Long-period-grating band-pass filters for actively mode-locked Er-doped fiber lasers

O. Deparis [(a)], I. Korolyov [(b)], S. A. Vasiliev [(b)], E. M. Dianov [(b)], R. Kiyan [(a)],

O. Pottiez [(a)], P. Mégret [(a)] and M. Blondel [(a)]

[(a)] Advanced Research in Optics group, Electromagn & Telecom. Dept., Faculté Polytechnique de Mons, 31 blvd Dolez, 7000 Mons, Belgium

[(b)] Fiber Optics Research Center at General Physics Institute, 38 Vavilov Street, 117756 Moscow, Russia

We present a novel type of all-fiber band-pass filter for wavelength selection in actively mode-locked Er-doped fiber lasers. The filters are based on π-shifted long-period gratings, have bandwidths from 10 to 20 nm and operate in transmission. The filter characteristics were found to be suitable for the generation of soliton-like pulses in the laser cavity, even at high powers where nonlinear effects lead to significant temporal shortening and spectral broadening of the pulses.

Actively mode-locked Er-doped fiber lasers are stable sources of pedestal-free soliton-like pulses at repetition rates in the GHz range [1,2]. To select the lasing wavelength, optical band-pass filters with bandwidths of several nanometers are used in the fiber laser cavity. In comparison with fiber-pigtailed Fabry-Perot or interference optical filters, filters based on fiber grating technology offer the advantages of full fiber compatibility, flexibility in the filter design, and low cost [3]. Fiber Bragg gratings (FBGs), which operate in reflection and exhibit a band-pass filter characteristic, have found applications in actively mode-locked Er-doped fiber lasers ([4] and references therein). However, the use of FBG in a ring laser cavity requires an optical circulator to convert its reflective mode into a transmission one.

A novel all-fiber band-pass filter is proposed here for wavelength selection in actively mode-locked Er-doped fiber lasers. The filters are based on π-shifted long-period gratings (LPGs). In contrast to fiber Bragg gratings, long-period gratings operate in transmission and their typical bandwidth is much higher (tens of nanometers). However, in their basic structure, they exhibit a notch filter characteristic. To obtain the desired band-pass characteristic, two possible structures of LPG filter can be suggested: two uniform LPGs that have spectrally separated resonance wavelengths and π-shifted LPG. A π-shifted grating exhibits a band-pass characteristic with two loss peaks located symmetrically with respect to the resonance wavelength. For experimental demonstration, filters based on π-shifted LPG were fabricated and incorporated into an actively mode-locked Er-doped fiber laser. To the best of our knowledge, this is the first application of π-shifted LPGs for wavelength selection in actively mode-locked Er-doped fiber lasers.

The gratings were fabricated in a hydrogen-loaded SMF-28 fiber by step-by-step technique using a CW frequency doubled argon-ion laser (244 nm) with a power of about 100 mW. Hydrogen-loading was performed by heat treatment of the fiber under 120 atm at +100°C during 12 hours. Power density of the focused laser beam was about 16 kW/cm^2. The grating period was 336 μm. The UV-induced refractive index change was estimated to be $2.5 \cdot 10^{-4}$. The π phase shift was made by introducing a non-irradiated fiber section of half-period length in the middle of the grating. Several gratings with two different lengths (24 mm and 65 mm) were fabricated. After the grating preparation, an additional heat treatment was applied in order to out-diffuse the remaining hydrogen. Then HF-acid etching of the gratings [5] was used to tune the central wavelength of the filter to the desired value. Transmission spectra of two π-shifted LPGs (#1 and 2) are shown in Fig. 1. The bandwidths (at –3 dB) of the band-pass central window are 22.3 nm and 9.4 nm, respectively and the peak wavelength is 1545 nm.

The actively mode-locked Er-doped fiber laser is depicted at Fig. 2. The sigma cavity is functionally equivalent to a polarization-maintaining ring cavity thanks to the use of a Faraday rotation mirror which cancels polarization fluctuations in the double pass section. The laser was designed to generate soliton-like pulses through active harmonic mode locking. Active harmonic mode locking is achieved by driving an electro-optic Mach Zehnder modulator with an external RF signal whose frequency is equal to a high harmonic (N) of the basic cavity frequency (or free spectral range FSR). The repetition rate of the pulse train, which is equal to the modulation frequency, is typically in the GHz range although the cavity FSR is typically four order of magnitude smaller. The gain is provided by an Erbium-doped fiber pumped by a 980 nm laser diode. A dispersion-shifted fiber provides a long interaction length (2×200 m) for nonlinear pulse shortening through the soliton effect. The effective length of the cavity is 525 m (FSR = 395 kHz). The average cavity dispersion was measured to be 2.42 ps/(nm×km) at 1545 nm with a slope of 0.034 ps/nm². A stabilization feedback loop [6] was used to adjust the cavity length to the appropriate value with respect to the modulation frequency. The π-shifted LPG was placed in the double-pass section of the sigma cavity.

We have performed two sets of experiments with LPG #1 and LPG #2 in the cavity, respectively. During experiments, the repetition rate of the laser was set to ≈3 GHz (limited by the available modulator bandwidth) and the feedback loop was turned on. Pulse optical spectra and autocorrelation traces were measured at the laser output as the intracavity power was varied by changing the pump power (Fig. 3 and Fig. 4). The intracavity power was determined by measurement of the average power at the laser output ($P_{cav} = P_{out} / C$, where C = 20% is the output coupling ratio). Each experimental autocorrelation trace was fitted to *sech²* function from which the FWHM duration of the soliton pulse can be determined ($\tau = w/1.543$, where w is the FWHM width of the *sech²* function). In both cases (LPG #1 and LPG #2), temporal shortening and spectral broadening of the pulse were observed as the intracavity power increases, confirming that nonlinear effects in the cavity (self-phase modulation) were important even at low powers. Side lobes observed in the pulse spectra at high powers are typical of soliton-like pulses. Physically they are caused by dispersive waves associated with periodic perturbations in the propagation of the soliton in the cavity. For similar values of the intracavity power, side lobes were more developed with LPG #1 in the cavity (Fig. 3) in comparison with LPG #2 in the cavity (Fig. 4). This difference is attributed to the effect of filtering on the soliton spectrum which is much less stronger, or even negligible, with the former LPG in comparison with the latter LPG. At high intracavity powers, pulses with small background were observed in the autocorrelation traces with LPG #1 in the cavity (Fig. 3) while pulses with pronounced pedestals are observed with LPG #2 in the cavity (Fig. 4). The appearance of pedestals is attributed to the stronger filtering of the latter LPG as the pulse spectrum broadens due to nonlinear effects.

In conclusion, we have presented a novel type of all-fiber band-pass filters for wavelength selection in actively mode-locked Er-doped fiber lasers. The filters are based on π-shifted long-period gratings. The filter characteristics were found to be suitable for the generation of soliton-like pulses in the laser cavity, even at high powers where nonlinear effects lead to significant temporal shortening and spectral broadening of the pulses.

Acknowledgment

This work is funded by the Inter-University Attraction Pole program (IAP IV/07) of the Belgian Federal Office for Scientific, Technical and Cultural Affairs (OSTC).

References

[1] T. F. Carruthers, Irl N. Dulling, III, M. Horowitz and C. R. Menyuk, 'Dispersion management in a harmonically mode-locked fiber soliton laser', *Optics Letters*, vol. 25, pp.153-155, 2000.

[2] K. S. Abedin, M. Hyodo, N. Onodera, '154 GHz polarisation-maintaining dispersion-managed actively modelocked fibre ring laser', *Electron. Lett.*, vol. 36, pp. 1185-1186, 2000.

[3] R. Kashyap, Fiber Bragg gratings, San Diego: Academic Press, 1999.

[4] O. Deparis, R. Kiyan, E. Salik, D. Starodubov, J. Feinberg, O. Pottiez, P. Mégret, and M. Blondel, 'Round-trip time and dispersion optimization in a dual-wavelength actively mode-locked Er-doped fiber laser including nonchirped fiber Bragg gratings', *IEEE Photon. Techn. Lett.*, vol. 11, pp.1238-1240, 1999.

[5] S.A. Vasiliev, E.M. Dianov, D. Varelas, H.G. Limberger, R.P. Salathé, 'Postfabrication resonance positioning of long-period cladding-mode-coupled gratings', *Optics Letters*, vol. 21, pp. 1830-1832, 1996.

[6] R. Kiyan, O. Deparis, O. Pottiez, P. Mégret and M. Blondel, 'Stabilisation of an actively mode-locked Er-doped fiber laser by minimising the inter-pulse noise power', *Electron. Lett.*, vol. 34, pp. 2410-2411, 1998.

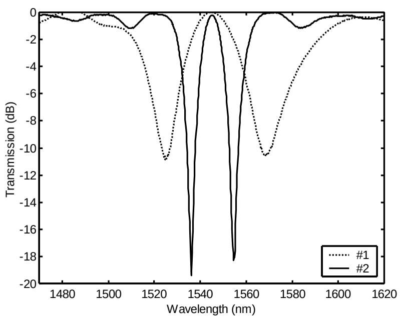

Fig. 1 Measured transmission spectra of π-shifted LPGs #1 and #2. Bandwidths (at –3 dB) of the central band-pass window are 22.3 nm and 9.4 nm respectively.

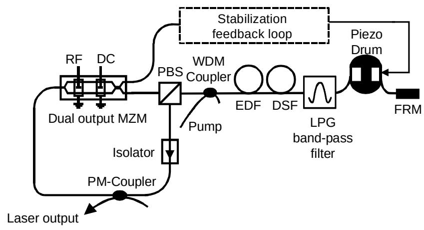

Fig. 2 Configuration of fiber laser. LPG : long period grating, PBS : polarization beam splitter, FRM : Faraday rotation mirror, EDF : erbium fiber, DSF dispersion-shifted fiber, WDM wavelength-division-multiplexing, MZM : Mach Zehnder modulator, PM polarization-maintaining.

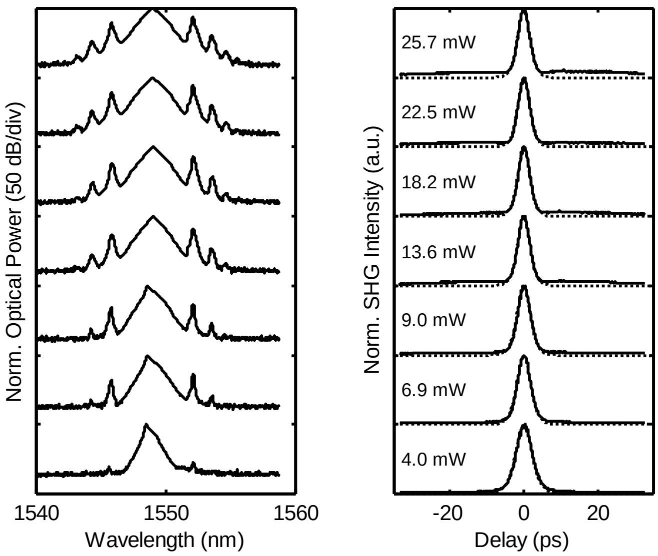

Fig. 3 Pulse optical spectra (left) and autocorrelation traces (right) measured at increasing intracavity power with LPG #1 in the laser cavity. Curves are shifted along Y-axis for clarity. Dashed curves : fitting of autocorrelation traces to sech² functions.

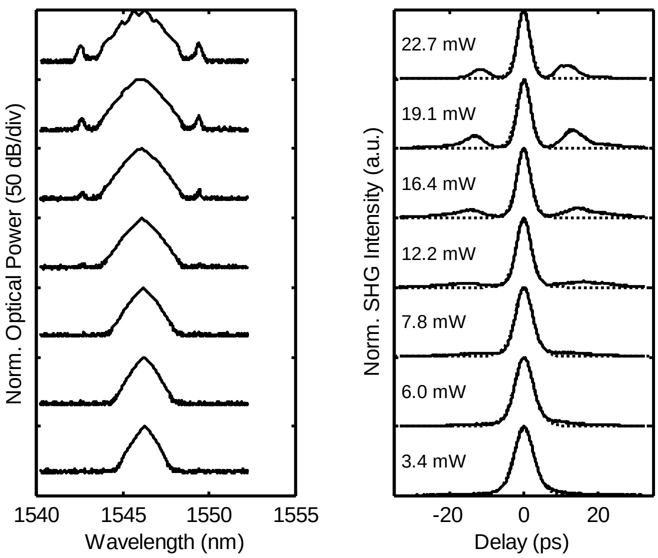

Fig. 4 Pulse optical spectra (left) and autocorrelation traces (right) measured at increasing intracavity power with LPG #2 in the laser cavity. Curves are shifted along Y-axis for clarity. Dashed curves : fitting of autocorrelation traces to sech² functions.