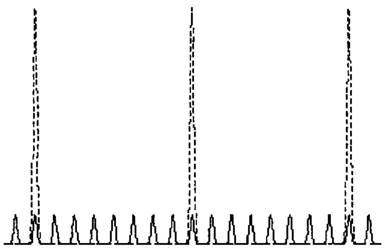
CTuK17 Table 1. One Typical Solution of the Phase adjustment Factors for N = 2 to 16

N	**Relative phase factors for each group m**
2	{0, −π/2}
4	{0, 0, π, 0}
8	{0, π, − π /2, π, π /2,− π /2, − π /2, − π /2}
16	{0, −π, π /2,− π /2, π /2, π /2,−π /2, −π /2,− π , 0, π /2, −π /2, −π /2, −π /2, −π /2, −π /2}
N	**Relative phase factors for each group m**
3	{0, 0, 2.094}
5	{0, -2π/5, 2.513, -2π/5, 0}
6	{0, π /2, π /2, - π /2, π /2, 0}
7	{0, 0.284, 1.795, 0.792, -1.336, -0.439, -2.798}
9	{0, -3.046, -1.65, -2.094, -3.117, 3.014, -0.818, -0.477, 2.467}
10	{0, 0.890, -2.566, 2.199, 2.294, -0.753, 0.8712, 0.557, -1.695, 0.723}
11	{0, 1.142, 2.285, -0.300, 0.842, 1.985, 0.571, -2.014, 2.856, -2.285, 1.414}
12	{0, -3.036, 2.094, 2.200, 2.094, -0.942, 0, 0.106, 2.094, -0.942, 2.094, 2.200}
13	{0, -2.099, 1.896, 2.251, 2.417, 1.450, -2.858, -1.616, 1.492, 0.525, 1.767, -1.408, 0.967}
14	{0, 0.653, 2.639, 1.632, 2.647, 2.454, 0.455, -0.723, 2.687, -2.081, 2.742, -1.189, 2.699, -2.980}
15	{0,-0.847,0.622,-0.639,-1.561,2.094,-1.533,-0.437,1.456,1.531,1.530,0.562,-1.472,1.755,-2.658}



CTuK17 Fig. 3. A numerical example with N = 8. Dash line: original pulse shape; Solid line: pulse shape after repetition rate multiplication.

Some typical solutions are listed in Table 1 for N = 2 to 16. It is interesting to note that solutions can be found for any given N and when N is an integer power of 2, the required phase-shifts have only four discrete values.

For practical implementation of our scheme, we propose to use cascade side-coupled ring resonators[3] as shown in Fig. 2(a). An ideal single side-coupled ring resonator is an all-pass filter with a phase spectrum as shown in Fig. 2(b). By carefully adjusting the equivalent path length of the ring resonators, one can achieve the required phase adjustments specified in Table 1 for each group. The number of required resonators is at most N − 1, and in practice it can be much less. (For example, for N = 4, only one resonator is needed.) Figure 3 shows a numerical example for N = 8 to prove the validity of previous analyses.

In summary, we have proposed and analyzed a novel scheme for losslessly increasing the intensity repetition rate of a steady pulse train by using optical all-pass filtering. The scheme should be useful in generating a highly repetitive optical pulse train with a repetition rate of tens and hundreds of GHz.

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CTuK18

Optical clock repetition rate multiplier

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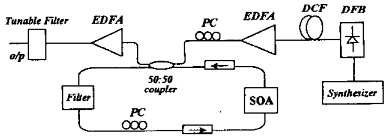
The rapidly maturing technologies of high performance, active and passive opto-electronic devices has helped to spurn an intense interest in several research groups for the development of ultra-high speed, all-optical logic circuits.[1] One essential subsystem for ultra high speed, optical logic circuits is a high repetition frequency optical clock source. A number of short pulse, high repetition rate laser sources have been demonstrated for this purpose,[2,3] but they almost always have to rely on high frequency microwave sources to provide the drive signal or narrow frequency linewidth and stabilised DFB laser sources and sophisticated compression techniques. In the present communication, we report a short pulse, high repetition rate laser source that is capable of producing 15 ps pulse trains, at a repetition frequency of up to 34.68 GHz. The principle of its operation relies on a master-slave oscillator arrangement. In this instance the master oscillator is provided by a 5.78 GHz gain switched DFB, to which a fiber ring laser is synchronised. This arrangement of obtaining the high repetition rate optical clock signal presents two significant advantages. (a) The high repetition frequency optical clock requires a low frequence and therefore less expensive rf signal generator. (b) The low repetition frequency rf and optical signal may be used as the universal reference signal of all the high repetition frequency optical clocks in the optical logic circuit. In this way data may be introduced into the logic circuit at a low rate, so that it is compatible with commercially available modulators.

The basis of the concept on which repetition rate multiplication is achieved in our laser source relies on two key observations. The first is that the fast saturation of a semiconductor optical amplifier (SOA) by an externally introduced picosecond optical pulse, may be used for gain modulation in a fiber ring laser and the generation of stable picosecond pulse trains from such a system.[4] The second observation is that by using this technique to mode-lock a fiber ring laser, it is possible to tune the frequency f_{ext}, of the externally introduced pulse train to $f_{ext} = (N + 1/n)\delta f_{ring}$, and to obtain an output pulse train at a frequency nf_{ext}. In this equation N and δf_{ring} is the order of harmonic mode-locking and fundamental frequency of the ring laser and n is an integer number. This method for repetition rate multiplication is only possible, if the gain modulation in the laser cavity is provided by a saturable amplifier so as not to present loss at any time.

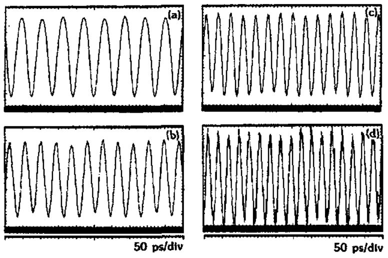


CTuK18 Fig. 1. Experimental setup.

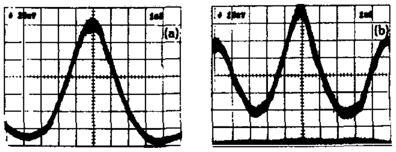
Figure 1 shows the experimental layout. All the components used in the cavity are pigtailed with standard single mode fiber. Gain was provided from a 500 μm InGaAsP/InP ridge waveguide SOA. The waveguide facets were angled at 10° and were antireflection coated. The SOA had a peak gain at 1535 nm and could provide 23 dB small signal gain at 250 mA dc drive current. Faraday isolators were used at the input and output of the SOA to ensure unidirectional oscillation in the ring cavity. After the SOA, a 3 dB fused optical fiber coupler was used to insert the externally introduced signal and to obtain the output from the source. A tunable filter with 5 nm bandwidth was used for wavelength selection. As the SOA exhibited a 2 dB gain dependence, a polarization controller was introduced at its input port. The total length of the ring cavity was 14.6 m corresponding to 13.9 MHz fundamental frequency. The external signal was provided from a gain switched DFB laser at 1548.9 nm, which was compressed in dispersion compensating fiber to produce 12 ps pulses at 5.78 GHz. The output of the DFB laser was amplified in an EDFA and its polarization state was controlled for optimum performance before entry into the ring.

With the synthesizer source of the DFB adjusted to a harmonic of the fundamental of the ring cavity (approx. 5.7 GHz) and the EDFA adjusted to provide 800 μW into the cavity, the ring laser breaks into stable, mode-locked operation at this frequency. By changing the driving frequency in the synthesizer source by 13.9/n MHz and n varying from 2 to 6, the laser produces pulse trains at 11.56 GHz, 17.34 GHz, 23.12 GHz, 28.9 GHz and 34.68 GHz. Figure 2 shows the output pulse trains at (a) 17.34 GHz, (b) 23.12 GHz, (c) 28.9 GHz and (d) 34.68 GHz monitored on a 40 GHz sampling oscilloscope. Figure 3 shows the corresponding second harmonic autocorrelation traces obtained at (a) 17.34 GHz (b) 34.68 GHz. The pulse widths obtained from the fiber ring laser were approximately 15 ps for all repetition frequencies and the output power was about 60 μW.

The process by which the ring oscillator mode-locks in the presence of the external pulsed signal relies on the fast saturation of the SOA. The mode-locked pulse experiences a



CTuK18 Fig. 2. Output pulse trains at (a) 17.34 GHz, (b) 23.12 GHz, (c) 28.9 GHz and (d) 34.68 GHz.



CTuK18 Fig. 3. Second harmonic autocorrelation traces obtained at (a) 17.34 GHz (b) 34.68 GHz. The time base in the traces corresponds to 5.88 ps.

sharp loss edge at its trailing edge because of the external pulse. As such it forms just ahead of the external pulse, at the point where the recovery of the SOA is maximum. The circulating mode-locked pulse has to rely on the recovery of the SOA for gain and as the fiber laser is tuned to increasingly higher harmonics of the external signal, the output pulse train develops a small modulation at the frequency of the external signal. This however may be eliminated at the high frequencies by using an SOA with low recovery time, or external driving frequency of a higher rate.

We have also examined multiplication factors obtained from even lower external frequencies. It has been possible to obtain up to 23.75 GHz output pule trains from 1.25 GHz external input, corresponding to a factor of 19 frequency multiplication.

We have demonstrated a novel technique for the multiplication of optical clock signal to high repetition frequencies, that is compatible with clock requirements for optical logic circuits. We have demonstrated up to 6 times multiplication factors and up to 34.7 GHz clock frequency.

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CTuK19

Fast all optical switching and logic operations using a two-section semiconductor optical amplifier

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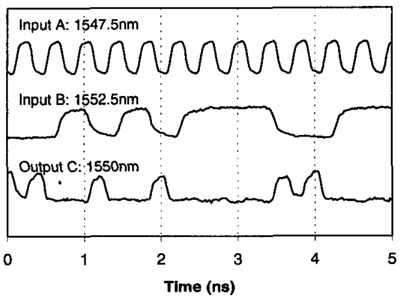
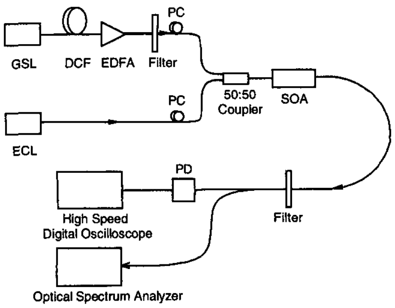
All optical switching, logic operation, and wavelength conversion devices are very important for the implementation of all-optical time-division-multiplexed (TDM) and wavelength-division multiplexed (WDM) systems. The semiconductor optical amplifiers (SOAs) with either cross-gain modulation (XGM) or cross-phase modulation (XPM) effects are ideal candidates for such applications.[1] It has been both theoretically and experimentally proved that to achieve very high-speed operations, a long SOA device with a very high bias current is needed.[2,3] Unfortunately, such an operation put a very high requirement on the quality of the antireflection (AR) coating at the device facets. A long SOA (>1000 μm) with a normally available AR coating at ~1% reflectivity can easily reach lasing situation at a bias below 100 mA. The gain of the device will thus be clamped at the threshold and the device will perform poorly on speed. In this work, we designed and fabricated a two-section SOA. By adjusting the injected carrier density of one of the two sections (shorter one) below its transparency carrier density, we can keep the device from lasing even when the long section is biased very high. The strict requirement of very low reflectivity AR coating is relieved with this device.

The device we made is a two-section (500 μm and 1500 μm long, respectively) multi-quantum well (MQW) SOA with a gain peak around 1.55 μm. To demonstrate all optical logic operation, we have used the device as a NOR gate. Figure 1 shows the experimental results. Three lights are injected into the SOA, where the long section is biased at 170 mA. Light A and B are used as the logic inputs. The input power of light C is kept constant (cw), and its output can be expressed as $\overline{A+B}$. Limited by the speed of bit-error-rate test set, the NOR gate is operated at 5 Gbit/s.

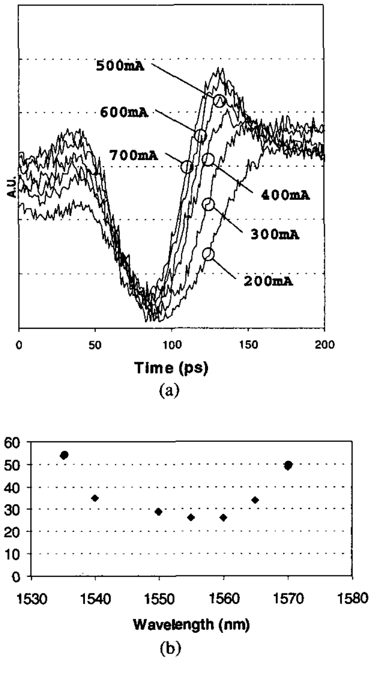


CTuK19 Fig. 1. Optical NOR logic operation: $C = \overline{A+B}$.



CTuK19 Fig. 2. The experimental setup of gain recovery measurement.

In order to study the speed of our device and to optimize the operation parameters, we have measured the gain recovery time using the probe-pump scheme at different probe wavelengths and injection current. The setup is shown in Fig. 2. We used a gain switched DFB laser (GSL) as the pumping source (wavelength 1547 nm). After the compression of a dispersion compensation fiber (DCF), the amplification of an EDFA, and the filtering of a FP Filter (1.3 nm bandwidth), a pumping pulse of 30 ps with a peak power near 1 W is obtained. The probe source is an external cavity tunable laser (ECL) with a tuning range from 1530 nm–1570 nm. After the SOA and a FP filter (Bandwidth 0.6 nm), the probe output is sent to a 40 GHz high speed photodetector (PD) and displayed with a 50 GHz digital oscilloscope.



CTuK19 Fig. 3. Gain recovery experimental results. (a) Probe output waveforms at different bias current. (b) Probe wavelength dependence of recovery time.