useful to obtain a more appropriate seed for an epitaxial regrowth.

In conclusion, we have shown that it is possible to grow a thick layer of GaAs with antiphase domains using hydride vapour phase epitaxy. We then obtained SHG from a CO_2 laser to assess the nonlinear efficiency of the layer. The conversion is lower in the layer than in the substrate but th use of a higher quality template as well as optimised growth conditions should result in an increase in the interface quality. Furthermore, as the domain interfaces were straight and vertical after a 100µm thick growth it is probable that thicker layers will be obtained in the future.

Acknowledgments: We wish to thank R. Luzeau and J. Loy for their help in the preparation of the GaAs template.

© IEE 1998 *28 October 1998*
Electronics Letters Online No: 19981660

L. Becouarn, B. Gerard, M. Brévignon, J. Lehoux, Y. Gourdel and E. Lallier (*Thomson-CSF/Laboratoire Central de Recherches, Domaine de Corbeville, 91404 Orsay, France*)

E-mail: loic.becouarn@lcr.thomson-csf.com

References

1 ARMSTRONG, J.A., BLOEMBERGEN, N., DUCUING, J., and PERSHAN, P.S.: 'Interactions between light waves in a nonlinear dielectric', *Phys. Rev.*, 1962, **127**, (6), pp. 1918–1939

2 GORDON, L., WOODS, G.L., ECKARD, R.C., ROUTE, R.R., FEIGELSON, R.S., FEJER, M.M., and BYBR, R.L.: 'Diffusion-bonded stacked GaAs for quasi-phase-matched second-harmonic generation of a carbon dioxide laser', *Electron. Lett.*, 1993, **29**, (22), pp. 1942–1944

3 LALLIER, B., BRÉVIGNON, M., and LEHOUX, J.: 'Efficient second-harmonic generation of a CO_2 laser with a quasi-phase-matched GaAs crystal', *Opt. Lett.*, 1998, **23**, (19), pp. 1511–1513

4 BECOUARN, L., LALLIER, B., BRÉVIGNON, M., and LEHOUX, J.: 'Cascaded second-harmonic and sum-frequency generation of a CO_2 laser using a single quasi-phase-matched GaAs crystal', *Opt. Lett.*, 1998, **23**, (19), pp. 1508–1510

5 LALLIER, B., BECOUARN, L., BRÉVIGNON, M., and LEHOUX, J.: 'Infrared difference frequency generation with quasi-phase-matched GaAs', *Electron. Lett.*, 1998, **34**, (16), pp. 1609–1611

6 PIKHTIN, A.N., and YAS'KOV, A.D.: 'Dispersion of the refractive index of semiconductors with diamond and zinc-blende structures', *Sov. Phys. Semicond.*, 1978, **12**, (6), pp. 622–626

7 FEJER, M.M., MAGEL, G.A., JUNDT, D.H., and BYER, R.L.: 'Quasi-phase-matched second harmonic generation: tuning and tolerances', *IEEE J. Quantum Electron.*, 1992, **QE-28**, (11), pp. 2631–2654

8 MYERS, L.E., ECKARDT. R.C., FEJER, M.M., BYER, R.L., BOSENBERG, W.R., and PIERCE, J.W.: 'Quasi-phase-matched optical parametric oscillators in bulk periodically poled $LiNbO_3$', *J. Opt. Soc. Am. B*, 1995, **12**, (11), pp. 2102–2116

9 YOO, S.J.B., CANEAU, C., BHAT, R., KOZA, M.A., RAJHEL, A., and ANTONIADES, N.: 'Wavelength conversion by difference frequency generation in AlGaAs waveguides with periodic domain inversion achieved by wafer bonding', *Appl. Phys. Lett.*, 1996, **68**, (19), pp. 2609–2611

10 EYRES, L.A., EBERT, C.B., FEJER, M.M., and HARRIS, J.S.: 'MBE growth of laterally antiphase-patterned GaAs films using thin Ge layers for waveguide mixing'. CLEO '98, OSA Tech. Dig. Series, 1998, Vol. 6, pp. 276

11 SHAW, D.W.: 'Kinetic aspects in VPE of III-V compounds', *J. Cryst. Growth*, 1975, **31**, pp. 130–141

Stabilisation of actively modelocked Er-doped fibre laser by minimising interpulse noise power

R. Kiyan, O. Deparis, O. Pottiez, P. Mégret and M. Blondel

A novel method is reported for stabilising an actively modelocked Er-doped fibre laser through minimisation of the average inter-pulse noise power. Long term stable operation of a harmonically actively modelocked fibre σ-laser is demonstrated using the proposed method.

Introduction: Harmonically actively modelocked Er-doped fibre lasers (HAML-EDFLs) are very promising sources of pico-femtosecond pulses at repetition rates up to few tens of gigahertz. However, to generate a stable optical pulse train the round trip time of the HAML-EDFL cavity must be adjusted with very high precision to an integer multiple of the period of the RF driving signal and stabilised at this point [1]. Several stabilising methods have been demonstrated for HAML-EDFLs [1 – 4]. In this Letter, we report a novel stabilising method for HAML-EDFLs which employs inter-pulse noise (IPN) optical power as the index of the laser cavity length detuning and controls the cavity length to minimise this noise power. To measure IPN power, a dual-output Mach-Zehnder electro-optical modulator (MZM) instead of a conventional single-output MZM is used as a modelocker. The advantages of this method are its simplicity and low cost implementation. Neither microwave devices nor wideband photoreceivers nor complicated electronics are required. We applied this method to stabilise an HAML-EDF σ-laser and generate a 17.9ps, 3GHz pulse train.

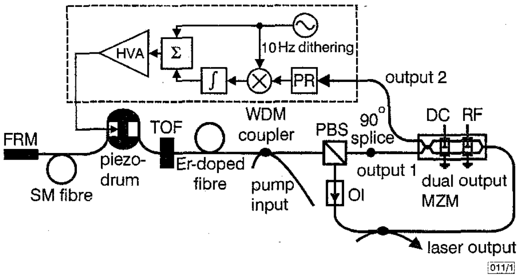

Fig. 1 *HAML-EDF σ-laser with novel stabilisation scheme*

PR: narrowband photoreceiver
PBS: polarisation beam splitter
FRM: faraday rotation mirror
OI: optical isolator

Principle of operation: To implement the proposed stabilisation scheme we modify a previously reported HAML-EDF σ-laser [6]. The only new feature of the modified σ-laser shown in Fig. 1 is that the single output MZM is replaced by a *dual* output MZM. When the dual output MZM is driven by a sinusoidal RF signal, input optical radiation is switched between optical outputs 1 and 2 in such a way that these outputs are complementary. If the laser cavity length and the modulating frequency are correctly adjusted for harmonic modelocking operation, optical pulses formed in the laser cavity are clocked so that they pass through the MZM when the input optical radiation is switched to output 1. In this case, only minimal inter-pulse noise radiation circulates in the cavity. This governs the minimal level of average optical power at MZM output 2. However, if detuning of the laser cavity length takes place, inter-pulse noise radiation grows directly with the detuning value. This noise radiation passes through the MZM when its input is switched to output 2. Therefore, the average optical power at MZM output 2 is a good measure of the inter-pulse noise and it can be used as an index of the laser cavity length detuning. Hence, a simple feedback loop that controls the cavity length to minimise the average optical power at MZM output 2 can be constructed in order to stabilise the HAML-EDF σ-laser.

Experiment: A 20m-long Er-doped fibre (440ppm) is placed in the singlemode (SM) part of the σ-laser and pumped by a pigtailed 980nm laser diode (~90mW maximum output power). The modelocker is a lithium-niobate dual output intensity Mach-Zehnder modulator with an insertion loss of ~3dB and a 3dB bandwidth of ~3GHz. The MZM is optically biased in such a way that input optical radiation is about equally divided between optical outputs 1 and 2 for zero voltage at its DC input and no signal at its RF input. No DC bias voltage was applied to the MZM so that it operated in the linear part of its modulation characteristic. The MZM was driven at ~3.00047GHz to generate a pulse train at the same repetition rate. The tunable optical filter (TOF) with 3nm FWHM bandwidth, installed in SM part of the laser, was tuned to run the laser at ~1540.3nm, which is the optimal wavelength for the MZM used in experiment. To compensate for high normal dispersion of the Er-doped fibre, 29m of standard singlemode fibre with a dispersion of ~16ps/km/nm at 1540nm is inserted in the SM part of the cavity. Part of the dispersion compensating fibre is wound on a piezo-drum that is used to tune the cavity length. The fundamental cavity frequency is ~1.7MHz The laser was placed in a foam plastic box for protection against environmental perturbations. However, without cavity length stabilisation, stable mode-locking operation and generation of the shortest pulses were possible only for a few minutes, after the cavity length was optimally tuned.

The average output optical power of pulse train was ~1.5mW. A background-free autocorrelation trace was measured with an SHG autocorrelator. The best fit was obtained with a Gaussian curve. The FWHM pulsewidth was estimated to be ~17.9ps. The FWHM optical bandwidth, measured by an optical spectrum analyser, was ~0.22nm resulting in a time-bandwidth product of ~0.49. The pulsewidth and time-bandwidth product were not influenced by the pump power. We believe that parts of the laser cavity act as independent dispersive sections and that there is no average soliton formation in the cavity.

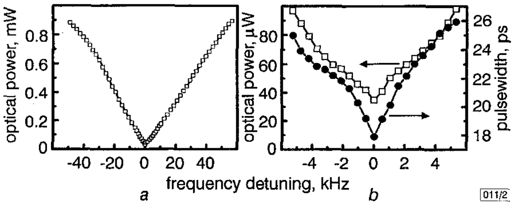

Fig. 2 *Average IPN optical power and pulsewidth against cavity frequency detuning*

a Full range
b Approximately zero detuning
□ optical power
● pulsewidth

The cavity detuning characteristics of average IPN optical power at the MZM second output and pulsewidth were measured at fixed modulating frequency when the cavity length was changed by the piezo-drum. Cavity length detuning is recalculated for the corresponding frequency detuning of the cavity (Δf). Zero frequency detuning corresponds to the cavity length that provides generation of the shortest pulses. Fig. 2*a* shows the detuning characteristic of average IPN power over the whole detuning range allowed by the piezo-drum. Fragments of this curve around $\Delta f = 0$ together with the detuning characteristic of the pulsewidth are shown in Fig. 2*b*. The latter is measured for the range of cavity detuning determined by the maximal pulsewidth that can be measured by the available autocorrelator. As can be seen from Fig. 2*b*, both minimal pulsewidth and minimal IPN power are achieved at zero detuning. It demonstrates that the average IPN power is a good index of the laser cavity length detuning, which can be used to stabilise the laser.

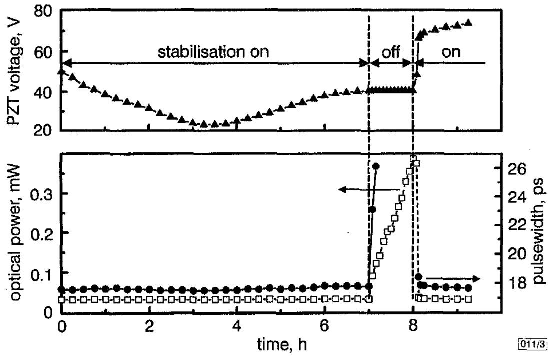

Fig. 3 *Long term temporal evolution of piezo-voltage, average IPN optical power and pulsewidth*

▲ piezo-voltage
□ optical power
● pulsewidth

For implementation of the stabilisation scheme, the simple feedback loop shown in Fig. 1 was constructed. To generate an error signal containing information about the sign of the cavity length detuning, a 10Hz small-amplitude dithering signal is applied to the piezo-drum (modulation amplitude corresponding to 52.9Hz cavity detuning). Dithering of the cavity produces intensity modulation of the average IPN power, which is detected by a narrowband photoreceiver (1kHz bandwidth). Its 10Hz component is converted via phase-sensitive detection into an error signal, which is related to both the direction and magnitude of the cavity length detuning. The error signal is integrated and summed with the dithering signal. The resulting signal is amplified by a high voltage amplifier (HVA) and applied to the piezo-drum.

Long term stable operation of the fibre σ-laser was achieved with this new stabilisation scheme. Both the pulsewidth and optical bandwidth of the pulses generated by the stabilised laser were the same as for the optimally tuned laser without stabilisation. The RF spectra of pulse trains detected by a 25GHz photoreceiver showed that relaxation oscillation noise was completely suppressed. Moreover, the supermode beat noise was ~50dB below the modulation peak, at the same level as for the optimally tuned laser without stabilisation.

Fig. 3 demonstrates the long-term operation of the stabilisation scheme. The stabilisation was turned on for 6h and a stable pulse train with pulsewidth of ~17.9ps was generated during that time. The stabilisation was then turned off (the voltage at the piezo-drum was fixed at a constant level) and, consequently, IPN power and pulsewidth increased. When the stabilisation scheme was turned on again, the laser returned back to stable operation.

Conclusion: We have demonstrated that the inter-pulse noise of a pulse train generated by an HAML-EDFL can be easily measured if a dual output MZM is used as a modelocker. The average optical power of the inter-pulse noise measured at the second output of the MZM gives a good indication of the laser cavity length detuning. A simple stabilisation scheme based on the minimisation of inter-pulse noise power was constructed and used to stabilise an HAML-EDF σ-laser for long term operation.

Acknowledgment: This work is funded by the Inter-University Attraction Pole program (IAPIV/07) of the Belgian government (SSTC).

20 October 1998
Electronics Letters Online No: 19981604

R. Kiyan, O. Deparis, O. Pottiez, P. Mégret and M. Blondel (*Advanced Research in Optics* (*ARO*), *Service d'Electromagnétisme et de Télécommunications, Faculté Polytechnique de Mons, 31 Boulevard Dolez, B 7000 Mons, Belgium*)

E-mail: Kiyan@telecom.fpms.ac.be

References

1 SHAN, X., CLELAND, D., and ELLIS, A.: 'Stabilising Er fibre soliton laser with pulse phaselocking', *Electron. Lett.*, 1992, **28**, (2), pp. 182–184

2 TAKARA, H., KAWANISHI, S., and SARUWATARI, M.: 'Stabilisation of a modelocked Er-doped fibre laser by suppressing the relaxation oscillation frequency component', *Electron. Lett.*, 1995, **31**, (4), pp. 292–293

3 SHAN, X., WIDDOWSON, T., ELLIS, A.D., and SIDDIQUI, A.S.: 'Very simple method to stabilise modelocked erbium fibre lasers', *Electron. Lett.*, 1996, **32**, (11), pp. 1015–1016

4 NAKAZAWA, M., YOSHIDA, E., and KIMURA, Y.: 'Ultrastable harmonically and regeneratively modelocked polarisation-maintaining erbium fibre ring laser', *Electron. Lett.*, 1994, **30**, (19), pp. 1603–1605

5 CARRUTHERS, T.F., and DULING, I.N.: '10GHz, 1.3ps erbium fibre laser employing soliton pulse shortening', *Opt. Lett.*, 1996, **21**, (23), pp. 1927–1929

6 FOURSA, D., EMPLIT, P., LENERS, R., and MEULEMAN, L.: '18GHz from a σ-laser with dispersion management and rational harmonic active mode-locking', *Electron. Lett.*, 1997, **33**, (6), pp. 486–488