Characterization and reduction of phase noise in passively mode-locked Ti:sapphire lasers with intracavity saturable absorbers

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We characterize the phase noises (or timing jitter) of argon-ion-laser-pumped femtosecond Ti:sapphire lasers with intracavity dye saturable absorbers or saturable Bragg reflectors (SBR's). The significance of the finite lifetime of the absorbers is identified for what is the first time to our knowledge. We show that timing fluctuations of the mode-locked lasers can be suppressed significantly by optimization of intracavity gain bandwidth and group-velocity dispersion. A new active stabilization technique, based on the optoelectronic phase locked loop, is also demonstrated. The rms timing jitter (100–500 Hz) of the femtosecond passively mode-locked Ti:sapphire/dye and Ti:sapphire/SBR lasers operating at an average power of 200 mW is reduced to ~650 and 290 fs (500 Hz), respectively. © 1998 Optical Society of America [S0740-3224(98)01506-9]

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1. INTRODUCTION

Phase noise (or timing jitter) is an important attribute of mode-locked lasers. Reduction of laser timing jitter is thus often desirable in applications such as optical communication, electro-optic sampling, and time-resolved spectroscopy. The above examples require either lasers with ultralow jitter or synchronization of one of the lasers with other lasers or external electrical signals. Phase noise of passively mode-locked Ti:sapphire lasers has been the subject of extensive studies recently because these lasers are currently the premiere light sources used in ultrafast optics and optoelectronics. Timing-jitter-related noise characteristics of regeneratively initiated self-mode-locked[1,2] and self-starting Kerr-lens-mode-locked (KLM) Ti:sapphire lasers[3,4] were reported. The timing jitter of a 10-fs Ti:sapphire laser pumped by frequency-doubled cw diode-pumped Nd:YVO_4 laser was also studied.[5] By active control of laser cavity length, nearly quantum-limited jitter values can be achieved.[4] The phase noise of a diode-pumped KLM Cr:LiSGAF laser was reported.[6] Subpicosecond time synchronization between two Ti:sapphire lasers was also realized.[2,7] A theory of phase noise in mode-locked lasers that applies to additive-pulse mode-locked and KLM Ti:sapphire lasers was developed by Haus and Mecozzi.[8] The theoretical prediction of $1/f^4$ behavior for the single-sideband laser phase noise spectrum was confirmed,[2] where f is the offset frequency from the carrier. Intuitively, laser parameters such as gain–bandwidth and intracavity group-velocity dispersion (GVD) are expected to contribute to laser timing jitter. This is also implied in the theoretical work.[8] To our knowledge, however, these relationships have not yet been experimentally confirmed in solid-state laser systems. On the other hand, the phase noise of passively mode-locked Ti:sapphire lasers with intracavity saturable absorbers[9,10] has not been investigated either. Recently there has been resurgent interest in this type of laser because of the successful development of all-solid-state saturable absorbers.[11,12] We demonstrate in this paper, for what is the first time to our knowledge, phase noise characteristics of passively mode-locked Ti:sapphire lasers with slow saturable absorbers (dye or saturable Bragg reflectors, SBR's). We show that, by optimization of intracavity gain bandwidth and GVD, the phase noise of the lasers can be suppressed. In this class of lasers the stability of solitonlike pulses depends on the pulse shortening force resulting from the finite gain windows of absorber saturation.[13] The role of the gain windows or the finite lifetimes of the real saturable absorbers in timing jitter is discussed. Finally, a new timing stabilization method that employs an optoelectronic harmonic mixer[14] (OEHM) in a phase-locked loop is demonstrated.

2. EXPERIMENTAL METHODS

We employed a standard six-mirror X-folded cavity for the passively mode-locked Ti:sapphire/dye or Ti:sapphire/SBR lasers. These are shown in Fig. 1. A 5-mm-long Ti:sapphire rod and a pair of SF10 prisms for intracavity dispersion compensation were used. The reflectivity of the output coupler was $R = 95\%$. A highly reflecting plane mirror was mounted on a piezoelectric transducer for active cavity stabilization. Both lasers were aligned such that the lasers could not self-start without the saturable absorber. For the Ti:sapphire/dye laser the dye [hexamethylindotricarbocyanine iodide (HITCI) + 3,3′-Dichloro-11-diphenylamino-3,3′-diethyl-10,12-ethylenethiatricarbocyanine perchlorate (IR140)] jet was placed at the focus of a pair of 5-cm radius-of-curvature high reflectors. For the Ti:sapphire/SBR laser we removed the dye jet and replaced one of the folding mirrors for the dye jet with a SBR. The structure of our SBR device is as follows. A distributed Bragg reflector with 15 pairs of high–low $\lambda/4$ layers of $AlAs/Al_{0.25}Ga_{0.75}As$ was

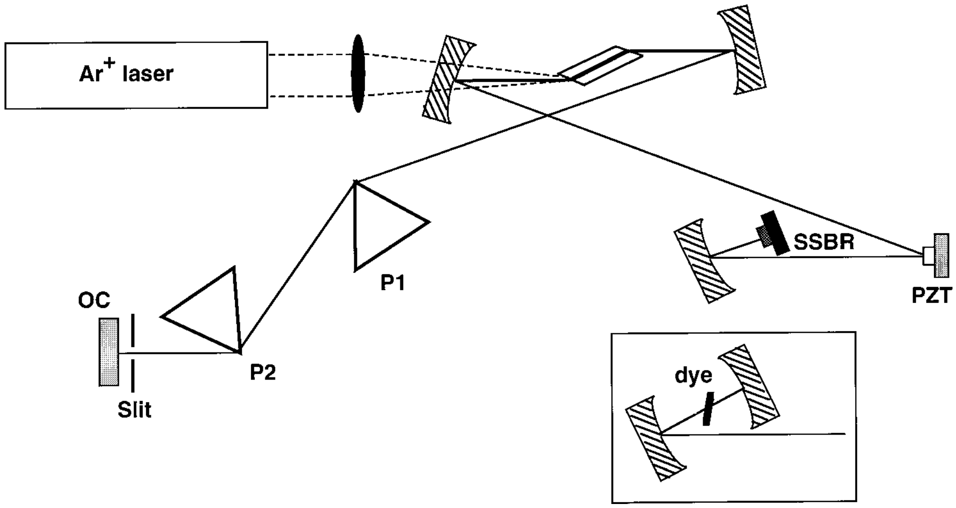

Fig. 1. Configurations of Ti:sapphire/SBR and Ti:sapphire/dye lasers. P1, P2, SF10 prisms; SSBR, strained SBR; PZT, piezoelectric transducer.

first grown by molecular beam epitaxy. An additional $\lambda/2$ layer of $Al_{0.25}Ga_{0.75}As$ was grown on the top layer of the distributed Bragg reflector mirror. Three strained quantum wells ($In_xAl_{1-x-y}Ga_yAs$) with separate and sequential absorption peak wavelengths were inserted into this layer. The spacing of the quantum wells was such that the peaks of the standing-wave patterns correspond to peak wavelengths of each of their absorption spectra. The pumping laser was an all-line large-frame argon-ion laser (Coherent Innova 400) operating nominally at 5 W. The output power, pulse width, and repetition rate of the Ti:sapphire/dye or Ti:sapphire/SBR laser are, respectively, 250 mW, below 100 fs, and 85 MHz. To reduce the thermal effect, the Ti:sapphire rod and the SBR were both regulated such that the residue peak-to-peak temperature fluctuation for each was below 0.1°C. The heating effect on the dye jet ($\Delta T \leqslant 0.5$°C) was expected to be minimal.

We used conventional noise power spectrum measurements for phase noise characterization.[15] The laser output as detected by a high-speed photodetector (Antel AR-S2, 18-GHz bandwidth) was fed to a spectrum analyzer (HP8650E, 3-GHz bandwidth, 1-Hz resolution). The average photocurrent was ~1 mA. The noise floor of the measurement apparatus was approximately −120 dBc/Hz, where dBc is decibels below the carrier. The power level of the detected laser harmonics up to $n = 35$ was higher than −25 dBm. The single-sideband phase-noise spectra of the laser pulse train at the fundamental and the thirtieth harmonic signals were measured. Laser timing jitter values were then calculated by use of the algorithms discussed in Ref. 3.

3. EFFECTS OF INTRACAVITY BANDWIDTH AND DISPERSION ON TIMING JITTER

To investigate the effect of gain–bandwidth on timing jitter, we change the width dp of the slit located near the output coupler. The corresponding change in the bandwidth, $\Delta\lambda$, is calculated using the formula[16]

$$\mathrm{d}p = \frac{4\sin(\epsilon/2)}{[1 - n^2\sin^2(\epsilon/2)]^{1/2}}\frac{\mathrm{d}n}{\mathrm{d}\lambda}\Delta\lambda L_p,$$

where $\epsilon \sim 60°$ is the apex angle. For SF10 prisms the refractive index $n \sim 1.71125$, and $\mathrm{d}n/\mathrm{d}\lambda \sim -004958\ \mu\mathrm{m}^{-1}$ ($\lambda = 800$ nm). The prism pair spacing L_p is 19.5 cm for the Ti:sapphire/dye laser and is optimized for the minimum pulse width ($D = -600\ \mathrm{fs}^2$). With dp increased from 1.0 to 1.7 mm, $\Delta\lambda$ broadened from 26.9 to 45.7 nm. Throughout this range the pulse train for the Ti:sapphire/dye laser remained transform limited, and the pulse width $\tau \approx 60$ fs. The rms timing jitter, on the other hand, increased by an order of magnitude, from 9.6 to 80 ps (100 to 500 Hz). This is shown in Fig. 2. For the Ti:sapphire/SBR laser, dp was changed from 0.8 to 1.6 mm. This corresponds to a change of bandwidth from 22.7 to 45.4 nm ($L_p = 18.5$ cm). Throughout this range the Ti:sapphire/SBR laser pulse train also remained transform limited, and $\tau \approx 85$ fs. The pulse width of the Ti:sapphire/SBR laser was limited by the reflectivity bandwidth of the SBR. Reduction of intracavity bandwidth beyond 0.8 mm results in laser pulses with a pedestal and unstable output. The timing jitter of the mode-locked Ti:sapphire/SBR laser, however, increased by approximately a factor of two, from 6 to 12 ps (100 to 500 Hz), as the bandwidth was increased. This is attributed to the reflectivity bandwidth limitation of the SBR. We found that the timing jitter saturated at 12 ps when the effective cavity bandwidth was larger than 40 nm. This is also shown in Fig. 2.

Next we examined the effect of GVD on timing jitter. For this experiment the gain–bandwidth for the Ti:sapphire/dye laser was set at 27 nm. The intracavity dispersion was varied by our employing laser crystals of different length and tuning the distance between the prism pair. With positive GVD and $\tau \approx 12$ ps, the rms timing jitter of the Ti:sapphire/dye laser was as large as 30 ps. The cavity with slightly negative dispersion ($D \approx -600\ \mathrm{fs}^2$) exhibited the shortest pulse width ($\tau \approx 60$ fs) and minimum timing jitter ($\sigma_j \approx 9.6$ ps). This is illustrated in Fig. 3.

Intuitively we can understand the bandwidth and dispersion dependence of σ_j as follows: Laser frequency is determined by gain and loss. If the cavity bandwidth is large, the laser frequency can drift. This translates into laser phase noise or timing jitter. Frequency fluctuation within the cavity bandwidth also induces change in the refraction index through dispersion. The effective KLM strength will also fluctuate. Because of dispersion, the group velocity will depend on frequency. The fluctuations of the pulse spectrum will also induce timing jitter. From Figs. 2 and 3 it is clear that a laser that is designed with its intracavity bandwidth and dispersion adjusted for minimum pulse width for ultrashort pulse generation will exhibit the lowest timing jitter.

It is also instructive to compare our experimental results with the theory of Haus and Mecozzi.[8] While they did not consider the effects of real intracavity saturable absorbers, they examined the coupling of frequency and time fluctuations through GVD. Femtosecond pulse generation in our lasers also involves appreciable self-phase modulation compensated by GVD. Following Ref. 8, the phase noise spectral density $S_p(f)$ (dBc/Hz) of a passively mode-locked laser can be written as

$$S_p(f) = \Omega_0^2\left(\frac{4D^2}{T_R^2}\left\{\frac{D_p}{(2\pi f)^2[(2\pi f)^2 + \tau_p^{-2}]}\right\} + \frac{D_t}{(2\pi f)^2}\right), \quad (1)$$

where

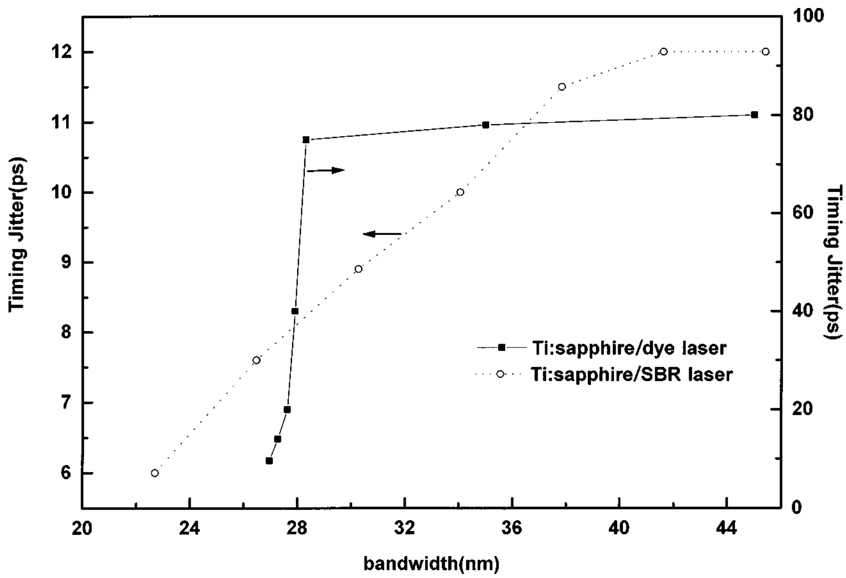

Fig. 2. Timing jitter of the free-running lasers as a function of gain bandwidth. The right-hand axis is for the Ti:sapphire/dye laser. The left-hand axis is for the Ti:sapphire/SBR laser.

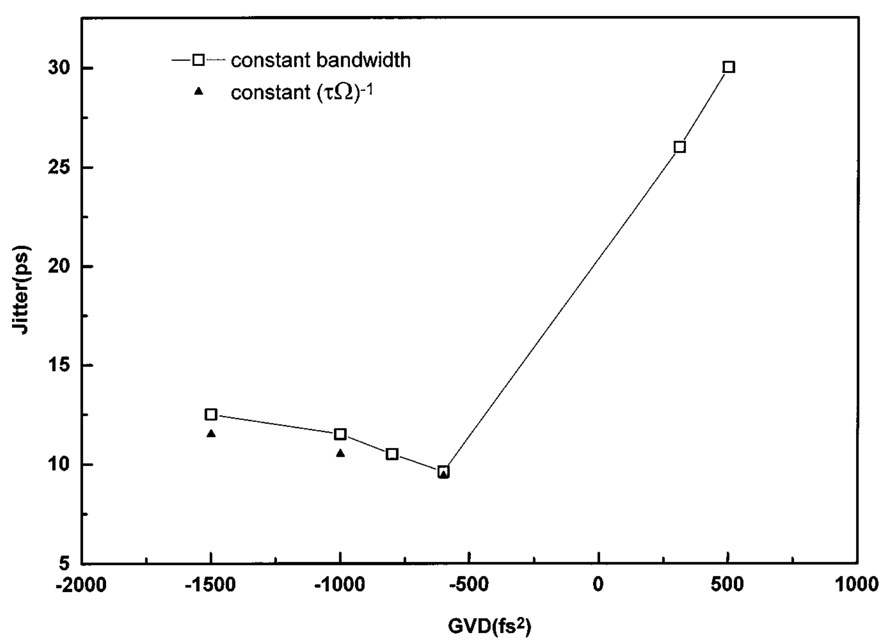

Fig. 3. Timing jitter of the free-running lasers as a function of intracavity dispersion. Open squares, data points for constant bandwidth; solid triangles, data points for constant time–bandwidth products.

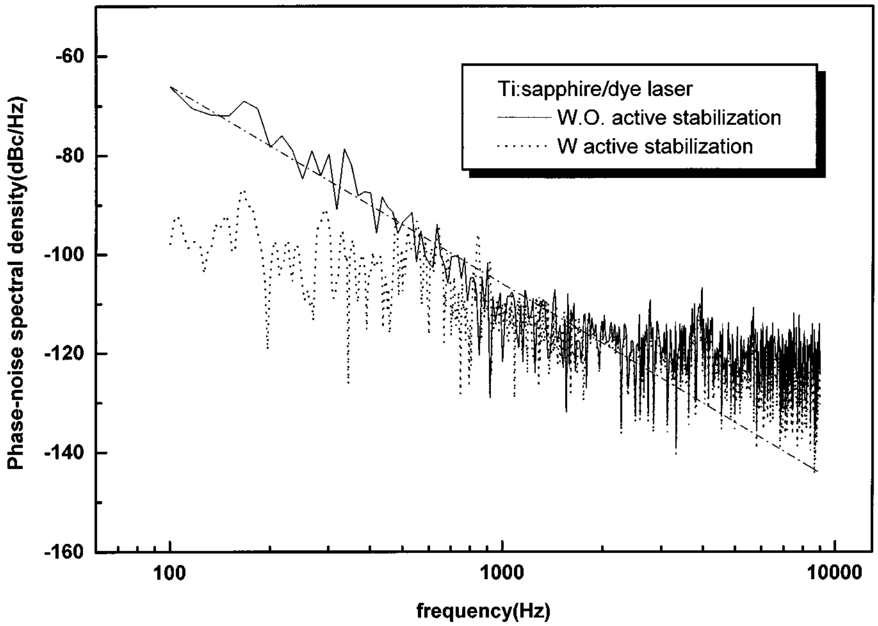

Fig. 4. Single-sideband phase-noise spectral density for the femtosecond Ti:sapphire/dye laser with and without active stabilization. The dotted-dashed line shows $1/f^4$ dependence.

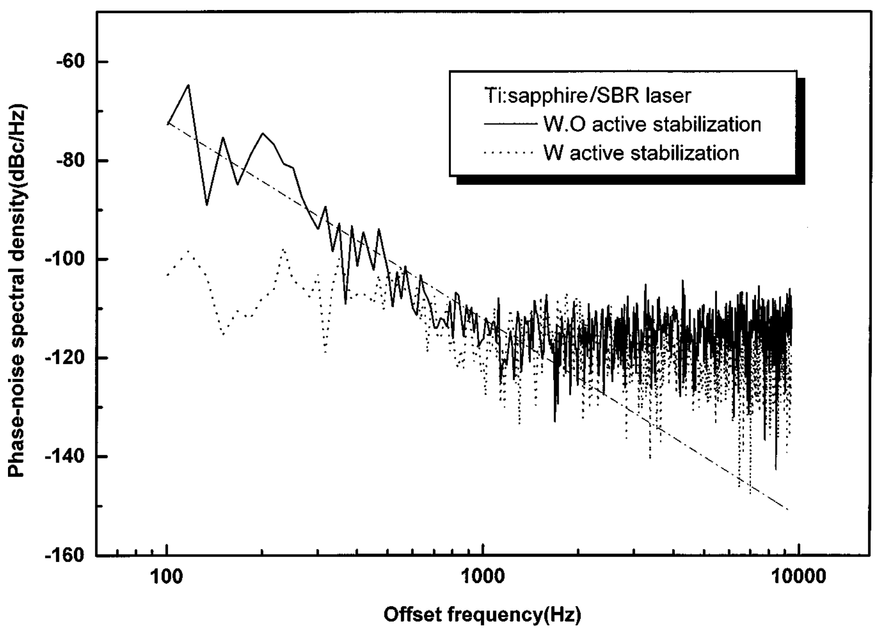

Fig. 5. Single-sideband phase-noise spectral density for the femtosecond Ti:sapphire/SBR laser with and without active stabilization. The dotted-dashed line shows $1/f^4$ dependence.

$$\tau_p = \frac{3T_R {\Omega_g}^2 \tau^2}{4g},$$

$$D_p = \frac{2}{3\omega_0 \tau^2}\, \theta\, \frac{2g}{T_R}\, h\nu, \qquad D_t = \frac{\pi^2 \tau^2}{3\omega_0}\, \theta\, \frac{2g}{T_R}\, h\nu.$$

For our lasers the round-trip time is $T_R = 12.5$ ns ($\Omega_0 = 2\pi/T_R$); the pulse widths τ are in the range 60 fs to 12 ps when the dispersion D is changed from -2500 to 500 fs^2; the saturated gain is $g = 0.3$; the intracavity energy is $\omega_0 = 70$ nJ. For $\Delta\lambda = 27$ nm, $\Omega_g = 8.0 \times 10^{13}$ s^{-1}. With $D = -600$ fs^2 and the bandwidth increased from 27.5 to 42 nm, Eq. (1) predicts that the rms timing jitter will grow by 3.67 dB. For a given bandwidth we also calculate that the phase noise will approach a minimum for a cavity with slightly negative dispersion. Both trends are qualitatively in good agreement with the experimental results, even though the effects of the real saturable absorbers are not included in the model. On the basis of our experimental data and numerical simulation, it is clear that a cavity that maximizes the ratio $(\tau\Omega_g)^{-1}$ will exhibit minimum timing jitter. On the other hand, if $(\tau\,\Omega_g)^{-1}$ is a constant, the cavity with optimum negative dispersion is most effective in suppress-

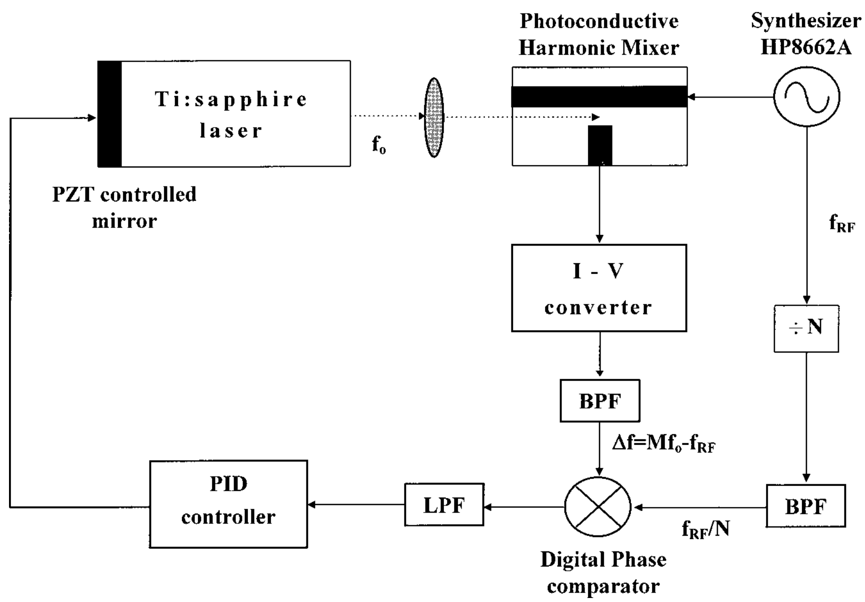

Fig. 6. Schematic diagram of the experimental setup for active timing stabilization. BPF, band-pass filter; LPF, low-pass filter; PID, proportional, integrating, differential; PZT, piezoelectric transducer.

ing phase noise. This trend is also observed experimentally, as is shown in Fig. 3. With excessive negative dispersion, but with $(\tau\Omega_g)^{-1}$ held constant, the pulse width broadens from 60 to 115 fs while the rms timing jitter concurrently increases from 9.6 to 12 ps.

Typical phase noise spectra for free-running Ti: sapphire/dye and Ti:sapphire/SBR lasers, after optimization of intracavity bandwidth, and dispersion are shown in Figs. 4 and 5. The corresponding rms timing jitters are 9.6 ps (100–500 Hz), 550 fs (500 Hz to 5 kHz), and 160 fs (5–10 kHz) for the Ti:sapphire/dye laser and 6.0 ps (100–500 Hz), 368 fs (500 Hz to 5 kHz), and 360 fs (5–10 kHz) for the Ti:sapphire/SBR laser. Below 1 kHz we have also observed the theoretically predicated $1/f^4$ dependence for the spectral noise density.[8] Previously Harvey *et al.*[17] reported that the timing jitter of a Rhodamine 6G DODCI colliding pulse mode-locked laser with two intracavity dye jets is as low as 5 ps (50–500 Hz). Their laser was pumped by a single-line Ar^+ laser at 3 W. Comparing their results with our results for the Ti: sapphire/SBR and Ti:sapphire/dye laser, we conclude that timing jitter due to flow instabilities and nozzle vibration is minimal. We also anticipate better phase noise figures from the Ti:sapphire/SBR laser because of its narrower gain window. A saturable absorber with a narrower gain window will provide a stronger pulse shortening force,[13] which will correctly amplify pulse peak and suppress random noise. The gain window for the Ti:sapphire/dye [excited-state lifetime of HITCI or IR140 dye, $\tau_{ext} \approx 200$ ps, Ref. 18] laser is approximately ten times wider than that for the Ti:sapphire/SBR ($\tau_{ext} \approx$ 20 ps with a fast component of 280 fs for the SBR) laser. Our results are also consistent with noise figures [$\sigma_j \approx 3.4$ ps (100–500 Hz)] for a KLM laser also pumped by an Ar^+ laser but at 3 W instead of 5 W.[4] Increasing pumping power from 5 W to 6.5 W, we find that σ_j for the Ti:sapphire/SBR laser rises monotonically from 6.0 to 8.5 ps. Extrapolating those data to 3 W, we expect the rms timing jitter of the Ti:sapphire/SBR laser to be identical to that of the KLM laser.

4. REDUCTION OF PHASE NOISE BY ACTIVE STABILIZATION

Our experimental setup for active timing stabilization is shown in Fig. 6. An optoelectronic phase-locked loop[14] was employed. The key component of optoelectronic phase-locked loop is a GaAs:Cr^+ photoconductive switch that acts as the OEHM. It is used for intermixing the Mth harmonics of the laser pulse train at f_0 with the reference (rf) signal biasing the switch to generate an intermediate frequency (IF) signal at $f_{IF} = Mf_0 - f_{RF}$, where M is an integer ($f_0 = 85$ MHz, $M = 12$, $f_{IF} = 340$ kHz). The average optical power incident upon the OEHM was 10 mW. The reference-frequency power biasing the switch was −5 dBm. The conversion loss (defined as the power ratio of the microwave to the intermediate-frequency signal) was 35 dB for $f_{RF} = 1020.34$ MHz. The intermediate-frequency signal was filtered, amplified, and fed to a phase comparator (Harris, ICL 8013), where it was compared in phase with another reference signal f_R. The intermediate-frequency reference signal was derived from the biasing reference frequency through a frequency divider (i.e., $f_R = f_{RF}/N$). The error signal generated from the phase comparator was then fed back to the piezoelectric transducer (Physik Instrumente P820.10) via a PID circuit for tracking the low-noise biasing reference-frequency signal from a frequency synthesizer (HP8662A). The bandwidths of the PID circuit and the piezoelectric transducer were experimentally measured to be 4 and 7 kHz, respectively. Examining the phase noise of both Ti:sapphire lasers shown as Figs. 4 and 5, we find that the major noise band contributing to timing jitter lies below 1 kHz. Thus the optoelectronic phase-locked loop should provide enough bandwidth for reduction of phase noise by active stabilization. Figures 4 and 5 also illustrate the single-sideband phase-noise spectra of the jitter-stabilized Ti:sapphire/dye and Ti:sapphire/SBR lasers. Significant reduction of the single-sideband phase noise is accomplished for frequencies below 500 Hz. The rms timing jitter of the stabilized Ti:sapphire/SBR laser when the twelfth harmonic is used is reduced by a factor of ~13 dB to 290 fs (100–500 Hz), 300 fs (500 Hz to 5 kHz), and 178 fs (5–10 kHz), respectively. For the Ti:sapphire/dye laser the rms timing jitter figures are also reduced by ~11.5 dB to 680 fs (100–500 Hz), 480 fs (500 Hz to 5 kHz), and 95 fs (5–10 kHz), respectively. The effectiveness of the active stabilization circuits is comparable with that in previous works. We expect the noise figure can be further improved by use of a diode-based solid-state green laser for pumping.

In our active stabilization scheme the OEHM replaces the photodiode and the biasing reference-frequency mixer–amplifier combination in conventional approaches pioneered by Rodwell *et al.*[19] It permits selection of almost any harmonic of the laser and the use of low-frequency electronics in the remainder of the phase-locked loop. The dark current is lower, as the switch was biased by an ac signal. Phase noise that is due to AM–PM conversion is also reduced, because the error signal was translated to an offset frequency. In conventional approaches AM–PM conversion is minimized by use of a chopper-stabilized phase detector,[19] which is more complicated. Another potential application of our approach is the synchronization of two mode-locked lasers through shining both lasers onto the OEHM. In conventional scheme two sets of stabilization circuits must be used.

5. CONCLUSIONS

In summary, we have characterized the phase noises (or timing jitter) of femtosecond Ti:sapphire lasers with intracavity dye saturable absorbers or saturable Bragg reflectors (SBR's). The significance of the finite lifetimes of the absorbers as gain windows on timing jitter is identified for the first time to our knowledge. We show that the rms timing fluctuation (100–500 Hz) of the free-running lasers can be suppressed significantly by optimization of intracavity gain bandwidth and group-velocity dispersion to 9.6 ps and 6.0 ps respectively. The physical mechanisms for the dependence of timing jitter on these parameters are explained. Qualitative agreements with existing theory are established. A new active stabilization technique, based on the use of an optoelectronic harmonic mixer in a phase-locked loop, is also demonstrated. The rms timing jitters (100–500 Hz) of the passively mode-locked Ti:sapphire/dye and Ti:sapphire/SBR lasers are reduced to approximately 650 and 290 fs, respectively.

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