Mode-locked laser cavities with a single prism for dispersion compensation

D. Kopf, G. J. Spühler, K. J. Weingarten, and U. Keller

We demonstrate the use of a single prism for adjustable dispersion compensation in a mode-locked laser cavity, instead of the standard approach with a prism pair. A simple model based on the prism-pair configuration is presented to determine the group-velocity dispersion by use of ray optics to trace the wavelength-dependent optical axes through the cavity. We experimentally demonstrated this concept with a passively mode-locked diode-pumped Nd:glass laser producing 200-fs pulses with a 200-mW average output power, using only one intracavity prism. The advantages of such a cavity design are simple alignment, reduced loss, and lossless wavelength tunability. This technique can be generalized to other angularly dispersive elements such as prismatic output couplers. © 1996 Optical Society of America

Femtosecond lasers usually require net negative intracavity group-velocity dispersion (GVD), which is most widely achieved with prism pairs.[1] The use of only one prism for wavelength tunability and dispersion compensation has been demonstrated with a dye ring laser[2] and explained with an extended *ABCD* matrix formalism.[3–5] Similarly, two angularly dispersive elements incorporated into the gain material and the output coupler (OC) have been used to obtain a compact femtosecond Ti:sapphire laser.[6] In this paper, we demonstrate the design of mode-locked single-prism cavities and apply a simple argument that provides strong physical insight for determining the cavity GVD. Experiments are demonstrated with a 200-fs diode-pumped Nd:glass laser with 200-mW output power. Compared with the standard approach with an intracavity prism pair[1] for negative GVD, the single-prism laser cavity has benefits such as easy alignment, fewer intracavity elements that induce losses, and lossless wavelength tunability, as no aperture is needed.

The general outline of our cavity setup is shown in Fig. 1(a). We divide the cavity into two sections. One side has a single dispersive prism close to a flat end mirror (EM), an OC in our case. We assume that the rest of the cavity optics (CO's) do not contain any angularly dispersive elements and model them with a standard *ABCD* matrix.[7] We additionally assume that the second-cavity EM is also flat. The lasing condition requires that the optical axis hits the cavity EM's at normal incidence for all wavelengths.

The optical axes can be traced through the laser cavity with standard ray optics (i.e., ideal plane waves). Because the cavity mode can be described as a superposition of monochromatic spatial modes,[3–5] we show two possible optical axes labeled blue for the shorter and red for the longer wavelength in the optical spectrum of the laser. As indicated in Fig. 1(a), the angular dispersion of the prism causes different frequencies to follow different optical axes throughout the cavity, in contrast to the prism-pair setup. If the CO's are properly chosen, there is an intersection point X. Note that X is generally not a beam waist of the Gaussian cavity mode. Given this intersection point X, we can obtain negative dispersion in the cavity section between OC and X with only one single prism, in full analogy to a two-prism configuration with the apex of the first prism, P1, at point X [Fig. 1(b)]. This means that we can use Fork *et al.*'s formula[1] for the GVD calculations. The laser output has to go through an external prism sequence to obtain a spatially coherent beam.

No additional dispersion besides material dispersion is obtained in the cavity section between X and

D. Kopf, G. J. Spühler, and U. Keller are with the Ultrafast Laser Physics Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg-HPT, CH-8093 Zürich, Switzerland. K. J. Weingarten is with Time-Bandwidth Products AG, ETH Hönggerberg-HPT, CH-0893 Zürich, Switzerland.

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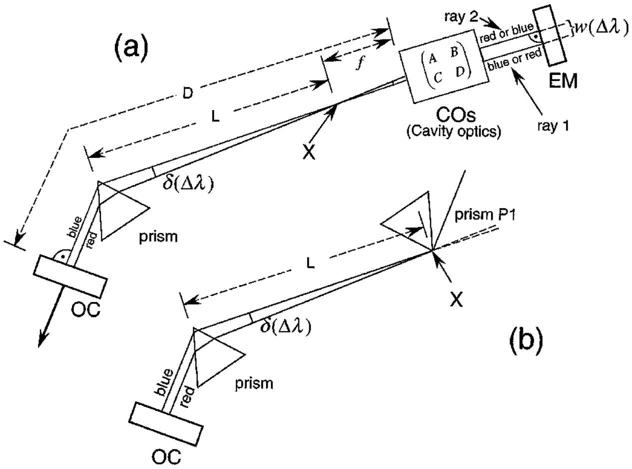

Fig. 1. (a) Single-prism laser layout. (b) The prism-pair approach with the first prism, P1, at intersection point X has GVD equivalent to the single-prism setup. OC's, output couplers.

the EM because the CO's, consisting, for example, of a thin lens, are assumed to produce no angular dispersion; i.e., the geometric path length is independent of the wavelength, assuming paraxial approximation and neglecting chromatic aberrations. This is confirmed by the argument that point X appears at the same geometric distance from the EM for two rays starting perpendicular at the EM [rays 1 and 2 in Fig. 1(a)] or, equivalently, for an ideal plane wave starting perpendicular to the EM and focused to point X. Therefore only material dispersion of this cavity section contributes to the cavity GVD. Note that this is an approximation because in our case the laser mode in general propagates with angular dispersion through any material placed in the CO's. However, the induced error from this effect is negligible compared with the material dispersion itself.

This schematic model makes the design very simple. The prism creates negative GVD proportional to the distance L (Fig. 1). The location of X is determined by the CO's only and can be found by propagation of different optical axes starting perpendicular to the EM. The amount of angular dispersion $\delta(\Delta\lambda)/\Delta\lambda$ at point X is determined by the angle dispersion $\partial n/\partial\lambda$ of the prism material and the prism insertion[1] and therefore gives us the spatial separation of two frequencies separated by $\Delta\lambda$, i.e., the angle $\delta(\Delta\lambda)$ at point X and the distance $w(\Delta\lambda)$ at the EM (Fig. 1).

If we use a general $ABCD$ matrix for the CO's, rays 1 and 2 (Fig. 1) will be transformed into

$$\begin{pmatrix} r \\ 0 \end{pmatrix} \mapsto \begin{pmatrix} Ar \\ Cr \end{pmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \times \begin{pmatrix} r \\ 0 \end{pmatrix} \tag{1}$$

on propagation through the CO's. Here r denotes the off-axis position of rays 1 and 2. The rays will intersect after an effective focal length of $f = -A/C$, which determines the location of X. The remaining length L then gives us the negative GVD from the prism. Depending on the $ABCD$ matrix, the effective focal length can take on any arbitrary value, meaning that point X can also be located close to the prism or even far behind it, which corresponds to positive GVD. Note that, in principle, CO designs with negative effective focal length f are possible, which makes the prism sequence length L longer than the cavity arm length D. This allows for designing more-compact dispersive cavities. To achieve a desired length L for negative GVD, we have to meet the requirement that

$$D \geq L + f = L - (A/C), \tag{2}$$

where D is the total length of the cavity arm containing the prism. The design depends on both selecting X according to Eq. (2) and ensuring that a Gaussian lasing mode exists; i.e., the total round-trip cavity matrix has eigenvalues, or the determinant condition

$$\left\| \begin{bmatrix} 1 & D \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} D & B \\ C & A \end{bmatrix} \begin{bmatrix} 1 & D \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \right\| \neq 0 \tag{3}$$

is fulfilled.[8,9] Therefore the single-prism laser provides negative GVD as long as Eq. (2) and inequality (3) are fulfilled.

Our first experiment demonstrating a mode-locked single-prism laser was a diode-pumped Nd:glass laser with two intracavity foci.[10] The first intracavity focus with the Nd:fluorophosphate gain medium has a larger mode area for improved mode matching[11] than the second intracavity focus, which holds a fused-silica platelet for increased self-phase modulation. From that setup, 120-fs pulses with 30-mW average output power could be generated at 1.1 W absorbed power from two diodes and 0.4% output coupling. The location of the crossing point X was close to the curved cavity mirror next to the prism[10] and could easily be moved in and out by several centimeters when the layout of the CO's was changed.

A more-compact diode-pumped Nd:glass laser, shown in Fig. 2(a), did not need a second intracavity focus because we more strongly focused the lasing mode into the gain medium for increased self-phase modulation in the gain medium.[11] Higher doping of the Nd:glass (4% doped Nd:phosphate LG-760) had to be chosen for mode matching to the diode pump beam. An antiresonant Fabry–Perot saturable absorber (the same as in Ref. 11) is used as the EM and starts and stabilizes mode locking. Figure 2(b) shows the propagation of the optical axes of different wavelengths through the cavity, showing that this cavity layout naturally fits the requirements for negative GVD with one intracavity prism. For a wavelength separation of $\Delta\lambda = 10$ nm an angle of $\delta(\Delta\lambda) = 0.014°$ and a separation of $w(\Delta\lambda) = 12$ µm were determined. Note that the crossing points of the optical axes do not correspond to the lasing mode waists, which are located at the Nd:glass medium and at both EM's. We generated 200-fs pulses [Fig. 2(c)] with an output power of 200 mW at an absorbed

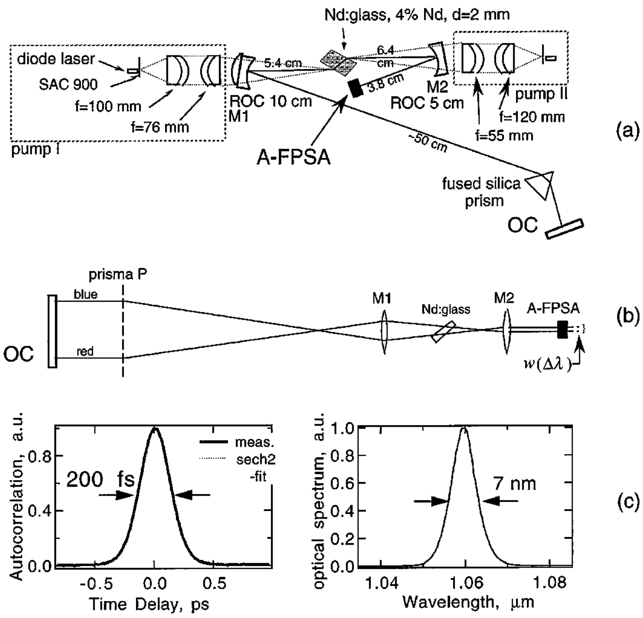

Fig. 2. (a) Diode-pumped mode-locked single-prism Nd:glass laser. (a) Plot of the optical axes with different wavelengths as they propagate through the cavity. (c) Autocorrelation and pulse spectrum as obtained from the above setup. ROC's, radii of curvature; M1, M2, mirrors; A-FPSA's, antiresonant Fabry–Perot saturable absorbers.

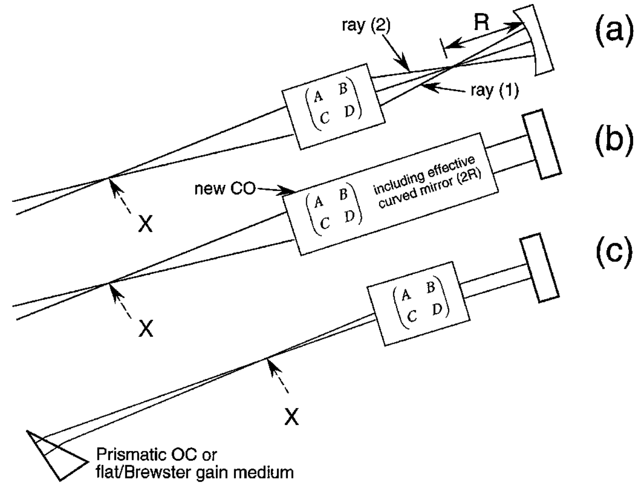

Fig. 3. (a) Simple way of looking at slightly changed boundary conditions with a curved cavity EM instead of a flat one. (b) The setup in (a) can also be modeled with an adapted *ABCD* matrix for the CO's. (c) Instead of a prism at the cavity end, a prismatic OC or—even more compact—a flat/Brewster-cut gain medium can be used.

pump power of 1.1 W from two diodes. With only one diode pump laser, a mode-locked output power in excess of 100 mW could be demonstrated. The diodes were not turned up to full power, as we observed damage in the gain medium at absorbed pump-power levels approaching 1.5 W, because of the short absorption length. However, the laser is more efficient than previously published results[11] because of higher output coupling (2%), minimized internal losses as a result of fewer optical elements, and improved mode matching because of higher doping.

To this point we have assumed that the EM is flat. Figure 3(a) shows that the same principles as above can be applied for a curved EM. The rays now start from the center of curvature of the EM so that they are again perpendicular to the surface of the EM, which is required for the lasing condition. Equivalently, one could include a curved mirror of twice the radius of curvature in the *ABCD* matrix of the CO and then model the layout as if it had a flat EM [Fig. 3(b)].

As an interesting modification in terms of compactness, the prism may be replaced by a prismatic OC,[6] or, even more simply, by a flat Brewster-cut gain medium [Fig. 3(c)]. However, the angle dispersion of half a prism is approximately half that of a full prism, so that Fork's formula will have to be used with a $\partial n/\partial\lambda$ twice as small as the actual prism-material parameter.

In conclusion, we have demonstrated the use of a single angularly dispersive element for dispersion compensation in a mode-locked cavity, instead of the standard approach of using a prism pair. We have presented a simple model for calculation of the negative GVD in such laser cavities by use of ray tracing of optical axes with different wavelengths through the CO's. We have verified this experimentally in two mode-locked diode-pumped Nd:glass lasers with 120-fs and 200-fs pulse widths and 30 mW and 200 mW average power, respectively. This cavity design has advantages that are important for compact mode-locked diode-pumped lasers. It has only one prism, which is simpler in alignment and reduces losses. The wavelength can be tuned by tilting the OC or shifting the pump beam sideways, without the need of an aperture, which introduces additional loss.

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