Dispersion management in femtosecond laser oscillators with highly dispersive mirrors

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Abstract: Recently the manufacture of highly dispersive mirrors with −1300 fs^2 group delay dispersion per reflection was reported. Here we demonstrate the intracavity applicability of these novel mirrors in Ti:sapphire oscillators for the first time, as well as their capability of compensating a substantial amount of material dispersion in the cavity (40 mm fused silica). We also studied the influence of net negative cavity dispersion, realized with these mirrors, on the achievable maximum pulse energy in long-cavity femtosecond oscillators before the onset of anomalous behavior (e.g. multi-pulsing). In addition, we demonstrate a 0.5 GHz Ti:sapphire oscillator the dispersion compensation of which is realized with a single highly dispersive mirror.

OCIS codes: (320.7090) Ultrafast lasers; (310.1620) Interference coatings.

References and links

1. R. Szipőcs, K. Ferencz, C. Spielmann, and F. Krausz, "Chirped multilayer coatings for broadband dispersion control in femtosecond lasers," Opt. Lett. **19**(3), 201–203 (1994).
2. F. X. Kärtner, N. Matuschek, T. Schibli, U. Keller, H. A. Haus, C. Heine, R. Morf, V. Scheuer, M. Tilsch, and T. Tschudi, "Design and fabrication of double-chirped mirrors," Opt. Lett. **22**(11), 831–833 (1997).
3. G. Tempea, V. Yakovlev, B. Bacovic, F. Krausz, and K. Ferencz, "Tilted-front-interface chirped mirrors," J. Opt. Soc. Am. B **18**(11), 1747–1750 (2001).
4. P. Dombi, A. Apolonski, Ch. Lemell, G. G. Paulus, M. Kakehata, R. Holzwarth, Th. Udem, K. Torizuka, J. Burgdörfer, T. W. Hänsch, and F. Krausz, "Direct measurement and analysis of the carrier-envelope phase in light pulses approaching the single-cycle regime," N. J. Phys. **6**, 39 (2004).
5. N. Matuschek, L. Gallmann, D. H. Sutter, G. Steinmeyer, and U. Keller, "Back-side-coated chirped mirrors with ultra-smooth broadband dispersion characteristics," Appl. Phys. B **71**(4), 509–522 (2000).
6. P. Dombi, V. S. Yakovlev, K. O'Keeffe, T. Fuji, M. Lezius, and G. Tempea, "Pulse compression with time-domain optimized chirped mirrors," Opt. Express **13**(26), 10888–10894 (2005).
7. G. Steinmeyer, "Brewster-angled chirped mirrors for high-fidelity dispersion compensation and bandwidths exceeding one optical octave," Opt. Express **11**(19), 2385–2396 (2003).
8. S. Rausch, T. Binhammer, A. Harth, J. Kim, R. Ell, F. X. Kärtner, and U. Morgner, "Controlled waveforms on the single-cycle scale from a femtosecond oscillator," Opt. Express **16**(13), 9739–9745 (2008).
9. R. Paschotta, G. J. Spühler, D. H. Sutter, N. Matuschek, U. Keller, M. Moser, R. Hövel, V. Scheuer, G. Angelow, and T. Tschudi, "Double-chirped semiconductor mirror for dispersion compensation in femtosecond lasers," Appl. Phys. Lett. **75**(15), 2166–2168 (1999).
10. F. Gires, and P. Tournois, "Interferometre utilisable pour la compression d'impulsions lumineuses modulees en frequence," C. R. Acad. Sci. Paris **258**, 6112 (1964).
11. I. T. Sorokina, E. Sorokin, E. Wintner, A. Cassanho, H. P. Jenssen, and R. Szipőcs, "Prismless passively mode-locked femtosecond Cr:LiSGaF laser," Opt. Lett. **21**(15), 1165–1167 (1996).
12. R. Szipőcs, A. Köházi-Kis, S. Lakó, P. Apai, A. P. Kovács, G. DeBell, L. Mott, A. W. Louderback, A. V. Tikhonravov, and M. K. Trubetskov, "Negative Dispersion Mirrors for Dispersion Control in Femtosecond Lasers: Chirped Dielectric Mirrors and Multi-cavity Gires-Tournois Interferometers," Appl. Phys. B **70**, S51–S57 (2000).
13. B. Golubovic, R. R. Austin, M. K. Steiner-Shepard, M. K. Reed, S. A. Diddams, D. J. Jones, and A. G. Van Engen, "Double Gires-Tournois interferometer negative-dispersion mirrors for use in tunable mode-locked lasers," Opt. Lett. **25**(4), 275–277 (2000).
14. V. Pervak, S. Naumov, F. Krausz, and A. Apolonski, "Chirped mirrors with low dispersion ripple," Opt. Express **15**(21), 13768–13772 (2007).

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15. V. Pervak, C. Teisset, A. Sugita, S. Naumov, F. Krausz, and A. Apolonski, “High-dispersive mirrors for femtosecond lasers,” Opt. Express **16**(14), 10220–10233 (2008).
16. S. Naumov, A. Fernandez, R. Graf, P. Dombi, F. Krausz, and A. Apolonski, “Approaching the microjoule frontier with femtosecond laser oscillators,” N. J. Phys. **7**, 216 (2005).
17. http://www.femtolasers.com
18. X. B. Zhou, H. Kapteyn, and M. Murnane, “Positive-dispersion cavity-dumped Ti: sapphire laser oscillator and its application to white light generation,” Opt. Express **14**(21), 9750–9757 (2006).
19. M. Siegel, N. Pfullmann, G. Palmer, S. Rausch, T. Binhammer, M. Kovacev, and U. Morgner, “Microjoule pulse energy from a chirped-pulse Ti:sapphire oscillator with cavity dumping,” Opt. Lett. **34**(6), 740–742 (2009).
20. T. Südmeyer, S. V. Marchese, S. Hashimoto, C. R. E. Baer, G. Gingras, B. Witzel, and U. Keller, “Femtosecond laser oscillators for high-field science,” Nat. Photonics **2**(10), 599–604 (2008).
21. P. Dombi, P. Antal, J. Fekete, R. Szipőcs, and Z. Várallyay, “Chirped-pulse supercontinuum generation with a long-cavity Ti:sapphire oscillator,” Appl. Phys. B **88**(3), 379–384 (2007).
22. A. Fuerbach, C. Miese, W. Koehler, and M. Geissler, “Supercontinuum generation with a chirped-pulse oscillator,” Opt. Express **17**(7), 5905–5911 (2009).
23. R. Graf, A. Fernandez, M. Dubov, H. J. Brueckner, B. N. Chichkov, and A. Apolonski, “Pearl-chain waveguides written at megahertz repetition rate,” Appl. Phys. B **87**(1), 21–27 (2007).
24. S. Dewald, T. Lang, C. D. Schröter, R. Moshammer, J. Ullrich, M. Siegel, and U. Morgner, “Ionization of noble gases with pulses directly from a laser oscillator,” Opt. Lett. **31**(13), 2072–2074 (2006).
25. A. Ozawa, J. Rauschenberger, Ch. Gohle, M. Herrmann, D. R. Walker, V. Pervak, A. Fernandez, R. Graf, A. Apolonski, R. Holzwarth, F. Krausz, T. W. Hänsch, and Th. Udem, “High harmonic frequency combs for high resolution spectroscopy,” Phys. Rev. Lett. **100**(25), 253901 (2008).
26. E. Sorokin, V. L. Kalashnikov, J. Mandon, G. Guelachvili, N. Picqué, and I. T. Sorokina, “Cr4 + : YAG chirped-pulse oscillator,” N. J. Phys. **10**(8), 083022 (2008).
27. P. Dombi, and P. Antal, “Invetisgation of a 200-nJ chirped-pulse Ti:Sapphire oscillator for white light generation,” Laser Phys. Lett. **4**(7), 538–542 (2007).
28. D. Herriott, H. Kogelnik, and R. Kompfner, “Off-axis paths in spherical mirror interferometers,” Appl. Opt. **3**(4), 523–526 (1964).
29. V. L. Kalashnikov, E. Podivilov, A. Chernykh, S. Naumov, A. Fernandez, R. Graf, and A. Apolonski, “Approaching the microjoule frontier with femtosecond laser oscillators: theory and comparison with experiment,” N. J. Phys. **7**, 217 (2005).
30. S. H. Cho, F. X. Kärtner, U. Morgner, E. P. Ippen, J. G. Fujimoto, J. E. Cunningham, and W. H. Knox, “Generation of 90-nJ pulses with a 4-MHz repetition-rate Kerr-lens mode-locked Ti:Al(2)O(3) laser operating with net positive and negative intracavity dispersion,” Opt. Lett. **26**(8), 560–562 (2001).
31. S. M. Kelly, “Characteristic sideband instability of periodically amplified average soliton,” Electron. Lett. **28**(8), 806 (1992).
32. Ch. Spielmann, P. F. Curley, Th. Brabec, and F. Krausz, “Ultrabroadband femtosecond lasers,” IEEE J. Quantum Electron. **30**(4), 1100–1114 (1994).
33. I. D. Jung, F. X. Kärtner, N. Matuschek, D. H. Sutter, F. Morier-Genoud, Z. Shi, V. Scheuer, M. Tilsch, T. Tschudi, and U. Keller, “„Semiconductor saturable absorber mirrors supporting sub-10-fs pulses,” Appl. Phys. B **65**, 137–150 (1997).

1. Introduction

Mirror dispersion compensation of Ti:sapphire oscillators with chirped mirrors (CMs) brought breakthrough advances in femtosecond laser technology in the middle of the nineties [1,2]. Since then, continuous development of novel multilayers has taken place to increase the bandwidth of CMs to enable ever shorter pulse generation. Recent developments include tilted-front interface [3,4], back-side-coated [5], time domain optimized [6] and Brewster-angled [7] mirrors, culminating in the generation of pulses as short as 3.7 fs directly from a Ti:sapphire oscillator [8]. Apart from the bandwidth requirement, mirrors exhibiting significantly less than the usual –20…-100 fs^2 group delay dispersion (GDD) of typical CMs would also be readily utilizable in novel lasers, both inside the cavity and in extracavity compression schemes. Standard CM technology, however, does not allow for thousands of fs^2 of GDD per bounce due to the large optical path difference and the correspondingly high optical thickness of the coating required for the generation of significant delay between the spectral components of the ultrashort pulse. A special chirped structure manufactured with semiconductor technology enabled the generation of –750 fs^2 per bounce at 1057 nm with a bandwidth of 40 nm [9]. Alternatively, standard Gires-Tournois interferometers (GTIs) [10,11] provide well-controlled negative GDD with a simple layer structure, however, only with a limited bandwidth in the proximity of the resonance point of the GTI cavity. More complex, multi-cavity GTIs can increase the bandwidth substantially and mirrors exhibiting –30…-50 fs^2 GDD over a bandwidth of >80 nm were demonstrated [12–14]. In spite of this

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progress, it was only in 2008 that a highly dispersive mirror (HDM) was designed and fabricated exhibiting an average of −1300 fs^2 GDD per bounce over a bandwidth of 40 nm [15]. This mirror exploited a combination of the penetration and resonance effects and proved to be useful for extracavity pulse compression.

It is of considerable interest to utilize HDMs in intracavity applications, too, especially in long-cavity femtosecond oscillators (LCOs) delivering pulses reaching 1 μJ energy (Ti:sapphire) [16–19] and pulses with several μJ energy (Yb-doped active materials) [15,20]. This performance exceeds that of standard oscillators by more orders of magnitude and enables experiments that had to rely on amplified fs laser systems previously, such as high-power supercontinuum generation [18,21,22], waveguide microfabrication [23], strong-field interactions [24] and high harmonic generation [25]. The potential of Ti:sapphire and Yb-based LCOs is far from being exploited and other laser materials also hold promise of enabling long-cavity architectures [26]. Motivated by this, we investigated the intracavity applicability of HDMs in various Ti:sapphire oscillators. It is especially interesting to use these mirrors for the compensation of long, bulk dispersive elements in the cavity, such as, for example, a cavity dumper [18,19], instead of using dozens of bounces off CMs [16,27] to compensate for air and glass dispersion. Here we demonstrate that dispersion compensation of 40 mm fused silica can be carried out in a LCO (83 m round-trip length) by replacing one of the cavity mirrors with a HDM, enabling the compensation of an efficient cavity dumper. In addition, we present the results of experiments where one to four bounces off HDMs are used in the cavity revealing an unprecedentedly broad net intracavity GDD range in which stable mode-locked operation was achieved. As a further HDM demonstration, we present a simple, 0.5 GHz, four mirror cavity the dispersion compensation of which is carried out with a single HDM. This laser type can be particularly interesting for telecommunication, spectroscopic and frequency metrology applications.

2. Experiments with positive cavity GDD

We performed the experiments with a home-built, Ti:sapphire LCO (Fig. 1). The cavity has a round-trip length of 83 m (pulse repetition rate of 3.6 MHz) realized with a Herriott-type multi-pass telescope system [16,27,28]. One of the end mirrors is a saturable Bragg reflector ($\Delta R \approx 5\%$), the other one is a 20% output coupler. 7 W cw pumping with a diode-pumped solid-state laser (Finesse, Laser Quantum Inc.) resulted in mode-locking with 190 nJ output pulse energy and the spectrum in Fig. 2 (a). In the operation regime of positive net cavity GDD (GDD = −250 fs^2), the system delivers pulses of 68 fs duration (full width at half maximum, FWHM, see Fig. 2(b)) after extracavity compression with 16 reflections off HDMs (identical to the ones described in Ref [15].). Pulse characterization was facilitated by a commercial background-free autocorrelator (APE GmbH). The pulse length is 1.13 × transform-limited. The difference is due to uncompensated high-order dispersion, as shown by the pedestal of the autocorrelation in Fig. 2(b).

In order to test the intracavity applicability of HDMs, we introduced one of these mirrors into this LCO together with 40 mm extra path length in fused silica achieved with prisms P1 and P2 in Fig. 1. Due to the fact that the −1300 fs^2 of the HDM does not compensate fully the 1440 fs^2 dispersion introduced, the amount of net GDD has increased to 390 fs^2 in the cavity. Its spectrum is also more irregular than previously due to higher order dispersion introduced by the HDM [15]. This is also in accordance with numerical simulations [29] which suggest that uncompensated higher order dispersion terms result in similar spectral irregularities of a positive-dispersion LCO. We observed that the output can still be compressed to 160 fs duration with a simple transmission grating compressor (1200 lines/mm), see Fig. 2(d).

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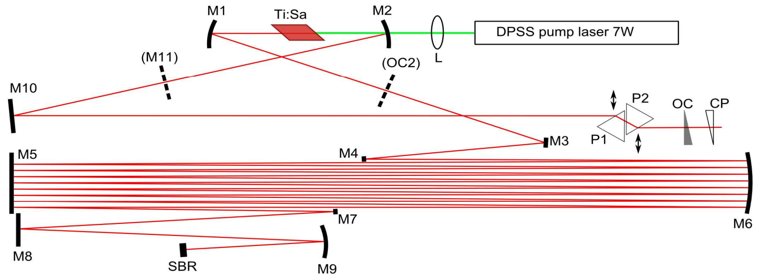

Fig. 1. The schematic setup of the long cavity oscillator used for the experiments. M1, M2: folding mirrors, M3-M10: chirped cavity mirrors (all flat except for M1, M2, M6 and M9 with radii of curvature $R_{M1} = R_{M2} = 10$ cm, $R_{M6} = 16$ m, $R_{M9} = 60$ cm), P1, P2: Brewster prisms for fine-tuning the intracavity dispersion, OC: output coupler, OC2: alternative output coupler, CP: compensation plate, L: lens with 60 mm focal length, SBR: saturable Bragg reflector. The beam in the M5-M6 telescope system is not depicted fully realistically for more illustrativeness. Successive bounces form a circular pattern on M5 and M6 instead of a linear one. An alternative, short, 4-mirror cavity composed of M1, M2, M11 and OC2 was also used.

This delivers a proof of stable, mode-locked operation even when a HDM with significant GDD oscillations is inside the cavity. A similar advantageous behaviour was also observed for the case of ultrabroadband pulse compression with mirrors exhibiting significant GDD oscillations [6]. Our experiments confirm that intracavity GDD oscillations do not hinder non-solitonic mode locking. More thorough analysis of pulse formation dynamics in these cavities is required, however, in order to optimize new HDM designs for LCOs.

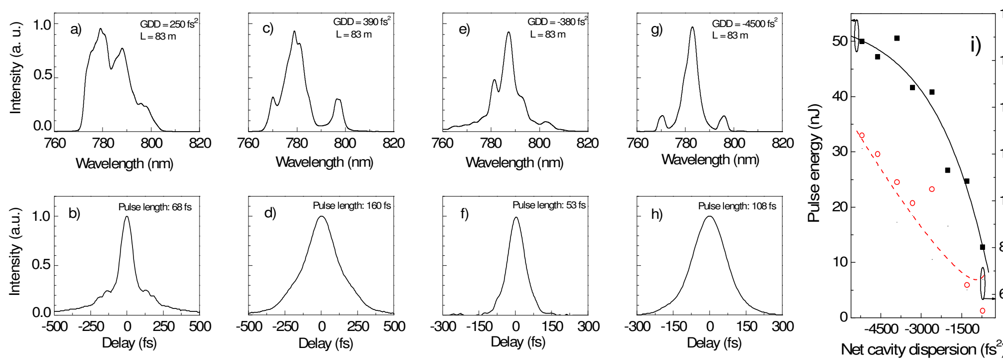

Fig. 2. Measured oscillator spetcra for long-cavity (cavity round-trip length: L = 83 m) Ti:sapphire oscillators with (a) 250 fs^2, (c) 390 fs^2, (e) −330 fs^2 and (g) −3900 fs^2 net cavity GDD produced with HDMs. The corresponding background-free autocorrelation curves of the oscillator pulses can be seen in (b), (d), (f), (h). We also depict the maximum outcoupled pulse energy (black squares and black solid fit) in single-pulse operation as a function of net cavity GDD in (i). We also show the corresponding measured and calculated pulse length (red circles and red dashed line) that can be achieved in each cavity configuration (see text for details).

This proof-of-principle demonstration of a new dispersion compensation method in an extremely long cavity together with a more powerful pump laser can result in the generation of >2 μJ pulses out of a Ti:sapphire oscillator alone, if cavity dumping is employed. This is supported by the fact that these types of oscillators can be pumped by up to 15 W with moderate crystal cooling [19] resulting in an intracavity pulse energy of 2.4 μJ for a relatively short cavity [19]. This can be conveniently increased by a factor of 2 by making the cavity × 2 longer and applying HDM dispersion compensation. Since the pulse formation mechanisms in the positive GDD regime result in chirped intracavity pulses, no nonlinear pulse break-up is expected (similarly to Yb-based lasers [15,20] with up to 25 μJ output).

3. Experiments with negative cavity GDD

By removing some fused silica material and leaving the HDM in the cavity, we have switched operation to the regime of negative intracavity GDD. In this regime of solitary pulse formation, the output pulses are close to transform limited, obviating the extracavity compression stage. A representative spectrum and intensity autocorrelation for this case with one bounce off the HDM, resulting in a net cavity GDD of -380 fs^2, are shown in Figs. 2(e) and 2(f), respectively. In contrast to the regime of positive dispersion, the spectrum exhibits less structure and the pulses have a duration of 53 fs which is close to the transform limit (49 fs) of the spectrum.

For increasing pulse energies, the operation regime of negative cavity GDD is known to suffer from the onset of instabilities, resulting in pulse breakup and multiple pulsing [30], setting an upper limit to the energy of a stable, near-bandwidth-limited single pulse in the cavity. We have accurately tested this limit for the first time with different methods: i) by changing the pump power and monitoring the oscillator output with a background-free autocorrelator (scan range: 15 ps) to observe the appearance of satellite pulses and ii) by generating the second harmonic of the laser output with a BBO crystal and monitoring the second harmonic signal as a function of the pump and laser output power. Any sudden drop in the second harmonic signal level with the increase of pump power is indicative of pulse breakup. This latter method detects the onset of multipulsing even if the satellites appear outside of the 15 ps scan range of our autocorrelator. Thus, we found that the maximum achievable single-pulse energy was only 13 nJ, at a pump power of 3.4 W.

In order to achieve stable mode-locked operation with higher pulse energy, we replaced more and more standard chirped mirrors with low negative GDD (~-50 fs^2) with HDMs in the LCO. Remarkably, in the extreme cases of 3-4 HDM bounces (-3900 fs^2…-5200 fs^2 net cavity GDD) and the corresponding high-amplitude dispersion oscillations, stable mode-locked operation was still observed. Thus, pulse shaping in the cavity is in accordance with previous experiments demonstrating efficient pulse compression with mirrors exhibiting significant dispersion oscillations [6]. A typical spectrum for 3 HDM bounces is depicted in Fig. 2(g) and the corresponding autocorrelation of the generated pulse is shown in Fig. 2(h). As expected, the spectrum is narrower and pulses are longer (108 fs). Most importantly, the maximum pulse energy allowing stable operation increases dramatically, to about 50 nJ. Kelly sidebands characteristic for this regime [31] are also visible.

We also tested the dependence of maximum achievable pulse energy and corresponding pulse duration versus net intracavity dispersion. These results are summarized in Fig. 2(i). By increasing the number of reflections off HDMs, the achievable pulse energy starts to increase rapidly, as expected. Its maximum levels off at about 50 nJ for intracavity GDD of about -4000 fs^2 and is attained at pump power levels of about 4 W. This means that there is no reason to decrease the cavity GDD any further or to apply more pump power. The pulse duration (Fig. 2(i), empty circles) increases according to a modified soliton formula: $\tau_p(D) = 3.53|D| / [\phi \times E_p(D)]$ (for the original formula, see e. g [32].), where D is the net cavity GDD and $\phi = 7 \times 10^{-7}$ W^{-1} is the self phase modulation coefficient. $E_p(D)$ stands for the maximum pulse energy allowing stable operation as a function of intracavity dispersion. From this, we expect a unique $\tau_p(D)$ dependence specific for LCOs. We used the solid black fit to measurement data in Fig. 2(i) to approximate the $E_p(D)$ function. The resulting $\tau_p(D)$ curve (Fig. 2(i), dashed red line) delivers a good approximation for the measured dependence of pulse duration on intracavity GDD, confirming the validity of our modified soliton formula in this broad range of net intracavity GDD and with varying pulse energy at the same time.

This model obviously does not explain the observed shape of the $E_p(D)$ curve that is highly dependent on the pulse formation dynamics at different values of GDD. $E_p(D)$ to be determined from theory necessitates the incorporation of saturable absorption, GDD and self

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phase modulation into a numerical model of the laser. This would also require a full charaterization of the SBR used. In our experiment, it was necessary to increase the intensity on the SBR to well above its saturation fluence (on the order of 10 μJ/cm^2) in order to mode-lock easily. Therefore, the multi-pulsing phenomenon observed is most likely caused by the saturable absorber end mirror (see for example [33]) rather than by non-linear pulse break-up arising in the crystal. (The latter was observed in long-cavity femtosecond lasers without SBR.) The current study, however, accurately predicts the observed pulse duration evolution as a function of GDD from the measured $E_p(D)$ stability limit curve as input. Thus, it can be established that maximum outcoupled peak power can be reached at ~-4000 fs^2 net GDD.

As a further demonstration of the utility of HDMs, we have set up a simple, compact four-mirror laser composed of the same Ti:sapphire crystal, two folding mirrors and two end mirrors one of which was a 10% output coupler and the other one was a HDM (Mirrors M1, M2, OC2 and M11 in Fig. 1, respectively). It had a repetition rate of 536 MHz and was mode-locked by pure soft-aperture Kerr-lensing. Resulting spectra and autocorrelations are depicted in Fig. 3. If the end mirror is a HDM with −380 fs^2 GDD per bounce, the net cavity GDD is −40 fs^2 and the spectrum in Fig. 3(a) is limited by the HDM bandwidth only. Output pulses have 68 fs duration (Fig. 3(b)) and 1.8 nJ energy at 7 W pumping. The same setup but with the −1300 fs^2 HDM (the same as that in [15]) delivers a much narrower spectrum (Fig. 3(c)) and correspondingly longer, 123-fs pulses with 2.0 nJ energy, depicted in Fig. 3(d). These experiments show that careful optimization of the HDM structure is necessary for a given cavity to be able to exploit the full mirror bandwidth in a GHz cavity. Proper optomechanical and mirror engineering can enable broader spectrum and the miniaturization of this 4-mirror cavity to serve those GHz applications where extremely broadband output is not required.

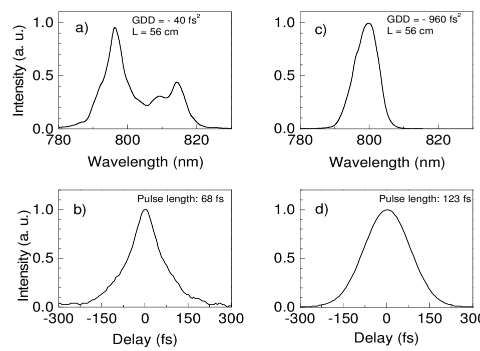

Fig. 3. The spectra and autocorrelations of output pulses from short, 0.5 GHz, 4-mirror cavities containing 1 HDM with a cavity round-trip length of L = 56 cm. (a) and (b) correspond to a cavity with a HDM with −380 fs^2 as the M11 end mirror (see Fig. 1), whereas (c) and (d) correspond to a cavity with a HDM with −1300 fs^2 as M11. The labels in (a) and (c) state the net cavity GDD values for each case.

4. Summary

In summary, we demonstrated the flexibility of HDMs with negative GDD in excess of −1000 fs^2 in the dispersion management of various femtosecond oscillators and their capability of allowing for stable sub-100-fs operation. The HDMs can cope with a considerable amount of dispersive material in the cavity and will improve the compactness of LCOs which previously had to rely on prisms or complicated chirped mirror combinations for intracavity dispersion control. These results also serve as a basis for the specification of more advanced HDMs tailored for various cavity designs allowing for the development of both ultra-compact, and ultra-long-cavity femtosecond oscillators with unprecedented pulse energy for a range of applications in telecommunications, micromachining and strong-field physics.

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