Highly Compact and Efficient Femtosecond Cr:LiSAF Lasers

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***Abstract*—Methods for developing more compact femtosecond Cr:LiSAF laser sources are examined. By careful modeling of the low threshold performance and intracavity dispersion characteristics of these cavities, a highly asymmetric z-cavity design with a single prism for dispersion compensation is developed. Transform-limited pulses as short as 113 fs and modelocked output powers up to 20 mW are demonstrated for less than 110 mW of laser-diode pump power. The complete laser system (including the laser diode pump system and drivers) has a footprint of 21.5×28 cm^2, about the size of a sheet of US letter or A4 paper.**

***Index Terms*—Diode-pumped lasers, modelocked lasers, ultrafast lasers, ultrashort-pulse generation.**

I. Introduction

THE development of low cost, compact, and robust ultrafast lasers suitable for application by a wider user community has long been the goal of researchers. Such ultrashort-pulse lasers would be ideal for a range of medical, microscopy, and imaging applications. Their portability and low-noise characteristics would make them especially useful for diagnostic measurements away from the confines of the laboratory. Presently, the majority of ultrafast lasers lack the portability and robustness to address this need. As a gain medium with the potential to be directly diode pumped, Cr:LiSAF is a prime candidate for this application. It was first mode-locked by Miller *et al.* [1] in 1992; however, this system was not diode pumped. French *et al.* [2] reported modelocking in a diode-pumped system the following year. These lasers were both Kerr–Lens modelocked (KLM). The first demonstration of semiconductor-saturable absorber mirror (SESAM) mediated soliton-modelocking [3]–[5], with the advantages of increased design flexibility and robustness that this permits, was in 1994 by Kopf *et al.* [6]. Recent demonstrations of directly diode-pumped Cr:LiSAF and Cr:LiSGaF lasers, producing output powers in the range of 125 mW [7]–[9] to 500 mW [10], and pulse durations as short as 10 fs [11] (KLM) and 45 fs [12] (soliton modelocking), represent a significant advance in the progression toward more practical and robust "real world" ultrashort-pulse laser systems. In this paper, we report a significant reduction in the size and complexity of low power, passively modelocked femtosecond lasers with the demonstration of a highly compact resonator design. There is also the possibility of the direct scaling of such compact lasers to higher powers in the future.

There are a number of approaches that can be used to reduce the "footprint" of an ultrashort-pulse laser. The first and most obvious method is to decrease the overall dimensions (and cost) of the laser cavity by using fewer optics. For example, three-mirror Ti:sapphire resonators have been developed by Ramaswamy-Paye, Bouma, and Fujimoto [13], [14] and, subsequently, demonstrated in both Cr^{4+}:YAG [15], [16] and Cr:LiSAF [17]. Such laser cavities have inherent size and mechanical stability advantages and have been shown to allow a simpler alignment procedure for Kerr-lens modelocking [14], [18]–[20]. The use of asymmetric cavity arrangements for the optimization of ultrashort-pulse lasers for direct diode pumping has also been suggested [21] and demonstrated [22]. These lasers retain the superior alignment stability properties of the standard four-mirror, seven-element cavities, while focusing the laser mode more tightly in the gain medium and reducing the overall cavity length. Further simplification of the pump arrangement has been demonstrated at St. Andrews by reducing the oscillation threshold to a level such that low-power, diffraction-limited, narrow-stripe, single-spatial-mode (SSM) AlGaInP laser diodes [17], [23] can be used. This has substantially reduced the cost and complexity of the laser diode pump sources. A summary of selected diode-pumped femtosecond Cr:LiSAF lasers is given in Table I.

A major limitation to the reduction of the cavity length and overall footprint has been the required minimum separation of the prism pair that is typically used to provide sufficient negative group velocity dispersion. Alternative dispersion-control schemes that offer greater, or potentially greater, physical compactness for femtosecond laser configurations have been demonstrated. [13]–[15], [24], [25] Recently, a prismless femtosecond titanium sapphire laser was reported [26] with a repetition frequency of 2 GHz, using a ring cavity with a roundtrip length of less than 150 mm.

By utilizing a SESAM as the modelocking element and working in the soliton mode-locked regime [3]–[5], increased design freedom is obtain by separating the modelocking element from the gain medium. This methodology allows for reliable and efficient modelocking even in low-threshold systems.

In this paper, we report a number of highly compact asymmetric resonators using conventional "off-the-shelf" components and pumped with SSM diodes. First, a cavity with a single dispersion-compensating prism in each arm of the laser is described. Second, on the basis of experimental

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TABLE I
PERFORMANCE OF SELECTED DIODE-PUMPED, FEMTOSECOND Cr:LiSAF LASERS (APPROXIMATE LAUNCHED PUMP POWERS LISTED)

Configuration	Pulse Width (fs)	Average Power (mW)	Pump Power (mW)	Reference
High Power Cavity, SESAM	110	500	15000	[10]
Symmetric Z-fold, KLM	10	2.3	850	[11]
Symmetric X-fold, SESAM	45	105	1000	[12]
3-mirror Cavity, KLM	60	1.57	84	[17]
Asymmetric Cavity, KLM	26	6.2	800	[22]
Asymmetric Cavity, SESAM	57	6.5	90	[23]
Prismless X-fold, SESAM	160	25	500	[25]

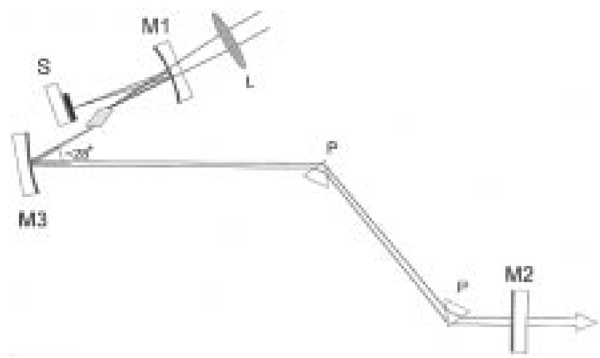


Fig. 1. Schematic of the highly asymmetric Cr:LiSAF laser. S: SESAM. M2: plane mirror. M1: 50-mm ROC mirror. M3: 75-mm ROC mirror. P: LaK31 prisms. L: 50-mm pump focusing lens.

observations and related dispersion analyzes, the design and demonstration of an ultra-compact and simplified femtosecond laser is reported. This laser has only a single prism for dispersion compensation and its footprint, including the pump source and drivers, is only 21.5×28 cm^2.

II. LOW-THRESHOLD FEMTOSECOND LASERS

The reduction of the continuous-wave (CW) lasing threshold, and the intracavity power requirements for modelocked operation, are obvious first steps to achieve, simple, compact and efficient laser oscillators. With this objective in mind, initial work at the University of St. Andrews demonstrated Cr:LiSAF lasers with extremely low pump power requirements. This permitted the use of narrow-stripe SSM laser diodes, with near-diffraction-limited output beams, as the pump source [17], [23]. Cr^{3+}:$LiSrAlF_6$ (Cr:LiSAF) was the chosen gain medium for this work because direct diode pumping of this crystal is achievable with commercially available AlGaInP laser diodes and the emission-cross-section upper-state-lifetime product $(\sigma\tau)$ of this crystal is high, thereby facilitating a low CW laser threshold [27]. Fig. 1 shows the basic cavity configuration reported in [23]. The Cr:LiSAF crystal was a 7-mm Brewster/Brewster cut crystal with 1.5% Cr^{3+} doping (this corresponds to a pump absorption coefficient, $\alpha_p \sim 9$ cm^{-1}). The high degree of asymmetry in folding angles around the Brewster-angle cut gain medium is a necessary condition for the lowest possible CW threshold [28]. The large angle between the long cavity arm and the folding section entirely compensates for the astigmatism introduced by the gain medium. Provided that the angle between the folding section and the short cavity arm is small, the cavity mode may be tightly focused in both the sagittal and tangential planes and made to coincide with the focused pump beam at the crystal facet. The asymmetry in cavity arm lengths permits the focussed spot size on the modelocking element (in this case a semiconductor saturable absorber mirror, SESAM [29], [30]) to be varied easily by adjusting the length of the short cavity arm when aligned in the low-misalignment-sensitivity (LMS) region [31]. This enables the saturation of the SESAM to be optimized for varying intracavity powers. The SESAM used throughout this paper was a low-loss antiresonant Fabry-Perot saturable absorber that is especially suited to low intracavity powers and is described elsewhere [10], [12]. Separating the modelocking element from the gain medium by using a SESAM to initialize, stabilize, and maintain soliton-mode-locked operation gave the cavity greater flexibility and stability at low intracavity powers.

The two pump laser diodes were polarization combined to provide up to ~90 mW of pump power. The use of such diffraction-limited sources allows simple coupling optics to be employed and a much more efficient pump/cavity mode overlap to be obtained. The diodes were collimated using standard 20× anti-reflection-coated microscope objective lenses. No reshaping of the 3:1 elliptical mode was employed. When a small battery pack containing six 1.5-V AA-type penlight batteries and a low dropout voltage regulator circuit (LP2952) powered the diodes, the laser operated for more than 14 h.

The CW threshold was below 20 mW (using a 1.5% output coupling mirror). Mode-locked operation ceased when the pump power was reduced below 22 mW. The laser produced 57-fs pulses at an average output power of 6.5 mW for an incident pump power of only 72 mW! The pulses were bandwidth limited, having a spectral width of 13.5 nm centred on 855 nm. This laser also had very low noise characteristics. The RMS timing jitter in the range 500–5000 Hz was just 73 fs [23].

With this demonstration of a low-threshold, low-noise, efficient—and potentially compact—laser comes new possibilities for femtosecond laser research, including the reduction of the overall cavity footprint allied to the maintenance of the low-loss characteristics of this laser.

III. COMPACT CAVITIES WITH A PAIR OF PRISMS FOR DISPERSION COMPENSATION

The majority of the excess space taken up by the laser in Fig. 1 results from the necessary separation of the dispersion-compensating prisms. Although much more compact dispersion-compensation schemes such as chirped mirrors [24] and dispersive SESAMs [25] exist, presently these have higher insertion losses

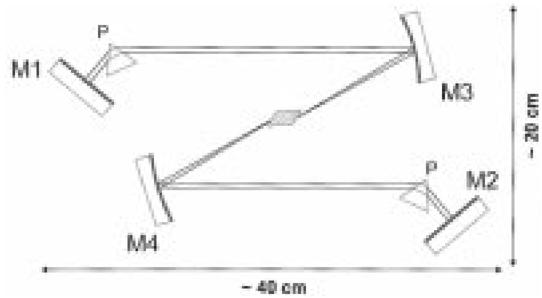


Fig. 2. Schematic of the four-mirror symmetric "Aoshima-type" Cr:LiSAF cavity described in [32]. M1 and M2: plane mirrors. M3 and M4: concave mirrors. P: prisms.

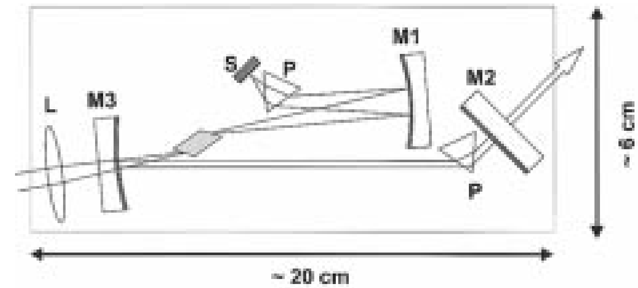


Fig. 3. Schematic of the four-mirror highly asymmetric Cr:LiSAF "Aoshima-type" cavity. M1: 75-mm ROC focusing mirror. M3: 50-mm ROC focusing mirror. M2: plane end mirror. S: SESAM. P: LaK31 prisms. L: 50-mm pump focussing lens.

and, therefore, are not suitable for SSM diode laser pumping. To control both the threshold and cost, compact cavities using off-the-shelf optical components and standard Brewster-angled prisms were investigated. This facilitated flexible cavity design whilst having the low insertion loss necessary for operation at low pump powers.

Aoshima *et al.* [32] showed that a standard prism pair could be incorporated in a more compact, symmetric, self-mode-locked z-fold cavity by placing one prism in each of the cavity arms. A schematic of this cavity is shown in Fig. 2. In this way, the necessary distance between the folding mirrors for tight focussing, and the required inter-prism path lengths, could be combined. This represents a considerable reduction in the size of an ultrashort-pulse laser. However, the pump lasers used in [32] (two SDL 7350-A6 Master Oscillator Power Amplifier laser diode systems) do not represent a very compact arrangement and although these provided diffraction-limited beams, the modelocking threshold was rather high ($\sim$370 mW).

The prism separation was determined on the assumption that they acted in the same way as when they occupied a single arm of the cavity. This resulted in a significant increase in pulse duration from 30 to 90 fs, which was attributed to a spatially dispersed beam in the Cr:LiSAF crystal acting as a bandwidth filter [32]. By adapting this type of cavity to include the threshold-reducing cavity improvements described in the previous section and the low-loss SESAM, we have been able to demonstrate a more compact version of this type of laser with significantly improved efficiency.

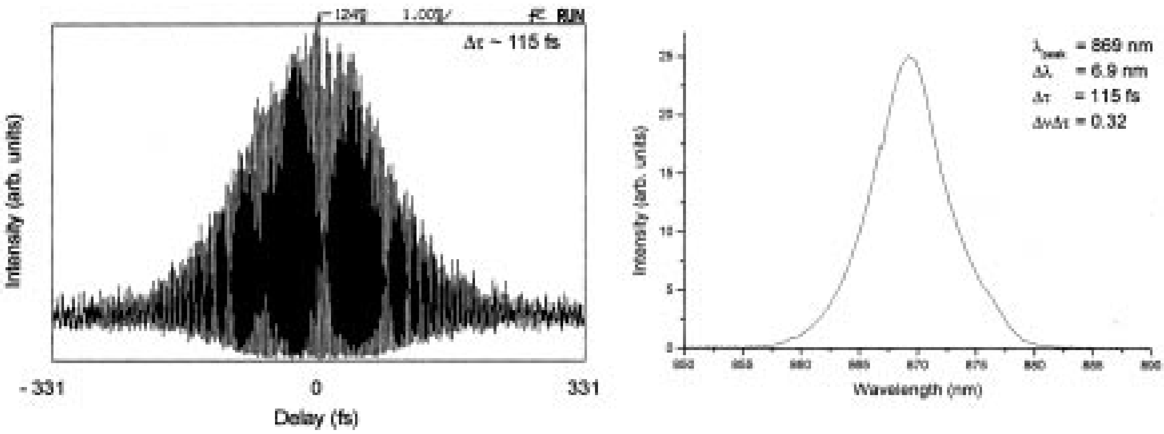
Fig. 3 shows a schematic of the highly asymmetric four-mirror Z-cavity with a prism in each arm. Again, the beam waist on the SESAM is easily varied by adjusting the length of the short cavity arm enabling the saturation of the SESAM to be optimized for a range of intracavity powers. The gain medium was the 7-mm Cr:LiSAF crystal described earlier. The plane end mirror was either a high-reflection coated mirror or an output coupler. The 75-mm radius of curvature (ROC) folding mirror M1 was set at a half-angle of 17° to compensate entirely for the astigmatism due to the Brewster-angled crystal, while M3 was set at near-normal incidence. The spot size at the SESAM was set at $\sim 15\ \mu$m. The pump lasers and optics were the same as those described previously and the cavity optics, including the pump lens, fitted within a 200×60-mm footprint. (We have also implemented this type of cavity in an all-solid state Kerr-Lens modelocked Cr^{4+}:YAG laser [16].)

The CW threshold of the laser was just 20 mW with the p-polarized SSM diode laser and all the cavity elements in place. With both diodes supplying a total of 76 mW at the pump lens, the Cr:LiSAF laser produced an average power of 1.5 mW with a high-reflecting plane end-mirror. The laser produced stable, bandwidth-limited pulses of 115-fs duration at a repetition frequency of 407 MHz (see Fig. 4). It was found, however, that tight focusing through the prism in the short arm severely limited the stability of the laser. This resulted in a larger insertion loss from this prism when attempting to optimize the pulse duration. For this reason, the laser could not be modelocked successfully with the 1.5% output-coupling mirror.

At first, it was assumed that the prisms should be oriented with their apices pointing in the same direction, as the standard description of the operation of a prism pair would imply a reversal of the ray direction through the cavity focus. Experimentally, however, we found that this simple ray picture did not accurately describe the behavior of the cavity. The prism in the longer of the arms was "flipped" so that its apex pointed in the opposite direction to the prism in the short arm. In this configuration, the laser produced 100–fs pulses at a repetition frequency of 353 MHz (the longer cavity length was necessary to achieve femtosecond pulse operation). The time-bandwidth product of the pulses was 0.43 indicating a "chirped" output. The average output power was $\sim$1.1 mW for a pump power of 76 mW and the modelocking threshold was 61 mW. This behavior was not predicted by a simple ray picture. A more detailed analysis of the Aoshima-type cavities was required to explain the role of the prisms and their contributions toward dispersion in the resonator. Such an analysis is presented in the next section.

IV. A Dispersive Model for the Compact Resonator Geometries

Kostenbauder [33] suggested a model for simplifying the analysis of complex dispersive optical systems, such as pulse compressors and femtosecond laser cavities. The model includes both spatial and temporal variations in the propagating signal and from it dispersive effects up to and including quadratic phase can be deduced. Basing his work on the ABCD matrix representation of paraxial optical systems, Kostenbauder used a 1×4 "ray-pulse" vector to describe the spatial displacement x, direction θ arrival time t and frequency f of a propagating monochromatic pulse with respect to a



(a) (b)

Fig. 4. (a) Interferometric autocorrelation and (b) spectrum of 115-fs pulses with an average output power of 1.1 mW obtained for 76 mW of pump.

spatially and temporally transform-limited midband reference pulse. This reference pulse provides a well-defined spatial and temporal origin at each transverse element plane within the system. The effect of any system of optical elements on an input ray-pulse vector can then be described by

$$\begin{bmatrix} x_{\text{out}} \\ \theta_{\text{out}} \\ t_{\text{out}} \\ f_{\text{out}} \end{bmatrix} = T \left\{ \begin{bmatrix} x_{\text{in}} \\ \theta_{\text{in}} \\ t_{\text{in}} \\ f_{\text{in}} \end{bmatrix} \right\} \tag{1}$$

where T is a 4×4 transfer matrix describing the optical system.

To model laser resonators, the transfer matrix $\tilde{T}$ that describes a complete round-trip of the cavity must be calculated and each ray-pulse of relative frequency f must be self-reproducing for it to exist within the cavity, such that

$$\begin{bmatrix} x \\ \theta \\ t_{\text{out}} \\ f \end{bmatrix} = \tilde{T} \begin{bmatrix} x \\ \theta \\ t_{\text{in}} \\ f \end{bmatrix}. \tag{2}$$

Combining this with the conditions for a stable resonator, the relative positions and direction of rays of different frequency, and the delays of pulses of different frequency may be calculated. The delay between propagating pulses of differing frequencies in the model can then be used to calculate a value for the quadratic phase or group velocity dispersion (GVD) of the cavity. The relative delay of a pulse from the reference pulse over a single roundtrip is given by

$$t_{\text{out}} = Gx_{\text{in}} + H\theta_{\text{in}} + If_{\text{in}} \tag{3}$$

where G, H and I are the (3, 1), (3, 2), and (3, 4) elements of the round trip matrix $\tilde{T}$.

By propagating several such pulses of different frequencies $f_1 \ldots f_5$ through the cavity, an expression for the GVD may be derived

$$\text{GVD} = \frac{\tau_1 - 8\tau_2 + 8\tau_4 - \tau_5}{24\pi\Delta f} \tag{4}$$

where Δ_f is the frequency separation of the pulses and τ_1, τ_2, τ_4 and τ_5 are the relative delays of the four pulses to the midband reference pulse $f_3 = 0, \tau_3 = 0$.

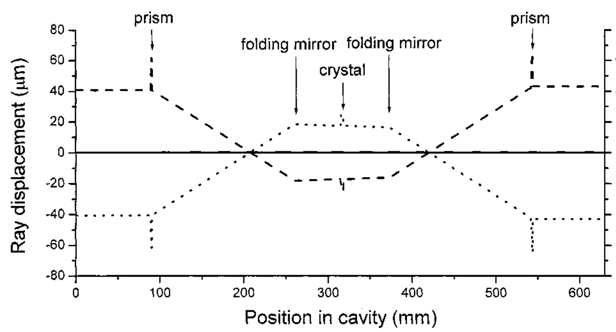


Fig. 5. Relative paths traced by two rays separated by 20 nm, 900 nm (dotted), and 920 nm (dashed) with respect to an arbitrary reference ray at 910 nm (solid) in the symmetric Aoshima-type cavity. The positions of the various optical elements are shown above.

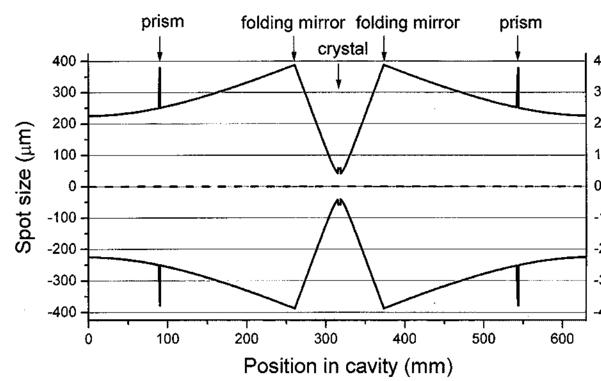


Fig. 6. Behavior of the transverse resonator mode in the symmetric Aoshima-type cavity. The positions of the various optical elements are shown above.

The roundtrip matrices for each element plane in the stable resonator are used to determine the relative position and direction of frequency upshifted and downshifted rays with respect to the midband reference ray. Fig. 5 shows the relative behavior of the rays in the symmetric cavity of Aoshima *et al.* [32]. (It is important not to confuse this ray picture with the behavior of the transverse resonator mode $(1/e^2)$, which is shown for this laser in Fig. 6.)

It can be seen from Fig. 5 that the rays in the space between the prisms and the end-mirrors are spatially dispersed but parallel, and therefore do not contribute to the GVD of the cavity.

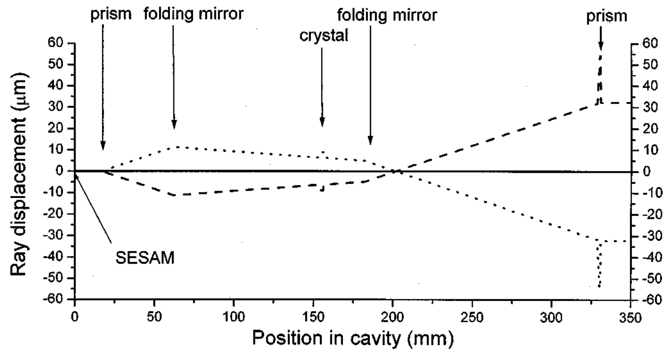


Fig. 7. Relative paths traced by two rays separated by 10 nm, 864 nm (dotted), and 874 nm (dashed) with respect to an arbitrary reference ray at 869 nm (solid) in the highly asymmetric Aoshima-type cavity. The position of the cavity elements are indicated above.

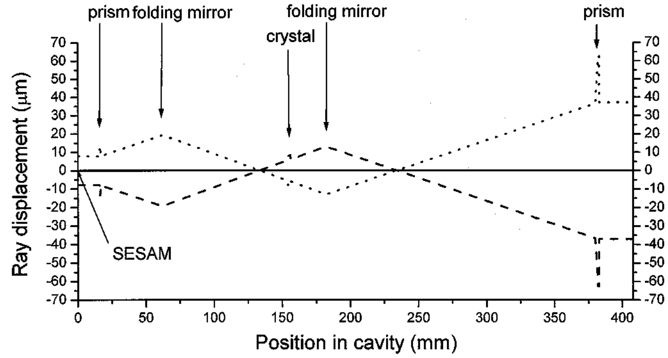


Fig. 8. Relative paths traced by two rays separated by 10 nm, 863 nm (dotted), and 873 nm (dashed) with respect to an arbitrary reference ray at 868 nm (solid) in the highly asymmetric cavity with oppositely oriented prisms. The position of the cavity elements are indicated.

The rays between the folding mirrors, and therefore in the gain medium, are also spatially dispersed, but more or less parallel suggesting no significant contribution to the GVD. In fact, the very slight angular dispersion visible in the folding section is due to the Brewster-angled gain medium, which if replaced with a plane cut crystal would result in the rays becoming parallel. It is clear from Fig. 5 that the majority of the dispersion compensation originates not from between the folding mirrors themselves, but from between the prisms and the folding mirrors. This is because the rays in this element space have a large angular dispersion. These ray paths suggest that the folding mirrors create "virtual"prisms at the ray crossing. This results in dispersive properties that are similar to the case where two pairs of oppositely oriented prisms exist in each cavity arm.

The quadratic phase for this cavity configuration was calculated to be -278 fs^2, which is less than a third of the value required for the shortest pulses [32]. This would seem to explain the lengthening in pulse duration from 30 to 90 fs observed by Aoshima and co-workers in moving to the new geometry from a standard prism configuration. Nevertheless, further investigation of this type of cavity must be made to determine the effect on the pulse duration of the spatially dispersed beam in the gain medium.

The most crucial parameter for dispersion control in this cavity appears to be the prism/folding mirror separation. Provided that this is of a suitable magnitude, the contributions from the "dead-space" between the prisms and the end-mirrors and the space between the folding mirrors may be ignored. This indicates, as we have confirmed experimentally, the feasibility of highly asymmetric cavities of this type. Modeling of the experimental highly asymmetric cavity shows a similar behavior, although the rays in the short arm fortuitously cross at the insertion point of the prism resulting in an undispersed beam being incident on the SESAM (see Fig. 7).

Modeling of the cavity with the "flipped" second prism (see Fig. 8) shows that the rays are dispersed spatially at both the output coupler (long arm) and the SESAM (short arm). The effect of rotating the prism in the long arm causes the rays to cross in the space between the folding mirrors, adding an opposite sign of angular dispersion in this section to the angular dispersion in the long arm. The calculated value for the net quadratic phase was only -50 fs^2, which may explain the frequency-chirped pulses produced with this cavity configuration.

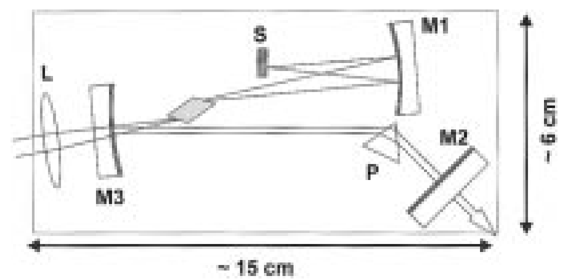


Fig. 9. Schematic of the compact femtosecond laser with a single LaK31 prism for dispersion compensation. L: 50–mm pump focus lens. M1: 75-mm ROC folding mirror. M3: 50-mm ROC folding mirror. M2: 0.75% output-coupling mirror. S: SESAM.

V. A Highly Compact Femtosecond Laser With a Single Prism for Dispersion Compensation

A direct conclusion from the modeling of the highly asymmetric cavities presented in the previous section is that the prism in the short arm does not contribute a significant amount of intracavity negative dispersion due to the short distance from this prism to the folding mirror. This implies that this prism should not be necessary to achieve an acceptable amount of negative dispersion, and so a single prism in the longer arm should suffice for femtosecond-pulse operation. At first, this would appear to be counter-intuitive in the absence of a plane/Brewster-cut gain crystal in the cavity, but the modeling clearly indicates this is not a requirement for sufficient negative dispersion. The removal of the prism from the tightly focussed short arm simplifies the laser cavity and removes the alignment and optimization problems associated with a prism in this arm. (Femtosecond pulse operation from a dye ring laser with a single prism has already been reported [34], as well as in a Cr^{4+}:YAG laser [35] and in a diode-pumped Nd:glass laser [36], for which an alternative, simple—but effective—ray optic analysis was presented.)

The laser cavity was set up as in Fig. 9, where the LaK31 prism used previously in the short arm was removed and the fold angle of the 75-mm ROC mirror set to 11°. The distance from this folding mirror to the Cr:LiSAF crystal was 95 mm, and the length of the short arm was ~60 mm. The 50-mm ROC pump folding mirror and second LaK31 prism were separated initially by 125 mm and the separation of the prism and the end-mirror was ~25 mm.

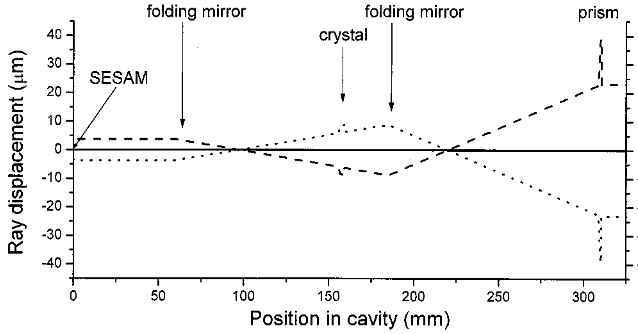


Fig. 10. Relative paths traced by two rays separated by 10 nm, 855 nm (dotted), and 865 nm (dashed) with respect to an arbitrary reference ray at 860 nm (solid) in the highly asymmetric compact cavity with single prism, the position of the cavity elements are indicated above.

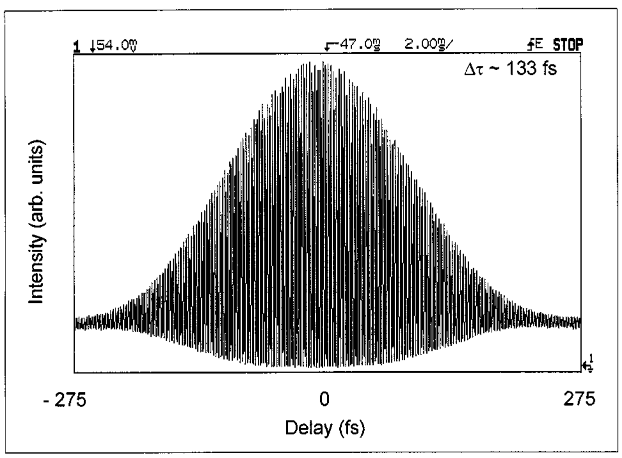


Fig. 11. Interferometric autocorrelation of 133-fs pulses with a repetition frequency of 315 MHz and an average output power of 5 mW obtained from the compact single-prism cavity for a 76–mW pump.

Fig. 10 shows the paths for two rays with wavelengths separated by ± 5 nm from a reference ray at 860 nm for this configuration. The rays again cross in the folding section (although this is not as pronounced) suggesting that this cavity is not optimum for maximizing negative dispersion.

The CW threshold was 26 mW, with a 0.75% output-coupling mirror at 856 nm. CW output powers as high as 7 mW for a 76-mW pump were recorded, and the laser mode-locked easily, producing 250–fs chirped pulses with an output power of $\sim$5 mW at a cavity frequency of 435 MHz. When optimized, stable pulses with durations as short as 160 fs and an average output power of 6.1 mW were produced over a period of many hours. The GVD or quadratic phase of the cavity was calculated to be -157 fs^2 with $\sim$2 mm of prism insertion. Unfortunately, spectral information was not available at the time these results were taken.

The pump folding mirror to prism separation was lengthened to 205 mm and the space after the prism to 70 mm. In this arrangement, with about $\sim$5 mm of prism insertion, the calculated quadratic phase was -253 fs^2 and the laser produced 133-fs pulses (see Fig. 11). The repetition frequency was 315 MHz and the average output power was $\sim$5 mW. One of the possible reasons for the longer, chirped pulses obtained from the shorter cavity is due to the spatially dispersed mode in the gain medium.

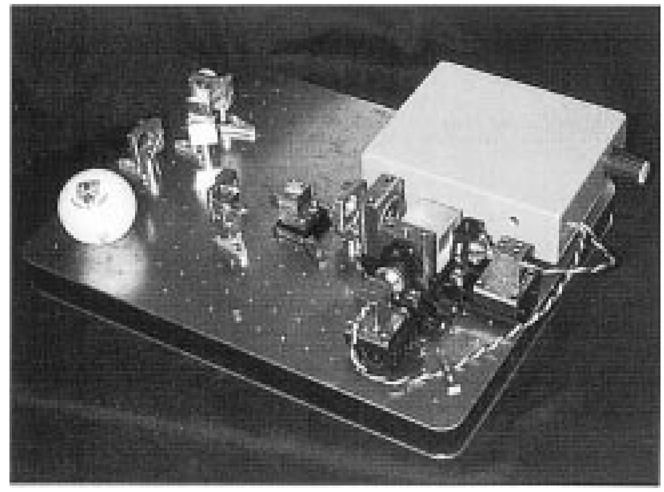


Fig. 12. Photograph of the compact single prism femtosecond laser on a self-contained breadboard, the battery power supply for the diodes is also included (a golf ball is included for scale).

This problem scales inversely with cavity length because the mode size increases as the cavity length is reduced. Possible solutions to this problem would be to ensure that the rays crossed inside the gain medium thereby removing some of the spatial dispersion at the cavity focus or to use yet smaller radius of curvature mirrors in the folding section.

To reconfigure the cavity within a smaller footprint, the Lak31 prism was replaced with an SF10 glass prism that exhibited larger dispersion. This prism was placed 100 mm from the 50–mm ROC pump folding mirror with a space after the prism of 75 mm. In this configuration, the calculated GVD was -368 fs^2, although the laser produced 330–fs pulses at a repetition frequency of 400 MHz. The footprint of the laser cavity was reduced to 15×6 cm and implemented using *Tiny Mounts*[1] [37] half-inch (12.7 mm) optics on a 21.5×28–cm bread board (about the size of a piece of A4 or US letter paper), which included a compact version of the laser diode pump system and a battery pack (see Fig. 12).

VI. Improved Performance Through Development of the Pump Optics

The major remaining factor limiting the performance of such compact, ultrafast Cr:LiSAF laser systems is the available pump power. The high beam quality of SSM diodes plays a vital part in achieving low thresholds and high efficiencies; thus, switching to expensive, higher power, broad area diodes is not attractive. Using SSM diodes, which are less than \$30 each, substantially reduces the cost of the laser system.

Currently, the output power of commercially available narrow stripe SSM diodes in the red spectral region is limited to 50–60 mW. One must thus minimize the losses in coupling the pump beam into the laser crystal and ensure a high degree of overlap between the pump and laser modes. The high ellipticity of most laser diode sources exacerbates the latter problem. In the case of high power pump diodes, this problem has been elegantly ameliorated using an elliptical resonator mode [10]. However,

[1]New Focus Inc., 2630 Walsh Avenue, Santa Clara, CA 95051-0905.

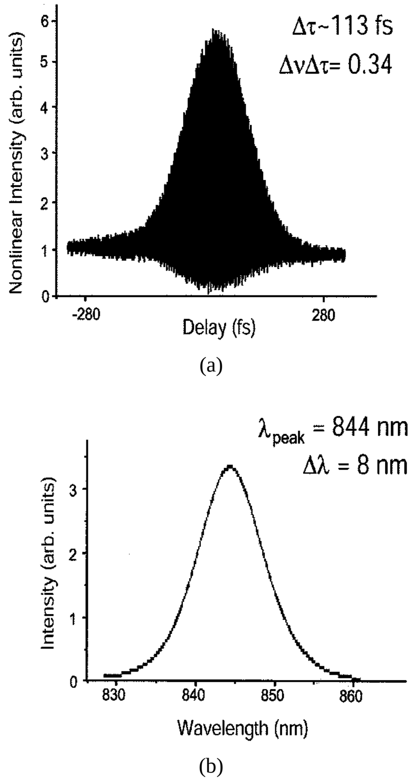


Fig. 13. (a) Interferometric autocorrelation and (b) spectrum of 113-fs pulses with a repetition frequency of ∼400 MHz and an average output power of 15 mW obtained from the compact single prism cavity for ∼100-mW pump.

the high beam quality of SSM diodes means that for these diodes, the simpler solution of circularising the pump mode can be utilized, and it is this approach that we have used in St. Andrews. Standard commercial diodes were custom microlensed[2] using a single cylindrical lens inside the existing diode can. The resulting circular beam can be easily handled by standard spherical optics.

To increase the available pump power, the lasers described in previous sections used two polarization-coupled pump diodes. This, however, is a rather inefficient method of beam combining. With the optics available to us, we achieved a coupling efficiency of 91% of the power emitted by the two diodes. However, the resulting beam is of mixed p and s polarizations. This has two disadvantages. First, the need to couple into a Brewster-cut gain crystal means there is a loss of approximately 10% on the s-polarized component of the pump beam. Second, the s-component experiences a lower absorption coefficient in the Cr:LiSAF crystal, reducing the slope efficiency and raising the threshold of the laser [27].

The wide absorption bandwidth of Cr:LiSAF in the red-region of the spectrum means that these problems can be avoided if wavelength combining [37] is used. We used an "off-the-shelf" dielectric mirror from Chroma-Technology Inc. (670DCLP) to combine a 660-nm ∼50-mW Hitachi HL6503MG diode with a 690 nm, ∼60-mW Mitsubishi ML1013R diode. In this way we were able to achieve ∼98% coupling efficiency and ∼96% absorption of the launched pump power in a 3-mm, 5.5-atm% Cr:LiSAF crystal. In the case of polarization coupling, only ∼86% of the launched power is absorbed in the same crystal.

[2]Blue Sky Research Inc.

This pump setup was used with a similar laser cavity to that described in Fig. 8, but with the 7-mm 1.5 atm% Cr:LiSAF crystal replaced with a 3-mm 5.5-atm% Cr:LiSAF crystal. A newer mirror set with marginally higher pump transmission was also used. This set-up generated modelocked output powers of greater than 20 mW in transform-limited pulses of around 151 fs. This represents an efficiency of 19% with respect to launched pump power and a remarkable electrical to optical pulse efficiency of almost 5%. At slightly lower average powers (∼15 mW) transform-limited pulses as short as 113 fs have been generated (see Fig. 13).

VII. Conclusion

In this paper, we describe directly diode-pumped femtosecond lasers that are both compact and efficient. By using a more complete analysis of the dispersive properties of the cavities, we have been able to demonstrate that simplifications in the design and improvements in performance can be made. In this way, we have demonstrated pulses as short as 113 fs with a single prism for dispersion compensation. Careful analysis of the low-threshold characteristics of the oscillators has led to mode-locked output powers of greater than 20 mW for less than 500 mW of electrical power.

The laser designs presented in this paper begin to address some of the problems that limit the application of ultrafast lasers outside of the laser lab. Many applications, particularly in the fields of biology and medicine, stand to benefit from ultrafast sources [38]. However, most biomedical research is not best performed in a laser laboratory. In these circumstances, robustness, portability, and running costs become vital issues. In this paper, we have presented laser designs which have the efficiency to be battery powered and potentially low cost. The cavities are simple, and the SESAM-based mode-locking mechanism is robust and self-starting, key factors in the drive for low-maintenance turn-key operation. Indeed, the footprint of the smallest of these lasers is such that whole system will easily fit in a briefcase.

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