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Control of the state of a mode-locked fiber laser using an intracavity Martinez compressor

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An intracavity Martinez compressor is incorporated into a fiber laser as a dispersion compensator and spectral filter. The Martinez compressor provides tunable dispersion from normal to anomalous. Inserting a mechanically adjustable slit into the compressor enables tunable spectral filtering independent of dispersion compensation. Mode-locking is achieved with laser bandwidths from 1.8 to 49.0 nm and compressor dispersions from +0.008 to –0.072 ps^2. The laser generates stable pulses with 0.9 nJ pulse energy, a fundamental repetition rate of 77.5 MHz, and dechirped FWHM pulse widths as short as 82 fs. © 2016 Optical Society of America

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Fiber lasers are important for communications, materials processing, microscopy, and optical metrology. Mode-locked Yb fiber lasers are particularly attractive due to their high gain, low quantum defect, and broad gain bandwidth [1–5]. Such fiber lasers can operate in a variety of regimes, ranging from soliton [6] to dissipative soliton [7] or self-similar operation [3,8,9]. The type of pulse generation depends on the interaction of dispersion, power, mode-locking mechanism, and spectral filtering in the cavity. The performance can be predicted using split-step numerical modeling [8,10] or analytical models such as the complex cubic-quintic Ginzburg–Landau equation [11,12]. However, applying simulation results to real-world device specifications can be challenging. Tunable dispersion and spectral filtering components can relax these specification requirements [13].

In many cases, pump power or output coupling strength can be varied to modify the intracavity power. The modulation from nonlinear polarization rotation can also be adjusted with wave plate orientation. Tuning the dispersion in the cavity can be less straightforward, particularly for Yb-fiber lasers operating in the 1 μm range, where anomalous dispersion fibers are hard to obtain. Some options include higher-order fiber mode propagation [14], photonic crystal fibers [15], and chirped mirrors. Chirped fiber Bragg gratings [16,17] provide set dispersion compensation while also acting as a bandpass filter/output coupler. However, each solution provides a fixed, non-tunable amount of dispersion, requiring *a priori* knowledge of the net cavity dispersion and an optimal operating point. Tunable dispersion compensation can be provided by grating pairs [13], but they provide only anomalous dispersion and can have difficulty supplying small amounts of dispersion (< -0.01 ps^2). Prism pairs can be a good solution for providing these small values. Conversely, they have difficulty supplying larger amounts of dispersion to reach the net anomalous regime, especially in a laser with a short cavity length. The Martinez compressor described in this Letter provides a nice tunable solution, with a large range of accessible dispersion values from normal to anomalous. Dispersion magnitudes from zero to ~0.2 ps^2 are within reach.

In addition, spectral filtering in the cavity is necessary for self-similar pulses and dissipative solitons. Both of these are attractive operating regions for fiber lasers, as they enable short pulses in the normal dispersion regime with large pulse energies. Self-similar mode-locking requires resetting the asymptotic spectral growth of the pulse in the cavity during every round-trip [8], so a spectral filter with a width that balances the other pulse shaping effects is required to enable stable pulses. However, finding the optimum bandwidth requires numerical simulations. Similarly for dissipative solitons, a spectral filtering effect is required to convert the intracavity chirp to self-amplitude modulation and, thus, guide the pulse evolution [16,17]. While dissipative solitons approach a fixed soliton solution in a laser cavity, and self-similar pulses grow asymptotically as broad as the gain bandwidth allows, both require spectral filtering for stable operation [18]. Common implementations of spectral filters include fiber Bragg gratings [19,20], birefringent filters [21], or diffraction gratings placed before a collimator [9,22]. Unfortunately, these options do not allow for continuous tuning of both the center wavelength and the filter bandwidth. An attractive alternative is presented in this Letter. Our Martinez compressor [23] system allows for continuous dispersion tuning through the normal and anomalous regime, along with adjustable spectral filtering of both the center wavelength and the bandwidth. While the Martinez compressor for intracavity dispersion compensation has been previously demonstrated [24,25], the simultaneous utility as both a high-precision tunable spectral filter and a dispersion compensator has not been shown. The ability to continuously adjust the dispersion and filter bandwidth of the laser with a single device is a powerful tool for laser optimization in both normal and anomalous dispersion regimes. We demonstrate the device in a high-repetition-rate Yb-fiber laser over a large continuous range of dispersions and spectral filter bandwidths. The direct control of the spectral filter bandwidth using the device allows us to select pulse widths from fs to ps from +0.04 to –0.04 ps^2 cavity dispersion. To the best of our knowledge, this is the first implementation of such a Martinez compressor spectral filter in a mode-locked fiber laser system.

We designed the laser system as a high-repetition-rate master oscillator for a synchronously pumped optical parametric oscillator. The laser setup is shown in Fig. 1. The fiber portion of the cavity consists of ∼1 m of a normally dispersive single-mode fiber, with 60 cm of an active Yb-doped fiber, 532 dB/m at 976 nm (CorActive Yb-164), and 40 cm of passive Corning HI-1060. The net fiber dispersion in the cavity is +0.033 ps^2. The free-space portion contains polarization optics and a Martinez compressor [23], along with an isolator to ensure unidirectional operation. A 500 mW single-mode 976 nm fiber-coupled diode pumps the fiber through a dichroic mirror. Mode-locking is achieved with nonlinear polarization evolution (NPE) using wave plates and a polarizing beam splitter (PBS). An additional PBS serves as the tunable output coupler to avoid the issue of lower pulse quality from the NPE rejection port. The Martinez compressor consists of a 600 lines/mm grating, 100 mm focal length lens, and a mirror placed one focal length

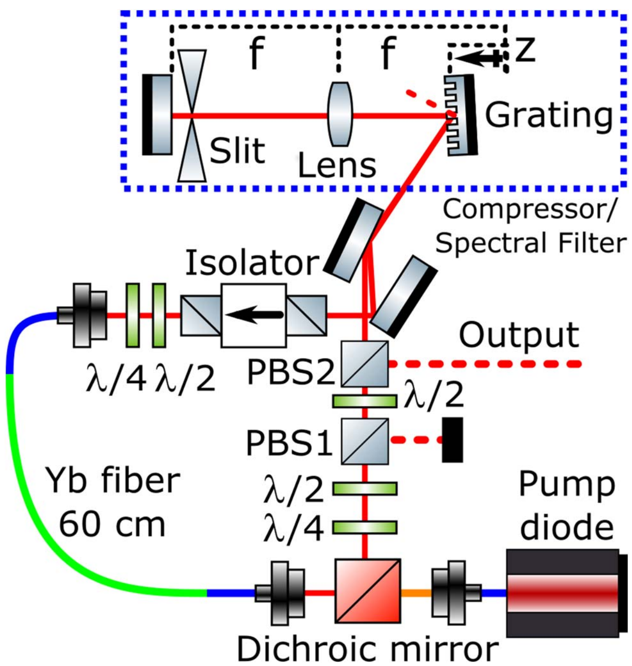

Fig. 1. Yb-fiber ring laser schematic. $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate; PBS1, polarizing beam splitter cube, NPE pump; PBS2, polarizing beam splitter cube, laser output; DM, dichroic mirror for pump coupling. The Martinez compressor is outlined in a blue, grating-lens-slit-mirror. Positive z corresponds to normal dispersion, while negative z provides anomalous. Setting the aperture slit width at the mirror provides an adjustable spectral filter.

away from the lens. By translating the grating toward or away from the lens (or by extension translating the lens/slit/mirror system toward/away from the grating), group velocity dispersion (GVD) is imparted on the outgoing beam. The GVD from this device was calculated using

$$\left.\frac{d^2\phi}{d\Omega^2}\right|_{\omega_l} = \frac{\omega_l}{c}\left(\left.\frac{d\alpha}{d\Omega}\right|_{\omega_l}\right)^2 z, \qquad \left.\frac{d\alpha}{d\Omega}\right|_{\omega_l} = \frac{-2\pi c}{\omega_l{}^2 d \cos\beta}, \quad (1)$$

where z is the deviation of the grating position from the lens focal point, d is the grating groove spacing, β is the incident angle on the grating, ω_l is the center frequency of the pulse, c is the speed of light, and $\frac{d\alpha}{d\omega}$ is the angular dispersion from the grating with respect to the frequency [26]. If the lens-mirror distance is kept equal to the focal length of the lens; the actual value for that focal length does not enter into the dispersion calculation. The Martinez compressor in this system can add tunable cavity dispersion from +0.14 to –0.21 ps^2. Continuous mode-locking operation in the laser under test was maintained with device dispersion from +0.008 to –0.072 ps^2. While a device that provides only anomalous dispersion such as a standard grating compressor can allow a fiber laser to operate still in net normal dispersion, the anomalous and normal range available with the Martinez compressor allows the far normal regime to be investigated, even with short fibers, while also allowing operation at zero GVD. An adjustable slit at the compressor mirror provides a continuously tunable spectral filter with bandwidths ranging from zero to 80 nm with 0.2 nm resolution.

This laser is ideally suited for dispersion compensation from a Martinez compressor, which can provide a large range of dispersions from normal to anomalous, as well as close to zero, with a resolution of 0.4 fs^2. The laser is particularly sensitive to spectral filter adjustments at large normal cavity dispersions (∼ + 0.03 ps^2) near-zero compressor dispersion. With the Martinez compressor, the spatial chirp at the back mirror is the same, regardless of the GVD. The spatial chirp is given by the angular spread from the grating, effectively decoupling the spectral filter from dispersion adjustments. This independent tunability in the Martinez compressor further aids in mode-locking optimization.

By adjusting the spectral filter at a given laser state, the output pulse width can be tuned continuously with only minor variations in the output pulse chirp. This performance is shown at ∼ + 0.003 ps^2 cavity dispersion in Fig. 2. Similar tuning can be performed at other dispersion values, limited only by the maximum bandwidth at a given state. Thus, the pulse width of the laser can be tuned continuously with only minor variations in power and chirp. The 0.2 nm bandwidth resolution of the spectral filter corresponds to a pulse width a tunability resolution from several femtoseconds down to tenths of a femtosecond, depending on the output bandwidth.

The Martinez compressor has many advantages over a grating pair. After a single pass through a grating pair at low dispersion, the spatial chirp on the beam is small and, therefore, the spectral filter resolution is poor. At the focus of the lens in a Martinez compressor at the same low dispersion, the spatial chirp can be quite large, allowing high spectral filter resolution. For a Martinez compressor at close to zero dispersion (–0.003 ps^2), an aperture with 0.001" mechanical resolution has a 0.2 nm spectral filter resolution. That same aperture in a grating pair at the same dispersion would have a spectral resolution of 16 nm. The Martinez compressor spectral filter

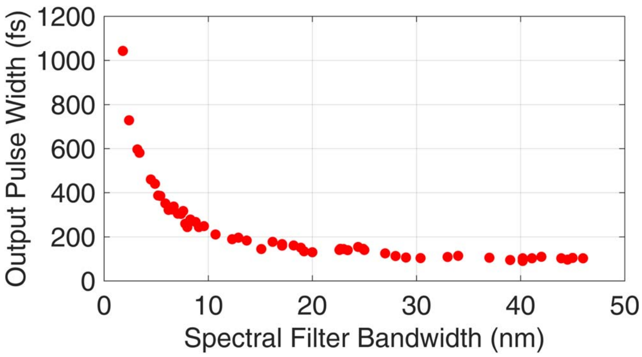

Fig. 2. Compressed output pulse width as tuned using the intracavity spectral filter bandwidth at ~0.003 ps^2 cavity dispersion. A similar performance can be achieved at other dispersion points. Adjusting the filter bandwidth here results in the pulse width tuning from <100 fs to more than a picosecond without a loss of mode-locking.

enables exquisite control of both the center wavelength and the bandwidth over the full dispersion range.

Optimizing the oscillator requires careful adjustment of the cavity dispersion and the spectral filter bandwidth. Here, we optimized for maximum 3 dB bandwidth while being mode-locked. The NPE and output coupler wave plates were also adjusted to maintain stable performance. The widest bandwidths were found close to zero cavity dispersion, as expected. It should be noted that while the laser shown here is mode-locked by NPE, tunable performance was also achieved using the Martinez compressor/spectral filter in the laser mode-locked by a semiconductor saturable absorber mirror. The choice of the mode-locking mechanism when using this device should have minimal impact on performance.

The power of our technique is shown in Fig. 3. Mode-locking was achieved continuously for net cavity dispersions from +0.04 to −0.04 ps^2, corresponding to Martinez compressor dispersions of +0.008 to −0.072 ps^2. All points shown correspond to high output pulse quality. The filter bandwidth, NPE strength, and output coupler efficiency were all continuously adjusted to maintain mode-locking throughout the dispersion range with the goal of maximizing the spectral bandwidth at each point. Mode-locking was maintained into the normal-dispersion regime of the Martinez compressor. In the cavity net normal regime, the maximum spectral bandwidth tuned from 10.0 nm in the far normal (+0.04 ps^2) to 49.0 nm at ~zero dispersion. Mode-locked operation in the anomalous regime could also be achieved, with maximum bandwidths from 49.0 nm at again close to zero dispersion to 22.2 nm in the far anomalous (−0.04 ps^2). At each dispersion point, the spectrum could also be tuned continuously using the spectral filter to bandwidths of ~1 nm, depending weakly on dispersion.

At close-to-zero cavity dispersion, the spectral filter slit is fully opened, and only weak Gaussian spectral filtering due to outgoing spatial chirp from the compressor remains (here at −0.028 ps^2 compressor dispersion). At nonzero dispersion, the Martinez compressor imparts some spatial chirp on the outgoing beam due to the single-pass-grating geometry. Coupling this return light into a collimator introduces an additional weak Gaussian spectral filter into the system. This effect is slight and does not significantly affect cavity performance. In the normal dispersion regime, the extra filter has a bandwidth ranging from 60–100 + nm and does not impact laser performance. In the anomalous regime from −0.033 to −0.072 ps^2 of compressor dispersion, the filter bandwidth is ~35–40 nm, significantly larger than the ~20–30 nm laser 3 dB bandwidth there. Near-zero net dispersion, the operating bandwidth is ~49 nm while the filter bandwidth is ~52 nm. This near-zero dispersion point is the only place where the collimation filter impacts the laser performance. It has the effect of smoothing the long wavelength edge of the spectrum, as seen in Fig. 3.

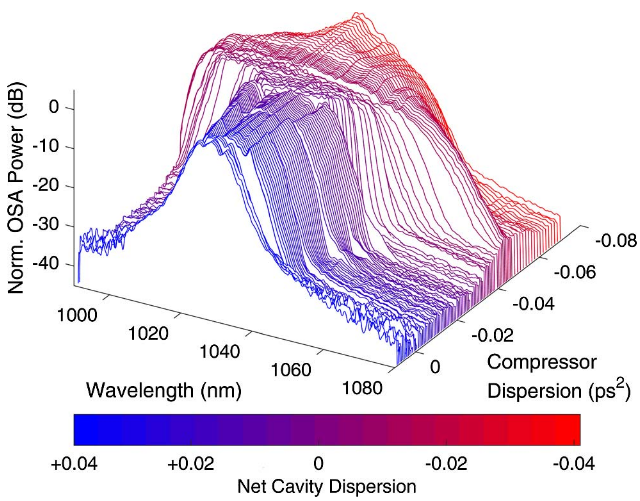

Fig. 3. Mode-locked laser spectra as compressor dispersion continuously tunes from normal through zero to anomalous. The spectral filter bandwidth is tuned to maintain mode-locking while maximizing the bandwidth at every point. The net normal dispersion is toward the bottom of the plot (blue), while the net anomalous is toward the top (red).

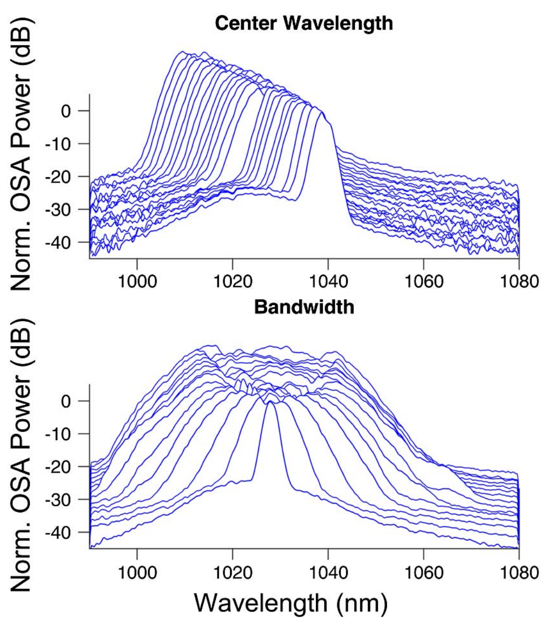

Fig. 4. (a) Laser can be tuned from 1011.9 to 1038.8 nm by adjusting the center position of the spectral filter. The laser operates at near-zero dispersion at ~ + 0.002 ps^2 with a spectral filter bandwidth of 5 nm. (b) Spectra as a function of the bandwidth of the spectral filter, ranging from 37 to ~2 nm. The dispersion is the same as in (a).

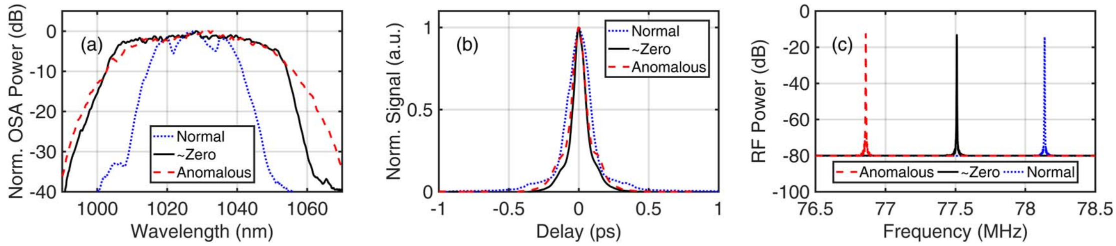

Fig. 5. Example laser states, normal dispersion (+0.015 ps^2, blue), ~zero dispersion (–0.002 ps^2, black), anomalous dispersion (–0.026 ps^2, red): (a) log spectra, (b) intensity autocorrelations, and (c) RF spectra of fundamental repetition frequency, >65 dB above the noise floor. The repetition frequency changes as the Martinez compressor changes length with dispersion.

Table 1. Laser Performance at Normal, ~Zero, and Anomalous Cavity Dispersion

Cavity Dispersion (ps^2)	Average Power (mW)	Repetition Rate (MHz)	Laser 3 dB Bandwidth (nm)	Pulse Width (fs)
+0.015	73	78.1	25.7	135
–0.002	75	77.5	40.0	82
–0.026	82	76.9	20.5	97

Figure 4 illustrates our ability to continuously tune the optimum operating bandwidth (37.3 to 1.8 nm) and the center wavelength (1011.9 to 1038.8 nm). These tests were performed at low normal dispersion, $\sim + 0.002$ ps^2, as there the spectrum was still quite broad, but required the spectral filter for mode-locking. Adjusting the center wavelength of the laser within the amplified spontaneous emission bandwidth did not impact the stability of the mode-locking operation state. Decreasing the spectral filter bandwidth below ~1 nm resulted in the loss of mode-locking. Representative data from the laser are shown in Figs. 5(a)–5(c) at three dispersion points, designated normal (+0.015 ps^2), ~zero (–0.002 ps^2), and anomalous (–0.026 ps^2) cavity dispersion, illustrating the versatility of the Martinez compressor and spectral filter. The performance values for each example state are given in Table 1.

We have experimentally demonstrated an intracavity Martinez compressor for dispersion compensation and tunable spectral filtering in a mode-locked Yb-fiber laser. We have achieved stable mode-locking operation from –0.04 to +0.04 ps^2 of net cavity dispersion and bandwidths of the mechanical spectral filter from 2 to 40 nm, with a maximum optical bandwidth of 49.0 nm. This laser makes use of the Martinez compressor's unique ability to provide tunable normal dispersion, mode-locking with compressor dispersion as far normal as +0.008 ps^2. The ability to continuously tune a mode-locked laser's state through a range of dispersion points and filter bandwidths provides a robust tool for further investigation of pulse propagation in fiber lasers, as well as simplifying normal dispersion laser design for future applications.

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REFERENCES

1. A. Chong, W. H. Renninger, and F. W. Wise, J. Opt. Soc. Am. B **25**, 140 (2008).
2. B. Oktem, C. Ülgüdür, and F. Ö. Ilday, Nat. Photonics **4**, 307 (2010).
3. C. K. Nielsen, B. Ortaç, T. Schreiber, J. Limpert, R. Hohmuth, W. Richter, and A. Tünnerman, Opt. Express **13**, 9346 (2005).
4. A. Hideur, T. Chartier, M. Brunel, M. Salhi, C. Özkul, and F. Sanchez, Opt. Commun. **198**, 141 (2001).
5. J. Liu, J. Xu, and P. Wang, IEEE Photon. Technol. Lett. **24**, 539 (2012).
6. A. Isomäki and O. G. Okhotnikov, Opt. Express **14**, 4368 (2006).
7. L. Zhao, D. Tang, X. Wu, and H. Zhang, Opt. Lett. **35**, 2756 (2010).
8. F. Ö. Ilday, J. R. Buckley, W. G. Clark, and F. W. Wise, Phys. Rev. Lett. **92**, 213902 (2004).
9. W. H. Renninger, A. Chong, and F. W. Wise, Phys. Rev. A **82**, 021805 (2010).
10. A. C. Peacock, R. J. Kruhlak, J. D. Harvey, and J. M. Dudley, Opt. Commun. **206**, 171 (2002).
11. J. M. Soto-Crespo, N. N. Akhmediev, V. V. Afanasjev, and S. Wabnitz, Phys. Rev. E **55**, 4783 (1997).
12. N. N. Akhmediev, V. V. Afanasjev, and J. M. Soto-Crespo, Phys. Rev. E **53**, 1190 (1996).
13. L. Nugent-Glandorf, T. A. Johnson, Y. Kobayashi, and S. A. Diddams, Opt. Lett. **36**, 1578 (2011).
14. J. W. Nicholson, S. Ramachandran, and S. Ghalmi, Opt. Express **15**, 6623 (2007).
15. Z. Zhang, Ç. Şenel, R. Hamid, and F. Ö. Ilday, Opt. Lett. **38**, 956 (2013).
16. K. Ling-Jie, X. Xiao-Sheng, and Y. Chang-Xi, Chin. Phys. B **21**, 094210 (2012).
17. B. G. Bale, J. N. Kutz, A. Chong, W. H. Renninger, and F. W. Wise, J. Opt. Soc. Am. B **25**, 1763 (2008).
18. P. Grelu and N. Akhmadiev, Nat. Photonics **6**, 84 (2012).
19. B. Ortaç, M. Plötner, T. Schreiber, J. Limpert, and A. Tünnermann, Opt. Express **15**, 15595 (2007).
20. I. Hartl, T. R. Schibli, A. Marcinkevicius, D. C. Yost, D. D. Hudson, M. E. Fermann, and J. Ye, Opt. Lett. **32**, 2870 (2007).
21. Y. S. Fedotov, S. M. Kobtsev, R. N. Arif, A. G. Rozhin, C. Mou, and S. K. Turitsyn, Opt. Express **20**, 17797 (2012).
22. C. Li, G. Wang, T. Jiang, P. Li, A. Wang, and Z. Zhang, Opt. Lett. **39**, 1831 (2014).
23. O. E. Martinez, IEEE J. Quantum Electron. **23**, 59 (1987).
24. I. Hartl, A. Romann, and M. Fermann, *Conference on Lasers and Electro-Optics (CLEO)* (IEEE, 2011), paper CMD3
25. M. Baumgartl, B. Ortaç, J. Limpert, and A. Tünnermann, Appl. Phys. B **107**, 263 (2012).
26. J. C. Diels and W. Rudolph, *Ultrashort Laser Pulse Phenomena* (Academic, 2006).

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