10 Simultaneously Mode-locked and Synchronized Channels at 30 GHz from Fiber Ring Laser

K. Vlachos, K. Zoiros, T. Houbavlis and H. Avramopoulos
Department of Electrical and Computer Engineering,
National Technical University of Athens, 157 73 Zographou, Athens, Greece
tel: +30-1-772 2076, fax: +30-1-772 2077, email: hav@cc.ece.ntua.gr

Summary

The introduction of wavelength division multiplexing (WDM) to satisfy the increasing demand in the capacity of optical fiber network systems, has created an intense interest to demonstrate multi-wavelength, high bit rate laser sources operating at 1.5 μm [1] and to qualify them in transmission experiments [2,3]. Multi-wavelength sources have so far been demonstrated using spectrum slicing with LEDs [4], super luminescent diodes [5], amplified spontaneous emission from EDFAs [6] or supercontinuum generation in fiber [7]. An advantage of spectrum slicing is that it forces relative wavelength stability between oscillating modes. A different approach that preserves relative wavelength stability has also been investigated and in this the multi-wavelength signal is obtained directly from actively mode-locked laser oscillators that use heterogeneously broadened gain media [8,9]. An important feature of this technique is that all the mode-locked wavelengths are simultaneously timed to the modulation signal and therefore synchronized to each other.

In this communication we demonstrate a compact fiber ring laser which generates 10 simultaneously mode-locked and synchronized wavelengths channels, each at 30 GHz producing nearly transform limited 7 ps pulses with less than 5% power variation between them. The principle of operation and the performance of the source presented here are based on three observations. The first observation is that multi-wavelength oscillation may be obtained easily from a semiconductor optical amplifier (SOA) with the use of an intra-cavity grating or Fabry-Perot etalon [8,9]. The second observation is that by periodically saturating the gain of a SOA with an external optical pulse train, it is possible to mode-lock a fiber ring laser cavity to obtain picosecond pulses [10,11]. In this arrangement the SOA plays the role both of the gain element and the modulator. The final observation is that it is possible to obtain repetition rate multiplication of the output pulse train of the mode-locked source compared to the external gain modulating pulse train, by increasing the frequency of the external source by $\delta f_{ext} = f_{ring}/n$ away from a cavity harmonic [12]. In this relation f_{ring} is the fundamental frequency of the fiber ring cavity, δf_{ext} is the frequency detuning of the external pulse train from a cavity harmonic and n is an integer which equals the repetition rate multiplication factor. As such the source is shown to provide 300 GHz of modulation capacity across its 10 wavelength channels and this is phase locked to the relatively low frequency 5 GHz optical pulse train that 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 if the source is used in a WDM transmission system, or as a master clock signal if the source is used to power all-optical digital logic circuits [13].

Fig. 1 shows the laser cavity which consists entirely of fiber-pigtailed components. The gain was provided by a 500 μm, bulk InGaAsP/InP ridge waveguide SOA, with facets angled at 10^0 and antireflection coated. The device has a small signal gain of 23 dB when driven with a 250 mA dc current, at 1535 nm and a recovery time of about 400 ps. As the SOA exhibited a small signal gain polarization dependence of 2 dB, a polarization controller was used on its input port. A 20:80 fused fiber coupler was used to insert the external signal and to tap the output signal from the laser. Faraday isolators were used to ensure unidirectional operation and to stop the externally introduced optical signal from circulating in the cavity. 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.

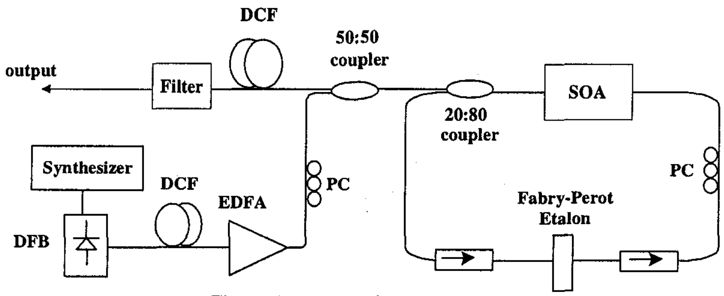

Fig. 1 Experimental setup

The total length of the cavity was 24.25 m corresponding to a fundamental frequency of 7.98 MHz. 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 a dispersion compensating fiber (DCF) and were amplified in an EDFA. For best performance, the polarization state of the external pulse train was adjusted with a polarization controller before insertion in the ring cavity.

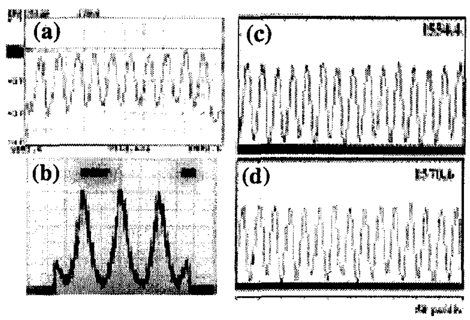

Fig. 2. (a) Spectrum of multi-wavelength laser in mode locked operation at 30 GHz, (b) autocorrelation trace corresponding to 6.7 ps pulsewidth, obtained at 1568.8 nm. The time base in the trace corresponds to 16.6 ps,(c) and (d) pulse trains at 1554.4 nm and 1570.6 nm.

With the 5 GHz gain switched pulse train switched on, its frequency tuned to a harmonic of the ring cavity and the EDFA adjusted to provide up to 1.6 mW into the cavity, the laser mode-locks at the same repetition frequency, simultaneously, at 10 wavelengths. By increasing the frequency of the signal generator driving the gain switched laser diode by $1/6^{th}$ of the fundamental frequency of the ring cavity, the laser produces pulse trains at 30 GHz repetition frequency. All other repetition frequencies from 5 to 30 GHz could also be obtained by appropriate adjustment of the frequency of the external pulse train. The output power of the different wavelengths was equalized by micro-adjustment of the current driving the SOA. The maximum power difference between the oscillating modes was less than 5% and the total output power of the source was 580 μW. Fig. 2 (a) shows the optical spectrum of the output of the laser, mode-locked at 30 GHz. The output pulses directly from the oscillator were 12 ps long and were not transform limited. They were subsequently compressed with a dispersion compensating fiber of -14.25 ps/nm dispersion and were filtered with a 0.6 nm tunable bandpass filter before detection. Fig. 2 (b) shows the second harmonic autocorrelation trace of the output pulse train at 1568.8 nm, indicating 6.7 ps pulse width assuming a squared hyperbolic secant. Figs. 2 (c) and (d) show the mode-locked trains at

1554.4 and 1570.6 nm, respectively, monitored on a 30 GHz sampling oscilloscope, indicating temporal synchronization. The temporal synchronization between all the mode-locked channels was also verified using the autocorrelator, as the composite autocorrelation trace of all 10 wavelengths had the same width as each individual wavelength.

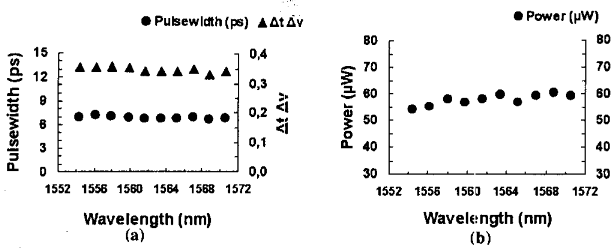

Fig. 3. (a) Variation of the pulsewidth and pulsewidth-bandwidth product vs wavelength, (b) Variation of the output power vs wavelength.

Fig. 3 (a) shows the variation of the pulse width and pulsewidth-bandwidth product for each mode-locked wavelength. It shows that the variation of the pulsewidth is within 4 % of 7 ps for all 10 oscillating wavelengths. It also shows that the pulsewidth-bandwidth product is within 3 % of 0.35 indicating that all generated wavelength pulse trains are formed from nearly transform limited pulses. Finally, Fig. 3 (b) shows the variation of the output power of each mode-locked wavelength and shows less than 5 % variation across them.

In summary, we have demonstrated a simple, totally fiber-pigtailed, laser source, capable of generating 10 simultaneous, synchronized wavelength channels, mode-locked at 30 GHz. The output pulses are 7 ps long, nearly transform limited for all oscillating wavelengths with less than 5 % power variation across them. The source provides a total of 300 GHz modulation capacity across its 10 channels which is phase locked to the relatively low frequency 5 GHz optical pulse train that is used to mode-lock it. The source may thus be used in a WDM transmission system where its 5 GHz mode-locking signal may be used for easy clock recovery. Alternatively, the source may be used as a master signal clock to power all-optical digital logic circuits, where the 5 GHz pulse train may be used as the gate synchronization signal.

References

1. J.J. Veselka and S.K. Korotky, IEEE Photon. Technol. Lett. **10,** 958 (1998).
2. A.R. Chraplyvy, A.H. Gnauck, R.W. Tkach, J.L. Zyskind, J.W. Sulhoff, A.J. Lucero, Y. Sun, R.M. Jopson, F. Forghieri, R.M. Derosier, C. Wolf, and A.R. McCormick, IEEE Photon. Technol. Lett., **8,** 1264 (1996).
3. L. Boivin, M. Wegmueller, M.C. Nuss, and W.H. Knox, IEEE Photon. Technol. Lett. **22,** 446 (1999).
4. K. -Y. Liou, U. Koren, K. Dreyer, E.C. Burrows, J.L. Zyskind, and J.W. Sulhoff, IEEE Photon. Technol. Lett. **10,** 270 (1998).
5. S.S. Wagner and T.E. Chapuran, Electron. Lett. **26,** 696 (1990).
6. J.S. Lee, Y.C. Chung, and D.J. DiGiovanni, IEEE Photon. Technol. Lett. **5,** 1458 (1993).
7. T. Morioka, K. Uchiyama, S. Kawanishi, S. Suzuki, and M. Saruwatari, Electron. Lett. **31,** 1064 (1995).
8. H. Shi, G.A. Alphonse, J.C. Connolly, and P.J. Delfyett, Electron. Lett., **34,** 179 (1998).
9. T. Papakyriakopoulos, A. Stavdas, E.M. Protonotarios, and H. Avramopoulos, Electron. Lett. **35,** 717 (1999).
10. T. Papakyriakopoulos, K. Vlachos, A. Hatziefremidis, and H. Avramopoulos, Opt. Lett. **24,** 1209 (1999).
11. K.L. Hall, J.D. Moores, K.A. Raushenbach, W.S. Wong, E.P. Ippen, and H.A. Haus, IEEE Photon. Technol. Lett. **7,** 1093 (1995).
12. Z. Ahmed and N. Onodera, Electron. Lett. **32,** 455 (1996).
13. K.L. Hall and K.A. Rauschenbach, Opt. Lett. **23,** 1271 (1998).