Optical clock repetition-rate multiplier for high-speed digital optical logic circuits

T. Papakyriakopoulos, K. Vlachos, A. Hatziefremidis, and H. Avramopoulos

Department of Electrical and Computer Engineering, National Technical University of Athens, 157 73 Zographou, Athens, Greece

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Repetition-rate multiplication has been shown by use of a fiber ring oscillator with a semiconductor optical amplifier as the gain medium and by use of fast saturation and recovery of the amplifier from an external optical pulse train. Repetition-frequency multiplication up to 6 times and up to 34.68-GHz frequency have been achieved. © 1999 Optical Society of America

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The rapidly maturing technology of high-performance optoelectronic devices has helped to focus an intense effort by a number of research groups to develop ultrahigh-speed all-optical logic circuits.[1–3] One of the essential subsystems required for optical logic circuits is a high-repetition-frequency optical clock source. A large number of short-pulse high-repetition-rate laser sources have been demonstrated. Two of these promising techniques rely on high-frequency microwave sources to provide a signal[4] and on narrow frequency-stabilized distributed-feedback (DFB) laser sources and compression techniques.[5] Along with the technical complexity that these approaches involve, they do not provide easily accessible low-rate rf–electrical signals that can be used for external electrical data interfacing with optical circuits.

Temporal synchronization of signals is a major issue in ultrahigh-speed logic circuits. To ensure synchronization in an optical logic circuit, one can use a single reference optical clock throughout the circuit. Optical logic circuits are likely to consist of a small number of ultrahigh-speed Boolean logic gates, synchronized to each other but running at different rates depending on the logic functions that they perform. The central optical logic processing units can be expected to run at rates of hundreds of gigabytes per second if one wants to keep the throughput of the circuit high, whereas optical processing units in the periphery of the optical circuit input–output can be run at significantly lower rates. Examples of such optical circuits are data-insertion multiplexer and data-extraction demultiplexer circuits. Assuming that a single reference clock is used throughout the optical logic circuit, this clock may be at the high rate of the optical logic processing units, in which case the low-rate signals at the input–output circuits will have to be obtained by local clock division. Alternatively, the reference clock can be run at the lower-frequency rate of the input–output interfaces, and the high-rate optical signals that are required at the optical processing units will be obtained by local multiplication of the reference clock. The advantages of using the low-frequency rate of the input–output interfaces as the reference clock are that (a) repetition-frequency multiplication is easier than repetition-frequency division, (b) input–output data-stream rates to and from the optical logic circuits will be lower than the optical gate processing rates, and (c) it is preferable, easier, and less costly to use low-frequency rf components for generation of the optical clock pulse train. To be able to use this low-frequency-rate reference-clock technique in high-speed optical digital circuits, one must be able to multiply the repetition rate from a laser source. In this Letter we report the demonstration of a simple optical clock multiplier circuit. We show up to 6 times frequency multiplication, from 5.78 to 34.68 GHz, and 19 times multiplication, from 1.25 to 23.75 GHz.

The principle on which repetition-frequency multiplication in our circuit is based relies on two 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 can be used for gain modulation in a fiber ring laser and generation of stable mode-locked picosecond pulse trains.[6] In this instance the externally introduced optical pulse and the comparatively slow gain recovery of the SOA define a short temporal gain window within which the mode-locked pulse can form. The second observation is that by tuning the frequency f_{ext} of the externally introduced pulse train to $f_{\mathrm{ext}} = (N + 1/n)\delta f_{\mathrm{ring}}$ one may obtain an output pulse train at a frequency nf_{ext}. In this equation, N is the order of harmonic mode locking of the ring laser, δf_{ring} is the fundamental frequency of the ring laser oscillator, and n is an integer number greater than 1. This technique for repetition-frequency multiplication has been found to be successful with lithium niobate modulators in cavities with a SOA[7] or an erbium-doped fiber amplifier[8] as the active medium and achieved up to 21- and 200-GHz output pulse trains, respectively.

Figure 1 shows the experimental layout. The optical frequency multiplier circuit was constructed entirely from fiber-pigtailed devices. The gain was provided by 500-μm bulk InGaAsP–InP ridge-waveguide SOA. The SOA had a peak gain at 1535 nm and could provide a 23-dB small-signal gain with a 250-mA dc drive current. We used Faraday isolators at the input and output of the SOA to ensure

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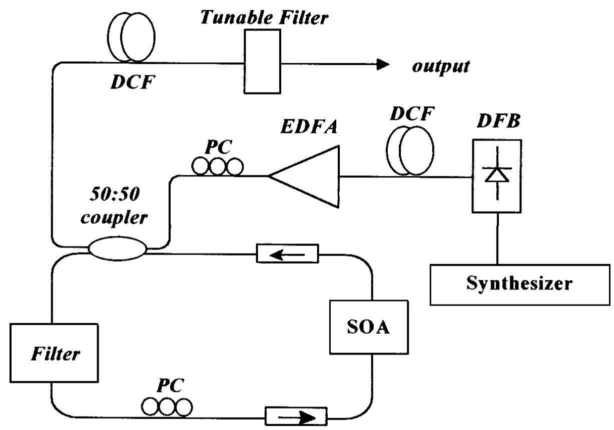

Fig. 1. Experimental layout: DCF's, dispersion-compensating fibers; PC's, polarization controllers.

unidirectional oscillation in the ring. As the SOA exhibited a 2-dB polarization gain dependence, a polarization controller was introduced at its input port. After the SOA a 3-dB fused optical fiber coupler was used to insert the external modulating signal and to obtain the output from the source. The externally introduced pulses were provided by a gain-switched DFB laser operating at 1548.9 nm. The gain-switched pulses were compressed to 8.3 ps with dispersion-compensating fiber, and after amplification in an erbium-doped fiber amplifier they were introduced into the multiplier oscillator through the 3-dB fused fiber coupler. The polarization state of the external signal was adjusted with a polarization controller for optimum performance before the signal was introduced into the multiplier circuit. To allow circulation of the external signal in the multiplier circuit and to select its oscillating wavelength, we used a tunable filter with a 5-nm bandwidth. The output from the multiplier circuit was obtained through the 3-dB fused fiber coupler and was isolated from the external seeding signal by a 0.6-nm optical fiber. The mode-locked pulses obtained directly from the multiplier circuit were compressed by a dispersion-compensating fiber with a total dispersion of -11.4 ps/nm that was placed at the output of the circuit. The total length of the multiplier ring cavity was 14.6 m, corresponding to a 13.9-MHz fundamental frequency.

When the frequency of the rf signal generator driving the DFB laser source was adjusted to a harmonic of the fundamental frequency of the ring cavity at 5.78 GHz, and with the erbium-doped fiber amplifier adjusted to provide 800 μW of power to the cavity, the ring laser broke into stable mode-locked operation at this frequency, producing 9-ps pulse trains. When the frequency of the signal generator was changed by $13.9/n$ MHz, with n varying from 2 to 6, the laser produced pulse trains at multiples of the 5.78-GHz repetition frequency. Figure 2 shows, the output pulse trains from the ring laser. Numerical fitting of the autocorrelation traces in Fig. 2(b) indicates that the output pulses have squared hyperbolic secant profiles. Figure 3 shows the optical spectrum of the signal from the multiplier circuit. The output power from the multiplier circuit was $\sim$60 μW. As the repetition frequency from the multiplier circuit increases away from the rate of the externally introduced pulse there is a gradual increase in the pulse width and a merging of adjacent pulses, as well as a weak pattern effect on the pulse-train output. Figure 4 shows the variation of the pulse width and the background-to-peak relation between pulses as a function of the repetition frequency, assuming squared hyperbolic secant profiles. We examined the rf bandwidth over which the multiplier circuit operated as the frequency of the external pulse train was varied. This bandwidth was found to be $\sim$300 KHz at 5.78 GHz, the frequency of the external pulse train, and decreased to 140 KHz at 34.68 GHz. This large locking bandwidth primarily is due to the short cavity of the multiplier circuit.

The process by which the ring oscillator mode locks in the presence of the external pulsed signal when its frequency is a harmonic of the ring oscillator relies on fast saturation of the SOA. The temporal gain profile from the SOA develops a sharp, periodic drop because

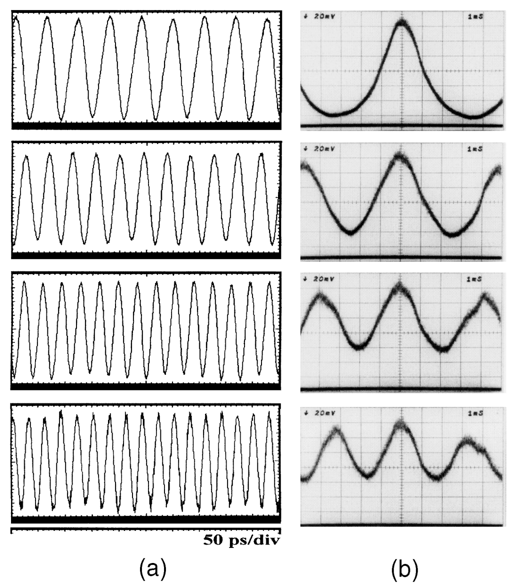

Fig. 2. (a) Output optical pulse trains monitored on a 40-GHz sampling oscilloscope and (b) corresponding second-harmonic autocorrelation traces. Wavelengths from top to bottom: 17.34, 23.12, 28.9, and 34.68 GHz. The time base in the autocorrelation traces corresponds to 8.3 ps.

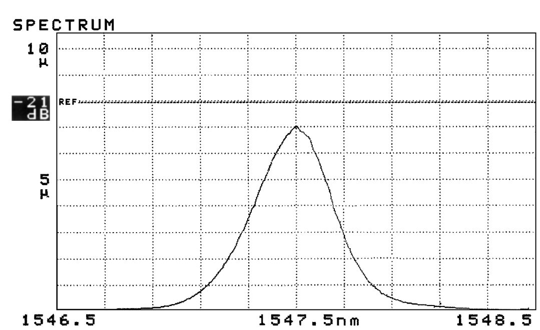

Fig. 3. Optical spectrum of the multiplier circuit output.

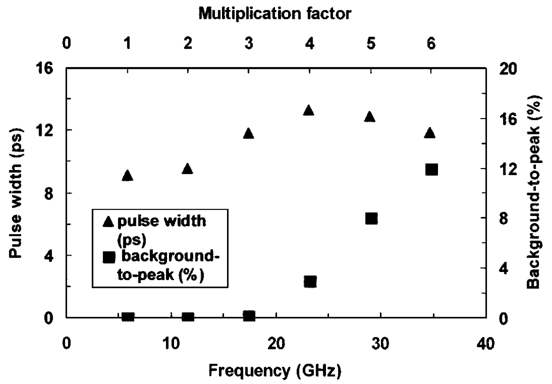

Fig. 4. Pulse width and background-to-peak as a function of the multiplication frequency factor.

of the saturation that the external pulse imposes upon it, at the frequency rate of the external pulse train. The mode-locked pulse develops just ahead of the external pulse, at the point where the recovery from the SOA is maximum. The pulse width of the mode-locked pulse train is defined by the length of the temporal window during which the total transmission coefficient in the cavity is positive. As such it relies on the width of the externally introduced optical pulse and the recovery time of the SOA, which in the present experiment was ~400 ps. The use of shorter external pulses and a SOA with a shorter recovery time can be expected to lead to shorter pulses from the laser oscillator. By comparison, the pulse width that is obtained from a mode-locked oscillator based on loss modulation depends on the curvature of the loss introduced by the modulator and therefore necessitates the use of a high-frequency rf drive signal for generation of short pulses from such a source, as the Kuizenga–Siegman theory of active mode locking predicts. When we adjust the repetition rate of the external pulse train to differ by $\delta f_{\mathrm{ring}}/n$ from a harmonic of the fundamental of the ring cavity, the externally introduced pulse train becomes temporally displaced by T_{ext}/n with each recirculation through the ring cavity with respect to its previous position, where T_{ext} is the repetition period of the external signal. The external pulse generates a sharp gain drop in the SOA, with a period T_{ext}/n, and causes the repetition frequency of the output of the circuit to be multiplied to nf_{ext}. As it takes n recirculations through the ring cavity for the externally introduced pulses to recover their position, a small modulation in the output pulse train that was observed from the multiplier develops, as shown in Fig. 2(a). It must be noted that, compared with that of other multiplication techniques,[7] the modulation of the multiplied output signal here is very low and never exceeds 6%. This low modulation is a result of a mode-locking process that uses the gain modulation of the SOA, which never presents loss, and is due to the fact that the external pulse is allowed to circulate in the multiplier cavity, nearly equalizing the gain of the SOA from pulse to pulse. By comparison, the technique for repetition-rate multiplication by loss modulation with a lithium niobate modulator results in a relatively strong pattern in the output pulse train because of the periodic loss that the modulator introduces into the cavity.

We also examined repetition-frequency multiplication from even lower external signal frequencies and found that it was possible to obtain up to 23.75-GHz output pulse trains from 1.25-GHz external input. This output corresponds to a multiplication factor of 19.

In summary, we have presented a technique for repetition-frequency multiplication of a mode-locked, optical pulse train. The technique is based on fast saturation of a SOA in a fiber ring cavity, induced by an externally introduced optical pulse train. With this technique it has been possible to demonstrate a factor-of-6 frequency multiplication up to 34.68-GHz frequency at the output of the multiplier circuit. The circuit is expected to have applications in clock multiplication and temporal synchronization circuits for ultrahigh-speed optical logic circuits.

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