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A 10-fs Ti : sapphire laser with a folded ring resonator

A.A. Babin, A.M. Kiselev, A.V. Kirsanov, A.N. Stepanov

***Abstract*. A 10-fs Ti : sapphire laser with a standard 1-cm-long rod is built. The laser uses a broadband (low-dispersion) dispersion compensator and an original ring resonator.**

Keywords: *femtosecond laser, dispersion compensator, ring resonator.*

In recent years, a significant progress has been achieved in generating light pulses with durations of a few optical cycles using both direct lasing [1, 2] and an external compression of the output femtosecond pulse [3, 4]. This was achieved by using mirrors with a controllable dispersion (so-called chirped mirrors), which compensate for the dispersion in a wide spectral range [5, 6]. However, the phase characteristics of such mirrors are highly sensitive even to insignificant variations in the layer thickness. This imposes stringent requirements on the accuracy of their design and manufacture.

To moderate these requirements, a positive dispersion that must be canceled by such mirrors should be as low as possible. For this purpose, first, short (2 – 3 mm) Ti : sapphire crystals with a large gain and, second, chirped mirrors combined with prisms made of a low-dispersion material [7 – 9] are used in a linear Fabry – Perot resonator. A pair of such prisms located in succession in the resonator compensates for a second-order positive dispersion introduced by the crystal, while a weak third- and higher order dispersion can be eliminated by chirped mirrors. In this case, the requirements to their manufacture accuracy are greatly reduced. Laser pulses with a duration shorter than two optical cycles (with the spectral width exceeding 400 nm) were generated for the first time in [8] using a Ti : saphire laser with chirped mirrors combined with prisms made of a low-dispersion material (CaF_2).

A ring resonator, in which the crystal-introduced dispersion automatically decreases by a factor of two, is also applied for the same purpose [10]. In Ref. [11], 13-fs laser pulses were obtained in a ring resonator with four intracavity fused-silica prisms. The use of ring resonators has a number of other advantages mentioned in [10, 11]. First, in this case, the laser is less sensitive to repeated beam reflections back into the resonator; second, the generation of satellites or double pulses is less probable in the ring resonator; and, third, a symmetrical arrangement of the ring resonator makes it possible to obtain a femtosecond lasing regime at the centre of the resonator stability range and, as a consequence, to optimise the laser output power.

In this work, we study a femtosecond laser with a folded ring resonator, in which a single pair of prisms is sufficient for the dispersion compensation, as it is in a linear resonator. To our knowledge, we were the first to use low-dispersion LiF prisms in such a resonator and have shown that such prisms best compensate for the active-element dispersion near the emission-band centre (at 800 nm).

A schematic in Fig. 1 shows the beam paths in the folded ring resonator proposed by us. From the left arm of the focusing system, which is formed by mirrors (*5*) and (*6*), radiation passes twice through prisms (*7*) and (*8*). In the first pass (in the forward direction), the light propagates above an auxiliary mirror (*3*). In the second pass, the light propagates in the back direction after being reflected from a mirror (*1*) at a small angle ($\sim 12'$) in the vertical plane. After the second passage through prism (*8*), the beam falls onto mirror (*3*), which, together with mirror (*4*), output mirror (*10*), and spherical mirror (*6*) in the right arm of the focusing system, closes the ring. In our opinion, such a resonator configuration is simpler to align and convenient in operation compared to a conventional ring resonator, in which the dispersion is compensated using two pairs of prisms [10, 11]. Our experiments have shown that to produce femtosecond pulses in a conventional ring resonator, the distances between the prisms in each pair should be equal to each other with a high accuracy (no worse than

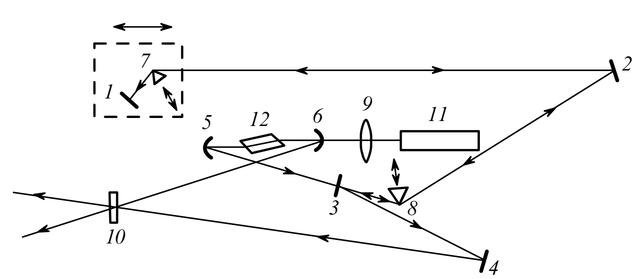

Figure 1. Scheme of a femtosecond Ti : sapphire laser with a folded ring resonator: (*1 – 4*) flat mirrors; (*5*, *6*) spherical mirrors; (*7*, *8*) prisms; (*9*) lens; (*10*) output mirror; (*11*) argon laser; (*12*) active element.

A.A. Babin, A.M. Kiselev, A.V. Kirsanov, A.N. Stepanov Institute of Applied Physics, Russian Academy of Sciences, ul. Ul'yanova 46, 603950 Nizhnii Novgorod, Russia; e-mail: aab@ufp.appl.sci-nnov.ru

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10 μm). Therefore, even slight changes in the position of any of the four prisms with respect to the beam will suppress the generation of femtosecond pulses.

This problem does not exist in our resonator because only a single pair of prisms is employed. The width and shape of the output spectrum were controlled by moving the prisms in the transverse direction relative to the laser beam. A Ti:sapphire crystal with the absorption coefficient $\alpha = 1.9$ cm^{-1} at 514 nm and Brewster facets was mounted in a copper holder cooled by thermally stabilised water at a temperature of 17 °C. The radiation from a 6-W LGN-512 argon laser was focused by lens (*9*) ($f = 12$ cm) into the centre of the crystal located between two dichroic spherical mirrors (*5*) and (*6*) ($f = 5$ cm). Flat mirrors (*1–4*) had a high reflectivity in the range 700–900 nm, and the transmission of output mirror (*10*) was 5 %. LiF prisms (*7*) and (*8*) were used to compensate for the dispersion. Prism (*7*) and mirror (*1*) mounted on a common translator, which made it possible to vary continuously the distance between prisms (*7*) and (*8*) without resonator misalignment. The total length of ring resonator was $L = 414$ cm, and the distance between prisms (*7*) and (*8*) was $d = 131.5$ cm. The distances between the elements of the laser were not critical parameters, except for the length l of the focusing system formed by spherical mirrors (*5*) and (*6*). The cw lasing stability region (with respect to the parameter l) had a width of ~ 1.5 mm. For our geometry of the laser resonator, femtosecond pulses could be generated only within a narrow (~ 0.2 mm) window in this stability region.

We observed two-directional cw lasing with the output power $P = 200 - 250$ mW in each direction. By changing the alignment, we obtained a unidirectional femtosecond lasing in the clockwise or counterclockwise directions. The stable lasing was maintained uninterruptedly for several hours. The spatial distribution of the femtosecond output radiation was close to the TEM_{00} mode, and the output power was $P = 300 - 350$ mW.

To select a pair of prisms whose dispersion is in best agreement with the crystal dispersion, we analysed the dispersion of a ring resonator containing a Ti:sapphire crystal and a pair of prisms made of low-dispersion materials CaF_2, SiO_2, and LiF. The dispersion of air was neglected in this analysis. Figure 2 shows the calculated group-delay dispersion $\varDelta$ introduced by the pairs of prisms under consideration for an optimal (ensuring the minimum group delay) distance between them. The crystal-introduced dispersion $\varDelta$ and the total dispersion in the resonator, which contains a 1-cm-long Ti:sapphire crystal and a LiF prism compensator, are also plotted in Fig. 2. As follows from this figure, the compensator with LiF prisms is the most broadband element for the spectral range of a Ti:sapphire laser.

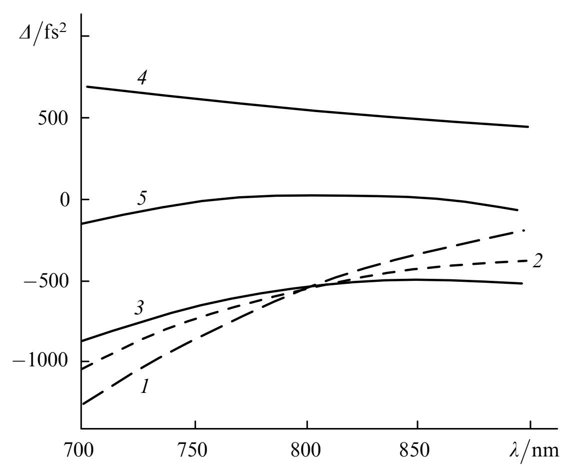

Figure 2. Group-delay dispersion $\varDelta$ in the ring resonator introduced by (*1*) CaF_2, (*2*) SiO_2, and (*3*) LiF prism compensators and by (*4*) a 1-cm-long Ti:sapphire crystal; (*5*) total group-delay dispersion in the ring resonator containing a Ti:sapphire crystal and a LiF prism compensator.

The duration of the output pulses was measured using an autocorrelator with broadband optical elements built according to a symmetrical collinear scheme [12]. The output spectrum was recorded by an optical spectrum analyser based on an MDR-12 monochromator. An additional external pair of LiF prisms (not shown in Fig. 1) was used to compensate for the dispersion of the output mirror substrate 7-mm thick. A typical intensity autocorrelation function and the corresponding spectrum of output pulses are shown in Fig. 3. Under the assumption that the time profile of the pulse intensity is described by the function $\mathrm{sech}^2 t$, it follows from the measurement data that the pulse duration at half-maximum (FWHM) is $\tau = 10$ fs at the FWHM of the spectrum $\Delta\lambda \sim 96$ nm. This corresponds to the product of the pulse duration by the bandwidth $\tau\Delta\nu = 0.43$, which is somewhat higher than the theoretical limit for sech^2-like pulses (0.315) and is probably explained by the difference between the actual and assumed pulse shapes.

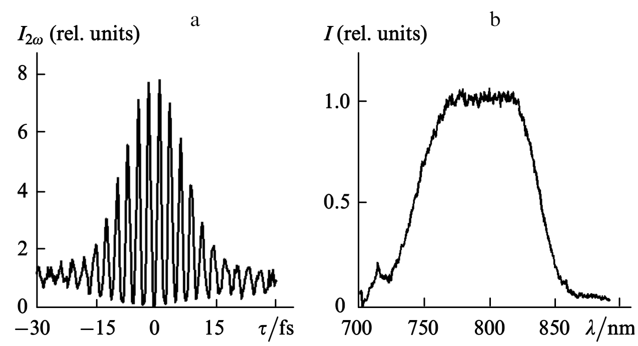

Figure 3. (a) Autocorrelation function and (b) output radiation spectrum of the femtosecond laser.

As was mentioned above, the spectral width of output pulses could be easily varied by moving the compensator prism in the transverse direction. The maximum spectral width that we managed to obtain in the laser was ~ 180 nm (at the base) and was close to the spectral width of the reflection band of the mirrors in use. However, the spectrum had two maxima, in this case, resulting, as is known [13], in the increase in the duration of the output pulse by a factor of ~ 1.5 compared to a smooth (Gaussian or sech^2-like) spectral profile with the same width.

Therefore, we have shown that a dispersion compensator consisting of LiF prisms is best suited for the generation of ultimately short pulses from a Ti:sapphire laser. The application of such a compensator combined with an original scheme of the ring resonator allowed us to obtain 10-fs output pulses using a Ti:sapphire crystal of length 1 cm without mirrors with a controllable dispersion.

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References

1. Xu L., Spielmann C., Krausz F., Szipöcs R. *Opt. Lett.*, **21**, 1259 (1996).
2. Xu L., Tempea G., Spielmann C., Krausz F., Stingl A., Ferencz K., Takano S. *Opt. Lett.*, **23**, 789 (1998).
3. Baltuska A., Wei Z., Psenichnikov M., Wiersma D. *Opt. Lett.*, **22**, 102 (1997).
4. Nisoli M., Silvestri S.D., Zvelto O., Szipöcs R., Ferencz K., Spielmann C., Sartania S., Krausz F. *Opt. Lett.*, **22**, 522 (1997).
5. Szipöcs R., Ferencz K., Spielmann C., Krausz F. *Opt. Lett.*, **19**, 201 (1994).
6. Kärtner F., Matuschek N., Schibli T., Keller U., Haus H., Heine G., Morf R., Scheuer V., Tilsch M., Tschudi T. *Opt. Lett.*, **22**, 831 (1997).
7. Jung I., Kärtner F., Matuschek N., Sutter D., Morier-Genoud F., Zhang G., Keller U., Scheuer V., Tilsch M., Tschudi T. *Opt. Lett.*, **22**, 1009 (1997).
8. Morgner U., Kärtner F., Cho S.H., Chen Y., Haus H., Fujimoto J.G., Ippen I.P., Scheuer V., Angelov G., Tschudi T. *Opt. Lett.*, **24**, 411 (1999).
9. Ell R., Morgner U., Kärtner F., Fujimoto J.G., Ippen E.P., Scheuer V., Angelov G., Tschudi T., Lederer M.J., Boiko A., Luther-Davies B. *Opt. Lett.*, **26**, 373 (2001).
10. Pelouch W.S., Powers P.E., Tang C.L. *Opt. Lett.*, **17**, 1581 (1992).
11. Beddard T., Penman Z., Reid D.T., Sibbett W. *Techn. Digest CLEO'99* (Baltimor, 1999, p. 84).
12. Spielmann C., Xu L., Krausz F. *Appl. Opt.*, **36**, 2523 (1997).
13. Rousseau G., McCarthy N., Piche M. *Proc. SPIE Int. Soc. Opt. Eng.*, **4087**, 910 (2000).