Ultrabroadband chirped mirrors for femtosecond lasers

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We report on the performance of widely tunable femtosecond and continuous-wave Ti:sapphire lasers that use a newly developed ultrabroadband mirror set. The mirrors exhibit high reflectivity ($R > 99\%$) and smooth variation of group delay versus frequency over a wavelength range from 660 to 1060 nm. Mode-locked operation with pulse durations of 85 fs was achieved from 693 to 978 nm with only one set of ultrabroadband mirrors.

Tunable laser sources are widely used for cw and time-resolved spectroscopic measurements.[1] In particular, cw, picosecond, and femtosecond (fs) Ti:sapphire (Ti:S) lasers[2] have become versatile tools in spectroscopy because of the large bandwidth of the Ti:S crystal of 3200 cm^{-1} (FWHM),[3] which allows a broad tunability range as well as the generation of ultrashort pulses by self-mode locking of the laser.[4] The limitations on the minimum pulse durations of prism-pair-controlled lasers due to third- and fourth-order dispersion have been considerably reduced by the development of chirped dispersive dielectric mirrors[5,6] (CM's). In contrast with prism-pair-controlled systems, these mirrors compensate not only the second-order dispersion, often referred to as group-delay dispersion (GDD), but also the third-order dispersion. Up to now, CM's have been developed solely as a means of designing ultrafast laser systems with pulses as short as possible[7,8] or to simplify cavity design and improve the efficiency of fs laser systems.[9,10] In this Letter we demonstrate that our newly developed ultrabroadband CM's (UBCM's) offer the possibility of tuning ultrabroadband fs laser systems without changing mirrors over the whole of the laser's operation range. These UBCM's enable us not only to generate pulses shorter than 100 fs from a mode-locked Ti:S system but also simultaneously to achieve high tunability of the laser over a range >300 nm.

The problem of designing ultrabroadband dielectric mirrors for fs laser systems is twofold. First, the mirrors have to have continuous high reflectivity over a broad spectral range without any drop in reflectivity regardless of wavelengths. Second, the mirrors have to exhibit a smooth, possibly negative variation of the group-delay versus frequency function over the whole tuning range, allowing fs mode-locked operation of the laser. The present commercially available broadband dielectric mirrors do not meet these requirements. The high-reflectivity bandwidth of our preferred UBCM's can be exceeded only with properly designed metallic mirrors with similarly smooth variation of group delay versus frequency; however, the reflectivity of metallic mirrors is considerably smaller than that of UBCM's and therefore metallic mirrors cannot be used as intracavity broadband mirrors in fs laser oscillators. Here we show that the two requirements are fulfilled by one solution: CM structures[5,6] with an increasing layer period toward the substrate of the coating. Additionally, the mirrors have to be transparent at the pump wavelength(s) to replace standard [quarter-wave ($\lambda/4$) stack] dichroic mirror coatings[11] in these fs laser cavities. Note that it is impossible to fulfill the latter requirement with metallic mirrors.

In the case of dielectric mirrors, a combination of materials with the highest refractive-index ratios (n_H/n_L) is usually preferred since the higher the ratio, the higher the theoretical reflectance and bandwidth of standard $\lambda/4$ stacks. Among its competitors, the TiO_2/SiO_2 pair has the highest ratio over the near-IR spectral range.[11] To produce a high-density coating with low scattering and absorption losses, ion-based technologies could be advantageous.[12] However, the total number of layers is strictly limited by the relatively high stress in such coatings, which does not allow the deposition of CM's formed by a relatively high number of thick layers in the near IR.[13] In the case of Ti:S lasers, for instance, the useful bandwidth of low-dispersion quarter-wave mirrors is limited to ~180 nm around 800 nm.[11] Previously proposed solutions to extend the high-reflectivity range of dielectric mirrors, such as deposition of low- (high-) pass stacks as a single coating[14] and deposition of multilayer stacks with variation of thickness in arithmetic or geometric progression[15] do not meet the above-listed requirements.[11,16–18] Briefly, all the previously used broadband dielectric mirrors exhibited rapid change of the reflected phase at specific wavelengths in the high-reflectivity zone of the broadband mirrors, causing resonant losses and extremely strong high-order dispersions around these wavelengths, thus preventing their use in broadly tunable fs oscillators.[11] Recently, it was demonstrated that these undesirable resonant features are effectively eliminated if their design is optimized by special computer algorithms.[6,19] From the theoretical point of view, we showed that it is possible to synthesize extremely broadband dielectric high reflectors that exhibit smooth, monotonic variation of group delay versus frequency throughout the complete high-

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