Femtosecond synchronization of radio frequency signals with optical pulse trains

J. Kim and F. X. Kärtner

Department of Electrical Engineering and Computer Science, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307

M. H. Perrott

Department of Electrical Engineering and Computer Science, Microsystems Technologies Laboratories, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307

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A synchronization scheme for extraction of low-jitter rf signals from optical pulse trains, which is robust against photodetector nonlinearities, is described. The scheme is based on a transfer of timing information into an intensity imbalance of the two output beams from a Sagnac loop. Sub-100-fs timing jitter between the extracted 2-GHz rf signal and the 100-MHz optical pulse train from a mode-locked Ti:sapphire laser is demonstrated. © 2004 Optical Society of America

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The use of femtosecond lasers for frequency comb generation has revolutionized frequency metrology.[1,2] As has been shown recently,[3] the extraction of a microwave signal from an optical pulse train emitted by a mode-locked laser by use of direct photodetection is limited in precision by excess noise. The origin of this excess noise has been identified as amplitude-to-phase conversion in the photodetection process, beam-pointing variations, and pulse distortions due to photodetector nonlinearities.[3] In frequency metrology this excess noise necessitates longer averaging times. For precise timing synchronization of a rf signal to an optical pulse train, the typical methods are limited by detector nonlinearities and are therefore confined in their achievable synchronization performance.

In this Letter a novel synchronization scheme that avoids these limitations is proposed. The scheme can be applied to extract microwave signals from optical clocks based on femtosecond laser frequency combs or to synchronize one or multiple mode-locked lasers to a rf signal, which is, for example, necessary for the seeding of free-electron lasers. The latter process also allows a precise synchronization of multiple lasers. As the first experimental demonstration, sub-100-fs timing jitter between the extracted rf signal and the optical pulse train is demonstrated.

The general idea for suppression of excess noise due to the photodetection process is shown in Fig. 1. While still in the optical domain the timing information is transferred into an intensity imbalance between two beams when the pulse train is sent through a pair of amplitude modulators. The modulators are driven by the output signal from a voltage-controlled oscillator (VCO) with a 180° phase difference. The intensity difference is detected with a balanced detector, and this signal controls the input to the VCO through a loop filter. So far, we have only shifted the problem of photodetector nonlinearities on the electronic side to the realization of amplitude modulators with drift-free bias points on the optical side. The 180° out-of-phase amplitude modulators can be realized by a simple Mach–Zehnder interferometer with a phase modulator in one arm. However, this scheme will suffer from phase drifts in the interferometer arms due to temperature fluctuations, air currents, and mirror vibrations.

To remove these problems, the interferometer can be implemented in a Sagnac-loop configuration. Figure 2 shows the synchronization scheme. A 100-MHz repetition-rate Ti:sapphire mode-locked laser is used as the pulse source. After passing a bandpass filter at 800 nm to limit the pulse width to approximately 100 fs, the input optical pulse train is sent into the Sagnac loop. A resonant phase modulator at 2 GHz is positioned in the Sagnac loop in such a way that the optical delay between counterpropagating pulses at the phase modulator is set to half of the rf signal period, i.e., 0.5 ns for the current 2-GHz VCO. This ensures that the two pulses experience opposite phase modulation. The output beams are detected by a balanced detector that generates a difference signal between the two photocurrents from two Si p-i-n photodiodes. The output current from the balanced

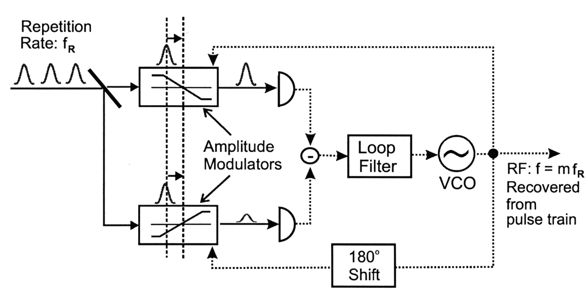

Fig. 1. Schematic setup for rf signal extraction from an optical pulse train. Each multiple of the repetition rate can be extracted.

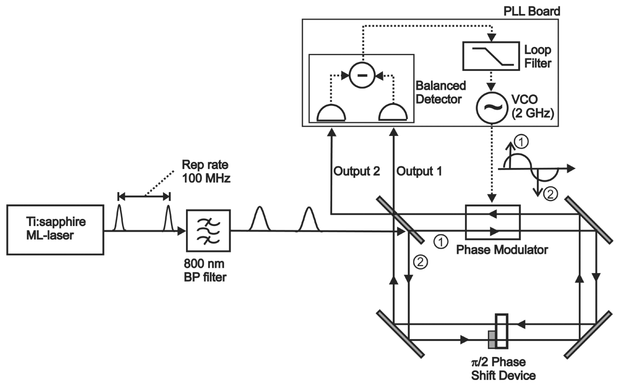

Fig. 2. Scheme for extraction of a 2-GHz signal from a 100-MHz repetition-rate Ti:sapphire laser. PLL, phase-locked loop; ML, mode-locked; BP, bandpass.

detector is transferred to a passive loop filter (type II, order 2 topology[4]) for proper filtering. The passive loop filter structure is advantageous over an active counterpart since it allows a simple circuit implementation and also ensures excellent noise performance. The loop filter output signal drives the VCO and changes the driving frequency of the phase modulator until it reaches a phase-locked state by balancing the two output powers from the interferometer. This closes the phase-locked loop operation. For stable and drift-free biasing of the interferometer an effective quarter-wave plate is inserted into one of the beams by use of a thin-film coating covering only half of the substrate. Stable and drift-free phase-locked operation is achieved with this scheme.

The phase noise of the rf output signal from the VCO is characterized in two ways: (i) by the frequency discriminator technique by use of a commercial phase noise measurement setup (PN9000, Aeroflex) and (ii) by mixing the output signal of the VCO in quadrature with the 2-GHz component of the directly detected pulse train to measure the relative phase noise between the optical pulse train and the extracted rf signal. Figure 3 shows the measurement setup. With method (i) the input is delayed and mixed with itself in quadrature to extract the phase noise of the input.[5] Method (ii) is a standard technique for measuring the residual phase noise between two locked rf signals,[6] where an oscilloscope is used to monitor that the two rf signals are in quadrature and a vector signal analyzer is used to measure the noise spectrum.

The measured single-sideband phase noise spectra from 1 Hz to 10 MHz are shown in Fig. 4. Curve 1 shows the phase noise spectrum of the free-running VCO measured with the Aeroflex phase noise measurement system. Curve 2 shows the phase noise measured by the same method when the system is locked. The locking is clearly visible in the spectrum covering the range from 100 kHz to 10 MHz. At lower frequencies the phase noise of the Ti:sapphire pulse train dominates. The phase noise level of the free-running Ti:sapphire laser[6] is upshifted by +26 dB due to the frequency ratio of 20 between the repetition rate and the VCO frequency. We performed behavioral simulations with a custom C++ simulator to verify the 26-dB factor.

To verify the assumption that the phase noise of the laser dominates at low frequencies in the frequency discriminator measurement results, we measured the relative phase noise between the pulse train and the rf signal by using the second phase noise characterization method. The result is shown in curve 3 of Fig. 4. Because of the noise floor of the vector signal analyzer (curve 4 in Fig. 4) and excess noise in the photodetector that generates the reference signal, the high frequency noise floor is increased in comparison with that of method (i). But this measurement clearly shows that the noise increase at a low

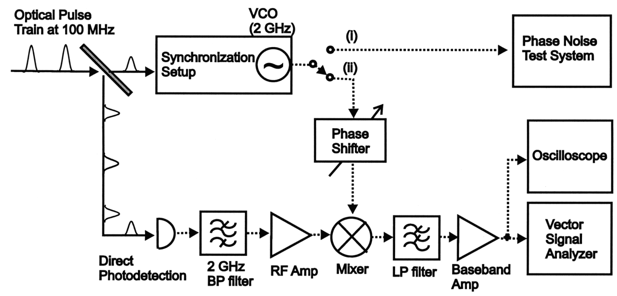

Fig. 3. VCO output is characterized (i) by a commercial phase noise test system and (ii) by mixing in quadrature with the 2-GHz component of the directly detected signal. The resulting signal is measured with a vector signal analyzer. The normalization constant for calibration to the rf phase is measured independently with an oscilloscope. LP, low-pass.

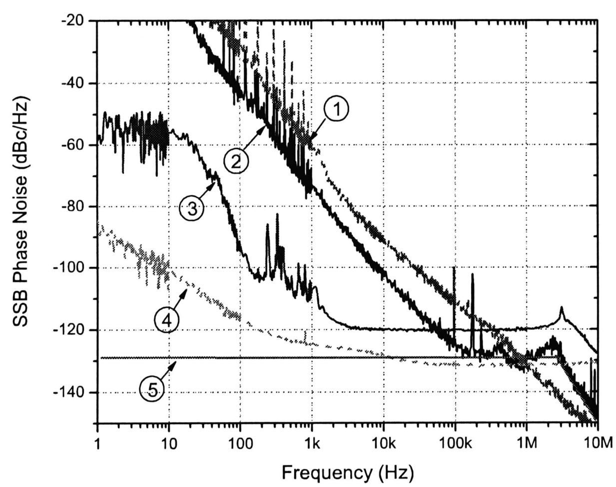

Fig. 4. Measured single-sideband (SSB) phase noise of (1) the free-running VCO and (2) the locked VCO using a commercial phase noise measurement system. Curve 3 shows the measured single-sideband phase noise between the extracted rf signal and the 20th harmonic of the directly detected pulse train using a mixer and vector signal analyzer. Curve 4 shows the noise floor of the vector signal analyzer. Curve 5 shows the estimated phase noise level of the extracted rf signal from the result of curve 2.

frequency in curve 2 is the phase noise of the free-running Ti:sapphire laser.

The origin of the enhanced phase fluctuations below 1 kHz may be either mechanical vibrations in the Sagnac loop or excess phase noise in the photodetection process that converts enhanced laser amplitude fluctuations into phase fluctuations. These hypotheses will be confirmed by building two rf extraction systems and beating the two outputs against each other in the near future. In any case, based on the current measurements, the relative timing jitter between the rf signal and the pulse train integrated from 100 Hz to 10 MHz can be estimated by the area underneath curve 5, which lines up with the high frequency noise of the Aeroflex measurement (curve 2 in Fig. 4) and results in an approximately 60-fs timing jitter.

For long-term stability a fiber implementation of the Sagnac loop is preferable. This will eliminate a large part of the drift problems from any thermal drifts of the output beam splitter that lead to an imbalance of the interference and a drift in phase.

The proposed scheme can also be applied in a different way to synchronize multiple mode-locked lasers. If a fixed rf signal is given and the feedback signal is used to control the repetition rate of the laser by means of a piezoelectric transducer, the laser is synchronized to the rf signal. Locking of multiple lasers to the same rf signal results in an effective synchronization of multiple lasers.

In summary, we have demonstrated a novel synchronization scheme for extracting low-jitter rf signals from optical pulse trains. Sub-100-fs timing jitter measured from 100 Hz to 10 MHz between the extracted rf signal and a 100-MHz optical pulse train has been demonstrated. The demonstrated timing jitter is not as low as that found when using pure microwave techniques based on high-speed photodetection and a much higher harmonic of the Ti:sapphire pulse train.[7,8] However, with improved system design and implementation, it is expected that this method will be able to reduce the relative jitter between a rf signal and an optical pulse train measured over the full Nyquist bandwidth to the subfemtosecond range, which has so far been achieved only by purely optical means.[9]

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