Noise suppression in Ti:sapphire laser-based electro-optic sampling

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(Received 23 July 1999; accepted for publication 3 October 1999)

We show that intensity and phase noise are highly correlated in a mode-locked Ti:sapphire laser. This allows electro-optic sampling noise, degraded by the combination of −184 dBc/Hz laser phase noise and birefringent system components, to be reduced 12 dB to the shot noise floor. Two multiorder waveplates can be combined to achieve shot-limited noise while preserving maximum detection efficiency. © 1999 American Institute of Physics. [S0003-6951(99)03148-4]

In a semiconductor laser, amplitude and phase fluctuations are strongly correlated through the carrier-density-dependent refractive index, allowing intensity noise suppression using phase-to-intensity noise conversion. In contrast, in passively mode-locked lasers such as the Kerr lens Ti:sapphire laser, it has been thought that phase noise, i.e., pulse timing jitter and pulse width fluctuation, are negligible at high detection frequencies (>1 kHz), and that amplitude fluctuations and phase noise are not correlated. Only recently, Poppe et al. observed a notable asymmetry in the noise power spectrum of an Ar ion pumped, mirror-dispersion-controlled, sub-10 fs Ti:sapphire laser, which was attributed to coupling between timing jitter and pulse intensity fluctuations.

Such lasers are often used in electro-optic sampling (EOS), which is a powerful technique for characterization of ultrafast electronic devices and integrated circuits. EOS measurement sensitivity is limited by the photodetector shot noise to values on the order of 0.1–1 mV/√Hz, depending on dimensions of the air gap, for typical setups using a LiTaO₃ sampling tip. This value is not much smaller than the sensitivity needed for rapid small-signal characterization of bipolar transistors. In addition, measurement systems have additional noise sources that can degrade the sensitivity from its fundamental shot-noise-limited value, and synchronous and differential detection have been used to minimize the 1/f and the intensity noise contributions, respectively.

In this letter, we show that in electro-optic sampling, laser phase noise can have an effect comparable to intensity noise through phase-to-intensity noise conversion, enhanced by the birefringent system components, even at a relatively high detection frequency. We show that laser amplitude noise is highly correlated with the phase fluctuations, which allows suppression of total noise by 12 dB to the shot noise floor. We also demonstrate that a two-multiorder waveplate approach achieves shot-limited noise while preserving maximum detection efficiency.

The EOS experiment is a conventional external-probe setup based on a LiTaO₃ sampling tip, and illustrated in Fig. 1. The laser source is an Ar ion-pumped, Kerr lens self-focusing, prism compensated, Ti:sapphire laser, operating at 830 nm, and producing 80 fs duration pulses at a repetition rate of 100 MHz. Following Fig. 1, laser pulses pass through polarizer (P), then the EO sampling tip (T). A multiorder optical compensator (C), which provides enough tuning of phase retardation, is used to adjust for the static birefringence of the sampling tip and yield circularly polarized light in the absence of an electrical signal. Tilting the compensator along its axis, which is aligned perpendicular to the optic axis of the EO crystal, can achieve continuously variable compensation. A Wollaston optical analyzer (W) follows the compensator, and the two output beams are detected by photodiodes and differentially amplified (A). These signals with a frequency of 1.02 MHz are mixed down to the audio frequency range by the frequency mixer (M) with those from the local oscillator (LO). Finally, the output signals are detected by a lock-in amplifier (LIA).

The root-mean-square (rms) noise at the lock-in output was determined from a large number of measurements. At the balanced condition, when the powers incident on the photodetectors are equal, the noise is 12 μV/√Hz. This shows reasonable intensity noise cancellation, as the noise levels of the two beams alone were determined as approximately 80 and 90 μV/√Hz, respectively. However, this level is still approximately 12 dB above the shot-limited noise of 3 μV/√Hz, which was estimated from the working parameters of the photodetectors and amplifiers, and also measured with laser noise exactly cancelled out in the absence of any birefringent components. This large noise is undesirable in small-signal device measurements since the signal to be measured is on the order of 10 mV, which corresponds to a 50 μV lock-in output in the present setup. It is difficult to improve signal-to-noise ratio by increasing acquisition time, because laser drift causes distortions of the measured waveforms.

In Fig. 2 we show noise as a function of the normalized optical power difference; exact balance occurs at the center...
of this plot, and the difference is adjusted by tilting the compensator. Circles and squares are measured with the slow axis of the waveplate parallel to, and perpendicular to, the optic axis of the EO crystal, respectively. From the data of Fig. 2 it is apparent that minimal noise is not obtained at the balanced condition, which is typically assumed to lead to optimal sensitivity. Nevertheless, minimum noise, which is equal to the shot noise limit, is achievable for offsets from exact balance; this cannot be explained by differences in photodetector responsivity. This behavior strongly suggests that total intensity noise is reduced due to amplitude-phase noise coupling in this Ti:sapphire laser, in analogy to the situation in semiconductor lasers.\(^1\)\(^2\) The phase-to-amplitude conversion is realized here with the birefringent components and differential detection in the EOS system.

To explain the data of Fig. 2, we account for the phase retardation introduced by both the EO material \(q_\text{EO}\) and the waveplate compensator \(q_p\). In addition, we consider variations in the field-induced birefringence in the EO material \(\Delta\epsilon_\text{EO}\), variations in the laser output power \(\Delta I\), and variations in the laser wavelength \(\Delta\lambda\). Applying Jones calculus,\(^10\) and expanding to first order in \(\Delta\lambda, \Delta I, \) and \(\Delta\epsilon_\text{EO}\), the normalized current difference is

\[
\frac{I_y - I_x}{I_m} = \cos(\pm q_p + q_e) + \Delta\epsilon_\text{EO} \times \sin(\pm q_p + q_e) \\
+ \left[ \frac{\Delta I}{I_m} \times \cos(\pm q_p + q_e) - (\pm q_p + q_e) \times \frac{\Delta\lambda}{\lambda} \right] \\
\times \sin(\pm q_p + q_e),
\]

where \(I_y\) and \(I_x\) are optical powers received by the two photodetectors, \(I_m\) is the total optical power, and \(\lambda\) is the laser wavelength. The plus and minus signs in Eq. (1) correspond to the cases where the slow and fast axes of the compensator are parallel to, and perpendicular to, the optic axis of the EO crystal, respectively. The operating condition normally assumed optimal is \((\pm q_p + q_e) = n\pi/2\), with \(n\) odd, where the EO efficiency is maximal and intensity noise cancels. However, this is not appropriate when the phase noise is significant, especially when the phase noise is accentuated by the multiple order waveplate, where \(q_p \sim 10 \times 2\pi\).

The total rms noise voltage \(V_{\text{total}}\) can be derived from Eq. (1) as

\[
V_{\text{total}}^2 = V_{\text{shot}}^2 + \langle V_I^2 \rangle \cos^2(\pm q_p + q_e) \\
+ \left[ \langle V_P^2 \rangle (\pm q_p + q_e)^2 \sin^2(\pm q_p + q_e) \right] \\
- \langle V_I V_P \rangle \sin(\pm q_p + q_e) \cos(\pm q_p + q_e),
\]

where \(V_{\text{shot}}\), \(\langle V_I^2 \rangle\), \(\langle V_P^2 \rangle\) represent the shot, intensity, and phase noises, respectively, and \(\langle V_I V_P \rangle\) describes the correlation between the intensity and phase fluctuations. The non-zero correlation term makes a reduction of the total noise possible. We fit the data with Eq. (2), and show the resulting fits by the lines in Fig. 2, which are in excellent agreement with the measured data. The parameters used in the fitting are \(q_p = 10 \times 2\pi\), \(q_e = 0.23 \times 2\pi\), and the best-fit noise values are \(\langle V_I^2 \rangle = 84.7\) and \(\langle V_P^2 \rangle = 0.171\) \(\mu\text{V}/\sqrt{\text{Hz}}\). Taking account of the 0.86 mA current level in each photodiode, this corresponds to intensity and phase noise levels of \(-130\) and \(-184\) dBc/Hz, respectively. This intensity noise level at 1 MHz is consistent with previous measurements of the noise power spectrum of Ar-pumped mode-locked Ti:sapphire lasers.\(^3\)\(^11\) The present measurements can also determine the value of the phase noise, which is well below the background noise floor of a spectrum analyzer and could not be measured previously.\(^3\)\(^11\) The above measurement procedure may provide a useful alternative approach to measurement of the phase noise spectrum.

The fitting also suggests that the intensity and phase noise are highly correlated, at this sampling frequency, with a normalized correlation coefficient \(\langle V_I V_P \rangle/\sqrt{\langle V_I^2 \rangle \langle V_P^2 \rangle} \sim 0.98\). This near-perfect correlation explains why the shot-limited noise can be achieved, as seen in Fig. 2, by adjusting the dispersive optical elements. The correlation coefficient appears to be much greater than in the sub-10 fs Ti:sapphire laser reported in Ref. 3, where data could only be measured at much lower frequencies, below 10 kHz. Further investigations are needed to understand the coupling mechanism, which Poppe et al. have suggested, for their system may originate in the finite response time of the Kerr nonlinearity.\(^3\)

Achieving minimum system noise level is highly desirable: a 16-fold reduction in acquisition time can be achieved by reducing the noise by a factor of 4 to the shot-noise limit, which is a large improvement; furthermore, drift is greatly reduced in the shorter acquisition time. The simplest way to obtain this minimum noise level is by tuning the tilt angle of the compensator until reaching the noise minimum seen in Fig. 2. However, the EO efficiency will not be maximum, degrading sensitivity. A more practical concern is that it is time consuming to determine the optimal operating point; in addition, this point can be expected to vary as the laser is adjusted, and therefore regular recalibration will be required.

From the fit shown in Fig. 2, the phase noise for the Ti:sapphire laser is determined to be much smaller (54 dB below) than the intensity noise. According to Eq. (1), it becomes significant and causes the minimum noise to occur away from the balance point, only because of the magnifying effect of the \((\pm q_p + q_e)\) prefactor. To confirm this, we repeated the measurements using a compound compensator consisting of two multorder waveplates with their fast axes oriented orthogonally. The tilt angles of the two compensators are adjusted independently to yield compensation over a...
range wide enough to compensate tip birefringence, while achieving small overall retardance. Experimental results using this approach are shown by the symbols in Fig. 3. Minimum noise equal to the shot noise level is achieved very near to the balanced condition. To model the two-compensator arrangement the \((\pm q_p \pm q_e)\) term in Eq. (2) must be changed to \((\pm q_{p1} \pm q_{p2} \pm q_e)\), where \(q_{p1}\) and \(q_{p2}\) are the two compensator retardances. Proper tuning of the two waveplate angles makes \((q_{p1} \pm q_{p2} \pm q_e)\) exactly equal to \(\pi/2\). Calculations using this modified form of Eq. (2) are shown as the solid line in Fig. 3, using the fitted parameters derived from Fig. 2. The results are in excellent agreement with the experimental data. This arrangement of optical components leads to maximum EO efficiency and minimum noise. In addition, the required compensator angles are independent of the relative contributions of intensity and phase noise from the source laser.

In summary, intensity fluctuation and phase noise are highly correlated in a prism compensated, passively mode-locked Ti:sapphire laser at the 1 MHz sampling frequency. This allows noise reduction to the shot-limited floor even in the presence of strong phase noise enhancement by birefringent components in the electro-optic sampling system. A two-waveplate setup achieves shot-limited performance, while preserving maximum detection efficiency.

This work has been supported by the Natural Sciences and Engineering Research Council of Canada under the Strategic Grants Program; two of the authors (M.K.J. and R.L.R.) would like to acknowledge fellowship support from the Killam Foundation, and the University of British Columbia, respectively. One of the authors (J.M.Z.) is indebted to Jeff Young for discussions. Thanks are also due to Paul Paddon for a critical reading of the manuscript.