Self-starting ultralow-jitter pulse source based on coupled optoelectronic oscillators with an intracavity fiber parametric amplifier

David Dahan, Evgeny Shumakher, and Gadi Eisenstein

Department of Electrical Engineering, Technion—Israel Institute of Technology, Haifa 32000, Israel

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A self-starting optical pulse source based on mutually coupled optoelectronic oscillators is described. The system employs a phototransistor-based microwave oscillator that is coupled to a fiber cavity optoelectronic oscillator with an intracavity fiber parametric amplifier. It self-starts and exhibits 3 ps pulses at a rate of 10 GHz with extremely low jitter of 30, 29, and 40 fs (for integration bandwidths of 100 Hz–15 kHz, 500 Hz–1 MHz, and 100 Hz–1 MHz, respectively). © 2005 Optical Society of America

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The demand for increasing information capacity has initiated intense research efforts toward the development of new optical sources with the capability of providing narrow optical pulses at high repetition rates. The timing stability of such pulse sources is a key issue for optically time-domain multiplexed communication and optical sampling systems. Several types of source that produce high-quality pulse trains have been described in the literature. The most common scheme comprises a fiber or semiconductor mode-locked laser driven by an independent high-quality oscillator.¹ Such actively mode-locked lasers exhibit the lowest timing jitter reported to date. However, the low-noise properties are determined mainly by a unique, ultralow phase noise, microwave drive oscillator that renders this solution impractical for most applications. Attractive alternatives for lowjitter pulse sources are various forms of self-starting optoelectronic oscillator whose configuration encompasses optical pulse generation. Examples include a double fiber loop oscillator,² mutually injectionlocked, mode-locked semiconductor laser-selfoscillating phototransistor combinations,³ and an optoelectronic oscillator with an electroabsorption modulator⁴ whose inherent nonlinearity forces the pulse operation. These various self-starting schemes yield very low jitter levels, of the order of tens of femtoseconds at repetition rates near 10 GHz, which are only slightly worse than those of the best actively driven pulse sources.

In this Letter we propose and demonstrate a new type of a self-starting low-jitter pulse source. It is based on mutual injection locking of an optoelectronic oscillator that includes an intracavity optical parametric amplifier (OPA) and a phototransistor-based microwave oscillator. The distributed nonlinear gain of the OPA is responsible for pulse generation within the optoelectronic loop, and the coupled oscillator configuration ensures superb jitter properties.⁵ The new self-starting system generates 3 ps pulses at 10 GHz with timing jitter of 30, 29, and 40 fs (using integration bandwidths of 100 Hz–15 kHz, 500 Hz–1 MHz, and 100 Hz–1 MHz, respectively).

The experimental setup (Fig. 1) consists of a strong pump signal (TL1 at $\lambda_p = 1543.5$ nm), which feeds an integrated phase-amplitude LiNbO₃ modulator.

A 1-Gbit/s, $2^{11}-1$ pseudorandom binary sequence (PRBS) signal is used for modulation (PM) to reduce the effects of stimulated Brillouin scattering. The am port of the modulator is driven by the amplified output of a 10 GHz phototransistor-based oscillator. The oscillator frequency is determined by a microwave bandpass filter (BPF) with a quality factor of approximately 1000. The phase noise at 10 kHz offset of the free-running 10 GHz oscillator is -100 dBc/Hz. The optical pump is amplified and filtered by a narrowband tunable optical filter (OBPF1) before being combined, through an array waveguide grating (AWG), with a weak signal (TL2 at $\lambda_s = 1559$ nm) and coupled into a 500 m long highly nonlinear fiber (HNLF). The large nonlinearity of the fiber and the high pump power (25.3 dBm average) ensure efficient parametric amplification. Because the parametric gain varies exponentially with pump power, the modulated pump turns into a sharp pulse at the signal and idler wavelengths. Two cascaded tunable bandpass filters (OBPF2 and OBPF3) with 3 dB bandwidths of 3.45 and 2.8 nm, respectively, are placed at the OPA out-



Fig. 1. Experimental setup: EDFA, erbium-doped fiber amplifier.

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Fig. 2. Pump spectra at the modulator output and corresponding time-domain pulse traces measured with a 30 GHz photodetector. Time scale, 50 ps/division Filters placed at (a) λ_p and (b) λ_1 .

put to enable either the signal or the idler to be selected while the adjacent channel cross talk is reduced. Half of the signal is used for characterization, and the rest propagates in a 10 km long dispersionshifted fiber (DSF) before being amplified, filtered (by filter OBPF4), and fed back into the optical port of the phototransistor, closing the optoelectronic loop. The optoelectronic and microwave oscillators are mutually injection locked now; the locked system exhibits ultralow noises, and consequently the jitter of the nonlinearly generated pulses is low. The dispersionshifted fiber's length was optimized to increase the Qfactor of the optical cavity while at the same time minimizing spurious modes. Previous experiments^{6,7} in which short pulses were

generated by an open-loop OPA used a sinusoidally modulated pump; however, shorter pulses can be obtained when the input is an optical pulse. To that end, we bias the Mach–Zehnder (MZ) modulator near its maximum transmission point and drive it with a 10 GHz sinusoidal signal, which yields distorted pulses at 20 GHz with a pulse width of \sim 14 ps, as depicted in the inset of Fig. 2(a). Observation of the corresponding spectrum reveals strong attenuation of the first two 10 GHz sidebands, which means that near the carrier (at λ_p) the spectrum resembles 20 GHz modulation. The rest of the symmetric spectrum comprises modes that are separated by 10 GHz. These modes are responsible for the time-domain distortion. The 0.4 nm bandwidth filter tuned originally to λ_p (OBPF1) is placed next to λ_1 to modify the spectrum as shown in Fig. 2(b). The 10 GHz spaced modes near λ_1 dominate the now asymmetric spectrum, resulting in a 10 GHz pulse train. However, the measurable residual power of the original carrier, at λ_p , and the attenuated 10 GHz modes near it add a 20 GHz component that manifests itself as subpulses whose power is 4.5 times smaller than that of the 10 GHz pulses; see Fig. 2(b).

The dependence of the parametric gain level and its bandwidth on power serve to discriminate among the various portions of the pulse train, yielding a large enhancement (and shortening) of the 10 GHz pulses and elimination of any trace of the weaker 20 GHz subpulses. The measured pulses in Fig. 2(a) are reproduced schematically as a dashed curve in Fig. 3(b). Figure 3(a) shows calculated parametric gain spectra for pump-power levels that correspond to the peak powers of the pulse and the subpulse. For the pump and signal wavelengths that we used, $\lambda_p = 1543.5$ and $\lambda_s = 1559$ nm, the corresponding gains differ by more than 26 dB, yielding 7.6 ps wide pulses at 10 GHz. These pulses can be linearly compressed to 3 ps as shown in Fig. 3(b).

Figure 4 shows detailed optical spectra of the 10 GHz pulse train at the signal [Fig. 4(a)] and the idler [Fig. 4(b)] wavelengths measured with a resolution of 0.01 nm. The input signal power was -4 dBm. Also shown are the respective time-domain traces measured with a 30 GHz bandwidth photodetector. The spectra are broad, with FWHM widths of $\Delta \lambda_s = 1.4$ nm and $\Delta \lambda_i = 1.5$ nm.

An autocorrelation measurement of the signal pulse revealed a rather broad pulse of \sim 7.6 ps (Fig. 5), which indicates significant chirp caused by pump-induced cross-phase modulation. A large portion of



Fig. 3. (a) OPA gain spectrum for two pump powers. (b) Normalized temporal trace of the 10 GHz signal pulses for a 10 GHz pulsed pump with 20 GHz subpulses.



Fig. 4. Optical spectra of (a) the signal and (b) the idler with the corresponding time-domain traces measured with a 30 GHz photodetector. Time scale, 20 ps/division.



Fig. 5. Autocorrelation traces of the original and compressed pulses.



Fig. 6. Mean timing jitter for the signal wave. Inset, single-sideband phase noise of the first four harmonics.

this chirp turns out to be linear; hence the pulses could easily be compressed by use of 310 m of standard SMF-28 fiber.⁷ The 3.4 ps wide compressed pulses [also shown in Fig. 2] had a time-bandwidth product of 0.58. Similar characteristics were found for pulses at the idler wavelength where the pulse width was reduced from 7.8 to 3 ps and the timebandwidth product was 0.57. The 310 m standard fiber used for the pulse compression can be placed either at the output port or inside the fiber loop, between the highly nonlinear fiber and the dispersion-shifted fiber. The results in the two configurations were essentially the same. The bias technique described here yields significantly shorter pulses than does quadrature bias. Using the same configuration and average pump power but quadrature bias, we can compress the signal and idler pulses to only 9 ps.

The mean cycle-to-cycle timing jitter of both signal and idler pulse trains was estimated from the von der Linde procedure.⁸ Four harmonics were used, with three integration ranges. We obtained jitter levels for the signal pulse train of 30, 29, and 40 fs by using integration bandwidths of 100 Hz–15 kHz, 500 Hz–1 MHz, and 100 Hz–1 MHz, respectively. Details are given in Fig. 6. The jitter for the idler pulse train was slightly higher, i.e., 50, 34, and 59 fs for the same integration bandwidths.

To conclude, we have demonstrated a low-noise self-starting optical pulse source based on mutually coupled microwave and optoelectronic oscillators with an intracavity OPA. The OPA is fed by optical pulses that are generated by nonlinear modulation of a Mach–Zehnder modulator. The mutually locked system generates 3 ps pulses at 10 GHz with a timing jitter of 29–40 fs. As the four-wave mixing response time is of the order of a few tens of femtoseconds, this technique is flexible in terms of repetition rates. The wavelength tunability is determined by the OPA bandwidth, which can be larger than 200 nm,⁹ by proper design of the characteristics of the highly nonlinear fiber and the pump power.

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