An Ultra Low Jitter Pulse Source Based on Coupled Optoelectronics Oscillators with an Intracavity Fiber Parametric Amplifier

E. Shumakher, D. Dahan, G. Eisenstein
Electrical Engineering Department, Technion, Haifa 32000, Israel
eshumakh@tx.technion.ac.il

Abstract: We present a low noise self starting optical pulse source which is based on coupled optoelectronic oscillators with an intracavity fiber parametric amplifier. *3 ps* pulses at *10 GHz* with a jitter of $29-40\ fs$ are demonstrated.

OCIS codes: (060.2320) Fiber optic, amplifier and oscillators; (060.4370) Nonlinear optics, fibers

Low noise optical pulse trains at high repetition rates constitute the corner stone of numerous applications in the fields of communications and digital signal processing. Several systems producing 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 mainly determined by a unique, ultra low phase noise, microwave drive oscillator which renders this solution impractical for most applications.

An attractive alternative for low jitter pulse sources are various forms of self starting optoelectronic oscillators whose configuration encompasses optical pulse generation [2]-[4]. These include a double fiber loop oscillator [2], mutually injection locked mode locked semiconductor laser - self oscillating photo transistor combinations [3], and an optoelectronic oscillator with an electro absorption modulator [4] whose inherent non linearity forces the pulse operation. These various self starting schemes yield very low jitter levels (of the order of tens of femtoseconds at repetition rates around 10 *GHz*). The resulting jitter levels are only slightly worse than the best actively driven pulse sources but have the significant advantage of not requiring any external microwave drive source.

In this paper 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 which includes an intra cavity optical parametric amplifier (OPA) and a phototransistor based oscillator. The distributed nonlinear gain of the OPA is responsible for the pulse generation within the optoelectronic loop. The use of four-way-mixing (FWM) to transform a sinusoidally modulated signal into a pulse train was first demonstrated in [5]. The incorporation of the OPA as an intra cavity element yields short pulses with the superb jitter properties of coupled optoelectronic oscillators [6]. The new system generates 3 *ps* pulses at 10 *GHz* with a timing jitter of 30 - 40 *fs*.

The experimental setup described in Fig. 1 consists of strong pump signal (TL1 at $\lambda_p = 1543.5\ nm$) which feeds an integrated phase and amplitude $LiNbO_3$ modulator. The AM port is driven by the amplified output of a 10 GHz phototransistor based oscillator. The oscillator frequency is determined by a microwave filter having a quality factor of approximately 1000. The phase noise at 10 *kHz* offset of the free running 10 *GHz* oscillator is $-100\ dBc/Hz$.

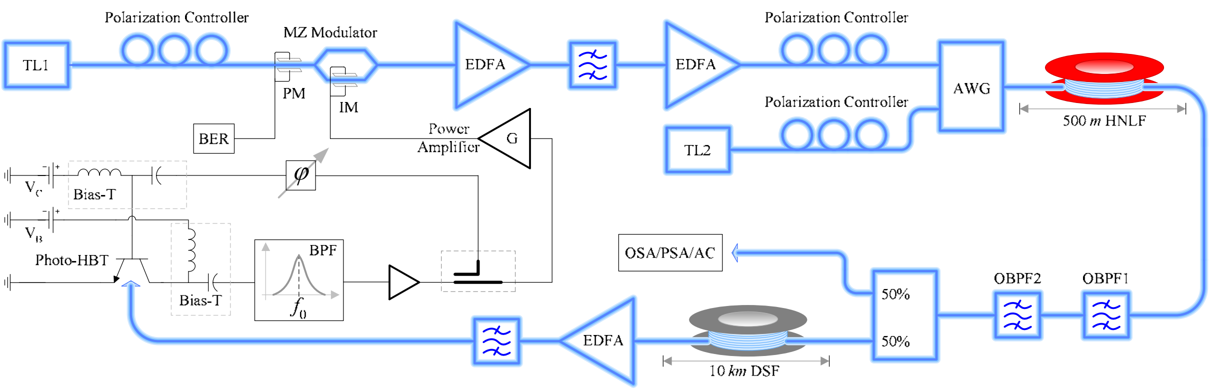

Fig. 1. Experimental setup

A $1\,Gbit/s$, $2^{11}-1$ PRBS signal is used to phase modulate the pump in order to broaden its spectrum, thereby eliminating the effect of stimulated Brillouin scattering (SBS).

The optical pump is amplified and filtered before being combined with a weak signal (TL2 at $\lambda_s = 1559\,nm$). Both are coupled to a $500\,m$ long highly nonlinear fiber (HNLF). The large nonlinearity of the fiber and the high pump power ($P_{p,in} = 25.3\,dBm$) result in efficient FWM. The phase matching conditions for this interaction are satisfied with the help of an idler wave whose frequency is $\omega_i = 2\omega_p - \omega_s$. The total gain experienced by the signal (TL2) after propagation in a fiber of length L can be approximated by [5] $G = 10\log_{10}\left(0.25\exp\left(2\gamma P_p L\right)\right)$ with G stated in a decibel scale, γ being the nonlinear coefficient [$W^{-1}km^{-1}$] and P_p the pump power [W]. The expression for the parametric gain is an approximation since it was derived for CW conditions. Nevertheless, it gives a rather accurate description as long as the pump spectrum is narrower then the bandwidth of the FWM process.

Since the pump power is modulated, and since the parametric gain varies exponentially with pump power, the modulated pump turns into a sharp pulse. Viewed in the frequency domain, spectral lines at a $10\,GHz$ detuning relative to the carrier generate additional tones (by the nonlinear gain) around the signal (TL2). As the nonlinear interaction length increases, the distributed tone generation causes a wide spectrum around λ_s which manifests itself as pulses in the time domain.

The signal is filtered at the HNLF output by two filters, OBPF1 and OBPF2 which ensure maximum rejection of the pump and split by a 50:50 coupler. Half the signal is used for characterization and the rest propagates in a 10 *km* long dispersion shifted fiber (DSF) before being amplified, filtered and fed back into the optical port of the phototransistor thereby closing the optoelectronic loop. The optoelectronic and microwave oscillators are mutually injection locked now with the locked system exhibiting ultra low noise [6] and consequently the jitter of the nonlinearly generated pulses is very low

Fig. 2.a depicts the simulated and measured optical spectra in an open loop configuration. The pump signal at $1543.5\,nm$ as well as the first order signal and idler spectra are clearly observable at $1559\,nm$ and $1528\,nm$, respectively. Higher order FWM products are also apparent in both the simulated and measured spectra. We note that the measurements are in good agreement with the simulation prediction. Detailed spectra of the signal and idler (respectively at λ_s and λ_i) are shown in Fig. 2.b. the spectra are broad with FWHM widths of $\Delta\lambda_s \cong 1.4\,nm$ and $\Delta\lambda_i \cong 1.5\,nm$ (Fig. 2.c).

Auto-correlation measurement of the signal pulse revealed a rather broad pulse of about 7.6 ps (Fig. 2.d). This indicates significant chirp caused by cross-phase-modulation (XPM) (due to the pump). A large portion of this chirp turns out to be linear and hence the pulses could be easily compressed using 310 m of standard SMF-28 fiber. The compressed pulses (also shown in Fig. 2d) were close to transform limited with a duration of 3.4 *ps*. Similar characteristics were found for the idler pulse where the pulse width reduced from 8 *ps* to 3 *ps*. The 310 *m* standard fiber used for the pulse compression can be placed at the output port or inside the fiber loop between the HLNF and the DSF. The results in both configurations were essentially the same. It should be noted that pump over-modulation (achieved by driving the modulator by a saturated amplifier and properly biasing it) widens the spectrum of the pulses by providing the non-linear gain with an initially broader spectrum.

The mean cycle-to-cycle timing jitter of both signal and idler pulse trains was extracted using the van der Linde procedure. Four harmonics were used with three integration ranges. We obtained jitter levels for the signal pulse train ranging from 29 *fs* to 40 *fs* . The details are listed in Fig. 2e. The jitter for the idler pulse train was slightly higher 35 *fs* to 51 *fs*.

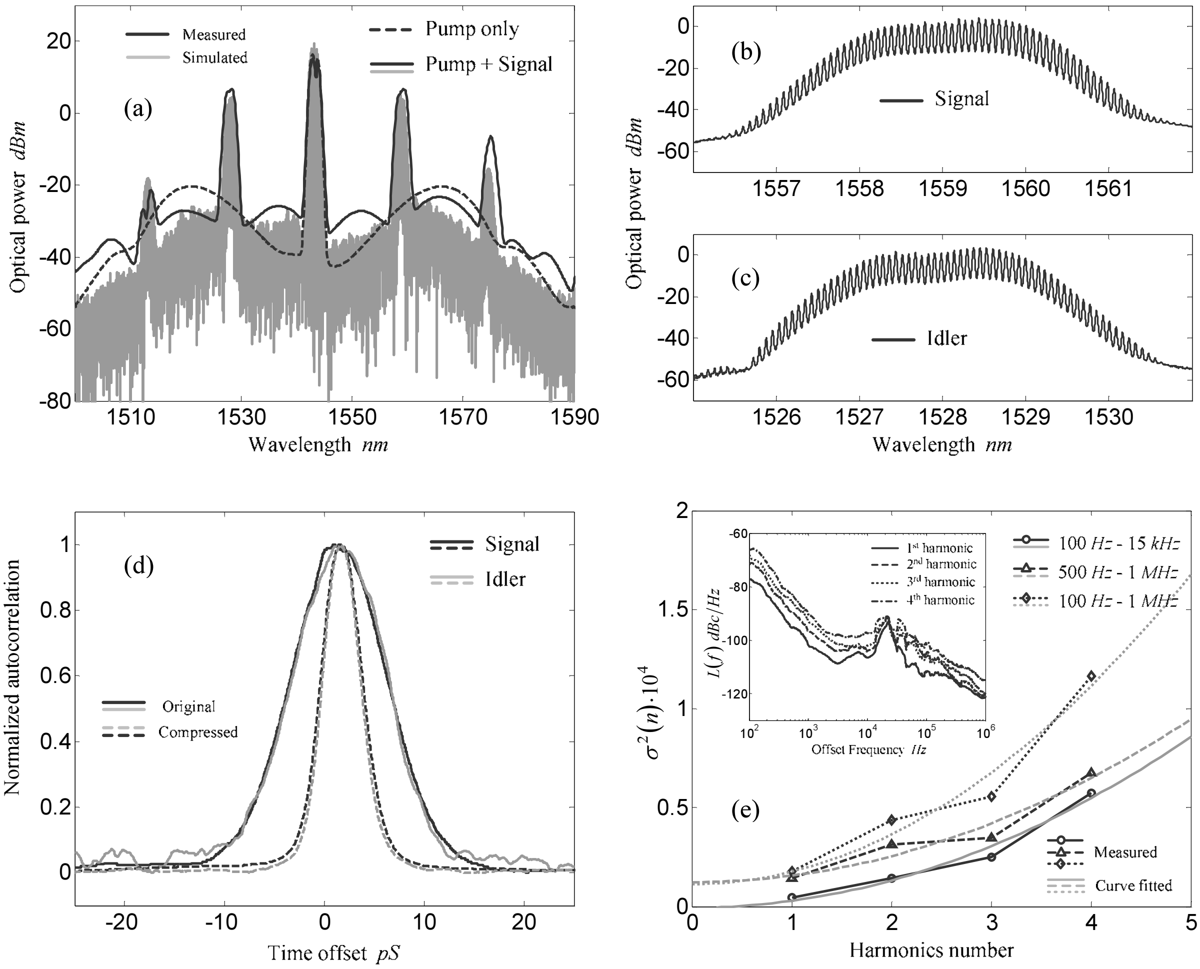

Fig. 2 Measurement results. (a) Broad optical spectrum , (b-c) Close-in optical spectrum of the signal and the idler, (c) Original and compressed pulses autocorrelation (d) Mean timing jitter estimation (insert shows the SSB phase noise of 4 first harmonics) for the signal wave

To conclude, we have demonstrated a low noise self starting optical pulse source based on mutually coupled optoelectronic oscillators with an intra-cavity OPA. 3 *ps* pulses at 10 *GHz* were demonstrated with timing jitter in the range of 29 *fs* to 40 *fs*.

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