DWDM channel spacing tunable optical TDM carrier from a mode-locked weak-resonant-cavity Fabry-Perot laser diode based fiber ring

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Abstract: A novel optical TDM pulsed carrier with tunable mode spacing matching the ITU-T defined DWDM channels is demonstrated, which is generated from an optically injection-mode-locked weak-resonant-cavity Fabry-Perot laser diode (FPLD) with 10%-end-facet reflectivity. The FPLD exhibits relatively weak cavity modes and a gain spectral linewidth covering >33.5 nm. The least common multiple of the mode spacing determined by both the weak-resonant-cavity FPLD and the fiber-ring cavity can be tunable by adjusting length of the fiber ring cavity or the FPLD temperature to approach the desired 200GHz DWDM channel spacing of 1.6 nm. At a specific fiber-ring cavity length, such a least-common-multiple selection rule results in 12 lasing modes between 1532 and 1545 nm naturally and a mode-locking pulsewidth of 19 ps broadened by group velocity dispersion among different modes. With an additional intracavity bandpass filter, the operating wavelength can further extend from 1520 to 1553.5 nm. After channel filtering, each selected longitudinal mode gives rise to a shortened pulsewidth of 12 ps due to the reduced group velocity dispersion. By linear dispersion compensating with a 55-m long dispersion compensation fiber (DCF), the pulsewidth can be further compressed to 8 ps with its corresponding peak-to-peak chirp reducing from 9.7 to 4.3 GHz.

OCIS codes: (250.5960) Semiconductor lasers; (140.4050) Mode-locked lasers; (320.1590) Chirping; (060.3510) Lasers, fiber.

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1. Introduction

Multiple-channel hybrid DWDM/OTDM optical sources based on fiber laser system have been proposed to exploit next-generation communication network capacity in both time and wavelength domains. For example, the multi-channel pulsed optical source with a repetition rate at 10 GHz (equivalent 100-ps period in time domain) and a channel spacing of 50-200 GHz is particularly suitable for being the optical time-division multiplexing pulsed carrier after encoding communicating data via external modulators. To meet this demand, the highly synchronized and multi-wavelength ultrashort pulses directly generated from mode-locked Erbium-doped fiber or semiconductor optical amplifier SOA based fiber ring lasers (EDFL or SOAFL) with appropriate frequency controlling system were proposed [1-3]. For DWDM channeling purpose, versatile techniques such as a set of wavelength dependent gain media associated with precise wavelength controllers and complex output couplers covering numerous DWDM channels have been employed as the wavelength and channel selector [4]. For example, the 10-channel multi-wavelength output of a mode-locked SOAFL with repetition rate up to 30 GHz and pulsewidth of 7 ps by adding a Fabry-Perot etalon in the fiber ring was ever achieved [5]. Similar method was employed to a passively mode-locked Er-doped fiber laser for generating mode spacing up to 3.36 nm [6]. The peak wavelength of the mode-locked fiber laser can be considerably tunable by adjusting the mode-locking frequency, however, which is usually associated with a significant pulse shape deformation and broadening under such operation [7]. In previous work, such a scheme provides an extremely narrow frequency detuning range of ±250 kHz for preserving the pulsewidth and shape of the fiber laser output. Later on, a 5 to 40 GHz rational-harmonic mode-locking of fiber ring laser was also reported with a mode spacing as small as 0.4 nm (equivalent to 50 GHz DWDM channel), which provides up to 48 channels with a pulsewidth of 2.5 ps by introducing a Fabry-Perot cavity within the fiber ring [8]. With the use of 5-m long polarization maintaining fiber (PMF) as another weak resonant cavity (caused by the interfacial reflection at both PMF-SMF end faces) in the mode-locked fiber ring laser, a DWDM/TDM hybrid carrier with 1.6 nm mode-spacing and channel wavelength tunable from 1491.1 to 1587.7 nm (nearly 100 nm) can also be achieved by detuning the mode-locking frequency [9]. Recently, the unbalanced Mach-Zehnder intensity modulator (UMZM) based wavelength filter could also meet the demand of obtaining multi-channel and picosecond pulse generation in a passively mode-locked EDFL [10]. In particular, the reflective SOA (with 0.01% and 100% reflectivity at front and back facet, respectively) could also be employed to play both the roles of gain medium and Fabry-Perot filter. Accompanying with the cross gain modulation (XGM) method, the 10 GHz mode-locked EDFL with 1.12 nm channel spacing and up to 14 channels has been reported [11]. By using a hybrid cavity with

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the sampled fiber Bragg gratings (SFBGs), the EDFL with 1.6-nm channel spacing and 14 channels mode-locking at frequency of 1 GHz was generated [12]. However, all of these multi-wavelengths mode-locked EDFLs or SOAFLs were implemented by additional channel filters with constant mode-spacing for individual DWDM formats. In this work, we employ a weak-resonant-cavity Fabry-Perot laser diode (FPLD) based fiber ring to implement harmonic mode-locking with its mode-spacing tunable and coincident with the ITU-T defined DWDM channel spacing from 50 to 200 GHz. The dual cavity (FPLD and fiber ring) induced mode-spacing multiplication and the mode-locked pulse features by adjusting the fiber ring length are discussed.

2. Experiment setup

The trace (a) in Fig. 1 illustrates a typical backward-optical-injection mode-locked SOAFL with a cavity length of 14 m reported previously,[13] which consists of one traveling-wave type SOA with central gain peak at 1530 nm, an optical circulator, a faraday isolator, an optical tunable band-pass filter (OBPF), and an output coupler (OC) with a power-splitting ratio of 50%. The SOA was DC-biased at 225 mA (well above its transparent threshold). The SOA with a broadened gain spectrum plays both the roles of a gain medium and an optically controlled modulator in this work. In contrast to the conventional mode-locking SOAFL, we employ a two-port FPLD of same cavity length but with the front and back facet reflectivities of 10%. The weak-resonant-cavity FPLD is generally working as a semiconductor optical amplifier in connection with a Fabry-Perot etalon filter of relatively low finesse. Such a weak Fabry-Perot resonant-cavity essentially results in an additional longitudinal mode selecting mechanism, which forces the rational harmonic mode-locking occurred at a least multiplication harmonic frequency of the FPLD and the fiber ring link, as shown in Fig. 1(b). The FPLD was DC-biased at 280 mA and 22^{o}C. To backward optical-inject the FPLD for harmonic mode-locking, tunable laser (TL, Agilent, 8164A) operated at 1555.7 nm and 25^{o}C was amplified by a 20dB-gain erbium-doped fiber amplifier (EDFA), and subsequently modulated by a Mach-Zehnder intensity modulator (MZM) nonlinearly driven with an electrical comb generator (COMB) triggered by an amplified sinusoidal wave at 10 GHz to form a dark-optical-comb. In our approach, such a dark-optical comb with comb pulsewidth of 32.4 ps and duty-cycle of 31 % at 1555.7 nm can be generated. The dark-optical-comb power was adjusted by a tunable attenuator (TATT) to optimize the gain depletion of FPLD. The backward injection of such a dark-optical-comb via appropriate control of its polarization with a polarization controller (PC) prior to the optical circulator results in a temporally sliced gain window within one modulation period to shrink the modulation window and to optimize the mode-locking of the FPLD based fiber ring laser.

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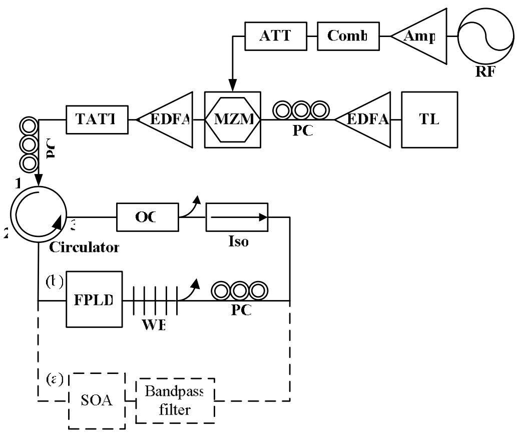

Fig. 1. The schematic diagrams of backward optical-injection mode-locked (a) SOA and (b) weak-resonant-cavity FPLD.

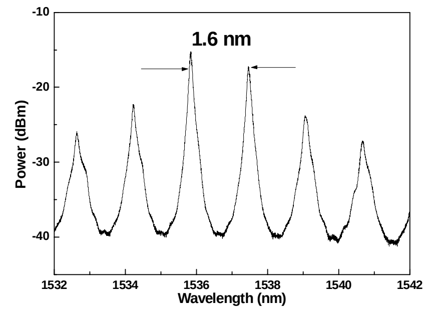

Fig. 2. Output spectrum of the mode-locked weak-resonant-cavity FPLD fiber ring laser.

In the weak-resonant-cavity FPLD based fiber ring laser cavity, the counter-clockwise propagated dark-optical-comb at 1555.7 nm is terminated by a fiber-Bragg-grating based wavelength blocker (WB) and a clockwise optical isolator (ISO) after passing through the FPLD. The clockwise short-wavelength harmonic mode-locking is achieved by backward injecting and gain-depletion modulating the SOA or weak-resonant-cavity FPLD with a periodically dark-optical-comb at a longer wavelength via a circulator. An additional polarization control on the clockwise circulated feedback in the fiber ring is mandatory, since the injection must be sufficiently high to saturate the gain and then depletes most of the excited-state electrons in the gain medium (weak-resonant-cavity FPLD). The harmonic mode-locked FPLD fiber ring laser was approached by narrowing the gain window and detuning the synthesizer frequency. In free-running case, the amplified spontaneous emission (ASE) of the long weak-resonant-cavity FPLD generates longitudinal modes with a spacing of 0.25 nm (corresponding to $\Delta\nu$ = 31 GHz), while the longitudinal mode-spacing of the fiber ring is about 9.63 MHz. By adding the weak-resonant-cavity FPLD into the fiber ring and adjusting the length of ring cavity appropriately, the least common multiple of each mode-spacing could be tunable to approach the DWDM channel. In general, either the fiber ring cavity length or the weak-resonant-cavity FPLD mode spacing can be adjusted via an intra-cavity piezoelectric ring or a temperature controller, respectively, to change the spacing of the lasing channels. In experiment, the mode spacing of the mode-locked FPLD and fiber-ring link is adjusted to 1.6 nm (see Fig. 2) and is characterized for potential application in the DWDM system with channel spacing of 200 GHz.

3. Results and Discussion

After harmonic mode-locking at 10 GHz, the spectra of the weak-resonant-cavity FPLD and fiber-ring link clearly reveals to the least-common multiplied longitudinal modes with a spacing of 1.6nm, and a single-channel spectrum obtained by adding external AWG band-pass filter after the laser output is also shown in Fig 3. With such a weak-resonant-cavity FP etalon effect, the output spectrum of the mode-locked weak-resonant-cavity FPLD based fiber ring laser can naturally generate up to 12 channel modes in its lasing spectrum, whereas the typical SOA device without a 10%-reflectivity FP etalon only generate one broadened spectrum after the dark-optical-comb injection mode-locking.

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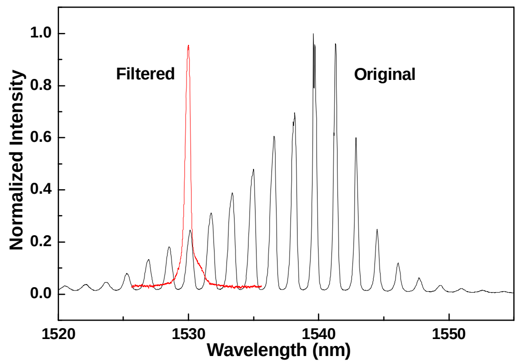

Fig. 3. The output spectrum: with FP etalon (black curve) and without FP etalon (red curve).

In comparison with the single-channel filtered output, the multi-channel pulsed carrier exhibit a slightly pulsewidth large broadened from 12 to 19 ps detected by auto-correlator, as shown in Fig. 4. Such a configuration with a simplified setup further benefit from the advantage of a flexible mode-spacing tunability as learned from the conventional figure-of-eight cavity dual fiber-ring laser. Under the control of either the FPLD temperature or the fiber-ring cavity length, the least-common multiplied longitudinal mode (or channel) spacing can easily be detuned to meet the demand of DWDM channeling. Typically, the synthesizer with its frequency detuned to a specific value also acts as a wavelength locker to mode-lock a desired single wavelength mode in the harmonic mode-locked FPLD fiber link. Nevertheless, the typical approach of detuning synthesizer frequency could lead to the reduction on the lasing modes of mode-locked weak-resonant-cavity FPLD fiber laser from 10 to 2 modes. Since the slightly frequency detuning has inevitably caused a mismatch of some side-modes with the mode-locked harmonic resonant frequency. As a result, these phase-mismatched side-modes travelling few round trips would be depleted by the fiber ring cavity loss.

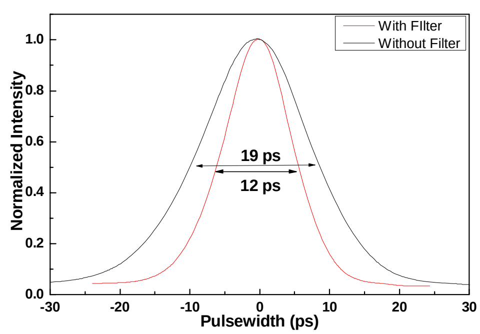

Fig. 4. Single-channel output with filter (red curve) and multi-channel output without filter (black curve)

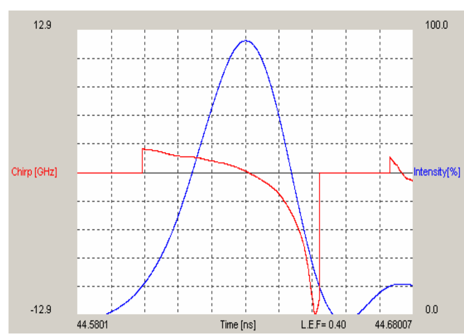

Fig. 5. Dynamic frequency chirp of a multi-channel pulse.

Since each mode in the weak-resonant-cavity FPLD fiber ring laser experiences different dispersion in fiber ring cavity, the more modes obtained the larger group velocity dispersion induced pulse broadening effect in fiber ring cavity would occur. In this case, such a simultaneously multi-channel operation inevitably lengthens the mode-locked FPLD fiber ring laser pulsewidth without channel filtering. Alternatively, the detuning on the channel wavelength can be done by using an intra-cavity polarization controller to change the feedback power from the fiber ring to the FPLD cavity, as the increasing feedback to the weak-resonant-cavity FPLD also means the increasing reflectivity [6]. In principle, the strong feedback tends to saturate the FPLD, leading to the gain compression and a shift of the gain peak toward the longer wavelength [14-15]. That is, the polarization controller can further function as a band selector in our system, which can detune the harmonic mode-locking spectrum toward longer wavelength by changing the feedback. Concurrently, the modes of FPLD fiber ring laser become more discriminated with increasing feedback power except their red-shifted wavelength.

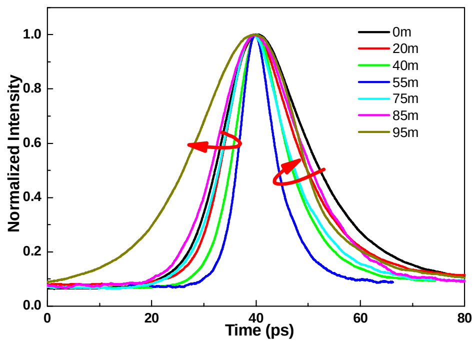

Fig. 6. The changed of mode-locked FPLD fiber ring laser pulse shape when increasing the DCF length. (oscilloscope)

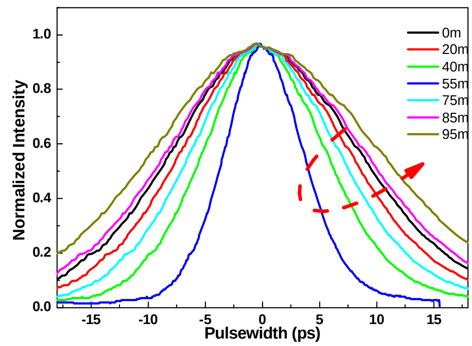

Fig. 7. Auto correlation traces of the mode-locked weak-resonant-cavity FPLD fiber-ring laser dispersion compensated at different DCF lengths.

Before dispersion compensation, the mode-locked FPLD fiber ring laser pulse induced a negative chirp (C<0) ranging from +2 to -13 GHz within the 20-ps wide pulse, as shown in Fig. 5, which can be linearly compensated by a segment of dispersion compensation fiber (DCF) with positive group velocity dispersion (GVD) parameter (β_2) based on $\beta_2 C<0$ condition[16]. Both the harmonic mode-locked FPLD fiber-ring pulse shapes obtained by digital sampling oscilloscope and auto-correlator are shown in Figs. 6 and 7, respectively, for determining the variation on the rising and falling edges of the pulse, and the exact pulsewidth after the linear dispersion compensation by DCF is analyzed. With increasing DCF length, both the rising and falling edges of the FPLD fiber ring laser pulse are steepened, as shown in Fig. 6. In particular, the falling edge of the negatively chirped pulse is shortened more faster than the rising edges with increasing DCF length, as the long-wavelength mode experiences a larger dispersion constant during propagating in the DCF (i.e. the DCF exhibits a negative $d\beta_2/d\lambda$ at C and L bands). However, such a steepening phenomenon disappears when introducing the DCF with its length longer than 55 m, while the rising edge turns to be slackened faster than the falling edge due to the overcompensation process. As a result, the auto-correlated pulsewidth rapidly shrinks from 19 to 8 ps as the DCF length increases up to 55 m, whereas the pulse greatly broadens to 22 ps with over-length DCF compensation. Without proper dispersion compensation, the corresponding time-bandwidth product of the mode-locked FPLD fiber ring pulse is 2.43 due to the extremely large chirp existed in such a multi-channel pulse.

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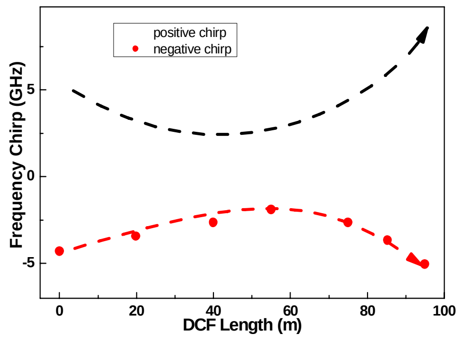

Fig. 8. Dynamic frequency chirp vs. DCF length.

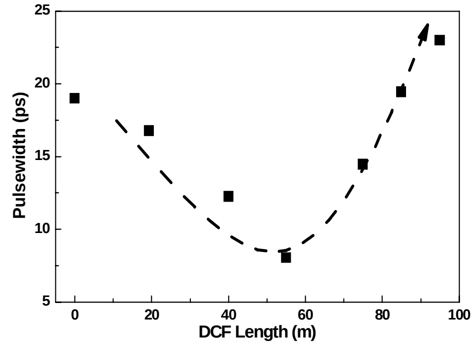

Fig. 9. Dispersion compensated pulsewidth vs. DCF length.

For each channel, the time-bandwidth product of the chirp compensated pulse is about 0.36. Such a small deviation from transform-limit condition reveals that only a tiny nonlinear chirp induced by highly-biased weak-resonant-cavity FPLD, which cannot be suppressed at linear dispersion compensation stage. With a proper compensation length of DCF, the peak-to-peak frequency chirp was reduced from 9.7 to 4.3 GHz within a pulse time period under 50-m DCF compensation, as shown in Fig. 8. The DCF compensation process causes the pulsewidth shortened from 19 to 8 ps, as shown in Fig. 9. Overcompensation inevitably induces a chirp enlarged from 4.3 to 13 GHz corresponding to a pulsewidth broadening from 8 to 22 ps. With a coarse wavelength detuning by tunable band-pass filtering, the shortest channel wavelength mode at 1520 nm of the mode-locked FPLD-fiber ring link is selected, and the maximum coarse detuning range can be up to 1568 nm limited by the gain profile of the weak-resonant-cavity FPLD itself, as shown in Fig. 10. Nonetheless, to avoid the cross-talk effect between the 1555.7 nm dark-optical-comb injection and the weak-resonant-cavity FPLD mode-locking spectrum, the central lasing spectrum of the FPLD based fiber-ring laser was maximized to 1553.5 nm. Without proper dispersion compensation scheme, the corresponding mode-locked pulse shown in Fig. 11 clearly reveals the corresponding pulsewidth variation with changing chirp at wavelength increasing from 1520 to 1553.5 nm.

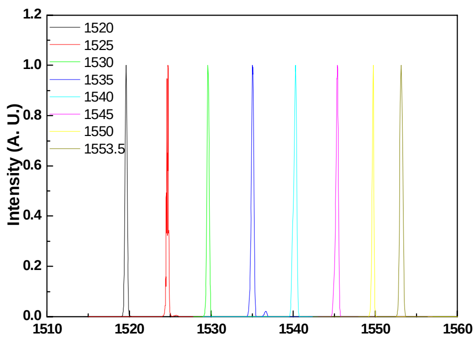

Fig. 10. Maximum coarse wavelength tuning range and single-mode spectra of the mode-locked FPLD based fiber ring link.

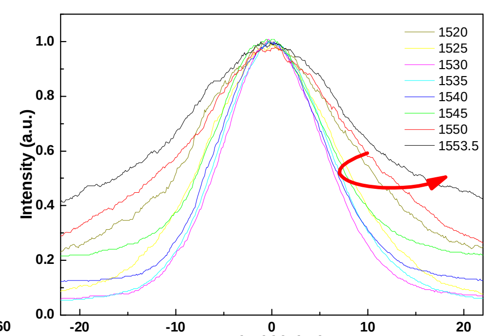

Fig. 11. Corresponding pulsewidth of the mode-locked FPLD based fiber ring link under a coarse wavelength detuning.

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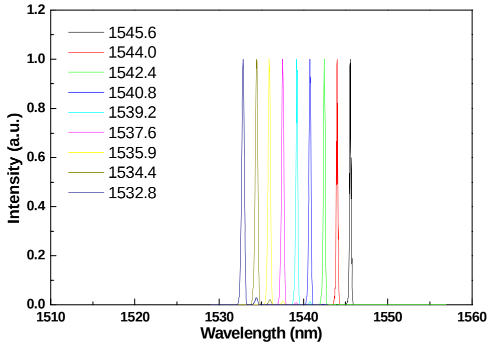

Fig. 12. Fine detuning 200GHz DWDM channel spectra of the mode-locked FPLD based fiber ring link.

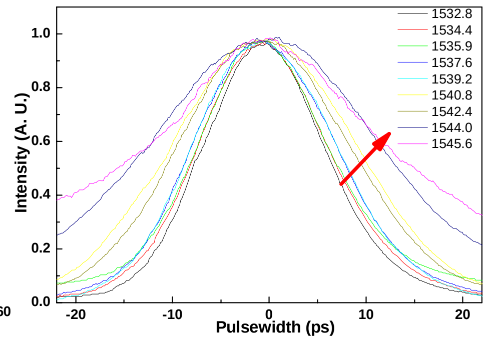

Fig. 13. Corresponding pulsewidth of the mode-locked FPLD based fiber ring link under a 200GHz DWDM channel filtering.

Since the optimized mode-locking spectrum of FPLD-fiber ring link is setting around 1535 nm, the channel-detuned mode-locking spectrum beyond or below such wavelength inevitably meet the additional gain depletion and the residual chirp problem. The insufficient gain failed to supply enough power for the channel mode to achieve the best mode-locking of FPLD-fiber ring link would cause the pulsewidth broadening, as shown in Fig. 11. However, it was totally different when mode-locking within the naturally mode-locking spectrum of the FPLD. In this case, a sufficient gain makes the mode-locking pulsewidth shrinkage again from 1530 to 1550 nm. The 200 GHz DWDM channel filtered FPLD-fiber ring link spectra are shown in Fig. 12, while the variation of the mode-locked pulse toward longer wavelength, exhibiting a broadened pulsewidth trend as the channel wavelength are gradually detuned over the best mode-locking condition, as shown in Fig. 13. In addition, even in coarse wavelength detuning or in 200GHz DWDM channel filtering case, the worst pulsewidth broadening is still within twice of its original value.

4. Conclusion

We demonstrate a novel optical TDM pulsed carrier with tunable mode spacing matching ITU-T DWDM channels generating from optically injection-mode-locked weak-resonant-cavity Fabry-Perot laser diode (FPLD) with 10%-end-facet reflectivity. The FPLD exhibits relatively weak cavity modes and a gain spectrum covering >33.5 nm. The least common multiple of the mode-spacings of the weak-resonant-cavity FPLD and the fiber-ring is tunable by adjusting length of the fiber ring cavity to approach the desired DWDM channel spacing of 1.6 nm. At a specific fiber cavity length, such a least-multiple selection rule between the longitudinal modes of fiber cavity ring and FPLD cavity results in 12 lasing modes between 1532 and 1545 nm naturally and a mode-locking pulsewidth of 19 ps broadened by group velocity dispersion at different modes. In our experiment, the mode-locking of such a weak-resonant-cavity FPLD based fiber ring laser generate TDM carriers with their mode-spacing matching the 200 GHz DWDM channels without adding intra-cavity filter. Furthermore, a broadband and coarse wavelength tuning range from 1520 to 1553.5 nm can also be achieved by inserting band-pass filter. In comparison with multi-channel pulse, the single-channel filtered output shortens the pulsewidth from 19 to 12 ps. After linear dispersion compensation with DCF, the negatively chirped pulse can further be compressed to 8 ps with associated frequency chirp reducing from 9.7 to 4.3 GHz at an optimized DCF length of 55 m.

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