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Polarisation-maintaining, harmonically modelocked soliton fibre laser with repetition rate stabilisation using optical pumping of saturable Bragg reflector

J.M. Roth, N.H. Bonadeo, K. Bergman and W.H. Knox

Well-organised harmonic modelocking with up to 12 pulses in a 1.5 μm polarisation-maintaining erbium soliton fibre laser is achieved. With eight pulses in the cavity, repetition rate timing jitter is suppressed by 7.3 dB through optical pumping above the absorber bandgap. This stabilised laser operates at 463 MHz with nearly transform-limited, 660 fs, 1 pJ pulses.

Introduction: Ultrafast, high repetition-rate sources are becoming exceedingly important components in 1.5 μm broadband lightwave systems, such as optical time-division multiplexing and spectrally-sliced wavelength-division multiplexing [1, 2]. The saturable Bragg reflector (SBR) is an elegant means to achieve ultrafast, sub-picosecond passive modelocking because it is simple and inexpensive to implement, can be self-starting, and the absorber can function in the erbium gain spectrum [3, 4]. In the anomalous average group velocity dispersion (GVD) regime multiple, identical solitons can exist in the cavity, enabling repetition rates in the 2 GHz range [3].

There are two important limitations with SBR modelocked erbium fibre lasers that detract from their usefulness in communications systems. Excessive timing jitter exists since even spacing between pulses relies primarily on the very weak, passive effect of gain depletion and recovery ($\sim 10^{-7}$ in erbium) [5]. In addition, achieving the essential characteristic of a fixed polarisation state has previously met with limited success. Neither the demonstration of polarisation-locked temporal vector solitons that exhibit a fixed polarisation state in an isotropic fibre cavity [6] nor SBR modelocking of a polarisation-maintaining (PM) cavity [4] exhibit stable, well-organised pulse trains with multiple pulses in the cavity.

In this Letter we address these two constraints using a harmonically modelocked soliton fibre laser constructed exclusively of anomalous GVD, PM erbium gain fibre and stabilised by timing the SBR through optical pumping above the bandgap of the absorber. Previous work using this stabilisation technique was limited to a non-PM cavity that produced a time-varying polarisation state [7].

Experimental setup: Fig. 1 is a schematic diagram of the implementation of the PM stabilised laser. The PM cavity is constructed exclusively of 1 to 2 m of panda erbium gain fibre, one side of which is butt-coupled to the SBR. One end is connectorised and then coated with a dielectric mirror to form the output coupler (OC). The OC is designed with 97% reflectivity at 1550 nm and 90% transmission at 980 nm. This scheme allows the 980 nm pump to enter efficiently into the cavity. The feedback stabilisation signal is generated by tapping the 24th harmonic of the laser cavity using a *pin* photodetector and an electrical bandpass filter. The signal after amplification directly modulates an ~1 mW 1310 nm distributed feedback (DFB) laser. This optical feedback signal is then inserted into the cavity through the OC which is designed with high transmissivity of 60% at the 1310 nm stabilisation wavelength. This method of modulating the SBR eliminates the bulk optics originally used [7] and demonstrates a more robust approach that involves minimal alignment. The SBR used has the same structure and peak differential reflectivity ($\Delta R/R$) at 1550 nm of 5.5×10^{-5} as that used in [7], although a nominal enhancement may occur in $\Delta R/R$ when pumping at 1310 nm owing to the higher photon energy.

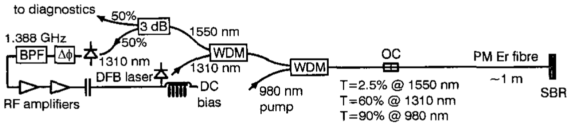

Fig. 1 *Schematic diagram of PM stabilised fibre laser cavity*

1310 nm DFB laser functions as feedback signal
OC: output coupler; SMF: singlemode fibre; SBR: saturable Bragg reflector; WDM: wavelength-division multiplexor; BFP: electrical bandpass filter

The PM gain fibre used exhibits a mode field diameter (MFD) of 7.7 μm and the beat length was measured to be 2.7 mm at 1510 nm. We measured GVD of +14.2 and +14.5 ps/nm/km on the fast and slow axes, respectively, at 1560 nm. No dispersion-compensating elements are required in this cavity to generate soliton harmonic modelocking, unlike in [3]. The relatively large MFD of the PM erbium contributes to its anomalous dispersion value, even though erbium fibre exhibits higher gain for a smaller MFD owing to increased pump and signal overlap. The low, 245 ppm Er^{3+}-ion doping concentration of the PM erbium also accounts for the low, 1.8 dB/m of unsaturated, small signal gain at 1560 nm. A longer length of PM erbium fibre is necessary for superior modelocking, as compared to other short-cavity lasers using non-PM co-doped Er/Yb fibre [3, 7]. Nevertheless splice losses and mode field mismatch between different fibres do not exist in our cavity. In addition, high fundamental repetition rates are possible since the lack of additional dispersion compensating fibre allows for a short cavity. More typical doping concentrations in the 500 ppm range [8] could enhance the gain without significantly affecting the dispersion. A decrease in the magnitude of the anomalous dispersion by decreasing the MFD may generate even shorter pulsewidths which are known to scale as the square root of average GVD in passively modelocked soliton lasers [9].

Results and discussion: Soliton harmonic modelocking is observed with as many as 12 evenly spaced transform-limited $\mathrm{sech}(\tau)^2$ pulses in the 400 to 700 fs range for a maximum aggregate repetition rate of 1.05 GHz. The time-bandwidth product in Figs. 2*a* and *b* yields 0.356, which exceeds the ideal value owing to use of a bandpass filter in the optical amplifier prior to the autocorrelator.

The laser output remains in a fixed polarisation state with >23 dB extinction ratio. The polarised optical spectrum in Fig. 2*a* reveals no dispersive waves co-polarised with the modelocked pulses and fits nearly perfectly to a $\mathrm{sech}(\lambda)^2$ over 30 dB of vertical range, indicating high purity of the soliton pulses. Dispersive waves at the orthogonal polarisation account for under 0.5% of total intracavity power.

In the case of no stabilisation the PM SBR laser exhibits less ordering of multiple pulses in the cavity compared to a non-PM SBR cavity. We attribute this harmonic behaviour to the low gain of the PM erbium fibre which requires that the pump fully inverts the entire length of erbium fibre to achieve sufficient gain for good modelocking. This gain situation exhibits less gain saturation (hence weaker gain depletion and recovery) since in erbium as the pump depletion is increased the absorption increases more rapidly than the gain at shorter wavelengths, whereas the opposite occurs at longer wavelengths. Harmonic modelocking in Er/Yb SBR lasers works best when the gain medium is not entirely inverted by the pump, since reabsorption of the short wavelengths then contributes to gain saturation which creates a flattened gain spectrum in the long wavelength region [3]. One alternative is to increase the length of the PM erbium fibre, however this makes the harmonic modelocking less appealing since it lowers the fundamental repetition rate.

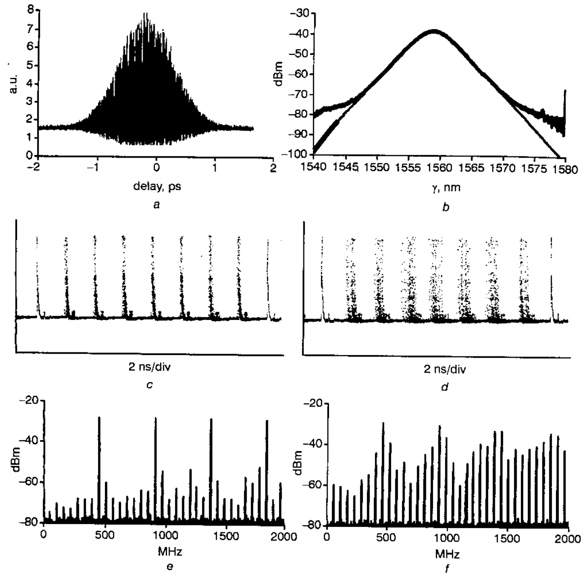

Fig. 2 *Autocorrelation and corresponding measured and predicted optical spectrum for temporal FWHM of 0.66 ps and time-bandwidth product of 0.356, and digital scope trace and RF spectra with and without stabilisation*

a Autocorrelation
b Optical spectrum ($\Delta\lambda = 4.3$ nm)
c Digital scope trace with stabilisation
d Digital scope trace without stabilisation
e RF spectrum with stabilisation
f RF spectrum without stabilisation

A significant improvement is observed in the quality of the pulse train when engaging the feedback stabilisation signal. Figs. 2*c* and *d* show the pulse train on a 50 GHz digital sampling scope with and without stabilisation, respectively, when the laser is running with eight pulses in the cavity at 463 MHz with the stabilisation at 1.388 GHz (the 24th cavity harmonic). The digital scope is triggered at the fundamental repetition rate using a 1-by-8 frequency divider, and for long persistence times ($\sim$1 s) the variance in the mistiming of the pulses can be determined from the pulsewidths displayed between triggering events. This method provides analogous information to an optical cross correlation when high resolution is not necessary. A reduction occurs from 280 to 53 ps in the root mean square timing jitter, corresponding to a 7.3 dB improvement. The RF spectrum of the modelocked pulse train also reveals the timing jitter suppression caused by the stabilisation effect. In Figs. 2*e* and *f* the suppression of the non-modelocked subharmonics increases from almost 0 to 23 dB out to 2 GHz with enabling the stabilisation.

Our timing jitter suppression technique works best when the pulse train is already well-organised and stable in the cavity [7], which we believe partially explains the less drastic improvement observed. Furthermore the non-depleted pump regime also leads to significant 980 nm pump leakage through the gain fibre that can bleach the SBR absorption.

Conclusions: We have demonstrated for the first time a soliton harmonically modelocked PM SBR laser that uses a single piece of PM erbium fibre, requires no dispersion compensation, exhibits a robust polarisation state, and produces pulses in the 400 to 700 fs range. We have used optical pumping above the bandgap of the SBR to achieve a 7.3 dB reduction in the amount of timing jitter. We expect that it should be possible to improve upon the stabilisation effect by enhancing the gain depletion effects in the cavity, filtering out residual pump light before it strikes the SBR, or adding quantum wells in the SBR for increased modulation depth.

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Strong 157 nm F_2-laser photosensitivity-locking of hydrogen-loaded telecommunication fibre for 248 nm fabrication of long-period gratings

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Strong (>20 dB) long-period fibre gratings were fabricated by combining F_2-laser photosensitivity-locking of hydrogen-soaked telecommunication fibre and KrF-laser grating formation. The 157 nm pretreatment permanently enhances the fibre photosensitivity response to the low-energy 248 nm photons. Thermal annealing at 120°C for 24 h improves the grating stability without diminishing the enhancement.

Introduction: In fibre grating fabrication, photosensitisation techniques such as hydrogen loading are normally required to generate large and rapid refractive index changes under UV laser irradiation [1]. However, hydrogen loading brings several disadvantages such as the short lifetime (approximately 1 day) of the photosensitivity enhancement and the instability of the index change following the UV exposure. Canning and co-workers [2, 3] first showed that such limitations could be overcome by an additional laser exposure step that locked in a strong photosensitivity response before grating inscription. High germanium and boron/phosphor-doped fibres were hydrogen-loaded and promptly exposed with uniform 193 or 244 nm laser radiation. The locked-in photosensitivity persisted for more than ten days at room temperature, and inscribed gratings showed superior temperature stability in contrast to the untreated fibres [3].

Our group [4, 5] recently extended photosensitivity locking to what we believe to be record short wavelength 157 nm F_2-laser radiation. A strong and stable photosensitivity enhancement was demonstrated by inscribing 40 dB Bragg gratings with 248 nm radiation into pretreated standard telecommunication (ST) fibre. Because the 7.9 eV F_2-laser