Polarization-Maintaining Fiber Bragg Gratings for Wavelength Selection in Actively Mode-Locked Er-Doped Fiber Lasers

O. Deparis, *Member, IEEE*, R. Kiyan, S. A. Vasiliev, O. I. Medvedkov, E. M. Dianov, O. Pottiez, *Student Member, IEEE*, P. Mégret, *Member, IEEE*, and M. Blondel

***Abstract*—Fiber Bragg gratings written in polarization-maintaining fiber are proposed for wavelength selection in actively mode-locked Er-doped fiber lasers. Combined with single-polarization optical circulator, they form unidirectional transmission filters that can be incorporated in polarization-maintaining laser cavities. We have fabricated such a grating in hydrogen-loaded PANDA fiber and we have incorporated it in a polarization-maintaining actively mode-locked Er-doped fiber laser designed to generate soliton-like pulses. Dependencies of pulse duration and spectral width on average intracavity power were measured. The power range over which soliton-like pulses were generated without pedestals was found to be ultimately limited by the grating's bandwidth.**

***Index Terms*—Mode-locked lasers, optical fiber gratings, optical fiber lasers, single polarization, solitons.**

ACTIVELY mode-locked Er-doped fiber lasers are stable sources of pedestal-free soliton-like pulses at repetition rates in the GHz range [1]–[3]. Fiber Bragg gratings (FBGs), on the other hand, are ideal components for wavelength selection in fiber lasers. Combined with optical circulator, FBGs can be incorporated in ring or sigma laser cavities and perform simple or more elaborated filtering functions. Actively mode-locked Er-doped fiber lasers incorporating FBGs have been reported in various configurations [4]–[6]. However, because FBGs were written in single-mode fibers, they did not permit to build polarization-maintaining (PM) laser cavity, which is required for long-term stability of the laser [1], [7]. In this letter, we introduce polarization-maintaining fiber Bragg gratings (PM-FBGs) for wavelength selection in actively mode-locked Er-doped fiber lasers. PM-FBGs offer flexibility for selection of the laser wavelength and have the advantage of preserving the long-term stability of the laser. For experimental demonstration, a PM-FBG was fabricated in PM PANDA fiber and incorporated in an actively mode-locked Er-doped fiber sigma laser.

The actively mode-locked Er-doped fiber sigma laser is depicted in Fig. 1. The sigma cavity [7] is functionally equivalent to a PM unidirectional ring cavity thanks to the use of a Faraday rotation mirror which cancels polarization fluctuations in the double-pass non-PM section of the cavity. All components in the ring are polarization-maintaining. The PM-FBG is combined with a single-polarization optical circulator to form a unidirectional transmission filter. The circulator also serves as an isolator in the ring. A dual-output Mach–Zehnder amplitude modulator (3-GHz bandwidth) is used for active harmonic mode locking. A stabilization feedback loop based on minimization of interpulse noise power [8] maintains the appropriate relation between cavity length and modulation frequency ($f_m \approx 3$ GHz). The gain medium is a 9.7-m-long Er-doped fiber which is pumped by 980-nm laser diode (150 mW max. power). 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 (free spectral range is 394 kHz). The average cavity dispersion was measured to be 2.42 ps/(nm$\times$km) at 1545 nm with a slope of 0.034 ps/nm^2. The laser output is extracted through a PM coupler (20% output coupling ratio). Note that the output coupler could be replaced by the circulator with coupling ratio being determined by grating reflectivity. At the repetition rate of 3 GHz (only limited by modulator's bandwidth), soliton-like pulses are generated when the average optical power in the cavity is higher than $\approx$1 mW.

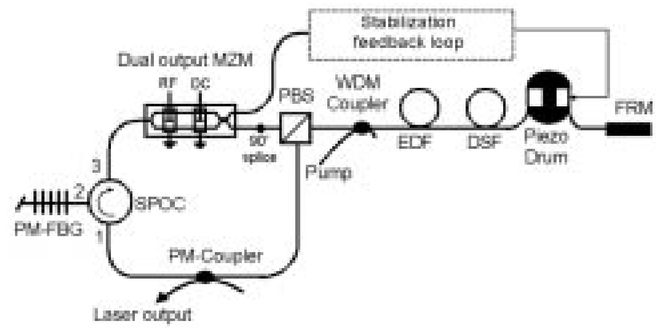

Fig. 1. Actively mode-locked Er-doped fiber laser incorporating polarization-maintaining fiber Bragg grating (PM-FBG): SPOC, single-polarization optical circulator; MZM, Mach–Zehnder modulator; PBS, polarization beam splitter; EDF, Er-doped fiber; DSF, dispersion-shifted fiber (200 m); FRM, Faraday rotation mirror.

In order to be used as filter in actively mode-locked laser, FBGs with high reflectivity and wide bandwidth are desirable [6]. Now, if the FBG is inscribed in a PM fiber, it can be incorporated into the laser cavity while preserving the

Manuscript received September 25, 2000; revised January 2, 2001. This work was supported by the Inter-University Attraction Pole program (IAP IV/07) of the Belgian Federal Office for Scientific, Technical and Cultural Affairs (OSTC).

O. Deparis, R. Kiyan, O. Pottiez, P. Mégret, and M. Blondel are with the Advanced Research in Optics group, Electromagnetism and Telecommunications Department, Faculté Polytechnique de Mons, 7000 Mons, Belgium.

S. A. Vasiliev, O. I. Medvedkov, and E. M. Dianov are with the Fiber Optics Research Center, General Physics Institute, 117756 Moscow, Russia.

Publisher Item Identifier S 1041-1135(01)03111-1.

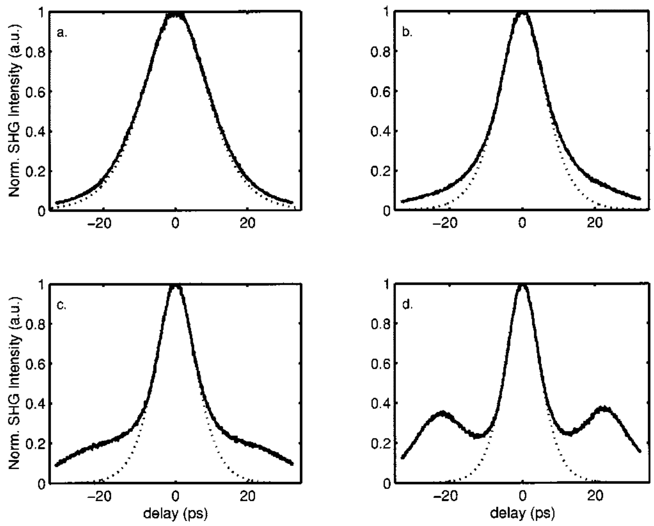

Fig. 2. Pulse autocorrelation traces measured at the output coupler (solid curves) for different values of average intracavity power; $P_{\mathrm{cav}} = 3.3$ mW (a), 7.8 mW (b), 12.3 mW (c) and 21.5 mW (d). Experimental data are fitted to sech^2 function (dashed curves). SHG: Second Harmonic Generation.

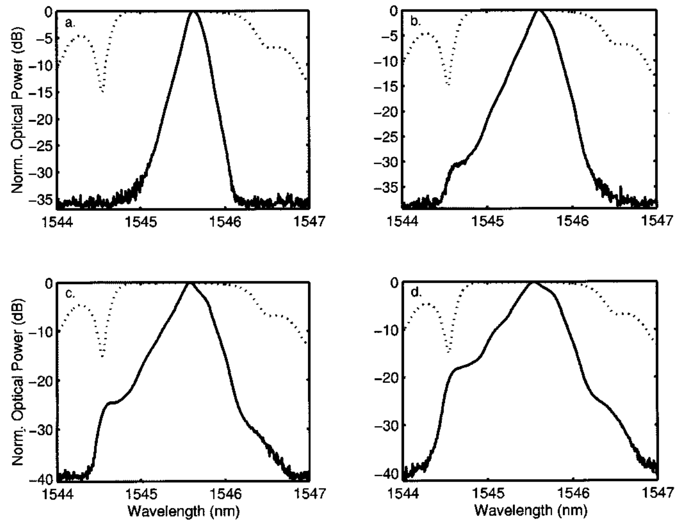

Fig. 3. Pulse optical spectra measured at the output coupler (solid curves) for different values of average intracavity power [same values as Fig. 2(a)–(d)]. Reflection spectrum of PM-FBG (measured with light linearly polarized along the slow axis) is also shown (dashed curve). Resolution $= 0.1$ nm.

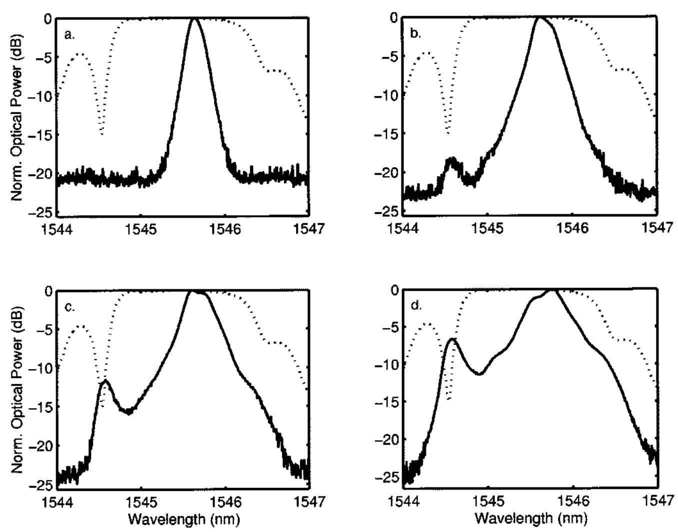

Fig. 4. Optical spectra of the pulse transmitted through PM-FBG (solid curves) for different values of average intracavity power [same values as Fig. 2(a)–(d)]. Reflection spectrum of PM-FBG (measured with light linearly polarized along the slow axis) is also shown (dashed curve). Resolution $= 0.1$ nm.

single-polarization property of the laser. When a PM fiber is exposed to UV-light for grating inscription, the resulting index modulation gives rise to two spectrally shifted Bragg peaks because of fiber's birefringence. In the following, grating's parameters are specified for light that is linearly polarized along the slow axis of the PM fiber. For experimental demonstration, a PM-FBG was fabricated by exposing a PM fiber (PANDA type) to continuous-wave (CW) 244-nm radiation from a frequency-doubled Ar-ion laser using the interferometer technique. Prior to UV inscription, the fiber was loaded with H_2 at 125 bars (100 °C) during 16 h in order to increase its otherwise low photosensitivity. Uniform grating of 1.2-mm length was then written by irradiating the fiber during 20 min at power density of about 80 W/cm^2. Peak wavelength, reflectivity, full-width at half-maximum (FWHM) reflection bandwidth of the PM-FBG were measured to be 1545.5 nm, 99%, and 1.6 nm, respectively. The estimation of refractive index change induced in the fiber core gave the value of about 3.4×10^{-3}. With respect to PM-FBGs reported in various types of PM fiber (e.g., [9]), to our knowledge, it is the strongest (nonchirped) FBG ever written in PM fiber.

With the PM-FBG incorporated in the laser, stable pulse train was generated at 1545.5 nm through harmonic mode locking ($f_m = 2.999\,840\,066$ GHz). Pulse autocorrelation trace and optical spectrum were recorded as the average intracavity power, P_{cav}, was varied by changing the pump power (Figs. 2 and 3, respectively). Average intracavity power was determined by measurement of average power at the laser output ($P_{\mathrm{cav}} = P_{\mathrm{out}}/C$, where $C = 20\%$ is the output coupling ratio). Optical spectrum of the pulse transmitted through PM-FBG was also measured (at free end of PM-FBG, see Fig. 1) as P_{cav} was varied (Fig. 4). Dependencies of pulse duration, spectral width and time-bandwidth product (TBP) on P_{cav} are shown in Fig. 5. TBP was about constant *versus* intracavity power and close to transform limit for sech^2 pulses (0.32). From Kuizenga-Siegman theory [10], which is valid when nonlinear effects can be neglected inside the cavity, we have calculated a pulse duration of 19.3 ps in the present case. At the lowest values of P_{cav}, the laser has already enough power to operate in the nonlinear regime, generating pedestal-free soliton-like pulses [Fig. 2(a)] whose duration is shorter than Kuizenga-Siegman limit. However, when P_{cav} exceeds $\approx$5 mW, pedestals appear in the autocorrelation trace [Fig. 2(b)]. As P_{cav} increases further (maximal power available in the experiment was 24.1 mW), pedestals grow while pulse duration decreases continuously [Fig. 2(c)–(d)]. The ratio of the total pulse energy (calculated from experimental data) to the soliton energy ($E_{\mathrm{sech}^2} = 2 \times \tau \times P_p$, with τ obtained by fitting experimental data to sech^2 function) is shown in Fig. 5 as function of P_{cav}. The growth of pedestals is attributed to the strong filtering of the PM-FBG when the pulse spectrum nonlinearly

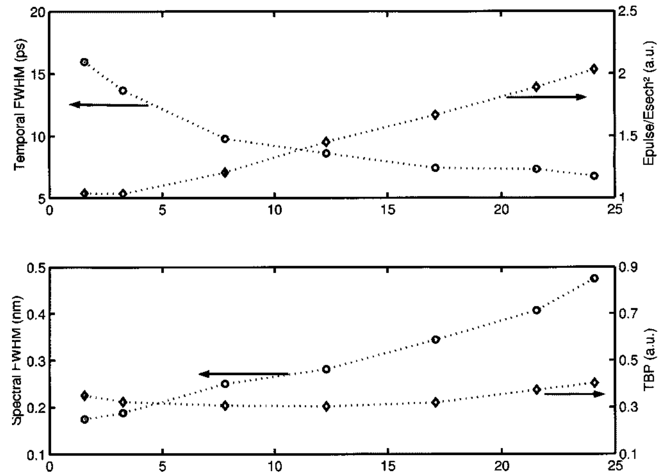

Fig. 5. Dependencies of pulse temporal FWHM width, ratio of total pulse energy to soliton energy, time bandwidth product and spectral FWHM width on average intracavity power.

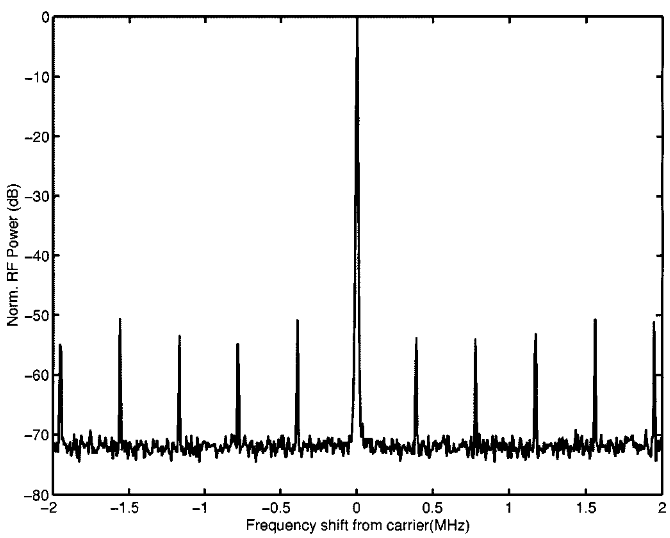

Fig. 6. Typical RF spectrum of the detected pulse train (resolution 3 kHz, center frequency 3 GHz). Super modes, separated by cavity's FSR ($\approx$0.4 MHz), are $\approx$50 dB down to carrier.

broadens as $P_{\rm cav}$ increases [Fig. 3(b)–(d)]. The growth of a component around 1544.5 nm observed in the spectra of the pulse transmitted through PM-FBG [Fig. 4(b)–(d)] indicates that the pulse spectrum broadens beyond the PM-FBG's 3-dB bandwidth (PM-FBG's transmission at 1544.5 nm is $\approx$97% while it is only 1% within the 3-dB bandwidth). The power range over which soliton-like pulses are generated without pedestal (≈ 1–5 mW) is found to be ultimately limited by the PM-FBG's bandwidth. Radio-frequency (RF) spectrum of the detected pulse train (Fig. 6) confirmed the long-term stability of the laser. Super mode noise was ≈ 50 dB down to carrier and relaxation oscillations were completely suppressed.

In summary, FBG was fabricated in PM PANDA fiber and incorporated in a PM actively mode-locked Er-doped fiber laser for wavelength selection. PM-FBGs offer flexibility for selection of the laser wavelength and have the advantage of preserving the long-term stability of the laser. They could also be used in PM laser cavities for switching between several wavelengths [4], [5]. The need of circulator, which is an expensive component, may be viewed as disadvantage in comparison with the use of classical interference filters. However, the circulator has the specific advantage that it can replace both isolator and output coupler in the PM ring.

REFERENCES

[1] M. Horowitz, C. R. Menyuk, T. F. Carruthers, and I. N. Dulling III, "Pulse dropout in harmonically mode-locked fiber lasers," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 266–268, Mar. 2000.

[2] B. Bakhshi and P. A. Andrekson, "40 GHz actively modelocked polarization-maintaining erbium fiber ring laser," *Electron. Lett.*, vol. 36, pp. 411–413, Mar. 2, 2000.

[3] K. S. Abedin, M. Hyodo, and N. Onodera, "154 GHz polarization-maintaining dispersion-managed actively modelocked fiber ring laser," *Electron. Lett.*, vol. 36, pp. 1185–1186, July 6, 2000.

[4] S. Li and K. T. Chan, "A novel configuration for multiwavelength actively mode-locked fiber lasers using cascaded fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 179–181, Feb. 1999.

[5] K. Chan and C. Shu, "Electrical switching of wavelength in actively modelocked fiber laser incorporating fiber Bragg gratings," *Electron. Lett.*, vol. 36, pp. 42–43, Jan. 6, 2000.

[6] 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. Technol. Lett.*, vol. 11, pp. 1238–1240, Oct. 1999.

[7] T. F. Carruthers, I. N. Duling III, and M. L. Dennis, "Active-passive modelocking in a single-polarization erbium fiber laser," *Electron. Lett.*, vol. 30, pp. 1051–1053, June 23, 1994.

[8] R. Kiyan, O. Deparis, O. Pottiez, P. Mégret, and M. Blondel, "Stabilization of an actively mode-locked Er-doped fiber laser by minimizing the inter-pulse noise power," *Electron. Lett.*, vol. 34, pp. 2410–2411, Dec. 1998.

[9] P. Niay, P. Bernage, T. Taunay, M. Douay, E. Delevaque, S. Boj, and B. Poumellec, "Polarization selectivity of gratings written in Hi-Bi fibers by the external method," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 391–393, Apr. 1995.

[10] D. J. Kuizenga and A. E. Siegman, "FM and AM mode locking of the homogeneous laser—Part I: Theory," *IEEE J. Quantum Electron.*, vol. QE-6, pp. 694–708, Nov. 1970.