A Self-Starting Hybrid Optoelectronic Oscillator Generating Ultra Low Jitter 10-GHz Optical Pulses and Low Phase Noise Electrical Signals

J. Lasri, A. Bilenca, D. Dahan, V. Sidorov, G. Eisenstein, D. Ritter, and K. Yvind

***Abstract*—In this letter, we describe a self-starting optical pulse source generating ultra low noise 15-ps-wide pulses at 10 GHz. It is based on a hybrid optoelectronic oscillator comprising a fiber extended cavity mode-locked diode laser which injection locks a self-oscillating heterojunction bipolar phototransistor. Average jitter levels of 40–43 fs and an amplitude noise of 0.1–0.15% over a frequency range of 500 Hz–15 kHz or 500 Hz–1 MHz were obtained, respectively. The noise is slightly larger, a 57- fs jitter and 0.2% amplitude noise, for a frequency range of 100 Hz–1 MHz. A 10-GHz electrical signal with a low phase noise (−108 dBc/Hz at 10-kHz offset from the carrier) is also generated.**

***Index Terms*—Heterojunction bipolar transistors, mode-locked lasers, optical pulse generation, optoelectronic oscillators, timing jitter.**

THE EVER increasing repetition rates of optically time domain multiplexed communication links [1] and sampling systems [2] require low noise high repetition rate short pulse sources. Amplitude noise and timing jitter limit the performance of such systems what led to an ongoing reasearch effort to study and reduce the noise of optical pulse generators [3].

High repetition rate pulse sources are usually implemented by active mode locking of fibers or diode lasers. Fiber lasers have long cavities and operate by harmonic mode locking with thousands of pulses circulating in the cavity [4]. Diode lasers use hybrid [5] or monolithic [6] extended cavities driven at the fundamental or a low harmonic of their resonance frequency. High repetition rates have also been demonstrated by harmonic optical injection locking [7], a process which also reduces noise.

Actively mode-locked lasers require a microwave driving source whose phase noise determines the resultant jitter [8]. Phase-locked loops and active cavity length adjustments are often employed to improve the performance [9]. Using an exceptionally low phase noise synthesizer, Clark *et al.* demonstrated a 10-GHz fiber laser with a jitter lower than 10 fs [10]. Similar results were obtained W. Ng *et al.* [11].

Passively mode-locked lasers are self-starting so the external microwave source is avoided, but they tend to have a large jitter. A different approach to self-starting pulse generators extends the concept of an optoelectronic oscillator to include the generation of low noise optical pulse trains together with a low phase noise microwave signal as proposed and demonstrated by Yao and Maleki [12], [13].

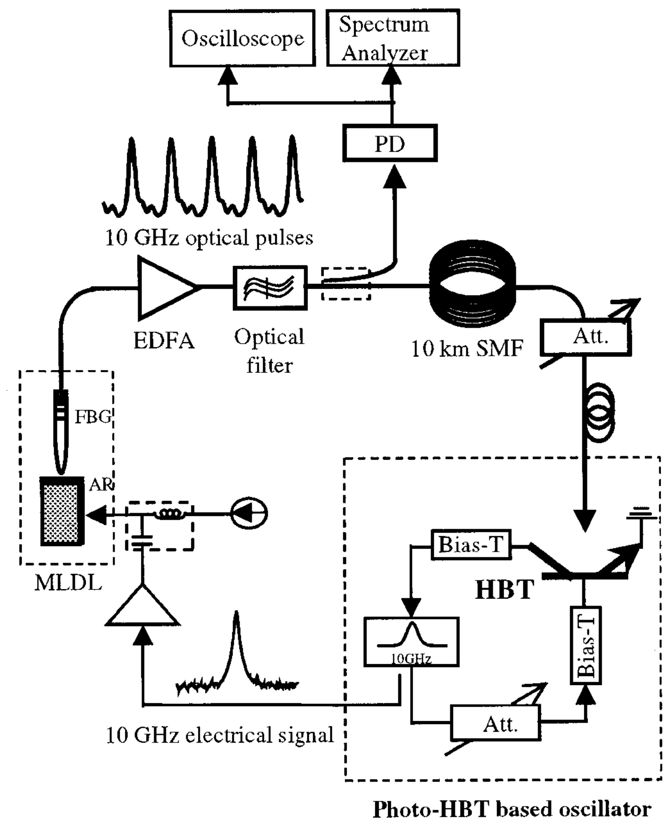

Fig. 1. Schematic of the hybrid pulse generator.

This letter describes a new type of self-starting hybrid optoelectronic oscillator based on an actively mode-locked diode laser (MLDL) and optical injection locking of a self-oscillating InGaAs–InP heterojunction bipolar phototransistor (photo-HBT) [14]. The hybrid source emits 15-ps pulses at 10 GHz which depending on the measurement frequency range has a timing jitter of 40–57 fs and an amplitude noise of 0.1%–0.2% . A 10-GHz electrical signal with a phase noise of −108 dBc/Hz at a 10-kHz offset from the carrier is also generated.

The hybrid source is described schematically in Fig. 1. The 10-GHz oscillator [14] is based on a fast InGaAs–InP photo-HBT ($f_T = 150$ GHz, $f_{\max} = 190$ GHz) operating in a common emitter configuration with the collector fed back

Manuscript received December 20, 2001; revised February 26, 2002.

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Publisher Item Identifier S 1041-1135(02)05294-1.

to the base via a narrow-band 10-GHz filter $(Q = 1000)$ and an attenuator. The oscillator feeds a MLDL which employs a fiber cavity designed for a 10-GHz resonance and terminated by a chirped grating reflector. The optical pulses are amplified and filtered before traversing a long (10 km) single-mode fiber whose output is coupled into the optical port of the photo-HBT for the purpose of injection locking. An attenuator is added in order to control the injection level to the transistor.

The optical feedback to the transistor results in mutual injection locking of three oscillators, the self-oscilalting photo-HBT, the MLDL, and the long cavity optoelectronic oscillator. A significant reduction of the phase noise in the generated electrical and optical signals takes place once injection locking occurs. The use of a long feedback fiber is a well-known technique to significantly reduce the phase noise, as it locks the oscillator to its delayed replica [12], [13]. The reduction in phase noise is proportional to the fiber length up to the point where the noise is dominated by fiber length fluctuations due to enviornmental effects.

The optical pulses were characterized using a 50-GHz p-i-n detector and a sampling oscilloscope. The pulse shape and duration (15 ps) were found to be the same for the open loop and locked cases. Closed loop corresponds to the injection-locked case, while open loop means that the optical feedback is absent. The corresponding optical spectra differed significantly, however, showing a very symmetric spectrum in the locked case and an almost transform-limited time-bandwidth product of $\Delta\tau\Delta\nu \sim 0.47$ for an assumed sech^2 pulse shape.

The jitter of the pulse train was determined by analyzing the spectral content of the detected signal harmonics [8], [15], [16] according to the procedure introduced by von der Linde [15].

Two sets of measurements are described below. In the first, we measured the spectra of five harmonics over a rather limited frequency range 500 Hz to 15 kHz. The low frequency regime near the carrier was dominated in this case by amplitude, and phase noise of the spectrum analyzer as well as by laser amplitude noise. The upper integration limit was set to $\omega_{high}/2\pi = 15$ kHz since contributions from higher frequencies could not be distinguished from the noise floor of the spectrum analyzer. The results are described in Fig. 2 where open Fig. 2(a) and closed Fig. 2(b) loop normalized sideband spectra measured for the first five harmonics at a resolution bandwidth (RBW) of 300 Hz are shown. We note, in both cases, the increase with harmonic number of the spectral skirt level and the improvement in phase noise for all harmonics in the closed loop case.

The second measurement was obtained in a separate experiment over a wider frequency range, 100 Hz to 1 MHz, but was limited to the first four harmonics. A wide band microwave preamplifier was used in this experiment which ensured that the phase noise was well above the noise floor of the spectrum analyzer over the entire frequency range and for all four harmonics. The results shown in Fig. 3(a) show the measured absolute phase noise with the predictable noise increase with harmonic number, as well as the monotonic reduction of noise with the frequency offset from the carrier over the entire spectral range for all four harmonics.

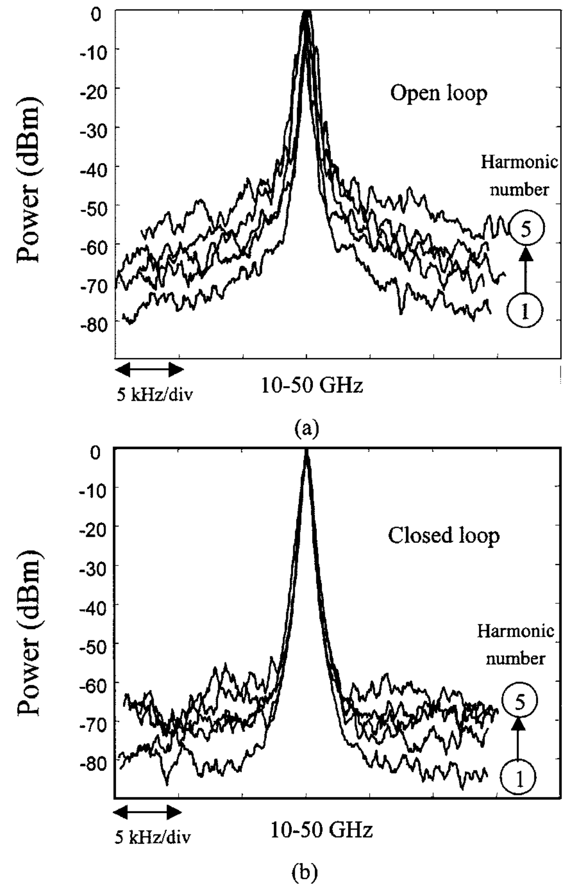

Fig. 2. Normalized single sideband spectra of the first five detected harmonics measured at a 300-Hz resolution bandwidth, and a power of -6 dBm coupled into the photo-HBT. (a) Open-loop. (b) Closed-loop.

Fig. 3(b) shows the spectrum of the 10-GHz electrical signal measured at a resolution bandwidth of 300 Hz. The optical power coupled to the photo-HBT was -6 dBm, and the phase noise at a 10-kHz offset from the carrier improved from -98 dBC/Hz in the open-loop case to -108 dBc/Hz when the system was locked.

The functional form of the harmonic number dependence of the rms noise σ_n^2 is according to [15] $\sigma_n^2 = a_0 + a_2 \cdot n^2$, where n represents the harmonic number and a_0, a_2 are constants that determine the amplitude noise and the jitter contributions, respectively. Since there is no jitter contribution at $n = 0$, the amplitude noise can be directly obtained from $\sigma_{n=0}^2$. The jitter contribution is then obtained from $\sigma_n^2 = a_0 + a_2 \cdot n^2$ by a parameter fit. Alternatively, it is common [8] to evaluate σ_n for large n values, a regime where the amplitude noise contribution is negligible and the jitter is obtained directly from the slope of σ_n versus n.

Fig. 4. shows the harmonic number dependence of σ_n^2 for the locked cases together with a fit to $\sigma_n^2 = a_0 + a_2 \cdot n^2$. For the 500 Hz to 15 kHz measurement, we obtain an RMS jitter of 40 fs accompanied by an amplitude noise of 0.1%. This is to compare with the open loop case (not shown in the figure) where the amplitude noise and jitter were 3.5% and 355 fs, respectively. The closed loop measurements were repeated for the first four harmonics with a higher resolution bandwidth (30 Hz) and the extracted jitter and amplitude noise values were identical.

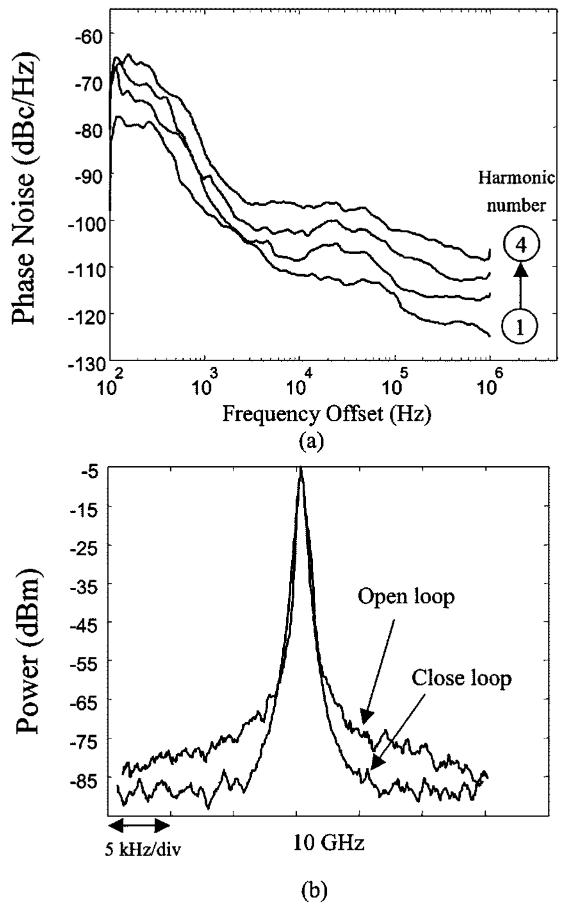

Fig. 3. (a) Phase noise spectra under closed loop conditions for the first four harmonics. (b) Spectral shape of the 10-GHz electrical signal in the open- and closed-loop configurations, measured with a 300-Hz resolution bandwidth. The optical power coupled into the photo-HBT was −6 dBm.

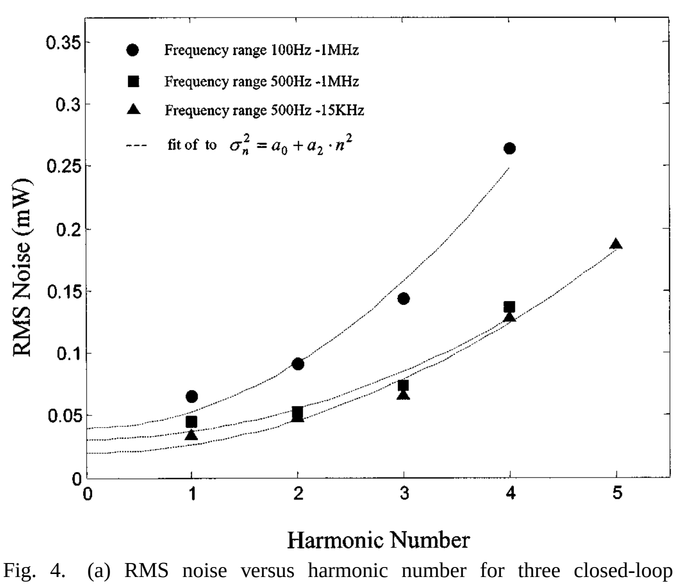

Fig. 4. (a) RMS noise versus harmonic number for three closed-loop measurements over different frequency ranges together with a curve fit to $\sigma_n^2 = a_0 + a_2 \cdot n^2$.

The jitter in the closed loop case was also measured as a function of the optical power coupled to the photo-HBT and the length of external fiber. The 40-fs jitter (with a power of −6 dBm) could not be improved with higher powers or longer fibers as it reached the limit imposed by the random fiber length fluctuations. The jitter increased to 46 fs at −9 dBm, 89 fs at −12 dBm, and 106 fs at −15 dBm.

The measured harmonic number dependence of σ_n^2 for the wider frequency range is also shown in Fig. 4. This fits to $\sigma_n^2 = a_0 + a_2 \cdot n^2$ yield a jitter of 43 fs for the range of 500 Hz to 1 MHz together with an amplitude noise of 0.15%. The corresponding values for the range of 100 Hz to 1 MHz are 57 fs and 0.2%.

To conclude, we have demonstrated a self-starting ultralow noise optical pulse source based on a MLDL which optically injection locks a self-oscillating photo-HBT. The source generates 15-ps-wide pulses at 10-GHz repetition rate with a timing jitter as low as 40–43 fs and an amplitude noise of 0.1%–0.15% over a frequency range of 500 Hz–15 kHz or 500 Hz–1 MHz, respectively. For a wider range 100 Hz to 1 MHz, the amplitude noise and jitter are slightly larger, 0.2% and 0.57 fs, respectively. A low phase noise 10-GHz electrical signal is also generated and can serve as a high quality synchronized reference.

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