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Double-chirped semiconductor mirror for dispersion compensation in femtosecond lasers

R. Paschotta,[a] G. J. Spühler, D. H. Sutter, N. Matuschek, and U. Keller
Ultrafast Laser Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg HPT, CH-8093 Zürich, Switzerland

M. Moser and R. Hövel
CSEM Zürich, Badenerstrasse 569, CH-8048 Zürich, Switzerland

V. Scheuer, G. Angelow, and T. Tschudi
TH Darmstadt, Institute of Applied Physics, Hochschulstrasse 6, 64289 Darmstadt, Germany

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A double-chirped mirror structure with broadband negative dispersion was realized with semiconductor technology. The necessary high precision of the fabrication was achieved by using special calibration structures. A single reflection on the obtained low-loss mirror produces sufficient negative dispersion for dispersion compensation in a femtosecond laser cavity. In this way we demonstrate 200 fs pulses from a compact Nd:glass laser without any additional dispersion compensation. © *1999 American Institute of Physics.* [S0003-6951(99)00341-1]

The generation of femtosecond pulses in a laser cavity usually requires operation in the regime of negative group delay dispersion (GDD) of the laser cavity where soliton-like pulses can be formed. The most common way to provide negative dispersion in a cavity is to insert a prism pair;[1] alternatives to that are dispersive mirror structures. Gires–Tournois interferometer (GTI) structures[2] have been used in various devices, including a semiconductor mirror with negative dispersion[3] and even a semiconductor saturable absorber mirror (SESAM) with negative dispersion.[4] GTI structures are simple and can provide very large dispersion, but only in a limited bandwidth. Another approach, allowing for a much larger bandwidth and compensation of dispersion in higher orders, is to use special multilayer dielectric mirrors. Computer optimized designs of multilayer dielectric mirrors have been demonstrated,[5] while the latest and most promising kind of dielectric mirror for broadband dispersion compensation, based on analytical work, is the double-chirped mirror.[6,7] Such a device can provide excellent dispersion characteristics over a large bandwidth. Here a chirp (spatial variation) of the Bragg wavelength leads to a deeper penetration of the longer wavelengths and thus to negative dispersion. Initially the problem of chirped mirrors was that a chirp of the Bragg wavelength alone causes large oscillations in the group delay which would make the mirror useless for femtosecond pulse generation. It was found[6,7] that these oscillations can be removed by introducing two additional techniques, resulting in a so-called double-chirped mirror: First, in addition to the chirp of the Bragg wavelength there is a chirp of the coupling strength (controlled via the thickness ratio of high- and low-index layers), which smooths the transition from zero coupling (outside the mirror) to full coupling in the mirror structure. Second, a broadband AR (antireflection) coating removes the interference effects from the Fresnel reflection on the mirror/air interface.

Such double-chirped mirrors have so far been realized in TiO_2/SiO_2 dielectric mirror technology. The very high accuracy of this technology lead to mirrors with high reflectivity and precisely controlled dispersion in a bandwidth of up to 400 nm. Such mirrors have been successfully used for the generation of pulses with less than 10 fs duration.[8–10] Unfortunately, the amount of negative dispersion which can be generated with such a mirror is limited; a single reflection on such a mirror is usually not sufficient to fully compensate the dispersion of a laser cavity so that typically several of these mirrors (or multiple bounces between two chirped mirrors) have to be used in one laser cavity.

In this letter we demonstrate the realization of a double-chirped mirror structure in semiconductor technology. We used GaAs and AlAs as high- and low-index materials with good transparency in the 1-μm-wavelength domain. As a

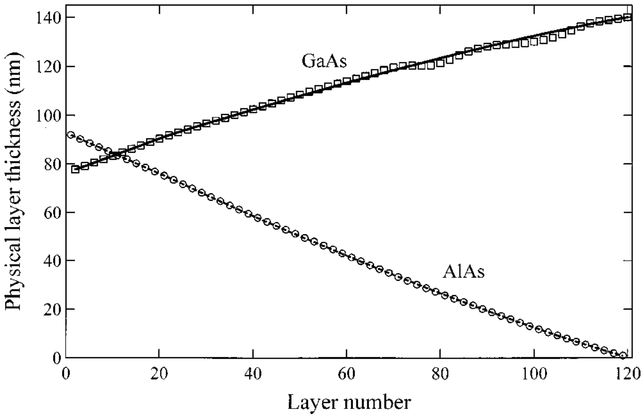

FIG. 1. Design of the GaAs/AlAs layer structure: analytical design (solid and dashed curve) and numerically refined values of AlAs (circles) and GaAs (squares) layer thickness. Layer number 0 corresponds to the GaAs substrate. (The AR coating is not shown.)

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[a] Electronic mail: paschotta@iqe.phys.ethz.ch

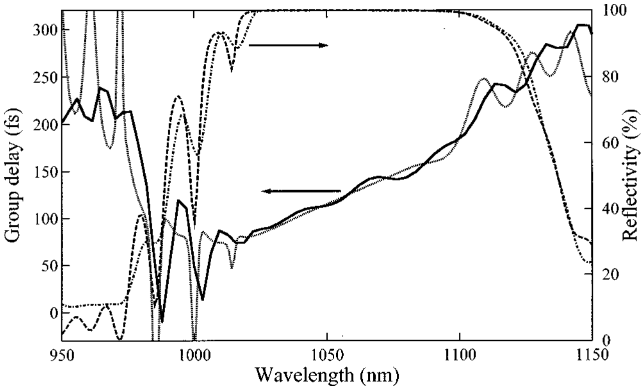

FIG. 2. Calculated (dotted line) and measured (solid line) group delay of the dispersive mirror, and calculated (dashed line) and measured (dashed-dotted line) reflection spectrum.

consequence of the relatively small index ratio between these materials, the chirp of the Bragg wavelength has to be weaker than in typical TiO_2/SiO_2 chirped mirrors because otherwise a sufficiently high reflectivity would not be achieved. Thus, a higher number of layer pairs is required for a given reflection bandwidth. While this may seem to be a serious limitation, such structures can be produced with high accuracy and low optical loss using either metalorganic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE). Moreover, the weak coupling strength and the weak chirp of the Bragg wavelength lead to a large negative dispersion as it increases the difference in penetration depth for a given pair of wavelengths. Therefore a single bounce on such a mirror can generate sufficient negative dispersion for dispersion compensation in a femtosecond laser cavity. Another attraction of using semiconductor materials is the potential for integration with a saturable absorber, resulting in a double-chirped SESAM which could be used in a compact femtosecond laser cavity and would at the same time provide negative dispersion for soliton-like pulses and stabilize the soliton mode-locking process.[11]

Our dispersive mirror was designed for a group delay dispersion (GDD) of $-750\ fs^2$ in a 40 nm bandwidth around 1055 nm. It consists of 60 GaAs/AlAs layer pairs (grown on a GaAs substrate with MOCVD), having a total physical thickness of $\sim 10\ \mu m$. On top of this structure, an AR coating with 3 layer pairs of TiO_2/SiO_2 was made with ion beam sputtering. The TiO_2/SiO_2 material system is required because the refractive indices of the semiconductor materials are not suitable to achieve sufficiently low reflection over this bandwidth.

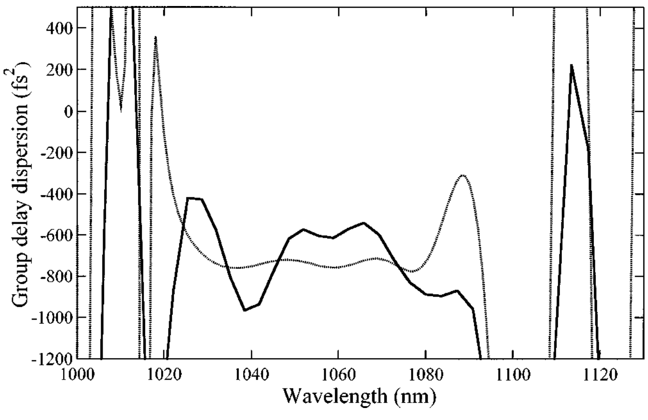

FIG. 3. Calculated (dotted line) and measured (solid line) group delay dispersion of the dispersive mirror.

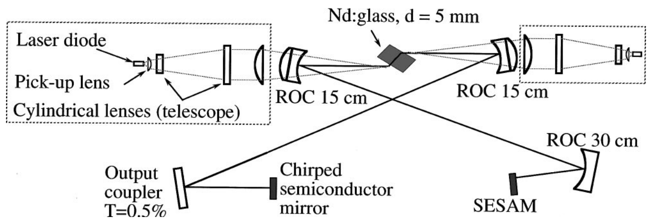

FIG. 4. The diode-pumped laser that produced 200 fs pulses, using the chirped semiconductor mirror. ROC=radius of curvature, SESAM =semiconductor saturable absorber mirror.

We started from an analytical design[6,7] for the MOCVD-grown structure and a numerically obtained design for the AR coating; we then numerically refined the whole structure for optimum flatness of the GDD (Fig. 1). A high precision of the layer thickness (~ 0.4 nm) is required to avoid strong oscillations of the GDD. This accuracy is currently just achieved in the MOCVD process. Directly before growing the actual mirror structure, we accurately calibrated the growth rates for GaAs and AlAs layers by fabricating and characterizing two periodic mirror structures where about 90% and 10%, respectively, of the optical thickness of a layer pair was made of GaAs, and the rest of AlAs.

Figure 2 shows the calculated and measured group delay versus wavelength, measured with a white light interferometer, as well as the reflection spectrum. In the GDD trace, the deviations from the design performance become more apparent (Fig. 3). However, they are still small enough to allow for femtosecond generation; the soliton-like pulses simply experience the average value of the GDD within their optical bandwidth as long as the phase differences between different wavelength components, caused by the wiggles in the GDD curve, are much smaller than 2π.

To demonstrate the usefulness of our dispersive mirror, we used a diode-pumped Nd:glass femtosecond laser similar to the one described in Ref. 12. Instead of a prism pair, we used one reflection on the chirped semiconductor mirror for

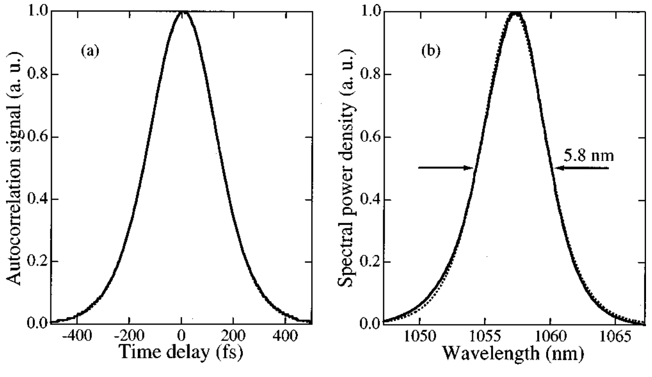

FIG. 5. (a) Autocorrelation and (b) optical spectrum of the generated pulses. The autocorrelation perfectly agrees with the autocorrelation of a $sech^2$ pulse of 200 fs duration. The measured spectrum (solid line) is close to the spectrum of a $sech^2$ pulse. The time-bandwidth product is 0.31, i.e., transform limited.

dispersion compensation, leading to a very compact laser cavity (Fig. 4). Mode locking was achieved with a separate (nondispersive) SESAM. We obtained clean transform-limited soliton pulses with 200 fs duration (Fig. 5), as expected from soliton mode-locking theory using the calculated total intracavity dispersion and Kerr nonlinearity. The output power was 36 mW on each of the two output ports. We estimated the insertion loss of the dispersive mirror to be only ~0.4%.

In conclusion, we have demonstrated a double-chirped semiconductor mirror for the generation of negative group delay dispersion. This device was used to generate 200 fs pulses in a Nd:glass laser without any additional means for dispersion compensation. Future work is aiming towards a dispersive mirror with integrated saturable absorber, combining dispersion compensation and a modelocker in a single compact device.

[1] R. L. Fork, O. E. Martinez, and J. P. Gordon, Opt. Lett. **9**, 150 (1984).
[2] F. Gires and P. Tournois, C.R. Acad. Sci. Paris **258**, 6112 (1964).
[3] S. R. A. Dods and M. Ogura, Appl. Opt. **36**, 7741 (1997).
[4] D. Kopf, G. Zhang, R. Fluck, M. Moser, and U. Keller, Opt. Lett. **21**, 486 (1996).
[5] R. Szipöcs and A. Kohazi-Kis, Appl. Phys. B: Lasers Opt. **65**, 115 (1997).
[6] F. X. Kärtner, N. Matuschek, T. Schibli, U. Keller, H. A. Haus, C. Heine, R. Morf, V. Scheuer, M. Tilsch, and T. Tschudi, Opt. Lett. **22**, 831 (1997).
[7] N. Matuschek, F. X. Kärtner, and U. Keller, IEEE J. Quantum Electron. **35**, 129 (1999).
[8] I. D. Jung, F. X. Kärtner, N. Matuschek, D. H. Sutter, F. Morier-Genoud, G. Zhang, U. Keller, V. Scheuer, M. Tilsch, and T. Tschudi, Opt. Lett. **22**, 1009 (1997).
[9] U. Morgner, F. X. Kärtner, S. H. Cho, Y. Chen, H. A. Haus, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, and T. Tschudi, Opt. Lett. **24**, 411 and 920 (1999).
[10] D. H. Sutter, G. Steinmeyer, L. Gallmann, N. Matuschek, F. Morier-Genoud, U. Keller, V. Scheuer, G. Angelow, and T. Tschudi, Opt. Lett. **24**, 631 (1999).
[11] F. X. Kärtner, I. D. Jung, and U. Keller, IEEE J. Sel. Top. Quantum Electron. **2**, 540 (1996).
[12] J. Aus der Au, D. Kopf, F. Morier-Genoud, M. Moser, and U. Keller, Opt. Lett. **22**, 307 (1997).