator (FI1) before being split equally to the two identical Fabry–Pérot transmission filters (FP1 & 2). These fibre-pigtalled devices have a 3 dB transmission bandwidth of 3.5 nm with a tuning range of 1.52–17.57 nm, with an insertion loss less than 1.4 dB. The two signals are re-combined in a second 3 dB fibre coupler, which also acts as the cavity output coupler. The radiation enters the input port of the NALM after passing through a second Faraday isolator, FI2, which absorbs any radiation rejected by the NALM. The diode-pumped ytterbium-erbium amplifier was a commercial device, supplied by IRE Polus, capable of generating up to 100 mW of saturated output power. The total cavity length was approximately 83 m with a peak-assumed dispersion of 5.4 ps nm⁻¹ km⁻¹.

By de-tuning the two FP filters to mismatch their transmission peaks, and with appropriate adjustment of the polarisation controllers, PC1 & 2, the laser could be mode-locked on two wavelengths simultaneously. Fig. 2 shows a typical output spectrum under these conditions. The measured pulse duration was 1.6 ps (see inset of Fig. 2), corresponding to a time-bandwidth product of 0.32. In the absence of any tuning elements in this laser the pulses had typical durations of ~640 fs and were almost transform limited, but exhibited some spectral structure. The polarisation-dependent autocorrelation measurement could be used to separate the two pulses, since they generally had different polarisation states (due to the polarisation- and wavelength-dependent transmission properties of the NALM). Both pulses contain pulses of the same duration, within experimental error. No spectral sideband components could be observed (to a resolution of better than ~20 dB) because of the stabilising effect of the filters. A photodiode trace revealed the pulsetrails to have different fundamental repetition rates due to the mismatched length of the two filter arms. The two pulsetrails could be arranged to exhibit the well-established temporal behaviour of such lasers, as has been described previously by a number of authors [1,2,5].

In order for both pulsetrails to contain approximately equal numbers of pulses care had to be taken to equalise their energies by tuning the two filters to wavelengths of equal gain. This restricted the tuning range of the laser since the two centre wavelengths were not truly independent. The restriction could be overcome by inserting a second Yb/Er amplifier in the cavity just after the filter FP2, which corresponded to the long-wavelength pulsetrail. Increasing the gain of this amplifier above unity could compensate for the relative gain decrease which the long-wavelength pulsetrail experienced as it was tuned away from the gain peak, extending the maximum tuning separation of the two channels to 20 nm. Fig. 3 shows a series of typical spectra indicating independent tuning of the channels. In each case the gain of the additional amplifier was adjusted to approximately equalise the energy in both channels. The cavity length mismatch between the two channels was increased by the inclusion of the second amplifier which had a length of approximately 10 m. A photo-
The diode trace indicated that there was no synchronisation of the two channels; a beat tone between the two pulse trains corresponding to the difference in their fundamental repetition rates could be observed. A RF spectral analysis revealed them to have two well-defined fundamental repetition rates of 2.85 MHz (FP1) and 2.48 MHz (FP2).

Fig. 3d shows that as FP1 is tuned away from the gain peak, located at 1.554 μm, a third mode-locked pulsetrain can be sustained, centred at the peak gain wavelength. It arises because both filtered channels are tuned to a low-gain spectral region. The narrow (3 nm) gain peak of the amplifier is dominant enough to compensate for the filtering action of FP1 at this wavelength, resulting in a third transmission window located at the gain peak.

The bulk Fabry–Pérot filters can be eliminated from the cavity by replacing them with fibre Bragg gratings. Since these devices typically operate in reflection mode the laser cavity had to be adapted, as shown in Fig. 4. It represents a single channel configuration. Radiation leaving the NALM is split by a 3 dB coupler. Half the light reaches the fibre grating, G, which has a peak reflection of 85% centred at a wavelength of 1.5436 μm, with a 3 dB bandwidth of 0.4 nm. Only small tuning ranges are possible using the Bragg reflectors. Tuning can be achieved either by stretching or heating the grating, where typically a variation of ~0.13 nm/°C can be obtained. Greater wavelength coverage can be obtained by simply replacing the grating with one of different pitch. The reflected light is split again in the 3 dB coupler; half of it is absorbed in the isolator, F1, the rest reaches the input port of the NALM via a second amplifier, Yb/Er2. This amplifier was necessary because of the high losses introduced in the re-designed cavity. The isolator F2 is included to prevent bi-directional laser oscillation of Yb/Er2 between the grating and the NALM input port. The cavity output was through a 10% fibre coupler.

Fig. 5 shows the spectral and temporal output of this laser. The generated pulses had a pulse duration of 12 ps and a spectral width of 0.39 nm, resulting in a time-bandwidth product of 0.60, indicating a high degree of chirp imposed on the pulses by the grating. This is to be expected since the pulse spectrum extends into the highly dispersive wings of the grating’s reflection profile. Due to the nonlinear nature of the chirp imposed by this grating it was not possible to readily compensate for it externally to the laser and so generate transform limited pulses. This laser could be easily adapted to operate in dual-wavelength mode, simply by inserting a second
grating into the spare arm of the 3 dB coupler. This allows independent temperature- or strain-tuning of the two channels' centre wavelengths. Alternatively, a dual-peaked grating in one arm of the 3 dB coupler would also operate in this mode, with the added advantage of automatic cavity-length matching for the two pulse trains, provided that the dispersion-induced relative delay between the two wavelengths had been accounted for in the grating positions. In the absence of active gain equalisation care should again be taken to locate the channels symmetrically about the amplifier gain peak.

An alternative cavity arrangement, which demonstrates the versatility of these lasers, is shown in Fig. 6. Based on the arrangement of Fig. 4, it utilises a Fabry–Pérot transmission filter in the 3 dB coupler's spare port, in conjunction with a butt-coupled, 100% retro-reflecting mirror, to create another pulse train at a second wavelength which also has a different pulse duration. Fig. 7 shows the spectral output of the laser, containing the grating channel, located at 1.5436 μm as before, and the F–P filter channel tuned, in this instance, to 1.5390 μm. The pulse durations and spectral bandwidths of the two channels were found to be identical to those measured with the previous cavity configurations, corresponding to 1.2 ps and 1.6 ps pulses for the F–P filter channel and the grating channel, respectively.

The cavity configurations described above allow independent repetition rate control of the two pulse trains. Together with independent control of the pulse durations and centre wavelengths this makes the possibility of performing pump-probe experiments with this single source attractive. However, a number of other applications would require the two pulse trains to be synchronised. Although the repetition rates of the channels could be made to be equal, true synchronisation would only be achieved by active control of the repetition rates, either externally applied or through one of the optical feedback mechanisms previously reported [11,12].

The gain equalisation method described above adds complexity and cost to the laser system. Implementing gain-flattening techniques, such as side-tapping gratings [13], would allow continuous, independent tuning of the channels with no additional active components. Care should be taken, however, to ensure that such devices do not destroy the soliton-formation processes.

In conclusion, controlled dual-wavelength operation of a passively mode-locked, diode-pumped ytterbium-erbium FBL has been demonstrated, implementing both bulk Fabry–Pérot transmission filters and integrated fibre Bragg reflection gratings. By appropriate cavity design we have demonstrated independent wavelength and pulse duration selection, resulting in an extremely versatile and convenient source of two mode-locked pulse trains. Three-wavelength operation could also be achieved by using the gain peak of the amplifier as a third transmission filter.

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References