Quantum-limited noise performance of a femtosecond all-fiber ytterbium laser

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Abstract: We report on quantum-limited noise performance of a mode-locked ytterbium all-fiber laser. The laser operates at a high normal net dispersion without dispersion compensation. We show that the naïve application of analytical models to such lasers leads to strongly underestimated timing jitter, whereas a numerical simulation is in reasonable agreement with measurements. The measured timing phase noise is found to be essentially limited by quantum noise influences and not by technical noise. Furthermore we show that the phase noise of different comb lines has a quasi-fix point at the center of the optical spectrum and that the jitter is translated into high carrier–envelope offset phase noise with a linewidth of around 3 MHz.

OCIS codes: (320.7090) Ultrafast lasers; (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (270.2500) Fluctuations, relaxations and noise.

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1. Introduction

Femtosecond fiber lasers have attracted great attention in recent years due to their excellent stability, small size, alignment insensitivity, and low cost. The noise performance of the laser system is relevant for many applications such as femtosecond laser frequency comb generation for frequency metrology, arbitrary waveform generation, timing and frequency distribution via optical fiber links, and high-speed optical sampling. Mode-locked fiber lasers with an all-fiber setup are promising candidates for low-noise lasers, because mechanical noise influences are minimized. Nearly quantum-limited noise performance has been demonstrated for a soliton fiber laser without any external stabilization [1]. In this paper, we consider wave-breaking-free fiber lasers, more precisely all-normal dispersion fiber lasers, with strong changes of the pulse parameters during one round trip. Such lasers allow for substantially increased pulse energies and therefore appear to be promising candidates for optical frequency metrology. However, little is known so far on their noise properties, which are influenced by more complicated processes than in soliton fiber lasers and also in most mode-locked bulk lasers. We therefore also addressed the question whether simplified models nevertheless correctly estimate the timing jitter, which previously has neither been measured nor theoretically investigated for such lasers. For this purpose, we employed numerical simulations, and also compared theoretical estimates with experimental measurements. In short, we found that the measured timing phase noise of our laser is higher than expected from using simplified models for calculating the quantum noise influences, but in good agreement with a more comprehensive numerical model.

Furthermore, we show that the phase noise of different comb lines has a quasi-fix point at the center of the optical spectrum, and that the timing jitter is related to high carrier–envelope offset phase noise with a linewidth of 3.3 MHz for our laser.

It is important to mention that two different meanings of the term “quantum noise limit” exist [2]. The first one is the fundamental limit to the noise properties of the pulses, which applies to any pulsed source not exhibiting squeezing effects. Similar to the shot-noise limit for the intensity noise, there is a fundamental limit for the timing jitter, which depends on the pulse energy and pulse duration. The other meaning (which is used in this paper) refers to the minimum possible timing jitter of some laser, as results from quantum noise influences, assuming that there is no technical noise and no kind of timing stabilization by using an external timing reference. Particularly at low noise frequencies, the resulting jitter is usually orders of magnitude above the mentioned fundamental quantum limit.

2. Theoretical Estimates

An early analytical model by Haus and Mecozzi was based on soliton perturbation theory [3]. It was found that the timing noise has two different contributions: a direct one, related to direct changes of temporal position induced by quantum fluctuations in the amplification process, and an indirect one, where spectral fluctuations are coupled to the temporal position via group velocity dispersion. Obviously, the assumptions made for this model are fulfilled only in soliton mode-locked lasers. Later it was found by Paschotta [2], that the central result of Ref [3]. for the timing jitter is still valid for typical mode-locked bulk lasers not using soliton pulse shaping, even though soliton perturbation theory clearly cannot be applied here. It was recognized that the noise dynamics of such lasers are not intimately related to the pulse shaping mechanism, which may e.g. be dominated by a saturable absorber. The two above-mentioned contributions to the timing jitter then exist in exactly the same way as for soliton mode-locked lasers. This raises the question whether these results might apply to an even wider range of lasers, including fiber lasers with strongly chirped pulses circulating in the resonator, and possibly with strong nonlinear spectral broadening and spectral filtering in each round trip. Details will be described in a forthcoming paper, but in the following we briefly describe the basic reasoning. A relatively simple adaptation of previously used models concerns the high round-trip gain and losses, leading to substantial changes of the pulse energy. Essentially, quantum noise influences are strongest where the pulse enters the active

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fiber with the lowest energy. For a given maximum pulse energy, a higher gain implies a lower minimum pulse energy and therefore stronger quantum noise influences. Further, the "restoring force" on the spectral position (optical mean frequency), as results from the finite gain bandwidth, depends on the pulse bandwidth. Assuming unchirped solitons, Haus and Mecozzi have calculated the bandwidth from the pulse duration [3], which we cannot do for strongly chirped pulses; we have to explicitly use the actual pulse bandwidth instead. Even with these adaptations, the model does not reflect the complicated pulse formation process. One might hope that the adapted results are correct or at least provide reasonable estimates. In order to test this, we used a numerical simulation, which is based on a much more detailed model of the laser, including the complicated pulse-shaping dynamics with strong nonlinear, dispersive and filtering effects. By simulating many resonator round trips under the influence of quantum noise, we can obtain the fluctuating pulse parameters such as the pulse energy, optical mean frequency, temporal position, etc. From such quantities, we can obtain an estimate of the power spectral densities e.g. of the pulse energy and the timing phase [4]. As shown in Fig. 3, the resulting timing noise is substantially higher than according to the simple analytical estimate, thus indicating that the aspects neglected in the adapted analytical models are essential.

3. Laser Setup

We investigated an all-fiber ytterbium laser of a kind where during one resonator round trip the pulses experience significant nonlinear, dispersive and filtering effects, leading to strong changes of the pulse energy, pulse duration, spectral width and chirp. The setup is shown in Fig. 1. It consists of a short ytterbium-doped fiber, a passive single-mode fiber, a fiber-coupled isolator, another passive single-mode fiber, a fiber coupler acting as a filter with a bandwidth of 9 nm, a fiber coupler providing a monitor port and a wavelength division multiplexer for coupling the pump light into the ring resonator. A similar setup has been described in detail by Schultz et al. [5]. For the laser used here the total fiber length was 6.21 m, corresponding to a pulse repetition rate of 32.86 MHz. The laser was pumped with up to 488 mW from a single-mode pump diode.

To achieve mode-locking by nonlinear polarization evolution, two polarization controllers are placed in front of and behind the optical isolator, respectively. Due to the all-normal dispersion fibers, the laser resonator had a net round-trip group delay dispersion of 0.139 ps^2. The output spectra had an r.m.s. width of 13.2 nm at a center wavelength of 1030 nm. The output pulse duration was 7.8 ps and could be dechirped to 195 fs in an external grating compressor. The maximum output power was 32 mW, limited by the available pump power. This corresponds to a pulse energy of 1 nJ. Single-pulse operation was verified by using a long-range autocorrelator and a fast photodiode (rise time < 70 ps) in combination with a 70 GHz sampling oscilloscope.

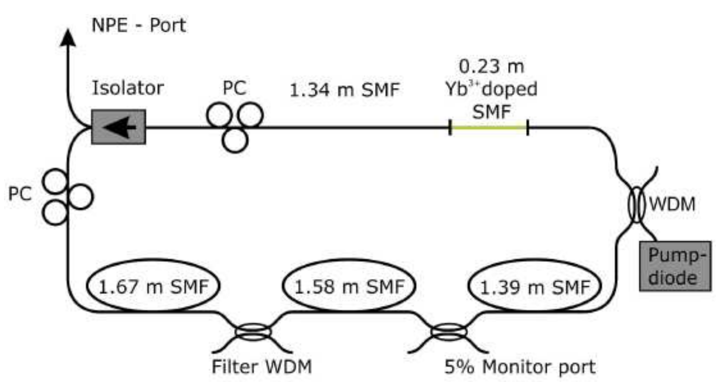

Fig. 1. Setup of the all-fiber laser. PC: polarization controller; SMF: single-mode fiber; WDM: wavelength division multiplexer.

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4. Timing Phase Noise

4.1 Von der Linde Method

For first measurements of the timing noise, we used the method developed by von der Linde [6]. It was shown that under the following assumptions the phase and amplitude noise can be determined from the power spectrum measured with a photodiode and a radio frequency analyzer: the amplitude fluctuations and the phase deviations (timing jitter) are small ($\langle\phi^2\rangle^{1/2} \ll 1$ rad) and the amplitude fluctuations and the timing jitter are not correlated. Phase noise (timing noise) and amplitude noise result in noise sidebands around the peaks associated with integer multiples of the pulse repetition rate. The power spectral density of phase noise contributions increases with the square of the order of the harmonic, whereas amplitude noise does not have this dependence on harmonic order. Therefore, phase noise contributions dominate for sufficiently high harmonic orders. The analysis is based on a linear expansion of the phase errors, which is potentially problematic for free-running passively mode-locked lasers where the timing errors can grow without bound. For free-running lasers, the analysis is still valid for a limited measurement time, leading to a lower limit of the accessible noise frequencies. Another problem arises from possible correlations between different pulse parameters such as pulse energy, temporal position and center frequency. Such correlations, which may arise both in the laser and via amplitude-phase coupling in the photodetector, would lead to additional contributions to the noise sidebands [7,8], and neglecting these results in errors of the timing jitter calculation. Furthermore, phase noise of the local oscillator of the spectrum analyzer may dominate the recorded noise. However, we used that technically simple method to obtain a first estimate of the timing jitter. The noise measurement setup is shown in Fig. 2 with the switch set to position (a). The light was detected by an InGaAs photodiode with a cut-off frequency > 10.2 GHz. We recorded the sidebands of the 92nd harmonic of the power spectrum around 3.023 GHz. Significantly higher harmonics were not taken into account due to the drift of the repetition rate of the free-running laser system during the measurement time. This drift results from temperature fluctuations in the laboratory acting on the fiber length and the refractive index, and from fluctuations of the pump power. At 3.023 GHz, the drift during the measurement time is negligible. In order to increase the signal-to-noise ratio, we used a bandpass filter with a passband from 3 GHz up to 4.3 GHz, and additional electrical amplifiers with a gain of ≈20 dB.

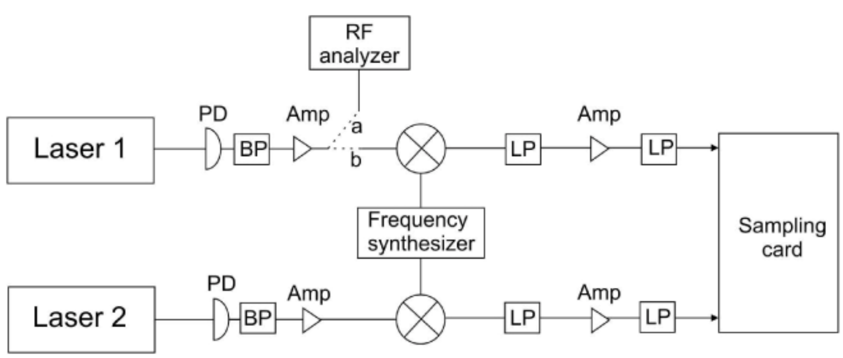

Fig. 2. Setup for phase noise measurements (a) setting for the von der Linde method [6]; (b) setting for the indirect phase comparison method [11]. PD: photodiode; BP: bandpass filter; Amp: amplifier; LP: low-pass filter.

The noise figure of the amplifier was 0.9 dB. The noise power spectral densities were then recorded with a radio frequency spectrum analyzer. We decided not to subtract data from the fundamental repetition rate for canceling amplitude noise contributions, as such methods (used e.g. by Son et al. [9] or Finch et al. [10]) are based on the uncertain assumption of negligible amplitude-to-phase coupling.

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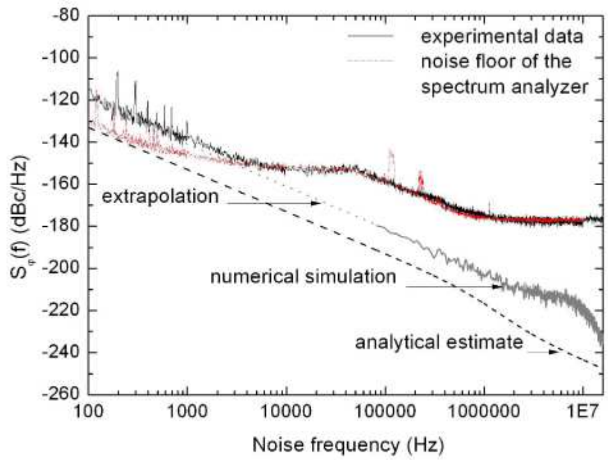

Fig. 3. Power spectral density of the timing phase noise obtained with the von der Linde method (solid black curve). The peaks at low offset frequencies result from parasitic electronic influences by the power supply. Above ≈10 kHz, the measurement is limited by the noise floor of the spectrum analyzer as indicated (red dash-dotted curve). Also shown are the numerical results (straight gray line, above 80 kHz) and the corresponding extrapolation to lower noise frequencies, assuming white frequency noise (dotted gray line). Finally, the analytical estimate is shown as the black dashed curve.

The calculated and measured timing phase noise power spectral densities are shown in Fig. 3. All curves show single-sided power spectral densities of the timing phase, which is defined (as usual) such that it advances by 2π per pulse period. The peaks at low offset frequencies in the experimental curve result from parasitic electronic influences by the power supply, as we verified with separate tests. For noise frequencies above 10 kHz the measurement is limited by the noise floor of the spectrum analyzer (see Fig. 3). Below 100 Hz (not shown here), thermal effects are dominant; note that the laser is not temperature-stabilized. The results of the analytical estimates and numerical simulations are also displayed. The numerically simulated data are available only for noise frequencies above 80 kHz due to the limited computation time (a few hours), allowing only for a limited number of simulated resonator round trips. The extrapolation of these data to lower frequencies, assuming white frequency noise (dotted gray line), fits well to the experimental results. This indicates that the timing noise is only limited by quantum noise influences in the range of 100 Hz to 10 kHz and not by technical noise. Integrating the timing phase noise power spectral density from 100 Hz to 10 kHz yields a timing jitter of 90 fs for the experimental and the extrapolated numerical results. The analytical result underestimates the timing noise by about 13 dB. This apparently results from the fact that the complicated pulse dynamics are not considered in the analytical model. We therefore must consider such models as being over-simplified for application to such kind of fiber lasers.

4.2 Indirect Phase Comparison Method

As mentioned above, phase noise from the local oscillator of the spectrum analyzer, which effectively serves as the timing reference, can influence the recorded noise spectra and determine the instrument noise floor. Therefore, we also used a second method, which eliminates such influences, essentially by comparing the timing of two similar lasers. A detailed description of this method is given by Paschotta et al. in Ref [11]. Besides eliminating the noise of the electronic oscillator, the method also allows to well separate amplitude and timing noise. This is in contrast to other methods such as the electronic phase detector method [12] or the optical phase detector method based on an optical cross correlation [13].

To use this method, we built a second laser similar to the first one. The fiber lengths and pulse parameters differ only by a few percent. The second laser had a repetition rate of 33.2 MHz and a maximum output power of 28 mW corresponding to a pulse energy of 0.85 nJ.

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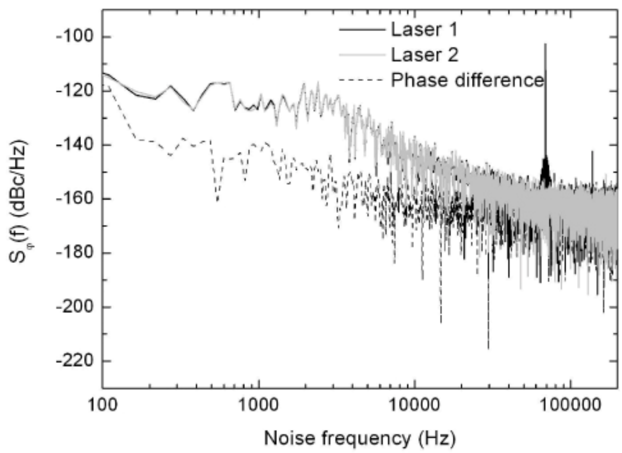

Fig. 4. Power spectral density of the timing phase noise calculated by Fourier analysis of the measured data obtained with the indirect phase comparison method. Black solid curve: first laser; gray solid curve: second laser; black dashed curve: difference of the phase values. The peak at about 70 kHz is an aliased parasitic signal.

The setup for the phase noise measurement is shown in Fig. 2 with the switch set to position (b).

In order to maximize the sensitivity for phase noise, we recorded the 92^{nd} harmonics of the pulse repetition rate of the first laser and the 91^{st} harmonics of the repetition rate of the second laser with two fast InGaAs photodiodes with a cut-off frequency > 10.2 GHz. Each signal was bandpass-filtered with a bandwidth of 1.3 GHz and amplified with electronic amplifiers having a gain of 23 dB, a bandwidth of 500 MHz around 3.55 GHz, and a low noise figure of 0.9 dB. The amplified signals were fed into mixers with an operation frequency range from 750 to 4200 MHz. As the local oscillator, a frequency synthesizer was used, providing a signal at 3.025 GHz. The resulting downconverted signals around 2 MHz were low-pass filtered and afterwards amplified again by electronic amplifiers having a gain of 24 dB, a bandwidth from 0.1 to 500 MHz, and a noise figure of 2.9 dB. After a second low-pass filter of 5 MHz, both signals were recorded by a sampling card in a personal computer. The card had a resolution of 12 bits allowing continuous sampling with a bandwidth up to 20 MHz. The data were analyzed as described in Ref [11]. The results are displayed in Fig. 4. It can be seen that the phase noise of the frequency synthesizer affected both recorded signals in the range of 100 Hz – 30 kHz and was canceled in the difference of the phase values, which thus reflect only the relative phase noise of the 92^{nd} and 91^{st} harmonics of the repetition rates. The integrated relative timing noise from 100 Hz to 10 kHz was 88 fs. This is the relative timing jitter of both lasers. For a single laser, the timing jitter is smaller by a factor $2^{1/2}$, if both lasers have equal and statistically independent jitter (which we cannot be sure of). The relative jitter value can be used as a conservative estimate. It is in good agreement with the result from the von der Linde method. It is to mention, that the peak at about 70 kHz results from aliased parasitic signals. The noise floor of about −165 dBc/Hz arises from noise of the frequency mixers and not from digital sampling; the noise floor does not depend on the sampling frequency. The theoretical limit for the noise floor of the sampling card was calculated to about −186 dBc/Hz for a sampling frequency of 20 MHz, according to Ref [11].

5. Optical Phase Noise and CEO Noise

Another important kind of noise is phase noise in different lines of the optical spectrum. A direct method for analyzing the phase noise in a single line is to analyze a beat note between the line and a stable single-frequency laser. In our experiments, we used a nonplanar Nd:YAG ring oscillator, emitting near 1064 nm. The spectral linewidth was ≈1 kHz for a measurement time of 100 ms. The setup for measuring the beat note is shown in Fig. 5 part (a). As the

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optical spectrum had an r.m.s. width of only 13.2 nm around 1030 nm, it had to be extended to the NPRO line using nonlinear effects. For that purpose, we first applied a fiber amplifier, containing a 40 cm ytterbium-doped fiber pumped by a single-mode diode with an output power of 500 mW via a dichroic fiber coupler. A 1% monitor port was implemented in front of the active fiber to monitor the output pulses of the laser. The chirped pulses from the oscillator were amplified to a pulse energy of 9.2 nJ. As the pulse duration of the oscillator was 7.8 ps, nonlinear effects were weak in the amplifier, leading to a nearly maintained optical spectrum. The pulses were externally compressed in a transmission grating arrangement to a pulse duration of 195 fs. The spectrum was subsequently broadened by self-phase modulation in a single-mode fiber to reach wavelengths around 1064 nm. The beam was heterodyned with the single-frequency laser, and the beat note was detected with an avalanche photodiode after separating the wavelength with a grating and a pinhole. Finally the data were recorded with a sampling card at a sampling frequency of 20 MHz. The recorded data trace was further processed numerically.

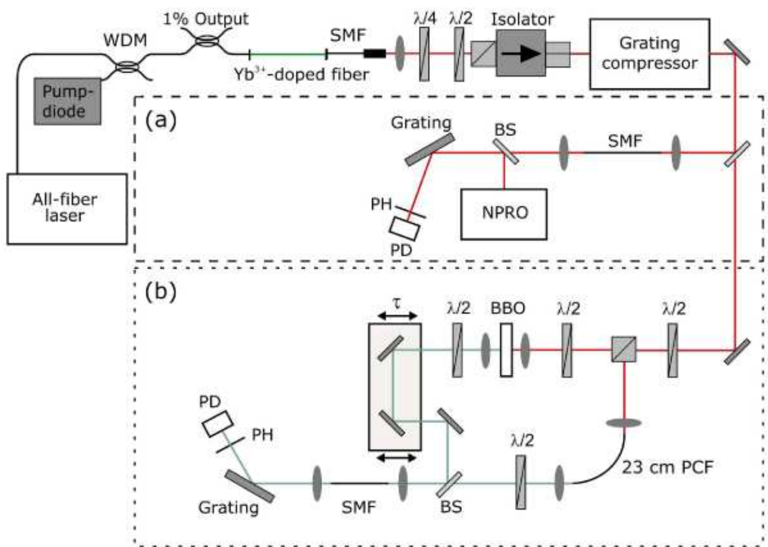

Fig. 5. Setup for measuring (a) the beat note between the fiber laser and the NPRO and (b) the CEO frequency. WDM: wave length division multiplexer; SMF: single mode fiber; BS: beam splitter; PH: pin hole; PD: photodiode.

Fourier techniques have been used to first obtain the time-dependent complex amplitude (phasor), then to extract the time-dependent instantaneous phase and estimate the power spectral density of the phase noise from this, which is the relative phase noise between the Nd:YAG laser and the nearest line of the spectrum of the mode-locked fiber laser. Figure 6 shows a typical phase noise spectrum, compared with the theoretical spectrum for a simple random-walk process with 10 kHz linewidth. From this we see that the short-term linewidth is even below 10 kHz at 1064 nm, whereas the low-frequency noise (below 500 Hz) is somewhat higher. Since intensity noise could be converted to phase noise in the spectral broadening process due to SPM, 10 kHz is an upper limit for the linewidth near the center of the optical spectrum.

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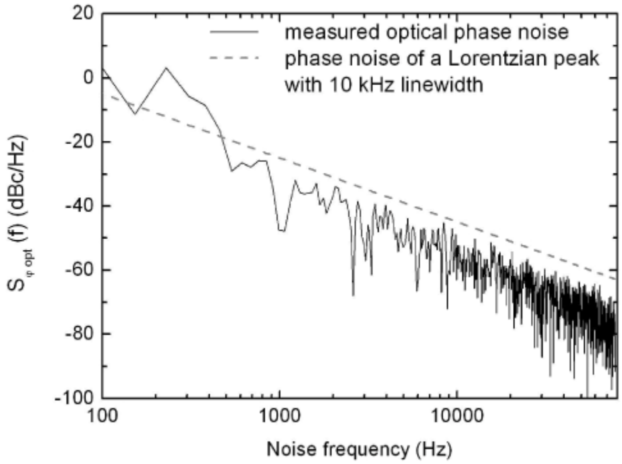

Fig. 6. Phase noise spectrum of the beat note (solid black curve), compared with the theoretical spectrum for a simple random-walk process with 10 kHz linewidth (dashed gray curve).

It is instructive to relate this level of phase noise to the timing jitter. If the timing jitter would simply result from fluctuations of the resonator length (fix-point at zero frequency in terms of the "rubber-band model" [14]), the power spectral density of the optical phase noise would be higher than that of the timing noise by a factor of $(\nu_{opt} / f_{rep})^2$, i.e., by roughly 140 dB. In reality, however, that difference is much lower: only ≈120 dB. As shown in Ref [15]. such characteristics are also observed for simpler lasers (without chirped pulses, strong filtering and nonlinear interactions), when the noise is dominated by quantum noise and the pulse duration is far above the optical period. This means that the phase noise in the different lines of the optical spectrum has a quasi-fix point near the center of the optical spectrum (see Fig. 4 (a) in Ref [15].). The phase noise is rather weak at that point, but increases with increasing distance from the quasi-fix point. If we extrapolate that phase noise to zero frequency, we obtain the much stronger noise of the carrier–envelope offset phase. The power spectral density of the carrier–envelope offset phase can be estimated as being the above-mentioned 140 dB higher than the timing phase noise, or roughly 20 dB higher than the measured optical phase noise in the spectrum. The expected linewidth of the carrier–envelope beat signal, as obtained with a *f*–2*f* interferometer, would thus be roughly 100 times that of the optical linewidth, resulting in a short-term linewidth of roughly 3 MHz.

To compare these results with the experiment, we measured the CEO frequency with an interferometer shown in Fig. 5 (b). The signal of the amplifier was split up at a polarization beam splitter in combination with a half wave plate. One part of the signal was frequency-doubled in a 1 mm thick BBO crystal, and the other part was broadened by the soliton fission process in a highly nonlinear photonic crystal fiber (PCF) generating a dispersive wave at 515 nm. Therefore, we used a PCF with a zero dispersion wavelength of 750 nm. Both signals were heterodyned at a beam splitter and, after spectral filtering with a grating and a pinhole, detected with an avalanche photodiode and a radio frequency analyzer. The measured beat signal with a linewidth of 3.3 MHz is shown in Fig. 7 for an optimum adjustment of the polarization controllers of the laser. This is in good agreement with the estimate done above.

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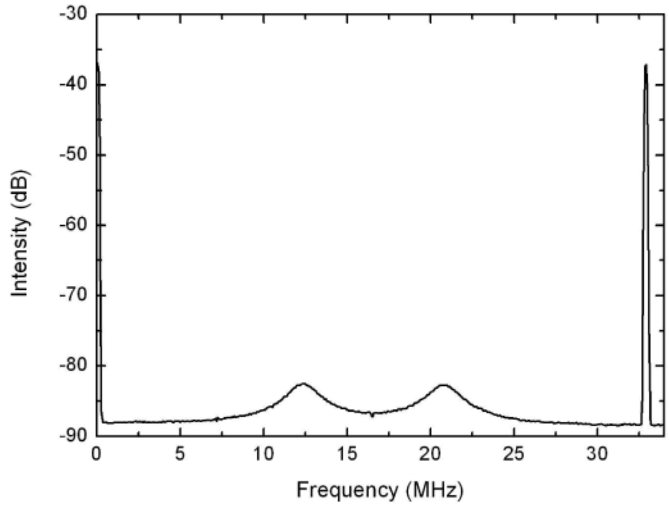

Fig. 7. Measured CEO beat signal. The peak at 32.8 MHz corresponds to the repetition rate of the laser.

For non-optimum adjustment of the polarization controllers, we obtained longer dechirped pulses and several times broader CEO beats. The reason for the latter is not clear, as the measured optical phase noise and timing jitter are compatible with significantly smaller changes with respect to the state of optimum alignment. This will need further investigation.

6. Conclusion

We have presented a detailed investigation of the noise characteristics of a completely fiber based all-normal dispersion, wave-breaking free ytterbium laser. To the best of our knowledge, these are the first noise measurements for a laser system of this type. The measured timing jitter at low noise frequencies agrees well with an extrapolation of data from a numerical simulation model to calculate the quantum noise influences, whereas substantially lower quantum-limited jitter would be predicted by a strongly simplified analytical model, which does not take into account the complicated pulse shaping process. We could show that the phase noise of different optical lines has a quasi-fix point at the center of the optical spectrum, as expected for quantum noise influences, whereas resonator length fluctuations would not have such characteristics. We also showed that the increased timing jitter is related to high carrier–envelope offset phase noise with a linewidth of 3.3 MHz. Therefore, that kind of laser appears not to be ideal for applications where a very low noise of the carrier–envelope offset is required.

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