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Reducing Nonlinear Limitations of Ytterbium Mode-Locked Fibre Lasers with Hollow-Core Negative Curvature Fibre

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Abstract: Ultralow nonlinearity hollow-core negative curvature fibre is used in a mode-locked Ytterbium fibre laser to prevent the onset of pulse breakup at low repetition-rates. Identical pulse peak-power limit at 37MHz and 11MHz is experimentally demonstrated.

OCIS codes: 140.3510, 140.3615, 140.4050

1. Introduction

Mode-locked fibre lasers are traditionally known for high repetition rates, typically 80MHz and above, and short (picosecond or below) pulse lengths. There are applications for which similarly short pulses at lower repetition rates are desirable, such as cold material processing. Mode-locked oscillators producing short pulses at a low repetition-rate can simplify laser system design by removing the need of additional amplification and pulse-picking. Lower repetition rates however require longer cavity lengths. For conventional soliton mode-locked fibre laser designs, longer cavity lengths and higher pulse energies both lead to an increase in nonlinear phase shift per round trip which leads to pulse break-up and undesirable mode-locking characteristics. The lowest repetition-rate reported for a mode-locked fibre laser is 37kHz, but it produced 10ns pulses due to the strong nonlinear evolution in the normal dispersion regime [1]. For a soliton mode-locked laser, the nonlinear phase shift, ϕ, which the pulse acquires in propagation through the cavity causes breakup at $\phi_{max} = \gamma L P_0 = \pi$ [2] where γL is the cavity nonlinearity, P_0 is the pulse peak power. Stable fundamental mode-locking occurs therefore in a finite range of pulse energies between the mode-locking threshold, where the pulse energy is sufficient to achieve stable pulses, and the multi-pulse threshold where the pulse breaks into harmonic or bunched pulse regimes. This paper experimentally demonstrates the possibility of using state-of-the-art hollow-core fibre as means to extend the cavity length of a 4ps soliton laser without adding nonlinear phase shift and distortion to the pulses.

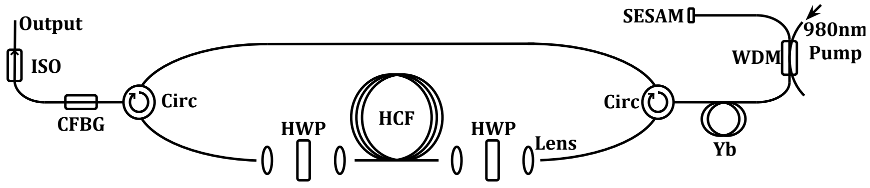

Fig. 1. Experimental setup of Yb mode-locked fibre laser based on ring cavity with hollow-core negative curvature fibre (HCF). ISO: optical isolator; HWP: half-wave plate; Circ: optical circulator; CFBG: chirped fibre Bragg grating; SESAM: semiconductor saturable absorber mirror.

2. Experiment

Our configuration is based on a polarisation maintaining ring cavity, Fig 1. The cavity comprises a SESAM mode-locking element and a chirped fibre Bragg grating (CFBG, used to periodically apply anomalous dispersion) incorporated via circulators. The Ytterbium gain fibre was pumped with a 980nm laser diode. A half waveplate was used to align the polarisation angles. We establish baseline data using a reference cavity with no hollow-core fibre and a free space coupling stage. After characterising the reference cavity we introduced different lengths of hollow-core fibre (HCF), 8m, 13m and 20m. The HCF is based on the negative curvature design with a core diameter of 34μm [3].

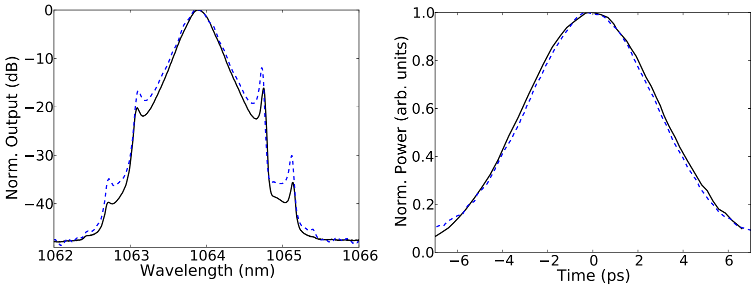

Fig. 2. Measured mode-locked pulses with (dashed line) and without (solid line) 20m of HCF. Left: Pulse Spectrum. Right: Autocorrelation.

3. Results

The reference cavity contained 5.4m of conventional solid-core fibre (in total) and oscillated at 37MHz. As the pump power was increased the laser evolved through operational states: CW, Q-switched mode-locking, desirable fundamental mode-locking then multi-pulsed mode-locking. Cavities with added HCF also showed this behaviour with similar pulses. Fig. 2 compares pulses from the reference cavity and a cavity with 20m of HCF oscillating at 11MHz.

Increasing the cavity length reduces the pump power needed for mode-locking, however the fibre attenuation introduced will increase the pump power needed. Using these effects and the reference cavity data, the mode-locking and multi-pulsing thresholds were calculated assuming a fibre attenuation of 0.04dBm^{-1} (Fig. 3(a)). The mode-locking and multi-pulsing thresholds were determined by examining the pulse spectra, oscilloscope and autocorrelation traces.

The mode-locking threshold shown corresponds to stable oscillations (although pulses were observed at lower pump powers). The stable mode-locking threshold can be affected by additional instabilities in the system from mode interference, polarisation effects within the hollow-core fibre and in the free space coupling. The multi-pulsing thresholds in Fig. 3(a) agrees well with the prediction indicating there is no additional nonlinearity in the cavity. This is reinforced by Fig. 3(b) which shows the calculated peak power for the reference cavity that would correspond to $\phi_{max} = \pi$.

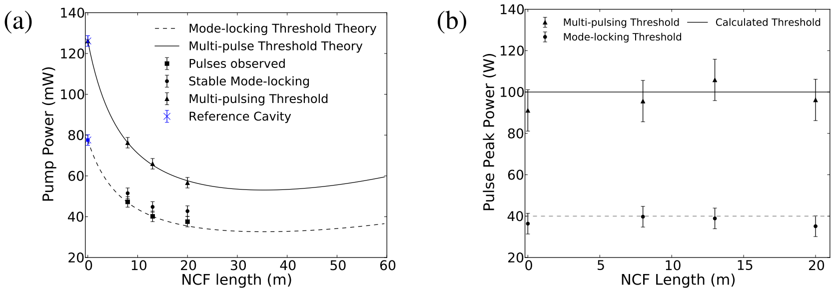

Fig. 3. (a) Predicted mode-locked ranges based on the measured reference cavity with experimental results. (b) Calculated peak pulse power corresponding to $\phi_{max} = \pi$ with measured intra-cavity pulse peak powers at lower and higher points of fundamental mode-locking.

4. Conclusion

Up to 20m of HCF has been added to an Yb^{3+} mode-locked fibre laser and shown not to introduce additional nonlinearity to the cavity. The results show that HCF can be used to extend short pulse Yb mode-locked laser length with minimum detriment to the pulses and could be a viable means to achieve low repetition rates. Further work can explore longer lengths of additional HCF and also the effect of different pulse lengths.

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References

1. Kobtsev, S.M. and Kukarin, S.V. and Smirnov, S.V. *Laser Physics* **20** (2010) pp. 375-378
2. Renninger, W.H. and Wise, F.W. *IEEE Journal of Selected Topics in Quantum Electronics* **21**, (2015) pp. 1-8
3. Yu, F and Knight, J.C. *Opt. Express* **21** (2013) pp. 21466-21471