10 × 30 GHz Pulse Train Generation from Semiconductor Amplifier Fiber Ring Laser

K. Vlachos, K. Zoiros, T. Houbavlis, and H. Avramopoulos

***Abstract*—A multiwavelength, fiber ring laser source, is demonstrated. It generates 10 wavelength channels, simultaneously mode-locked and synchronized at 30 GHz, each producing 7-ps pulses. The mode-locking technique relies on the gain saturation of the semiconductor amplifier from an external optical pulse train to impose the simultaneous mode-locking of the 10 wavelengths.**

***Index Terms*—Mode-locked fiber ring laser, multiwavelength source, rational harmonic mode-locking, , semiconductor optical amplifier.**

I. INTRODUCTION

THE RAPID growth in bandwidth demand from optical fiber network systems, has intensified research efforts to demonstrate multiwavelength and high bit rate laser sources [1] and to qualify them in transmission experiments [2]. In order to increase the product (number of channels) × (channel repetition rate), a large number of approaches have been taken, aiming to increase either terms of this product. One of the successful techniques that has been employed so far is that of spectrum slicing. Spectrum slicing has been used with LED's [4], superluminescent diodes [5], amplified spontaneous emission from EDFA [6], supercontinuum generation in fiber [2], [3] and femtosecond pulses [7], [8]. A significant advantage of spectral slicing is that it overcomes the difficulties associated with wavelength stabilization if independent diode lasers are used instead. A different approach has also been investigated in which the multiwavelength signal is obtained directly from actively mode-locked laser oscillators [9], [10]. This approach preserves the advantage of relative wavelength stability between all oscillating modes, while it results in relatively simple experimental configurations. With this technique, all the mode-locked wavelengths are simultaneously timed to the modulation signal in the laser oscillator and so they are also synchronized with each other. This is an important feature in these sources, which may be used for powering high-speed digital optical logic circuits [11], [12], for which precise synchronization is essential.

In this letter, we report on a compact, fiber pigtailed laser source which generates 10 synchronized wavelength channels, each mode-locked at 30 GHz, producing nearly transform limited 7-ps pulses with less than 5% power variation across them. The source provides a total of 300-GHz modulation capacity cross its ten wavelengths and this is phase locked to a relatively low frequency 5-GHz optical pulse train, which is used to mode-lock it. This is a particularly attractive feature of this source, as the low frequency optical pulse train may be used for easy clock recovery in a transmission system or as a master clock in a high speed all-optical digital logic circuit. Finally the source is simple to build and has been constructed entirely from commercially available components.

The principle of operation of the source presented here relies on three key observations. The first is that the fast saturation of the gain of a semiconductor optical amplifier (SOA) by an externally introduced picosecond optical pulse train pulse, may be used for gain modulation in a ring cavity to obtain mode-locked picosecond pulse trains [13]. Optical modulation of the gain of the SOA may be more easily performed at a higher rate than electrical gain modulation. In the present experiment the externally introduced pulse train is obtained from a relatively low repetition rate, gain switched DFB diode laser. The second observation is that the use of a heterogeneously broadened gain element as a semiconductor amplifier, allows the simultaneous oscillation of a number of wavelengths in the same oscillator cavity.

In the present embodiment, the multiwavelength oscillation in the laser source has been achieved with the use of a Fabry–Perot etalon. The third observation is that repetition rate multiplication to nf_{ext} of the output pulse train may be achieved, by tuning the frequency f_{ext} of the externally introduced pulse trains to $f_{\mathrm{ext}} = (N + 1/n)\delta f_{\mathrm{ring}}$, [14]–[16]. In this equation, N is the order of the harmonic mode-locking of the ring laser, δf_{ring} is the fundamental frequency of the ring laser oscillator and n is an integer. When the repetition rate of the external pulse train is adjusted to differ by $\delta f_{\mathrm{ring}}/n$ from a harmonic of the fundamental of the ring cavity, it becomes temporally displaced by T_{ext}/n on each recirculation through the ring cavity with respect to its previous position. In this T_{ext} is the repetition period of the external signal. In the present experiment it has been possible to multiply the repetition frequency of each wavelength up to 30 GHz or six times the rate of the external optical pulse train.

II. EXPERIMENT

Fig. 1 shows the experimental layout. The laser ring cavity has been constructed entirely from fiber-pigtailed devices. Gain was provided from a 500-μm bulk InGaAsP–InP ridge waveguide SOA with 10° angled and antireflection coated facets. The SOA had a peak gain at 1535 nm with 20-nm bandwidth, providing 23-dB small signal gain with 250-mA dc drive current

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and had 400-ps recovery time. Faraday isolators were used at the input and output of the SOA to ensure unidirectional oscillation in the ring and to stop the externally introduced signal from circulating in the cavity. Immediately after the SOA, an 80 : 20 optical fiber coupler was used so as to insert the external signal and to tap the output signal from the laser. The wavelength selecting element was a Fabry–Perot etalon, constructed from an uncoated fused quartz substrate with 1.8-nm free-spectral range and 0.4-nm bandwidth. The SOA exhibited 2-dB polarization gain dependence and a polarization controller was used at its input port for optimization. The total length of the ring cavity was 24.25 m corresponding to a 7.98-MHz fundamental frequency. The external pulse train was generated from a 5-GHz gain switched DFB laser diode operating at 1548.5 nm. These pulses were compressed to 7.5 ps with dispersion compensation fiber before amplification in an EDFA.

Before injection into the ring laser cavity via the 80 : 20 controller, the polarization state of the pulses was adjusted to optimize the quality of the mode-locked pulses from the ring.

III. Results and Discussion

With a 5-nm tunable bandpass filter and in the absence of the external modulating pulsed signal, the fiber ring laser source tunes between 1523–1576 nm. With the Fabry–Perot etalon inserted in the cavity and in order to obtain the maximum number of oscillating modes, the SOA was driven with 240 mA, close to the maximum permissible current. As the SOA drive current was increased, the laser oscillation shifted toward longer wavelengths and as a result of this the maximum number of simultaneous wavelength oscillations was obtained between 1554–1570 nm.

With the 5-GHz gain switched pulse train turned on, its frequency tuned to a harmonic of the ring cavity and the EDFA adjusted to provide 1.6 mW into the cavity, the SOA fiber ring source mode-locks simultaneously at 10 wavelengths. For this condition the drive current to the SOA is adjusted to 235 mA. By increasing the frequency of the signal generator away from this value by 1/6th of the fundamental frequency of the ring cavity, the laser produces pulse trains at 30-GHz repetition frequency. This is six times higher repetition frequency than the repetition frequency of the external pulse trains. It should be noted here that all other repetition frequency multiplication factors up to 6 could be obtained easily by appropriate frequency tuning of the external pulse trains. The broad and nearly wavelength independent cw tuning range of the ring cavity allows in any case for nearly equal power distribution across the 10 oscillating wavelengths. Micro-adjustment within a few microamperes from the value at which the source mode-locks, however, was used to further reduce this power variation to less than 5%. The total output power of the source was 580 µW.

Fig. 2(a) shows the optical spectrum of the mode-locked output from the laser, showing the 10 simultaneously mode-locked wavelengths at 30 GHz. The output pulses were 12 ps long and were not transform limited due to the frequency chirp imposed on them by the refractive index change of the SOA from its fast time-dependent saturation. Subsequently these were linearly compressed with dispersion compensating

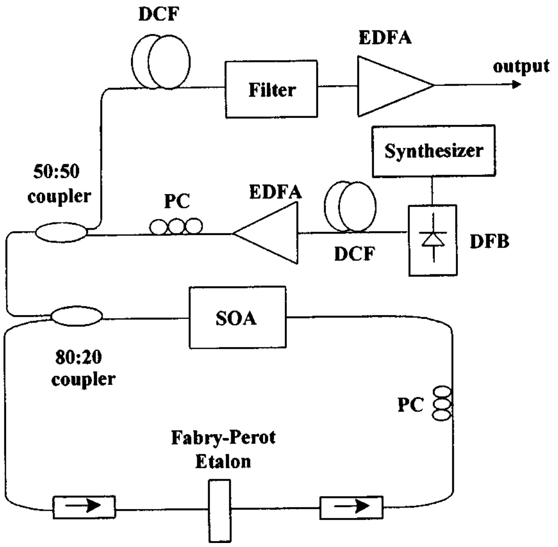
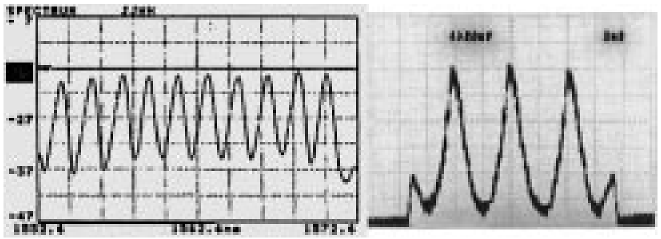


Fig. 1. Experimental setup.



(a) (b)

Fig. 2. (a) Spectrum of multiwavelength laser in mode locked operation at 30 GHz and (b) autocorrelation trace, corresponding to 6.7-ps pulsewidth. The time base in the trace corresponds to 16.6 ps.

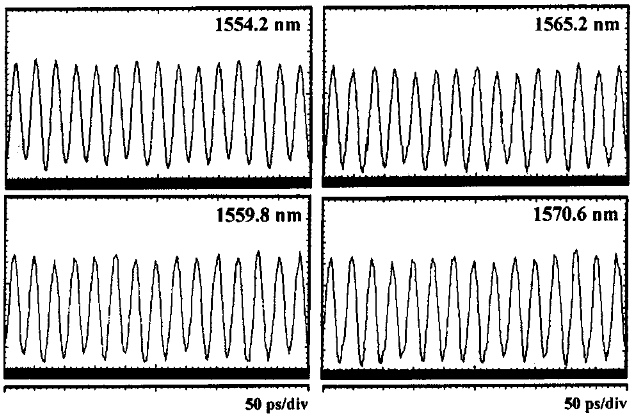
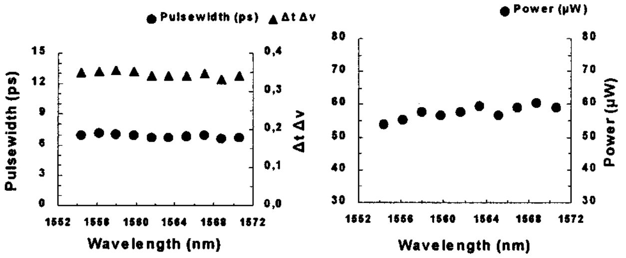


Fig. 3. Simultaneous pulse train for four wavelengths. The time base is 50 ps.



(a) (b)

Fig. 4. (a) Variation of the pulsewidth and pulsewidth–bandwidth product versus wavelength. (b) Variation of the output power versus wavelength.

fiber of total dispersion −14.25 ps/nm and were filtered with a tunable optical bandpass filter of 0.6 nm width before detection. Fig. 2(b) shows the second-harmonic autocorrelation trace of the pulse train obtained at 1568.8 nm, indicating 6.7-ps pulse width assuming a squared hyperbolic secant profile. It was not possible to obtain good quality pulse trains for repetition rates beyond 30 GHz primarily because of the length of the recirculating mode-locked pulses and the external pulses.

Fig. 3 displays the mode-locked pulse trains after filtering at $\lambda_1 = 1554.4$ nm, $\lambda_2 = 1559.8$ nm, $\lambda_3 = 1565.2$ nm, and $\lambda_4 = 1570.6$ nm monitored on a 30-GHz sampling oscilloscope and shows temporal synchronization between them. Fig. 4(a) displays the variation of the pulsewidth and the pulsewidth-bandwidth product for each mode-locked wavelength. This figure shows that the pulsewidths for all 10 wavelength pulse trains, are within 4% of 7 ps. Similarly this figure shows that the pulsewidth–bandwidth products for all pulse trains are within 3% of 0.35, indicating that the pulses profiles are all close to squared hyperbolic secant. It is worth noting here that the composite autocorrelation trace of the 10-wavelength pulse trains revealed the same pulse width as each of the individual wavelengths, confirming their temporal synchronization. Fig. 4(b) shows the output power for each of the mode-locked wavelengths indicating less than 5% variation across them.

In summary, we have demonstrated a simple, totally fiber-pigtailed laser source, constructed from commercially available components, which is capable of generating 10 synchronized wavelength channels, each mode-locked at 30 GHz. The oscillator produces nearly transform limited, 7-ps pulses for all wavelengths with less than 5% power variation across them.

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REFERENCES

[1] L. Boivin, M. Wegmueller, M. C. Nuss, and W.H. Knox, "110 Channels × 2.35 Gb/s from a single femtosecond laser," *IEEE Photon. Technol. Lett.*, vol. 22, pp. 446–468, 1999.

[2] S. Kawanishi, H. Takara, K. Uchiyama, I. Shake, and K. Mori, "3 Tbit/s (160 Gbit/s × 19 channel) optical TDM and WDM transmission experiment," *Electron. Lett.*, vol. 35, pp. 826–827, 1999.

[3] T. Morioka, K. Uchiyama, S. Kawanishi, S. Suzuki, and M. Saruwatari, "Multiwavelength picosecond pulse source with low jitter and high optical frequency stability based on 200 nm supercontinuum filtering," *Electron. Lett.*, vol. 31, pp. 1064–1066.

[4] M. H. Reeve, A. R. Hunwicks, W. Zhao, S. G. Methley, L. Bickers, and S. Hornung, "LED spectral slicing for single-mode local loop applications," *Electron. Lett.*, vol. 24, pp. 389–390, 1988.

[5] S. S. Wagner and T. E. Chapuran, "Broadband high density WDM transmission using superluminescent diodes," *Electron. Lett.*, vol. 24, pp. 696–697, 1990.

[6] J. S. Lee, Y. C. Chung, and D. J. DiGiovanni, "Spectrum-sliced fiber amplifier light source for multichannel WDM applications," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 1458–1461, 1993.

[7] E. A. De Souza, M. C. Nuss, W. H. Knox, and D. A. B. Miller, "Wavelength-division multiplexing with femtosecond pulses," *Opt. Lett.*, vol. 20, pp. 1166–1168, 1995.

[8] S. A. E. Lewis, M. J. Guy, J. R. Taylor, and R. Kashyap, "All-fiber periodic spectral filter for simultaneous generation of multiple WDM channels from broad bandwidth pulsed sources," *Electron. Lett.*, vol. 34, pp. 1247–1249, 1998.

[9] H. Shi, G. Alphonse, J. Connolly, and P. Delfyett, "20 × 5 Gbit/s optical WDM transmitter using single-stripe multiwavelength modelocked semiconductor laser," *Electron. Lett.*, vol. 34, pp. 179–181, 1998.

[10] T. Papakyriakopoulos, A. Stavdas, E. N. Protonotarios, and H. Avramopoulos, "10 × 10 GHz simultaneously modelocked multiwavelength fiber ring laser," *Electron. Lett.*, vol. 35, pp. 717–718, 1999.

[11] K. L. Hall and K. A. Rauschenbach, "100-Gbit/s bitwise logic," *Opt. Lett.*, vol. 23, pp. 1271–1273, 1998.

[12] B. K. Mathason, I. Nitta, H. Shi, G. A. Alphonse, J. C. Connolly, and P. J. Delfyett, "All-optical multiwavelength switching for hybrid WDM/TDM demultiplexing and signal processing," in *Tech. Dig.*, 1999, CThA2.

[13] T. Papakyriakopoulos, A. Hatziefremidis, T Houbavlis, and H. Avramopoulos, "10 GHz mode-locked ring laser with external optical modulation of a semiconductor optical amplifier,", TuB1 OFC 99, 1999.

[14] Z. Ahmed and N. Onodera, "High repetition rate optical pulse generation by frequency multiplication in actively modelocked fiber ring lasers," *Electron. Lett.*, vol. 32, pp. 455–457, 1996.

[15] E. Yoshida and M. Nakazawa, "80–200 GHz erbium doped fiber laser using a rational harmonic mode-locking technique," *Electron. Lett.*, vol. 32, pp. 1370–1371, 1996.

[16] T. Papakyriakopoulos, K. Vlachos, A. Hatziefremidis, and H. Avramopoulos, "Optical clock repetition rate multiplier for high speed digital optical logic circuits," *Opt. Lett.*, vol. 24, pp. 717–719, 1999.