Piezoelectric-transducer-based optoelectronic frequency synchronizer for control of pulse delay in a femtosecond passively mode-locked Ti:sapphire laser

Gong-Ru Lin, Yung-Cheng Chang, Tze-An Liu, and Ci-Ling Pan

We propose a piezoelectric transducer- (PZT-) based optoelectronic frequency synchronizer to control simultaneously changes in the repetition rate, the relative pulse delay, and the phase noise of a passively mode-locked femtosecond Ti:sapphire laser with an intracavity saturable Bragg reflector absorber with respect to an electronic frequency reference. An optoelectronic phase-locked-loop-based PZT feedback controller with a proportional, integral, and differential (PID) circuit and a tunable voltage regulator is designed to achieve frequency synchronization, phase-noise suppression, and delay-time tuning. When the controlling voltage is tuned from −2.6 to 2.6 V, the maximum pulse-delay range, tuning slope, and tuning resolution of the laser pulse-train are 11.3 ns, 2.3 ps/mV, and 1.2 ps, respectively. Setting the gain constant of the PID circuit at 10 or larger causes the delay-time tuning function to be linearly proportional to the controlling voltage. In the delay-time tuning mode the uncorrelated single-side-band phase-noise density of the frequency-synchronized laser is approximately −120 dBc/Hz at an offset frequency of 5 kHz, which is only 7 dBc/Hz higher than that of the electrical frequency reference. The proposed system also supports linear, continuous switching, and programmable control of the delay time of Ti:sapphire laser pulses when they are frequency synchronized to external reference clocks. © 2003 Optical Society of America

OCIS codes: 120.0120, 120.5050, 320.7160.

1. Introduction

Repetition rate, relative delay time, and phase-noise controls are the most important functions for synchronizing mode-locked Ti:sapphire lasers with electronic frequency references. Control of the repetition rate and the phase noise of passively mode-locked Ti:sapphire lasers relies strictly on stabilization of the cavity length the or pulse-repetition rate with respect to an ultralow phase-noise time base. To meet this demand, versatile feedback servo loops have been demonstrated for actively mode-locked Ti: sapphire lasers with frequency or phase tracked mode lockers[1] and for passively mode-locked Ti:sapphire lasers with slow saturable absorbers (for example, mixed of HITIC and IR140 dyes).[2] Recent progress with phase-locked loops in stabilizing the relative timing jitters between actively mode-locked Ti:sapphire lasers has come close to including the subfemtosecond regime.[2] However, control of the relative delay time between Ti:sapphire lasers and the electrical frequency reference is also important for applications such as free-space distribution of an optical clock, optical-time-division multiplexing communications, electro-optic sampling, and time-resolved spectroscopy. Typically, this control can be achieved by use of a reflection-type optomechanic delay line that externally adjusts the delay time of a laser pulse train by tuning the optical path length. Unfortunately, the need for time-consuming alignment and a bulky design disadvantages of such a true time-delay module that is meant to prevent the transverse shift in beam position that causes measuring distortions. To overcome these drawbacks, the attempts to control the pulse delay that is inherent in ultrafast lasers has aroused resurgent interest. Not long ago, a delay-time-tunable, actively mode-locked

The authors are with the Institute of Electro-Optic Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 300, Taiwan. G.-R. Lin's email address is grlin@faculty.nctu.edu.tw.

Received 8 October 2002; revised manuscript received 15 January 2003.
0003-6935/03/152843-06$15.00/0

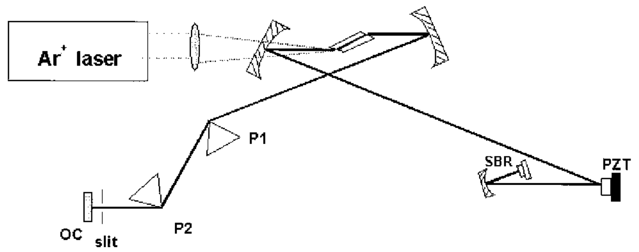

Fig. 1. Diagram of a typical passively mode-locked Ti:sapphire SBR laser: P1, P2, intracavity prism compensators; OC, optical coupler.

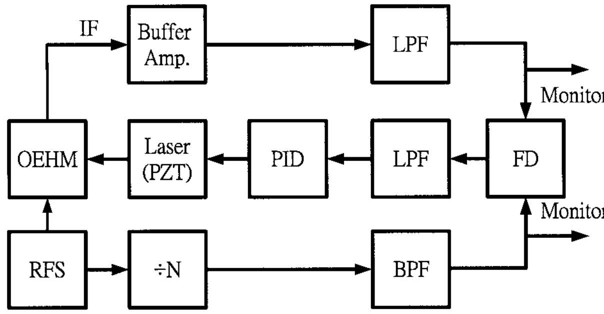

Fig. 2. Block diagram of a PZT-based optoelectronic stabilizer: ÷N: frequency divider with divisor N; Buffer Amp., buffered amplifier, BPF, bandpass filter; FD, frequency discriminator; LPF's, low-pass filters; RFS, referenced frequency synthesizer; other abbreviations defined in text.

Nd:YAG laser was demonstrated by phase shifting of the rf clock of a mode locker with an analog phase shifter.[3] A similar concept was recently employed to control the relative delay time of the pulse train from two individual Ti:sapphire lasers.[4] Most electrical pulse-delay schemes have been based on waveguide-type or voltage-controlled analog phase shifters with nonlinear (sinusoidal) function of the tuning voltage. To eliminate a nonlinear transfer function in an analog phase-shifting scheme, a modified phase-locked loop (PLL) technology has produced a digital and programmable phase shifter.[5] Subsequently, the new PLL phase shifter circuitry has been employed for *in situ* delay-time control of gain-switched semiconductor[6] and actively mode-locked fiber[7] lasers. However, such an inherent and programmable control of the delay time of passively mode-locked lasers has not yet been achieved with PLL phase shifters. Using a passively mode-locked Ti:sapphire laser with a slow saturable Bragg reflector (SBR) absorber (hereafter referred to as a Ti:sapphire/SBR laser) as an example, we describe an optoelectronic frequency synchronizer based on a piezoelectric transducer (PZT) integrated with a digital PLL phase shifter circuit to implement both the inherent delay-time-tuning and phase-noise-suppressing functions. By feedback control of the cavity length by means of a PZT adhesive end mirror and addition of a voltage-controlled phase-delay circuit the stabilizer, characteristics such as maximum delay time, tuning resolution, and linearity; pulse width; and minimum single-sideband phase-noise density of delayed laser pulses from a Ti:sapphire SBR laser are measured.

A passively mode-locked Ti:sapphire SBR laser with a standard six-mirror X-folded cavity is shown in Fig. 1; it consists of a 5-mm-long Ti:sapphire rod, a pair of SF10 prisms for intracavity dispersion compensation, a SBR as the folded reflector, an output coupler with 95% reflectivity, and a PZT adhesive planar mirror ($R > 99\%$) for active cavity stabilization. The laser was carefully aligned to prevent self-starting without a saturable absorber. We obtained the SBR by first growing a distributed Bragg reflector that comprised 15 pairs of $\lambda/4$-thick AlAs/$Al_{0.25}Ga_{0.75}As$ layers periodically changed from high to low refractive index, and a $\lambda/2$-thick $Al_{0.25}Ga_{0.75}As$ top layer.[8] Three strained InAlGaAs quantum wells with separated but sequential absorption peaks at adjacent wavelengths were deposited to extend the absorption linewidth.[2,9,10] The output power, pulse width, and repetition rate of the Ti:sapphire SBR laser at a pump power of 5 W (with an all-line large-frame argon-ion laser; Coherent Innova 400) are 250 mW, <100 fs, and 85 MHz, respectively. The Ti:sapphire rod and the SBR were both temperature regulated for control of the residual thermal fluctuation below 0.1 °C. A SBR with a narrower gain window provided a stronger pulse-shortening force to amplify the peak pulse and suppress random noise.[2] Before an experiment, the uncorrelated phase-noise density of a free-running Ti:sapphire SBR laser is optimized by tuning of the intracavity gain bandwidth and the group-velocity density by an intracavity optical slot. Figure 2 illustrates schematically an active optoelectronic frequency synchronizer that consists of an optoelectronic PLL-based frequency synchronizer, a proportional, integral, and differential (PID) controller,[2] and a tunable voltage regulator for simultaneous frequency synchronization, phase-noise suppression, and delay-time tuning. In the experiment the Ti:sapphire SBR laser is frequency synchronized to an ultralow-noise electrical frequency reference (Hewlett-Packard HP8662) by a frequency synchronizer. First, an optoelectronic harmonic mixer (OEHM) with a conversion loss (defined as the power ratio of the microwave to the intermediate-frequency signal) of 35 dB is used to mix the harmonic component of repetitive optical pulses from the Ti:sapphire SBR laser with an ultralow-noise frequency reference. The homemade OEHM is in general a GaAs photoconductive switch, which consists of a microwave transmission line with an optoelectronic interaction gate. The operating principle of the OEHM is shown in Fig. 3. The extension of discriminating frequency from fundamental to higher harmonics facilitates better frequency and phase tracking with suppressed phase noise. In our case the 12th harmonic of the laser pulse train (with a power of 10 mW) repeated at $f_0 = 82.342$ MHz is mixed with the reference signal ($f_{REF} = 988.104$ MHz, with a power of -5 dBm) in the OEHM to generate an intermediate frequency (IF) signal at

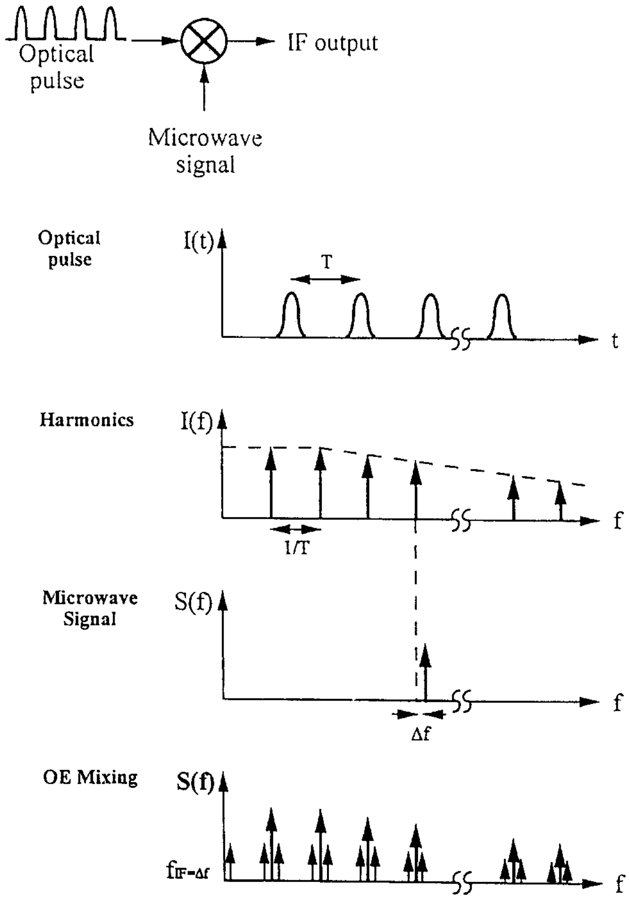

Fig. 3. Operating principle of the optoelectronic (OE) harmonic mixer illustrated in the frequency domain.

f_{IF} = 321.6 kHz. The operation of the PLL at the IF band will benefit from a better signal-to-noise ratio than that at the base band because the cutoff frequency of the Ti:sapphire laser noise spectrum is ~10 kHz. The IF signal was filtered, amplified, analog-to-digital converted, fed to a phase and frequency detector (Harris ICL8013 or Motorola MC4044), and then compared with the frequency-divided reference (frequency prescaled from the HP8662 reference) to generate a feedback signal (V_{err}). After passing through the PID circuit, signal V_{err} was used to control the PZT (Physik Instrumente, P820.10). The 3-dB frequency bandwidths of the PID circuit and the PZT were determined as 4 and 7 kHz, respectively. Offsetting signal V_{err} with dc voltage (V_{REF}) from a tunable voltage regulator[11] allowed the optical pulse train from the passively mode-locked Ti:sapphire SBR laser signal to be frequency synchronized but pulse-timing shifted with respect to the frequency reference. A high-speed photodetector (Antel AR-S2 with f_{3dB} = 18 GHz) in connection with a spectrum analyzer (HP 8560E; resolution bandwidth, 1 Hz) and a sampling oscilloscope (HP54750A) was used to monitor the phase-noise spectrum and the relative delay time of the optical pulse train. The pulse width and the optical spectrum of the laser tuned to different delay times were monitored by an autocorrelator and an optical spectrum analyzer, respectively. We further subtracted the fundamental from the 12th harmonic single-sideband (SSB) phase-noise spectrum to evaluate the relative timing jitter without the influence of intensity noise.[12]

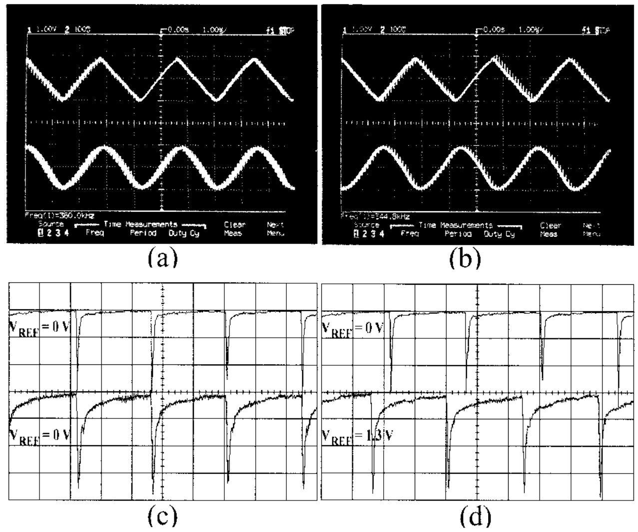

Fig. 4. Frequency-synchronized IF signals with (a) V_{REF} = 0 V (lower trace, in phase) and (b) V_{REF} = 2.6 V (lower trace), compared with those of the reference clock (upper trace, out of phase). The relative shifts in delay time of the laser pulse train (c) with V_{REF} = 0 V (lower trace) and (d) with V_{REF} = 1.3 V (lower trace) are compared with the original shifts (upper traces).

To characterize the performance of the PZT-based optoelectronic stabilizer in controlling the relative delay time between the laser pulse train and the reference clock, we monitored the IF signals from the OEHM and the frequency-prescaled reference clock. It can be seen from Fig. 4(a) that the two signals are in phase without a controlling voltage (V_{REF} = 0 V). By setting V_{REF} = 2.6 V we observed the downconverted IF trace (from the OEHM) to be nearly 180° out of phase with the reference clock; this corresponds to a leading shift in delay time of as much as 6.0 ns at a laser repetition frequency of 82.34 MHz, as shown in Fig. 4(b). Figures 4(c) and 4(d) further illustrate the measured shift in the real delay time of the optical Ti:sapphire SBR laser pulse train under different controlling voltages. In comparison with the upper trace, which defines the original pulse train, the lower trace in Fig. 4(c) reveals the in-phase laser pulse train at V_{REF} = 0 V, whereas the lower trace in Fig. 4(d) shows a leading pulse train with a relative delay time of ~3 ns at V_{REF} = 1.3 V.

It was previously established that the gain constant of a phase detector is a decisive circuit parameter in wide delay-time tuning with a PLL-based phase shifter. A digital phase frequency detector (PFD) is thus more suitable for the proposed system owing to its relatively larger phase sensitivity ($K_d \cong$ 1.141 V/rad) and phase-sensing range ($\theta_{PD} = 4\pi$) than those of analog PFDs (with $K_d \cong$ 0.89 V/rad and $\theta_{PD} = \pi$). We obtained the optimal circuit parameters by individually adjusting the gain and the band-

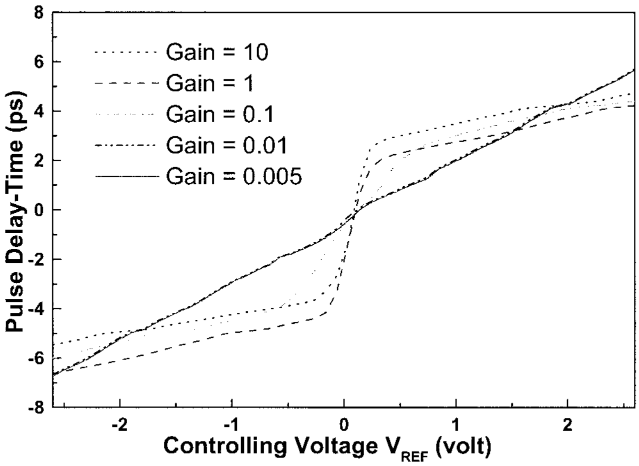

Fig. 5. Relative delay time of the passively mode-locked Ti:sapphire SBR laser pulse train as a function of controlling voltage (V_{REF}) measured at several gain constants of a PID circuit.

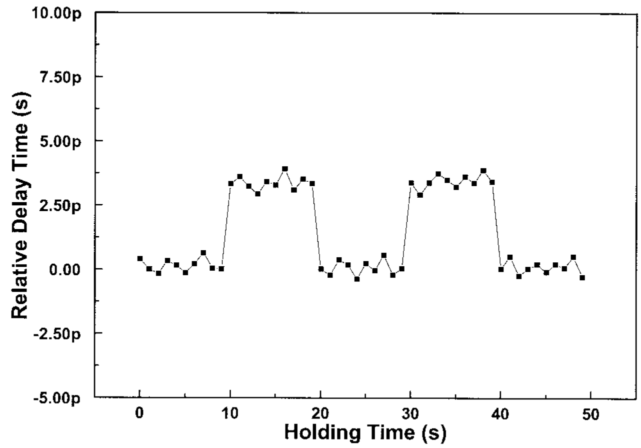

Fig. 7. Short-term switching and holding test for delay-time tuning of the passively mode-locked Ti:sapphire SBR laser pulse train.

width of the PID loop filter. The larger gain of the PID circuit, although it helps to suppress phase noise beyond the PID bandwidth, however, has restricted the scanning rate of the delay-time controlling process. Furthermore, the delay-time tuning function is in approximately linear proportion to V_{REF} only when the gain constant of the PID circuit is below 0.01, as shown in Fig. 5. That is, the largest and most stable delay-time tuning can be achieved in this case. As the gain constant increases to 0.1 or larger, the transfer function of the proposed system becomes nonlinear and varies with the shrinkage of the maximum delay-time tuning range. In addition, a saturation effect of the PID circuit that shrinks the delay-time tuning range becomes more pronounced as the gain constant of the PID circuit increases to 10 or larger. The relative delay time and repetition rate of the laser pulse train with respect to the microwave reference clock can be plotted as a function of controlling voltage by use of a lock-in detection technique. As shown in Fig. 6, the maximum delaying

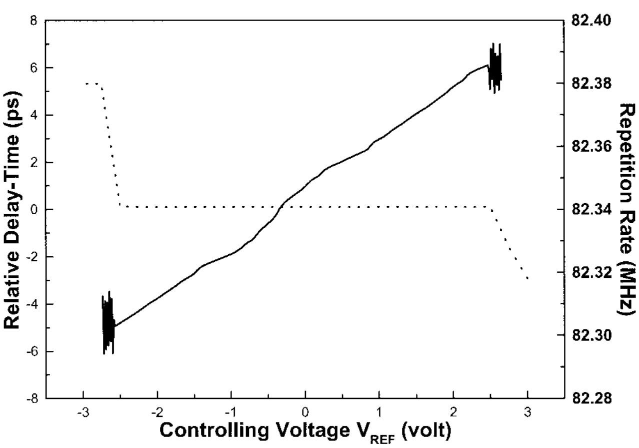

Fig. 6. Relative delay time (solid curve) and repetition rate (dotted curve) of the passively mode-locked Ti:sapphire SBR laser pulse train as a function of controlling voltage.

time is 11.3 ns for a tuning responsivity of 2.3 ns/V. However, the frequency-discriminating (or tracking) process can no longer be sustained as V_{REF} exceeds the limits (-2.6 V $< V_{REF} <$ 2.6 V), which inevitably randomizes the repetition frequency, phase, and delay time of a laser pulse train with respect to a microwave clock.

The accuracy and stability of delay-time tuning of a laser pulse train is characterized by a switching and holding test, as shown in Fig. 7. The switching period and the duty cycle are set as 20 s and 50%, respectively. Faster switching speeds of as much as 10 ms can be achieved but are, however, beyond the measuring limitations of lock-in detection. We observed that the phase-switching error of an optoelectronic PLL-type frequency synchronizer is $\sim 0.1°$, which is limited by the short-term drift in output voltage of a thermally stabilized high-precision regulator (National Semiconductors LM399 with a drifting slope of 3.4×10^{-3} °/min). Such a switching error corresponds to a change in delay time of ~ 1.2 ps. It is worth noting that a smaller tuning responsivity is required for obtaining a subpicosecond tuning resolution as small as 0.1 ps. Although this can resolution be achieved by use of a digital phase detector and a PID circuit that permits a larger input of controlling voltages (for example, V_{REF} can be at least ± 26 V), increasing the repetition rate of a Ti:sapphire laser by shortening its cavity length is an alternative approach.

In addition, the repetition frequency (f_{rep}) and the double-sided band spectrum of the laser operated at various values of V_{REF} were monitored by a spectrum analyzer with a resolution bandwidth of 1 Hz. For example, it is shown in Fig. 8 that f_{rep} remains invariant when V_{REF} varies from -1.3 to 1.3 V. Precise measurement of the repetition rate with a microwave frequency counter further confirms the frequency-discriminating stability of the PZT-controlled frequency synchronizer within ± 0.1 Hz. By measuring the 12th harmonic components of the laser pulse train ($f \cong 0.98$ GHz) with an average

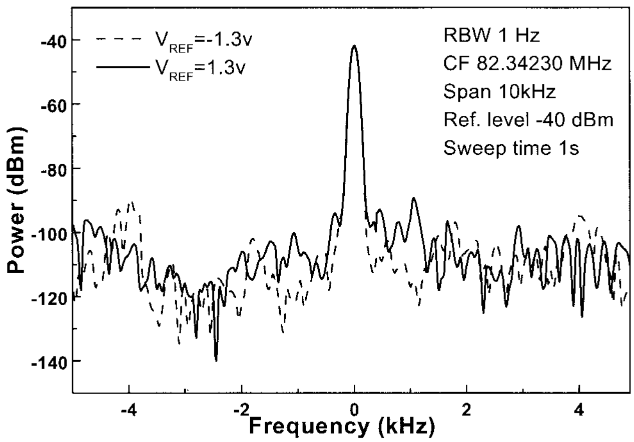

Fig. 8. Radio frequency spectra measured by monitoring of the optoelectronic-converted signal from the passively mode-locked Ti: sapphire SBR laser pulse train with its delay-time switching for two values of V_{REF}: RBW, resolution bandwidth; CF, center frequency.

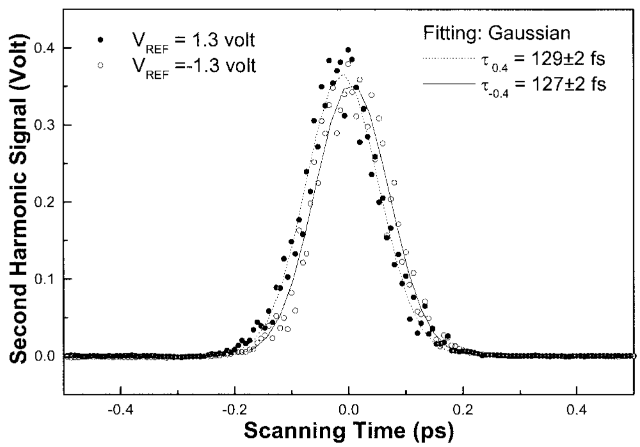

Fig. 10. Autocorrelated traces of passively mode-locked Ti:sapphire SBR laser pulses monitored at two controlling voltages.

photocurrent and a detected power level of 1 mA and >-25 dBm, respectively, we characterized the SSB phase-noise spectrum of the laser. Both correlated (with offset frequency $f_{\mathrm{off}} < 500$ Hz) and uncorrelated ($f_{\mathrm{off}} > 500$ Hz) phase-noise density of the Ti:sapphire SBR laser in controlling mode can be further reduced by 10 dB or more. We observed that the phase noise of the Ti:sapphire SBR laser reached the noise floor of the measurement apparatus (-120-dBc/Hz at an offset frequency of 5 kHz). The inverse frequency dependency (a $1/f^4$ relationship) below 1 kHz of the measured phase-noise spectra is also in good agreement with theoretical predictions.[2,11,12] We should also address the contribution of the OEHM to the PZT-based frequency synchronizer that permits the selection of much higher harmonics of the laser at relatively low intensity noise owing to its restricted AM–PM conversion and microwave biasing regime. Note that no significant degradation in noise performance of the laser during delay-time tuning was found. The nearly unchanged SSB phase-noise spectra that result from tuning V_{REF} from 1.3 to -1.3 V at a switching rate of ≥ 1 Hz) are shown in Fig. 9. Furthermore, the autocorrelated traces of the Ti:sapphire SBR laser pulses controlled at various values of V_{REF} are nearly identical to their FWHM of approximately 127–129 fs, as shown in Fig. 10. The stabilizer enjoys the advantages of a linear voltage-tuning function and programmable control not found in other circuitry.[13,14] The present scheme is also suitable for relative delay-time tuning of two individual mode-locked Ti:sapphire lasers.

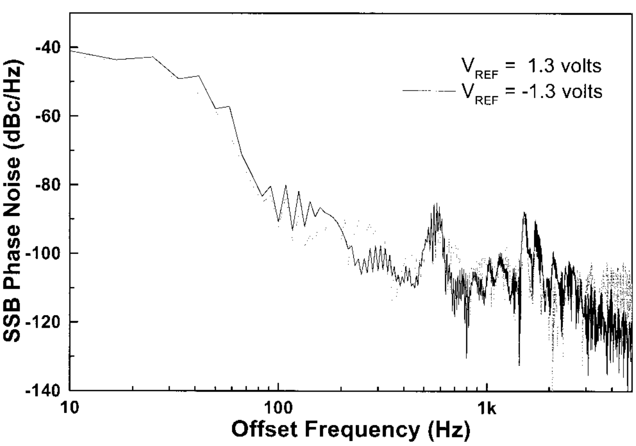

Fig. 9. SSB phase-noise density spectra of the 12th harmonic of the passively mode-locked Ti:sapphire SBR laser pulse train monitored at two controlling voltages.

In conclusion, we have demonstrated a novel PZT-controlled frequency synchronizer to implement a delay-time tunable, passively mode-locked Ti:sapphire saturable Bragg reflector laser. An optoelectronic phase-locked-loop-based PZT feedback controller with a proportional, integral, and differential controller and a tunable voltage regulator was designed to achieve simultaneously frequency synchronization, phase-noise suppression, and delay-time tuning. Adjusting the controlling voltage from -2.6 to 2.6 V provides optimal performance of the synchronizer in continuous delay-time tuning with maximum delay range, tuning responsivity, and tuning resolution of 11.3 ns, 2.3 ps/mV, and 1.2 ps, respectively. The delay-time tuning function is linearly proportional to the controlling voltage when the gain constant of the PID circuit is set at 10 or larger. Our system facilitates linear, continuous, switching, and programmable control of delay times of Ti:sapphire laser pulses when it is frequency synchronized to external reference clocks. In feedback control mode, the pulse width, the repetition rate, and the single-sideband phase noise of a Ti:sapphire SBR laser remained invariant during delay-time tuning or switching. Synchronization and relative delay-time tuning between two mode-locked Ti:Sapphire lasers by use of the proposed scheme is straightforward.

This research was supported in part by the National Science Council of the Republic of China under grants NSC90-2215-E-027-008 and NSC91-2215-E-009-039.

References

1. R. K. Shelton, S. M. Foreman, L.-S. Ma, J. L. Hall, H. C. Kapteyn, M. M. Murnane, M. Notcutt, and J. Ye, "Subfemtosecond timing jitter between two independent, actively synchronized, mode-locked lasers," Opt. Lett. **27,** 312–314 (2002).
2. J.-M. Shieh, S.-C. Liu, and C.-L. Pan, "Characterization and reduction of phase noise in passively mode-locked Ti:sapphire lasers with intracavity saturable absorbers," J. Opt. Soc. Am. B **15,** 1802–1806 (1998).
3. C. K. Johnson and J. Qian, "Picosecond laser timing by rf phase shifting," Rev. Sci. Instrum. **61,** 1158–1160 (1990).
4. L.-S. Ma, R. K. Shelton, H. C. Kapteyn, M. M. Murnane, and J. Ye, "Sub-10-femtosecond active synchronization of two passively mode-locked Ti:sapphire laser oscillators," Phys. Rev. A **64,** 021802 (2001).
5. G.-R. Lin, T.-S. Hwang, Y.-H. Chuang, S.-C. Wang, and C.-L. Pan, "Broad-band ($\geq$20 GHz) laser-diode-based optoelectronic microwave phase shifter," IEEE Trans. Microwave Theory Tech. **46,** 1419–1426 (1998).
6. G.-R. Lin, "Optoelectronic delay-time controller for laser pulses," Opt. Lett. **25,** 799–801 (2000).
7. G.-R. Lin and Y.-L. Cheng, "Tuning the delay-time of harmonically mode-locked erbium-doped fiber laser pulses by a frequency-discriminated phase shifter," Microwave Opt. Technol. Lett. **30,** 168–170 (2001).
8. J.-M. Shieh, T.-C. Huang, K.-F. Huang, C.-L. Wang, and C.-L. Pan, "Broadly tunable self-starting passively mode-locked Ti:sapphire laser with a triple-strained quantum-well saturable Bragg reflector," Opt. Commun. **156,** 53–57 (1998).
9. S. Tsuda, W. H. Knox, S. T. Cundiff, W. Y. Jan, and J. E. Cunningham, "Mode-locking ultrafast solid-state lasers with saturable Bragg reflectors," IEEE J. Sel. Top. Quantum Electron. **2,** 454–464 (1996).
10. M. J. Hayduk, S. T. Johns, M. F. Krol, C. R. Pollock, and R. P. Leavitt, "Self-starting passively mode-locked tunable femtosecond Cr^{4+}:YAG laser using a saturable absorber mirror," Opt. Commun. **137,** 55–58 (1997).
11. D. E. Spence, J. M. Dudley, K. Lamb, W. E. Sleat, and W. Sibbett, "Nearly quantum-limited timing jitter in a self-mode-locked Ti:sapphire laser," Opt. Lett. **19,** 481–483 (1994).
12. H. A. Haus and A. Mecozzi, "Noise of mode-locked lasers," J. Quantum Electron. **29,** 983–996 (1993).
13. G.-R. Lin and Y.-C. Chang, "Demonstration and optimization of an optoelectronic phase-locked phase shifter for optical microwave signals," IEEE Photon. Technol. Lett. **12,** 1555–1557 (2000).
14. D. Von der Linde, "Characterization of the noise in continuously operating mode-locked lasers," Appl. Phys. B **39,** 201–217 (1986).