Experimental Study of Noise Properties of a Ti:Sapphire Femtosecond Laser

Eugene N. Ivanov, Scott A. Diddams, and Leo Hollberg

***Abstract*—The fidelity of a coherent link between optical and microwave frequencies is largely determined by noise processes in a mode-locked femtosecond laser. This work presents an experimental study of the noise properties of a Ti:sapphire femtosecond laser. It includes measurements of pulse repetition rate fluctuations and shot noise exhibited by the Ti:sapphire femtosecond laser. Based on the results of noise measurements, the fractional frequency stability of a microwave signal produced by the femtosecond laser has been evaluated.**

I. Introduction

A femtosecond Ti:sapphire laser is one of the major research tools in optical frequency synthesis. Such a laser is capable of producing a comb of equidistant optical frequencies with a spectral width of many tens of terahertz [1], [2]. Octavewide optical combs, obtained by passing the femtosecond light pulses through the photonic crystal fiber, have recently been used to build the optical frequency synthesizer [3], [4]. The latter can either transfer the frequency stability of a microwave clock to the optical domain or down-convert the signal from an optical frequency standard to the microwave region. In both cases, it is important to know the limitations imposed on frequency stability of synthesized optical signal by intrinsic fluctuations of the femtosecond laser as well as fluctuations in the optical readout system.

II. Measurement of Pulse Repetition Rate Fluctuations of a Mode-Locked Laser

The experimental setup for measuring fluctuations of pulse repetition rate of a femtosecond laser is shown in Fig. 1. A high-speed photodetector is illuminated with a train of ultrashort light pulses produced by the Ti:sapphire laser using a pair of prisms for intracavity dispersion control [5]. The frequency comb that results at the output of the photodetector is band-pass filtered at n-th harmonic of pulse repetition rate ($n\,f_R$). Phase of the filtered signal is compared to that of a low-noise radio frequency (RF)-synthesizer in a double-balanced mixer (first mixer in Fig. 1). The error signal from the first mixer is used to control the length of the laser resonator enabling the phase stabilization of pulse repetition rate. Once the pulse repetition rate is stabilized, both phase and amplitude fluctuations of a signal at frequency f_R are measured against another RF-synthesizer operating at the same frequency as the first one.

To adjust the pulse repetition rate, the length of the laser resonator was altered with an end mirror attached to a piezoelectric transducer (PZT). This type of frequency tuning was characterized by almost linear dependence of f_R on PZT bias voltage, U_{pzt}, with a gradient $df_R/dU_{\mathrm{pzt}} \approx 0.63$ kHz/V and overall tuning range, $\Delta f_R^{\max} \approx 250$ Hz. Parameter df_R/dU_{pzt} also was measured in a broad range of modulation frequencies in order to locate spurious mechanical resonances in PZT mirror mounts. This was essential for the design of a stable repetition rate control system.

Another criteria, which was taken into account in designing the repetition rate control system, was its ability to cope with a drift of pulse repetition rate with time. Such a drift was caused by variations of ambient temperature and was of the order 120 Hz/hour. Introducing an integrator into the control loop enabled us to keep the pulse repetition rate locked to an RF-synthesizer for almost an hour, which was sufficient for conducting the noise measurements described here.

By using the measurement system in Fig. 1, the spectrum of pulse repetition rate fluctuations of a free-running femtosecond laser $S_\varphi^{\mathrm{rep}}(f)$ was deduced from the spectrum of voltage noise fluctuations at the output of the second mixer $S_u(f)$ in accordance with:

$$S_\varphi^{\mathrm{rep}}(f) \approx \frac{|1+\gamma|^2}{n^2\,S_{PD}^2}\,S_u(f), \tag{1}$$

where n is a number of harmonic of pulse repetition rate (n = 9), γ is an open loop gain of the phase-locked loop (PLL), f is a Fourier frequency, and S_{PD} is a phase sensitivity of the readout system based on the second mixer. The latter parameter was maximized by adjusting the phase shift φ (Fig. 1).

The range of Fourier frequencies, within which (1) is applicable, is found from $S_u(f) \geq (3\ldots5) S_u^{n/f}(f)$, where $S_u^{n/f}$ is the voltage noise floor of the measurement system. Such a noise floor is set by phase fluctuations in both RF-synthesizers and is given by:

$$S_u^{n/f} \approx 2\,S_{PD}^2\,S_\varphi^{\mathrm{synth}}, \tag{2}$$

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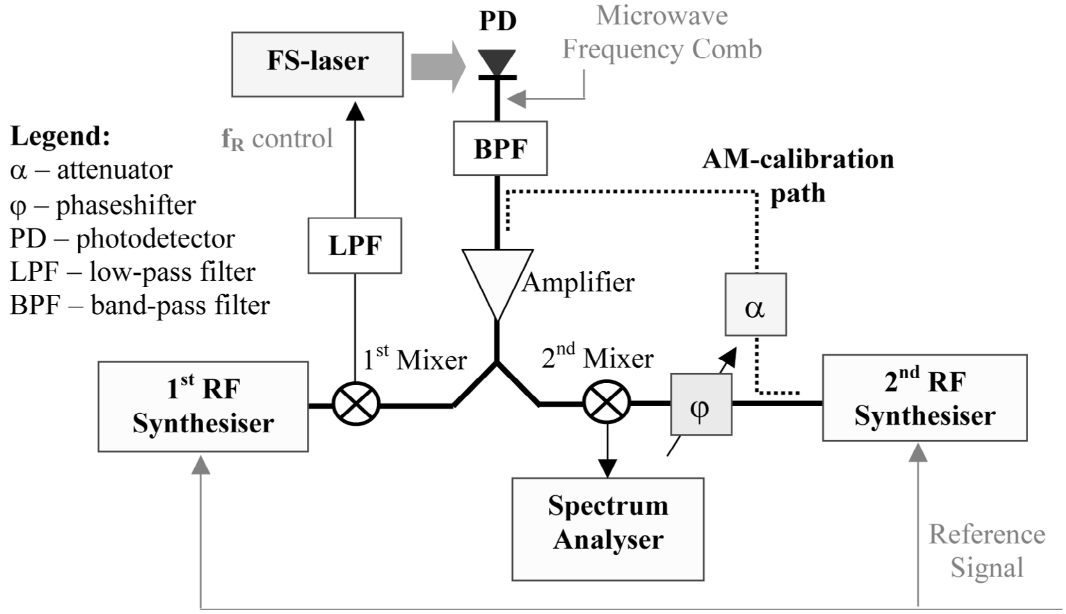

Fig. 1. Experimental setup for measuring fluctuations of pulse-repetition rate of a femtosecond laser.

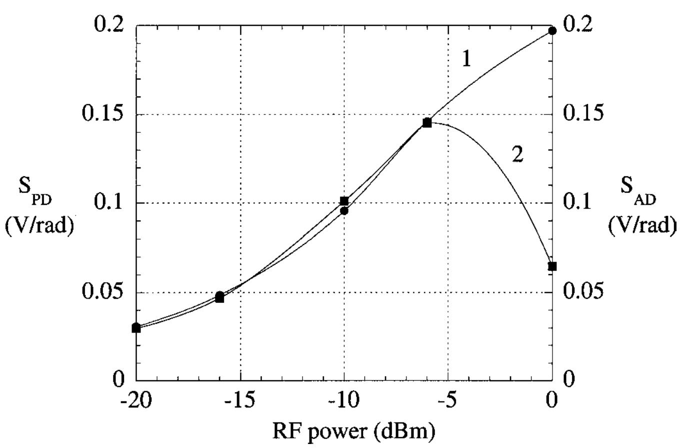

Fig. 2. Phase-to-voltage conversion (curve 1) and amplitude-to-voltage conversion (curve 2) efficiency of two-oscillator measurement system as a function of signal power at the RF port of the mixer.

where $S_\varphi^{\rm synth}$ is the spectral density of phase noise of a single RF-synthesizer.

The lower boundary of the allowed frequency range is a function of the PLL bandwidth and gain; the upper boundary depends on the shape of two spectra $S_\varphi^{\rm rep}(f)$ and $S_\varphi^{\rm synth}$.

The phase sensitivity S_{PD} was calculated by modulating the frequency of the second RF-synthesizer and measuring the amplitude of a signal at a frequency of modulation at the output of the second mixer. To simplify these calculations, the modulation frequency was chosen to be beyond the PLL bandwidth. The S_{PD} as a function of a signal power at the RF port of the mixer is shown in Fig. 2 (curve 1).

The last parameter involved in the noise reconstruction algorithm (1) is the PLL gain, γ, which is a complex function of frequency:

$$\gamma(\omega) = n\, \tilde{S}_{PD}\, \frac{K_F(\omega)}{j\omega}\, \frac{df_R}{dU_{\rm pzt}}. \tag{3}$$

In this equation, $\omega = 2\pi f$, $K_F(\omega)$ is the transfer function of the loop filter and $\tilde{S}_{PD}$ is the phase-to-voltage conversion efficiency of the first mixer. The $\tilde{S}_{PD}$ is measured by following the earlier described calibration procedure, except that the frequency of the first RF-synthesizer is modulated.

Results of noise measurements are presented in Fig. 3. Curve 1 corresponds to the phase noise floor of two-oscillator measurement system. Curve 2 is the spectrum of joint phase fluctuations of the ninth harmonic of pulse repetition rate of a phase-locked femtosecond laser and the second RF-synthesizer. Curve 3 characterizes the noise suppression factor (NSF) of the PLL: NSF $= 1/\left|1+\gamma\right|^2$. Curve 4 is the reconstructed phase noise spectrum of a ninth harmonic of pulse repetition rate of a free-running femtosecond laser, $S_\varphi^{\rm rep(9)}$. Ignoring the excess noise at frequencies 100 Hz to 400 Hz caused by the vibration sensitivity of the laser resonator, the spectrum $S_\varphi^{\rm rep(9)}$ varies approximately as $3.16/f^4$ rad^2/Hz.

Taking into account the relationship between the noise spectra $S_\varphi^{\rm rep(9)}$ and $S_\varphi^{\rm rep}$: $S_\varphi^{\rm rep(9)} = 81 S_\varphi^{\rm rep}$, the power law fit to the spectrum of repetition rate fluctuations of a free-running Ti:sapphire laser is given by:

$$S_\varphi^{\rm rep}(f) \approx 3.9 \cdot 10^{-2}/f^4 \ \ ({\rm rad}^2/{\rm Hz}). \tag{4}$$

This type of noise spectra corresponds to the random walk of frequency and is likely to be caused by temperature-

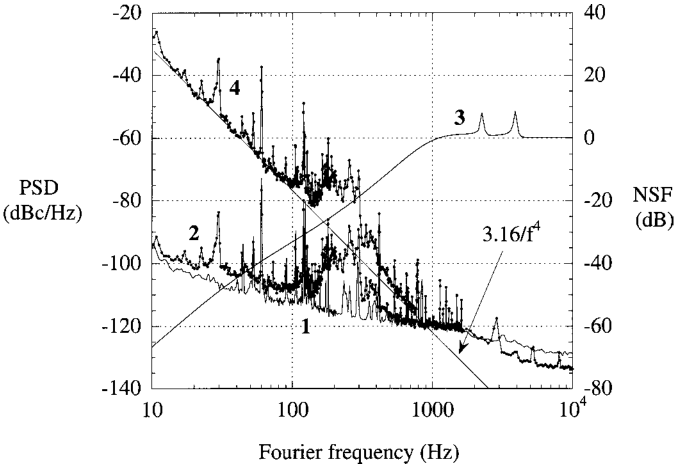

Fig. 3. Noise floor of two-oscillator measurement system (curve 1); phase noise of a phase locked femtosecond laser (curve 2); noise suppression factor of the PLL (curve 3); reconstructed phase noise spectrum of ninth harmonic of a pulse-repetition rate of a free-running femtosecond laser (curve 4).

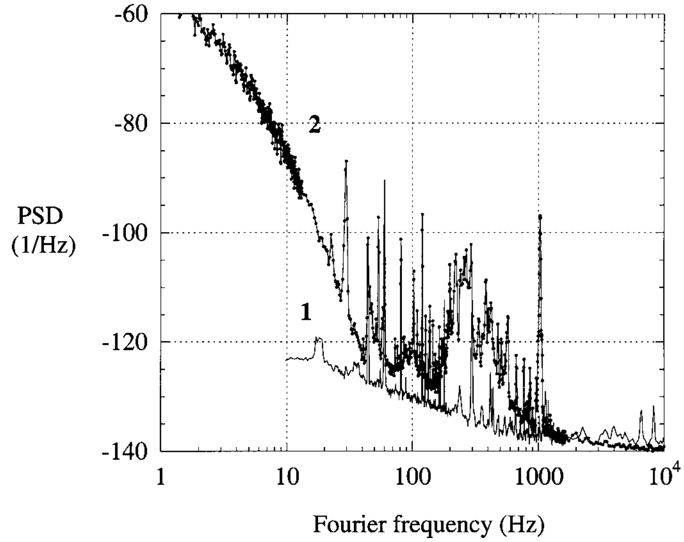

Fig. 4. Amplitude noise of the RF-synthesizer (curve 1); amplitude noise spectrum of a ninth harmonics of pulse-repetition rate of a femtosecond laser (curve 2).

induced fluctuations of the laser resonator. Such a conjecture is supported by direct measurement of ambient temperature fluctuations, as well as observations of frequency fluctuations in other types of electromagnetic oscillators, including microwave oscillators based on the sapphire-loaded cavity resonators [6].

Making the measurement system in Fig. 1 sensitive to power fluctuations of the input signal, amplitude noise of the ninth harmonic of the pulse-repetition rate also was measured. Such a tuning was accomplished by adjusting the reference phase shift φ, until the direct current voltage at the output of the second mixer was maximum. In such a case, the spectral density of amplitude fluctuations S_{AM}^{rep} was calculated from:

$$S_{AM}^{\mathrm{rep}}(f) \approx S_u(f)/S_{AD}^2, \tag{5}$$

where $S_u(f)$ is the spectral density of output voltage noise and S_{AD} characterizes conversion from signal amplitude to output voltage.

To measure S_{AD}, the laser light was blocked and a photodetector signal was substituted with a signal from the second RF-synthesizer. The power of the synthesizer signal was modulated with the relative depth m giving rise to an alternating current signal at the output of the second mixer with amplitude U_m. The amplitude-to-voltage conversion was calculated from: $S_{AD} = U_m/m$. The S_{AD} as a function of signal power at the RF port of the mixer P_{RF} is shown in Fig. 2 (curve 2). At low power levels ($P_{RF} < -7$ dBm) both phase and amplitude conversion ratios are almost equal each other: $S_{PD} \approx S_{AD}$. The latter result is valid for different types of mixers operating both at RF and microwave frequencies. Knowing that phase and amplitude conversion coefficient are equal (in a small signal regime) simplifies the process of noise measurements by eliminating the need for an additional calibration when switching from amplitude to phase noise measurements.

Results of amplitude noise measurements are presented in Fig. 4. Spectrum 1 shows the amplitude noise of the RF-synthesizer. Curve 2 is the amplitude noise spectrum of a ninth harmonics of pulse-repetition rate of a phase-locked femtosecond laser. As expected, the spectral density of amplitude noise was much less than that of a phase noise at the same frequency of 900 MHz. For example, at Fourier frequencies below 100 Hz the difference between two noise spectra was more than 40 dB.

A strong correlation was measured between power fluctuations of the femtosecond laser and pump laser. In those experiments, one photodetector was used for demodulating power fluctuations of the pump laser. Another photodetector was illuminated by light pulses from the femtosecond laser. The output of each photodetector was low-pass filtered, and spectra of voltage fluctuations were measured. The results of these measurements are shown in Fig. 5. For example, curve 1 shows the voltage noise spectrum resulting from the demodulation of pump laser light. Curve 2 shows the cross-spectral density of voltage fluctuations between two photodetectors. Spectra 1 and 2 are almost indistinguishable in the frequency range 400 Hz . . . 20 kHz, which indicates that power fluctuations of the femtosecond laser are caused by those of the pump laser.

III. Shot Noise Measurements

Spectrum of a microwave signal at the output of a photodetector illuminated by ultrashort light pulses consists of discreet spectral lines at harmonics of pulse repetition rate and a broadband pedestal due to the random arrival of photons (shot noise). The goal of the experiments described below was to measure the spectral density of the shot noise and evaluate its effect on the accuracy of time transfer from optical to microwave frequencies.

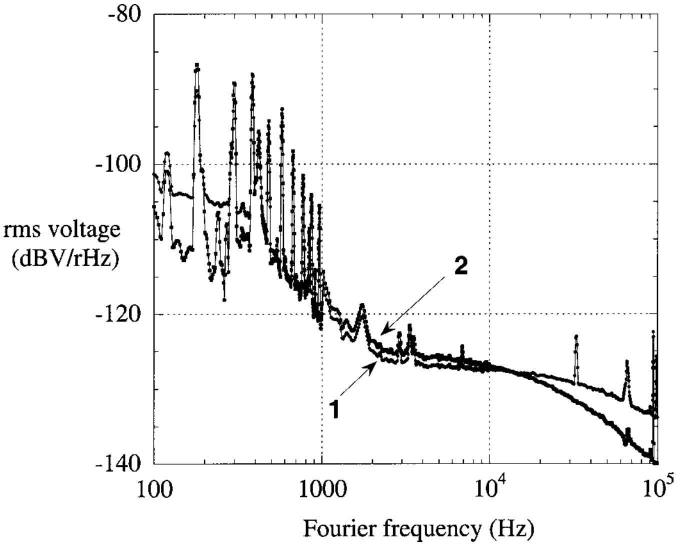

Fig. 5. Voltage noise spectrum at the output of a photodetector monitoring power of the pump laser (curve 1); cross-spectral density of voltage fluctuations between photodetectors monitoring power of the pump and femtosecond lasers (curve 2).

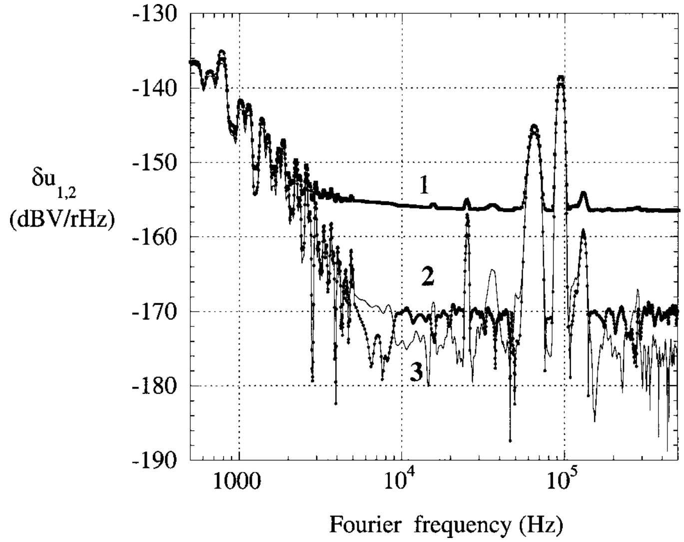

Fig. 7. Voltage noise spectrum at the output of a single-channel measurement system (curve 1); cross-spectral density of voltage noise induced by femtosecond laser (curve 2); noise floor of a two-channel measurement system measured with a 50 ohm termination in place of the photodetector.

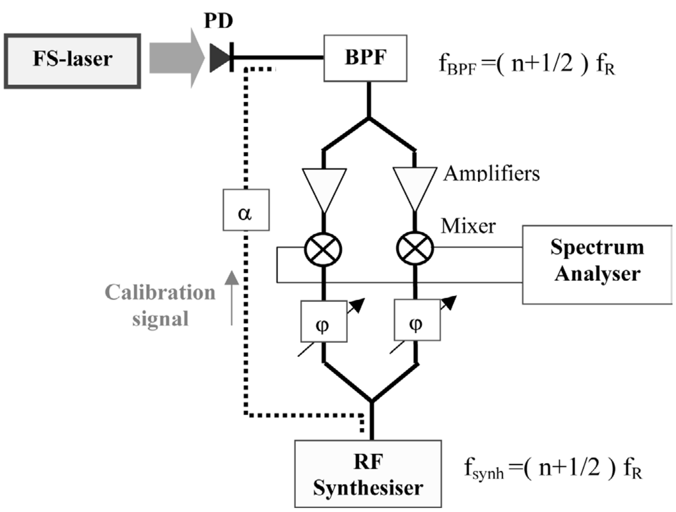

Fig. 6. Two-channel readout system with cross-correlation signal processing for measuring shot noise of a femtosecond laser.

The schematic diagram of the shot noise measurement setup is shown in Fig. 6. Electrical signal from the photodetector is bandpass filtered at frequency $f_{BPF} \approx (n+1/2)f_R$. This eliminates carriers from the output of the photodetector and ensures that no technical noise sources affect the results of measurements. Carrier suppression also allows a low-noise amplifier to be introduced in front of the nonlinear mixing stage, reducing the relatively high contribution of the mixer to the overall effective noise temperature of the readout system. A low-noise RF-synthesizer in Fig. 6 operates at frequency $f_{\text{synth}} \approx f_{BPF}$. This permits a frequency down-conversion of the photodetector noise and its study with a fast Fourier transform (FFT) spectrum analyzer.

Splitting the photodetector signal between two channels and calculating a cross-spectral density of voltage fluctuations further benefits the accuracy of noise measurements due to the suppression of uncorrelated noise sources in each channel. The advantage in sensitivity associated with the application of cross-correlation signal processing is of the order $\sqrt{N_{\text{avg}}}$, where N_{avg} is the number of averages taken by the FFT spectrum analyzer. In the following experiments, N_{avg} was chosen to be $\sim$1000 to ensure at least an order of magnitude improvement in the measurement resolution.

Another reason for choosing a two-channel readout system for precision noise measurements is related to its immunity to thermal fluctuations. As shown in [7], [8], the noise floor of the two-channel measurement system can be 10 to 15 dB below the standard thermal noise limit.

The results of the shot-noise measurements are shown in Fig. 7. Curve 1 corresponds to the root mean square (rms) voltage fluctuations at the output of a single-channel measurement system, δu_{rms}. Curve 2 corresponds to rms cross-voltage noise, $\delta u_{1,2}$, with the light from femtosecond laser incident on the photodetector. Curve 3 shows the noise floor of two-channel measurement system, obtained with a photodetector replaced with a 50 ohm termination. From the comparison of spectra 1 and 2 in Fig. 8, it is clear that sensitivity of a single channel readout system is not sufficient to allow accurate measurements of the shot noise.

The above measurements were conducted in the presence of a weak 950 MHz calibration signal. Such a signal causes flicker noise in front-end amplifiers and degrades sensitivities of both single and two-channel measurement systems at relatively low Fourier frequencies below 10 kHz. The average power of the optical comb incident on the photodetector was equal to 5 mW. A high speed Si photodetector with responsivity of 0.45 A/V and peak sensitivity

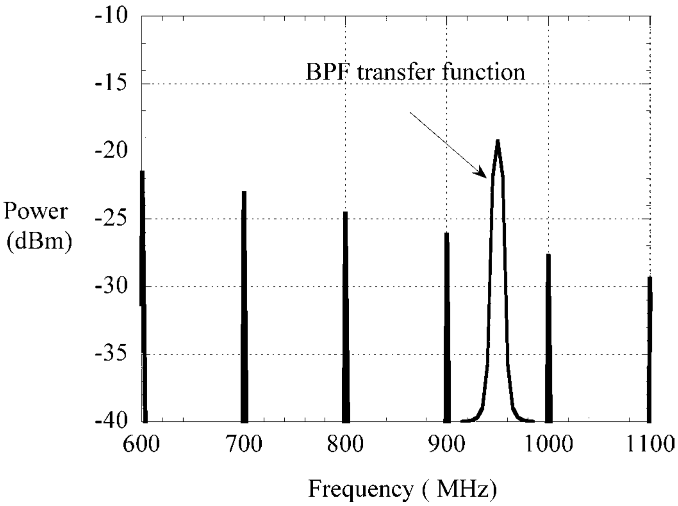

Fig. 8. Spectrum of the frequency comb at the output of the photodetector.

wavelength of 800 nm was used for the demodulation of light pulses.

The spectral density of a phase noise of the signal at n-th harmonic of pulse-repetition rate is deduced from the measured cross-voltage noise as

$$S_{\varphi}^{\text{shot}} = \left(\delta u_{1,2}/S_{AD}\right)^2, \tag{6}$$

where S_{AD} is the amplitude sensitivity of a single-channel readout system in Fig. 6 measured at power of the calibration signal equal to that of 10th harmonic of pulse repitition rate. Substituting the measured values $\delta u_{1,2}$ and S_{AD} into (6) results in $S_{\varphi}^{\text{shot}} \approx -152$ dBc/Hz.

Assuming that n-th harmonic of pulse-repetition rate is selected from the microwave frequency comb with a high-Q resonator, fractional frequency stability of such a signal is given by [9]:

$$\sigma_y^{\text{shot}}(\tau) \approx \frac{\sqrt{3 S_{\varphi}^{\text{shot}}\, \Delta f}}{2\pi\, \tau n\, f_R}, \tag{7}$$

where τ is an integration time and Δf is the effective noise bandwidth of a high-Q resonator. Substituting $S_{\varphi}^{\text{shot}} \approx -152$ dBc/Hz, $n\, f_R \approx 1$ GHz, and $\Delta f = 100$ kHz (typical bandwidth of a 1 GHz dielectric resonator) into (7) yields $\sigma_y^{\text{shot}}(\tau) \approx 5 \cdot 10^{-15}/\tau$, which is comparable to the frequency stability of an optical Ca frequency standard over 1 s of integration time [10]. By filtering a 100th harmonic of pulse repetition rate and taking $\Delta f = 100$ kHz (bandwidth of a room temperature sapphire-loaded cavity resonator), the shot noise limit (7) becomes: $\sigma_y^{\text{shot}}(\tau) \approx 5 \cdot 10^{-16}/\tau$. Alternatively, one can think of reducing the effective noise bandwidth Δf by phase locking an external RF-synthesizer to the harmonic of the pulse-repetition rate. In such a case, the improvement in frequency stability of the output signal gained due to the use of a narrow-band filter in the feed-back loop will be largely lost due to the flicker fluctuations in RF-electronics of the control system. For instance, voltage noise of a typical 1 GHz mixer limits the fractional frequency stability of the phase-locked oscillator at the level of 10^{-15} over 1 s of integration time.

IV. Discussion

In this section we demonstrate that an analytical description of the shot noise produced by a femtosecond laser is similar, within an experimental error, to that of a continuous wave laser. Indeed, let us assume that rms fluctuations of the electric current produced by the photodetector illuminated with a train of ultrashort light pulses are given by:

$$\delta i_{\text{rms}} = \sqrt{2 q \eta \overline{P}} \tag{8}$$

where q is an elementary electrical charge, η is a responsivity of the photodetector, and $\overline{P}$ is an average power of the optical comb. In such a case, spectral densities of voltage fluctuations at the output of single-channel and two-channel readout systems, S_{u1} and $S_{u1,2}$, respectively, can be found from

$$S_{u1} = \chi^2\, \tilde{K}_{\text{amp}} q \eta \overline{P}\, R_L + \chi^2\, \tilde{K}_{\text{amp}} k_B T_{RS}, \tag{9}$$

$$S u_{1,2} = \chi^2\, \tilde{K}_{\text{amp}} q \eta \overline{P}\, R_L, \tag{10}$$

where χ is the mixer power-to-voltage conversion ratio, $\tilde{K}_{\text{amp}}$ is the total gain of the measurement system (including insertion loss of the bandpass filter), k_B is the Boltzmann constant, T_{RS} is the effective noise temperature of the measurement system, and R_L is the load resistor of the photodetector.

The first term in (9) shows the shot noise contribution to the voltage noise spectrum of a single-channel readout system. The second term in (9) characterizes the combined effect of thermal and technical noise sources. These noise sources dominate single-channel measurements making observation of the shot noise impossible.

However, the effect of technical and thermal fluctuations on resolution of spectral measurement averages out, when the cross-spectral density of voltage fluctuations is calculated. This leaves the shot noise as the only contributor to the voltage noise cross-spectrum, provided that the integration time (number of averages N_{avg}) is sufficiently large.

Substituting the experimental data and physical constants into (10) results in $\sqrt{S_{u1,2}} = \delta u_{1,2} \approx -160$ dBc/Hz, which is almost 10 dB higher than experimentally measured (see Fig. 7). Such a discrepancy can be explained, if one takes into account the low-pass filtering of the shot noise by the photodetector. As follows from the spectrum of the frequency comb at the output of the photodetector (see Fig. 8), the equivalent time constant of the photodetector, $\tau_{eqv} \approx 5.3 \cdot 10^{-10}$ s.

Accounting for the low-pass filtering mechanism, the analytical expression for the cross-spectrum voltage noise becomes:

$$S_{u1,2} = \frac{\chi^2 \tilde{K}_{\mathrm{amp}} q \eta \overline{P} R_L}{1 + (2\pi f_{\mathrm{synth}} \tau_{eqv})^2}. \quad (11)$$

The low-pass filtering introduces an additional attenuation of 10.5 dB at frequency $f_{\mathrm{synth}} = 950$ MHz. This almost eliminates the discrepancy between the experimental data and theoretical estimate and can be considered as an indication that the initial assumption (8) regarding the analytical description of the shot noise of a femtosecond laser was correct.

V. Conclusions

Summarizing the results of this work: fluctuations of the pulse-repetition rate of a free-running Ti:sapphire femtosecond laser were measured; a strong correlation between power fluctuations of the pump and femtosecond lasers was observed; a dual-channel measurement system with cross-correlation signal processing was developed for studying the shot noise of femtosecond lasers; an analytical description of the shot produced by a femtosecond laser was found to be similar to that of a continuous wave laser; the effect of shot noise on the accuracy of time transfer from optical to microwave frequencies was evaluated.

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In 1991, Dr. Ivanov joined the Gravitational Radiation Laboratory at the University of Western Australia (UWA), Crawley, Western Australia, where he constructed a microwave readout system for monitoring the vibrational state of the cryogenic resonant-mass gravitational wave detector Niobe.

In 1994–1997 Dr. Ivanov was working on applications of microwave circuit interferometry to precision noise measurements. This research resulted in the development of microwave oscillators with the phase-noise performance more than 20 dB better than the previous state-of-the-art. It also has permitted the design of real-time noise measurement systems with sensitivity approaching the standard thermal noise limit.

In 1999–2002 Dr. Ivanov was a guest researcher at Time and Frequency Division of National Institute of Standards and Technology (NIST), Boulder, CO. He was involved in the study of noise properties of femtosecond lasers and coherent time transfer between optical and microwave domains.

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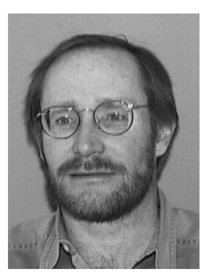
Scott Diddams was born in Gallup, New Mexico in 1967. He received the B.A. in Physics from Bethel College, St. Paul, MN, in 1989 and the Ph.D. degree in Optical Science from the University of New Mexico in 1996. Between 1996 and 2000, he did post-doctoral work at JILA (a joint institute of the National Institute of Standards and Technology and the University of Colorado) where he was supported in part by a National Research Council fellowship. Currently he works as a staff physicist in the Time and Frequency Division of NIST in Boulder, Colorado, where his research interests fall within the fields of nonlinear optics, ultrafast lasers and phenomena, and precision spectroscopy and metrology.



Leo Hollberg was born in Denver, Colorado in 1952, and graduated from Stanford University in 1976 with a B.S. in physics. His Ph.D. in physics was awarded in 1984 by the University of Colorado for research in high-resolution laser spectroscopy done with Jan Hall at JILA. Most of 1984 and 1985 were spent at AT&T Bell Laboratories as a post-doc working with Steven Chu on laser cooling, and with Richart Slusher on squeezed states. Since then has been at NIST doing research on high-resolution spectroscopy of laser-cooled and trapped atoms, the development of semiconductor lasers for scientific and technical applications, optical coherence effects of driven multilevel atoms, and on optical frequency standards and measurements, much of this done in collaboration with scientists from around the world.