Ensuring Compactness, Reliability, and Scalability for the Next Generation of High-Field Lasers

John Nees, Subrat Biswal, Frédéric Druon, Jérôme Faure, Mark Nantel, Gérard A. Mourou, *Fellow, IEEE*,
Akihiko Nishimura, Hiroshi Takuma, Jiro Itatani, Jean-Christophe Chanteloup, and Clemens Hönninger

(Invited Paper)

***Abstract*—If further developments in high-field lasers are to be accessible to universities and institutes, new laser materials and phase control techniques, which will result in compact, reliable systems with higher peak power, must be adopted. The choice of high-saturation-fluence gain material and the measurement and active control of temporal and spatial phase distortions for compact chirped-pulse amplification (CPA) systems of the future are discussed. Using the proper material and phase control a focused intensity of 10^{25} W/cm^2 is theoretically possible.**

***Index Terms*— Deformable mirrors, diode-pumped solid-state lasers, high-focused intensity, high-peak power, petawatt, terawatt, ytterbium glass, ytterbium laser materials.**

I. INTRODUCTION

OPTICAL nonlinearities in solids were inaccessible until lasers were introduced with focused intensities near 10^{10} W/cm^2 [1]. Likewise, the discovery of Q-switching [2], [3] opened the investigation of nonlinearities in gases near 10^{14} W/cm^2 [4]. In more recent years, relativistic nonlinearities have become accessible due to the introduction of chirped-pulse amplification (CPA) [5], [6] and the use of focused intensities above 10^{17} W/cm^2 [7].

Beginning with the first terawatt (TW) lasers built for fusion applications and proceeding to the modern table-top TW lasers, a wealth of scientific discovery has been based on the interaction of strong optical fields with matter. Critical to these studies is the availability of high-focused-intensity lasers. Along with the development of femtosecond oscillators [8], the introduction of CPA has had a profound influence on the way ultrafast and high-field science is done. By bringing reliability and compactness to high intensity lasers, these advances allow research to be done not only in national laboratories but, also, at the level of universities and industry. Scaling to higher intensity sources will require continued attention to compactness and reliability.

In order to realize of the full potential of the laser amplification process to form high focused intensity, we should use a gain material which can be pumped by simple free-running lasers or laser diodes [9]. Both the density of energy stored and the excited-state lifetime of the material must be exploited. We must also choose a gain material with sufficient bandwidth to allow short pulses to be formed. Finally the temporal and spatial characteristics of the amplified pulses must be known and manipulated to deliver a well-behaved optical pulse to the experiment.

Following the notion that broad usage will enhance the development of applications and support, one can reason that the path to fully utilizing optical amplifiers lies in the direction of compact and efficient laser technology. As illustrated by the development of electronics, the compactness, reliability and scalability of a technology have a strong impact on its growth. The use of the transistor, coupled with the further invention of the printed circuit board and the microchip, brought about the current phenomena of microcomputers and telecommunications. These changes were made because the new technology offered compactness, reliability and scalability.

In a similar way, the invention of CPA brings a phenomenal reduction in scale to the production of high focused intensity. Before the introduction of CPA, high intensity ultrafast pulses were generated by dye or eximer lasers. The use of solid-state materials with their superior energy storage capability was restricted to nonosecond-pulse amplification. Using these technologies, a TW laser was the size of a building. With the technique of CPA, the scale of TW lasers is reduced by orders of magnitude to table-top dimensions. The requirement for pump power is also reduced by orders of magnitude. As a result, the cooling rate and the ease of cooling are improved. The size of optics and the probability of damage are reduced. The result is that TW lasers are widely available and used by a growing number of researchers in universities, institutes and industry.

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J. Nees, S. Biswal, F. Druon, J. Faure, and G. A. Mourou are with the Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48108 USA.

M. Nantel was with the Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48108 USA. He is now with Photonics Research Ontario, ON, M5S 1A7 Canada.

A. Nishimura and H. Takuma are with the Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan.

J. Itatani was with the Institute for Solid State Physics of the University of Tokyo, Minato-ku, Tokyo 106, Japan. He is now with the Laser Technology Laboratory, Institute for Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan.

J.-C. Chanteloup is with the Laboratories pour l'Utilization des Lasers Intenses (LULI), CNRS UMR 100, Ecole Polytechnique, 91128 Palaiseau cedex, France.

C. Hönninger is with the Institute of Quantum Electronics, Ultrafast Laser Physics Laboratory, ETH Zurich ETH Hönggerberg, HPT D20 CH-8093 Zurich, Switzerland.

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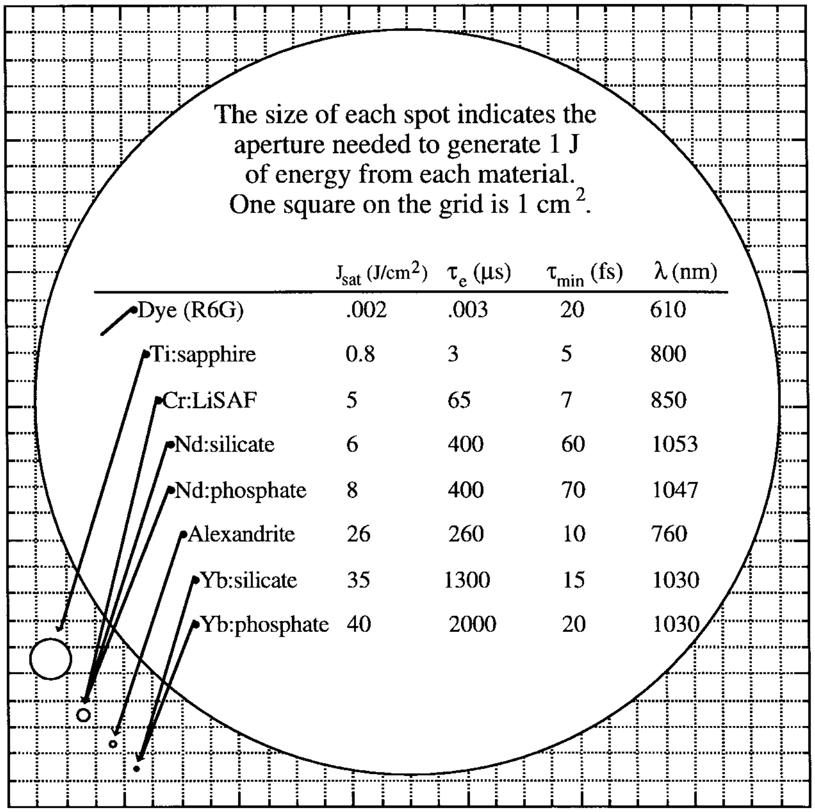

The size of each spot indicates the aperture needed to generate 1 J of energy from each material. One square on the grid is 1 cm^2.

	J_{sat} (J/cm^2)	τ_e (μs)	τ_{min} (fs)	λ (nm)
Dye (R6G)	.002	.003	20	610
Ti:sapphire	0.8	3	5	800
Cr:LiSAF	5	65	7	850
Nd:silicate	6	400	60	1053
Nd:phosphate	8	400	70	1047
Alexandrite	26	260	10	760
Yb:silicate	35	1300	15	1030
Yb:phosphate	40	2000	20	1030

Fig. 1. Emission cross section, lifetime, and minimum pulse duration of various laser materials. Materials with larger areas require larger apertures to generate a given energy. Estimation of minimum pulse duration is taken from the FWHM of the emission cross-section spectra.

Where can improvements in compactness, reliability, and scalability take high-field science? This question is naturally open-ended. Immediate applications in medicine [10], [11], precision machining [12], laser film deposition [13], XUV and X-ray generation [14], and particle acceleration [15]–[19] provide some indication of practical directions for high-field lasers. Continued exploration of relativistic effects in laser-plasma and laser particle-interactions can also be projected. Though the stellar goal of exploiting vacuum nonlinearity in the abscence of other particles at 10^{29} W/cm^2 [9], [20] remains hidden by several orders of magnitude in intensity, this too gives a sense of direction to the development of compact, ultra-intense light sources.

In this paper, we discuss the choice of laser materials and its effect on compactness and scalability of ultra-intense lasers. We also discuss the importance of both measuring and controlling the temporal and spatial pulse features in such lasers.

II. OPTICAL GENERATION OF HIGH FIELDS

High-intensity lasers produce ultra-intense pulses by concentrating a given amount of optical energy both temporally and spatially. The temporal limit is imposed by the time-bandwidth product, $\tau_{\min} \cong 1/\Delta\nu$; spatially, the limit of focus is $\Delta x_{\min}^2 \cong \lambda^2$. ($\tau_{\min}$ is the minimum pulse duration, $\Delta\nu$ is the fluorescence bandwidth, $\Delta x_{\min}$ is the minimum focal diameter, and λ is the wavelength.)

A. Energy Storage in Laser Materials

Compact and efficient storage of optical energy depends on the use of materials with high doping density. The second factor which is critical to the suitability of the gain material is its fluorescence lifetime, τ_f. This factor determines the rate at which the stored energy is depleted due to spontaneous emission, and the pump power which is needed to create a population inversion in the gain material. The pump power, I_{pump}, required to achieve the stored energy limit, is the total stored energy divided by the fluorescence lifetime of the gain material and the quantum defect:

$$I_{\text{pump}} = \frac{NLh\nu_e}{\eta\tau_f} \tag{1}$$

(h is Planck's constant, ν_e and ν_{pump} are the emission frequency and pump ferquency, respectively, $\eta = \nu_e/\nu_{\text{pump}}$, L is the gain length, and N is the number of active ions per unit volume).

The fundamental relationship between the minimum pulse duration, the emission cross section, and the upper state lifetime in a two-level laser transition is given by [21]:[1]

$$\tau_f = \kappa\frac{\tau_{\min}\lambda^2}{\sigma_e n^2}. \tag{2}$$

(κ is a numeric constant depending on emission line shape and n is the optical index of the material.) From this relation it

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[1] Spontaneous emission rate A_{21} is replaced by $1/\tau_f$ and $\tau_{\min}$ is taken to be $1/\Delta\nu$. The remaining numerical factors are taken up in κ.

can be seen that materials with smaller emission cross-sections have the advantage of longer excited state lifetimes.

B. Energy Extraction at the Saturation Fluence of Laser Materials

With these factors it is also important to have a high-saturation fluence in the amplifier in order to reduce the aperture size. Saturation fluence is defined as [22][2] $U_{\rm sat}$.

$$U_{\rm sat} = \frac{h\nu_e}{\sigma_e}. \tag{3}$$

(σ_e is the emission cross section at frequency, ν_e.) This factor varies widely from one gain material to another.

Fig. 1 shows the effect of saturation fluence on the aperture size of an amplifier system producing a given energy. The aperture required to generate 1 J of optical energy at saturation fluence using a typical laser dye would be about 600 cm^2. Using solid-state materials the same energy can be produced by an aperture of only 0.02 cm^2—30 000 times reduction in area. Dye amplifiers are also inherently difficult to pump because of their high rate of spontaneous emission. This limits the storage time of dyes to only a few nanoseconds. In contrast, solid-state materials can store energy in the excited state for 2–3 ms—six orders of magnitude longer than dyes. The long lifetimes of materials such as Yb:glass allow energy from pump lasers to be accepted over a long interval. As a result pump sources for these materials may be free-running multimode lasers or laser diodes. Smaller aperture leads to faster cooling and lower cost optics.

C. Theoretical Peak Power of Laser Materials at Saturation Fluence

The theoretical limit of peak power, $P_{\rm max}$, which can be generated from a 1-cm^2 area of laser material scales as the saturation fluence divided by the minimum pulse duration,

$$P_{\rm max} \cong \frac{h\nu_e}{\sigma_e \tau_{\rm min}}. \tag{4}$$

As shown in Fig. 2, the theoretical limit for the mature technologies of Nd:glass and Ti:sapphire lie in the range of 100 TW/cm^2 of laser aperture. In this figure, the bandwidth of the material is taken to be the full-width-at-half-maximum of the emission spectrm. Practically, this gives a value for $\tau_{\rm min}$ a factor of two below that generated directly from a dispersion controlled modelocked oscillators. Yb:glass displays both the bandwidth and the saturation fluence necessary to exceed 1 PW/cm^2 if the potential for energy storage and extraction, and phase control can be met.

Ultimately, the focused intensity which can be obtained from a centimeter-squared aperture of gain material is limited to

$$I_{\rm max} \cong \frac{P_{\rm max}}{\Delta x_{\rm min}^2} \cong \frac{U_{\rm sat}}{\lambda^2 \tau_{\rm min}}. \tag{5}$$

Producing peak power at the theoretical limit from any laser material is dependent on extracting the stored energy from the material with the necessary bandwidth to form a short intense pulse.

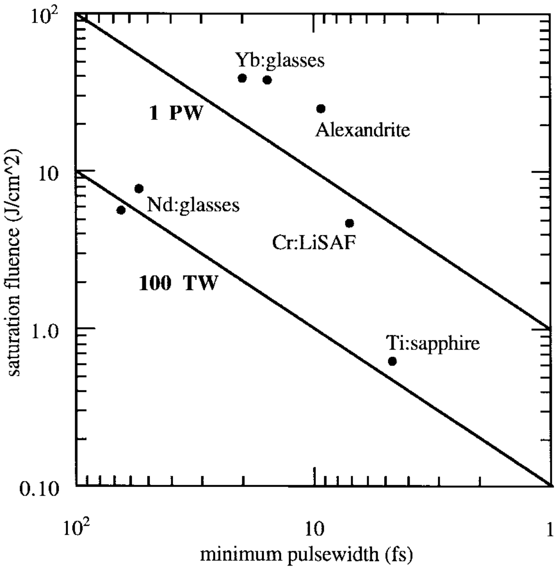

Fig. 2. Theoretical peak power per centimeter-squared aperture for various laser materials.

D. Avoiding Nonlinear Phase Accumulation and Surface Damage

Before the introduction of CPA, solid-state lasers were operated far below their potential for peak power generation to avoid damage arising from nonlinear phase accumulation. This is described by the B integral:

$$B = \frac{2\pi}{\lambda} \int n_2 I(z)\, dz \tag{6}$$

which sets the upper limit on the peak intensity of amplified signals to the order of a few GW/cm^2, or mJ/cm^2 for picosecond pulses. Such an operating level is several orders of magnitude below saturation fluence in solid-state amplifiers and lead to gross inefficiency.

Following the most widely used recipe for CPA, a short, broad-band pulse is generated by a mode-locked oscillator. A single pulse is selected from a 10^8-Hz pulse train and stretched in a grating-based stretcher; the degree of stretching being determined by the limit of nonlinear phase accumulation. The stretched pulse is then used to seed a regenerative or multipass amplifier. After passing through one or more stages of amplification the pulse is compressed by a grating pair to form a short highly intense pulse.

During this process the peak power of the pulse in the amplifying medium is reduced by the ratio of stretched pulse duration, $\tau_{\rm stretched}$, to the minimum pulse duration, $\tau_{\rm min}$. This ratio can be in excess of 10^5. The resulting nonlinear phase accumulation is also reduced in proportion.

The product, $\sigma_e N$, defines the small signal gain coefficient, g_0. The length of material, L, necessary to achieve the desired overall gain G_0 can be calculated according to:

$$L = \frac{\ln(G_0)}{g_0} = \frac{\ln(G_0)}{\sigma_e N}. \tag{7}$$

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[2] Each laser text uses different notation for saturation fluence. This notation is modified from Siegman.

Lower emisssion cross section results in both longer gain length and higher intensity, leading to a higher B-integral. But, the length of material which contributes to nonlinear phase accumulation can be reduced by adopting gain material with higher doping concentration.

Another challenge in working with high-saturation-fluence materials is avoiding surface damage. The threshold for damage of optics subject to 3 ns, near the limit of present stretching technology, is 20 J/cm^2 (published in product liturature for Litton Airtron's MaxCoat High reflectivity and Antireflection coatings). In practice, it is necessary to operate a factor of two below this level to prevent damage. Maintaining active control of beam wavefront can allow operation closer to the damage threshold.

When the saturation fluence is greater than the damage threshold of a laser material, it is possible to efficiently extract stored energy with a signal well below the saturation fluence. This is accomplshed by depleting stored energy over multiple passes up to the limit of B-integral accumulation in a low-gain low loss regenerative amplifier [23]. Though this concept does not lead to operation of the laser at the saturation fluence, it does allow the use of materials with longer upper-state lifetimes as related in (2).

To better use of high-saturation-fluence materials, new techniques to allow pulse stretching into the 10–100-ns regime, or improvement of damage threshold would be needed. Finally, because the aperture of the gain material will be smaller than that offered by low-saturation-fluence materials, the probability of finding an impurity-related source of damage within the laser aperture is reduced.

From these arguements we can see that the use of a broad-band material with saturation fluence near the damage threshold limit is desirable for making a small aperture laser system and that the choice of materials allowing high concentrations of lasing ions leads to reduced effects due to nonlinear phase accumulation. With the higher saturation fluence comes the fundamental advantage of long fluorscence lifetime, a particular advantage for pumpability by laser diodes and long-pulse free-running lasers. Though it is not a requirement for the generation of high focused intensity, the intrinsic efficiency and compactness of diode pump lasers is an attractive addition to laser technologies when scaling average power.

III. PROMISING NEW STORAGE MATERIALS

Now, we can begin to consider an alternative to Nd:glass systems which maintains diode pumpability, but also supports shorter pulses and would allow higher peak power to be developed. A diode pumpable alternative to Ti:sapphire is also needed. Candidates should have high saturation fluence, broad bandwidth emission, long excited-state lifetime, and high doping concentration. Absorption in a wavelength range where high-average-power diode lasers are available is also advantageous.

A. Properties of Yb-Doped Materials

A range of materials which incorporate Yb^{3+} as an active ion including Yb:YAG [24]–[26], and other crystals [27], Yb:SFAP (apatite) [28], [29], Yb:KGW (tungstate) [30], [31] and Yb:glass [32]–[34] has recently attracted the attention of many investigators. In all of these materials, Yb^{3+} displays a simple energy level structure. Since energy levels above the excited-state manifold do not exist there is no excited-state absorption. Concentration quenching is neglegible, a problem which limits the doping density in Nd glasses. The lack of intermediate levels and the large separation between the excited state and the ground state manifolds reduces nonradiative decay. All these materials display a pump band in the 900-nm range with a long upper state lifetime which is optimal for laser diode pumping. The spectral proximity of the emission wavelength to the pump band results in a quantum defect less than 10%, reducing the amount of heat left in these materials by excess pump energy.

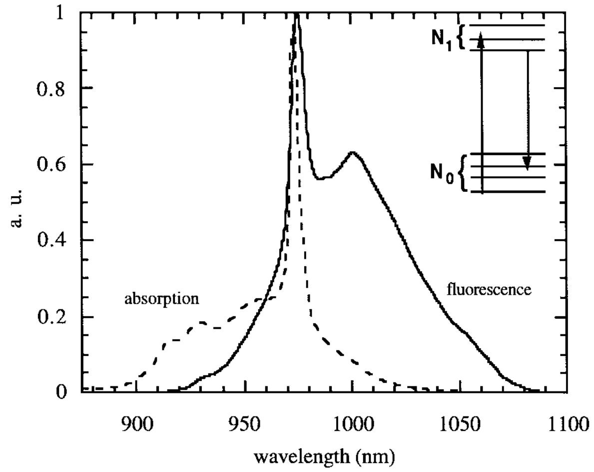

Fig. 3. Emission and absorption curves for Kigre QX:Yb glass. Its low emission cross section, long fluorescence lifetime, and broad bandwidth make it suitable for super-intense pulse generation.

Each of the two levels of the laser transition in Yb^{3+} is split by local fields into manifolds. In many hosts the energy levels within these manifolds overlap to form continuous spectra due to broadening of the transitions, though in crystalline hosts the individual transitions tend to be more pronounced. With the wide variety of Yb-doped glasses and crystals available, the choice among the foregoing laser parameters is quite flexible.

Of these materials, those most capable of high peak power generation due to high saturation fluence, broad bandwidth and long upper-state lifetime are the glasses. These materials also offer greater flexibility in fabrication. The curve in Fig. 3 shows the absorption and emission cross sections for Kigre QX:Yb glass. It has a saturation fluence of 40 J/cm^2 at the secondary flourscence peak wavelength of 1.00 μm and bandwidth to support 20-fs minimum pulse duration. The 2-ms fluorescence lifetime of QX:Yb sets the requirement for pump power to the order of 40 kW/cm^2. This opens the path for simple pump lasers and laser diode pumping. The density of Yb^{3+} ions which can be incorporated into this material is as high as 2×10^{21}/cm^3 [35]. Thus, if signals at the saturation fluence could be obtained without phase distortions a petawatt laser could be made from a piece of glass the size of a dime (1-mm thick and 1.7-cm diameter). Applying the theoretical peak intensity formula (5) to this material yields more than 10^{23} W/cm^2 for each cm^2 of gain aperture.

B. Experiments Involving Yb:Glass

Numerous experiments have been done to demonstrate the utility of Yb:glass for a variety of applications. CPA was demonstrated by Walton *et al.* [36] in a CW Ti:sapphire pumped Yb:germano-silicate fiber producing fluence up to 15J/cm^2 from the fiber core. The utility of multipulse depletion of gain was demonstrated in this system. Researchers at Lucent Technologies [37] and Polaroid [38] have demonstrated high-power CW operation of Yb-doped fiber lasers. Under diode pumping, Hönninger was able to achieve 100 mW at 60-fs pulse duration, mode-locking with a semiconductor saturable absorber mirror [39]. Using a similar cavity and pump configuration, Hönninger and collaborators at the Center for Ultrafast Optical Science (CUOS) in Michigan used CPA in a regenerative amplifier to produce 50-μJ pulses at several hundred Hz [40].

Using a free-running flashlamp-pumped Ti:sapphire laser as a pump source, QX:Yb glass was gain switched with $>$50% slope efficiency and $>$30% efficiency with respect to absorbed pump energy [41]. With the addition of a Pockels cell and polarizer, CPA has been performed at an efficiency of nearly 10% with respect to absorbed pump power [42]. Further optimization of the fluence in the regenerative amplifier is the subject of a paper by Biswal for publication in this issue. Experiments are planned at the Center for Ultrafast Optical Science which will employ a flashlamp pumped Ti:sapphire [43] laser to simulate diode pumping to the level of 5 to 10 J.

Using current stretching and compression techniques, further development of Yb-doped crystals with broadband characteristics or Yb-doped glasses with larger emission cross sections could produce a better match damage threshold and operating intensity.

IV. MANIPULATION AND CONTROL OF TEMPORAL PHASE FOR HIGH-FIELD GENERATION

As experiments probe to higher intensities, the light which strays from the focal interaction either temporally (along the beam axis) or spatially (in the transverse dimensions) provides an increasing level of unwanted signal. In some cases the generation of excitation prior to the desired interaction may be so great as to screen or eliminate the desired process [44]. Hence, for the purpose of maintaining a well-behaved beam, increased attention to the measurement and correction of temporal and spatial distortions will be necessary.

The initial spark which launched solid-state materials into the femtosecond domain was the introduction of phase control to laser [5], [6], [8], [45].[3] Within the oscillators, the degree of stretching and compression is typically small. In CPA, the stretcher coupled with matched compressor so dramatically modifies the phase of a short pulse that the time-bandwidth product may be changed by a factor exceeding 10^5 [46]. The nearly quadratic phase function (phase as a function of time) used for the stretched pulse in the CPA system is an analog of propagation after the quadratic phase delay of a lens in the spatial domain [47]. In either case, the presence of phase errors produces unwanted broadening of the minimum pulse features. In addition to phase distortions in the dispersive optics of the system, the problem of background spontaneous emission from the amplifiers also poses a disturbance to which some experiments are sensitive [44].

The problems of phase measurement have already attracted considerable interest, as was recently demonstrated by the appearance of several papers detailing methods of frequency-resolved optical gating and related techniques for deriving the functional form of ultrashort-pulse electric fields [48].

The problem of correcting for phase distortions has also been addressed in the field of ultrafast optics for some time now. Beginning with the first paper on conjugate stretching and compression for amplification [49], it has been recognized that the dispersive properties of the materials used in CPA would make exact recompression difficult. As the bandwidth of CPA systems continues to grow, the compensation of higher orders of phase error is becoming increasingly important.

The usual approach taken in producing a bandwidth limited output from a CPA system is to balance positive and negative dispersion in each order of phase, beginning with quadratic and proceeding through quartic or quintic [50]–[53]. By analyzing the effect of different materials and optical elements on phase, certain elements can be added or adjusted to effect, primarily one order. This process is linked with the measurement of the electric field to determine the final outcome. The use of fixed optics in this way to produce a desired phase function has been successful in producing pulses as short as 18 fs at the milijoule level [46].

A more flexible approach involves the introduction of an addressable phase element into a zero-dispersion stretcher to impress an adaptable phase on the pulse [54]. Such a system could in principle be used to compensate for a limited amount of nonlinear phase distortion. Descrete 128-element spatial phase modulators are now commercially available and new nonpixelated devices are helping to elliminate some of the diffractive distortions found in the Fourier plane of the progarammable phase controllers [55]. The availability of new liquid crystal devices and deformable membrane mirrors [56] makes this approach attractive for systems requiring flexibility in pulse form or automated pulse-to-pulse adjustment. The degree of phase error which can be controlled by these techniques depends on the devices used, but compensation from 80 to 13 fs is demonstrated by Yelin *et al.* in [57].

Through the use of high-order phase control and pulse cleaning, the loss of energy from the peak of the intense laser pulse can be minimized. As a result, the efficiency of conversion from energy stored in the amplifying medium to energy in the short pulse will be increased. These means of obtaining higher focused intensities does not require the addition of large pump lasers, the increase of the laser aperture or larger gratings. It is a potentially inexpensive way to increase focused intensity.

For experiments involving solid-density targets, the measurement and control of amplified spontaneous emission (ASE) is especially important. However, it cannot be addressed by the

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[3] Reference [45] refers to the original work in dye lasers.

foregoing techniques. Light which is spontaneously emitted in the amplifier during the first pass of the signal overlaps the signal temporally, spatially, and spectrally. This poses a problem both for measurement and for control. Through the amplification system, ASE maintains its initial ratio of intensity with the signal yet it lacks the coherence necessary to undergo compression. The result is that the compressed pulse is accompanied by a pedestal of energy nearly equal to its own energy in some cases. The duration of the background signal is on the order of a few nanosecond and lies between 4 to 6 orders of magnitude below the signal in intensity. This dynamic range is sufficient to frustrate most measurement techniques, yet the power is sufficient to pre-ionize experimental targets and disable many solid-density plasma interactions.

In a paper submitted to this issue, Nantel *et al.* [44] discuss the problem of temporal contrast in Ti:sapphire lasers. They detail the use of a high-dynamic-range correlation and a plasma-shuttered streak camera to analyze the pulse contrast. The authors also discuss the suppression of prepulse energy through the use of a short-pulse preamplifier and a saturable absorber. Contrast improvements of two orders of magnitude are demonstrated experimentally.

Though the measurement and management of temporal phase has a cost in terms of complexity, time and table-space, it provides reliable information about the pulses and, by active control, can result in the enhancement of focussed intensity and the reduction of upfront system costs such as pump laser energy, thermal loading and the like.

V. MEASUREMENT AND MANAGEMENT OF SPATIAL DISTORTIONS

In a similar way, the spatial quality of the beams throughout the CPA system should be preserved or corrected, because these corrections can significantly enhance the intensity of light at focus. Considering the problem of concentrating light at focus in the presence of wavefront distortions, it is common to refer to the Rayleigh criterion when choosing optics for beam focusing [58]. This criterion states that the presence of a $\lambda/4$ purely spherical aberration decreases the maximum focal intensity by 20% from the theoretical limit. It may be argued, however, that the optical system of a CPA laser offers far more complexity than the simple case of spherical aberration. CPA systems often include gaussian thermal lensing, uneven intensity, and aperturing due to nonuniform pump intensity, and slight nonlinear distortion. The Maréchal criterion is more general. It guarantees 80% of the theoretical maximum intensity at focus provided that distortions are less than $\lambda/14$. To maintain such a tolerance through the entire optical system to the compression gratings would be quite expensive. Spatial filtering and wavefront correction are alternatives. In contrast to spatial filtering, where stray energy is discarded, the use of deformable mirrors for wavefront correction brings stray energy back into the focal spot. Consequently, the use of deformable mirrors to correct for wavefront distortions will become a decided advantage.

Before applying a figure to a deformable mirror to correct distortion, it is necessary to measure the wavefront. One particularly useful interferometric wavefront measurement device was recently introduced by Primot [59], [60]. This device uses a hexagonal phase grating to produce three-beam sheering interference. By resolving the three-beam interference pattern into orthogonal directions, two-dimensional wavefront distortions may be recorded. Like many temporal phase retrieval techniques, the achromatic three-wave lateral shearing interferometer (ATWLSI) produces redundant information which may be used to check the accuracy of the phase measurement. This technique has the advantage over the more prominent Shack-Hartman wavefront sensor in that it has an adjustable sensitivity from levels greater than a wave of distortion to as low as one-hundredth of a wave. Furthermore, the diffractive nature of the beam splitter in the ATWLSI makes it inherently achromatic and broadband.

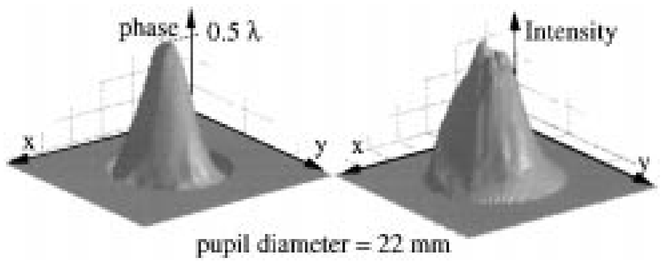

Fig. 4. Nonlinear phase distortion from a 50-fs 45-mJ $2 \times 3\text{-cm}^2$ beam propagating through 1 cm of BK-7 glass. Wavefronts are measured single-shot using an ATWLSI.

Applying this device to the single-shot measurement of beam distortions as a function of output energy in a 50-fs CPA laser has already given valuable insight into the degree of whole-beam self-focusing arising in materials at the 45-mJ level [61]. In order to separate thermal distortions in the amplifier chain from the nonlinear self-focusing, a piece of glass was placed both in the compressed beam and in its weak reflection. By taking the difference in the wavefront between these cases, the degree of nonlinear effect in the glass can be measured. Operating at a pulse intensity of 45 mJ in a 2-cm elliptical beam, the peak nonlinear effect produced a $\lambda/2$ wavefront distortion as shown in Fig. 4.

By controlling the phase of the optical pulse approaching the experimental volume, a more accurate determination of the conditions in the experiment may be made. Furthermore, the wavefront may be modified to enhance the experimental conditions. To first approximation, this means correcting for wavefront distortions to achieve a diffraction limited focus. But, by using focal profiles other than gaussian, it would be possible to reduce the degree of unwanted background signal. Just as reduction of prepulse energy reduces the interference of preplasma, a reduction of stray light would reduce low-intensity-induced background signals arising in the material surrounding the desired interaction volume.

The use of deformable optics to maintain excellent wavefront quality in high-intenstiy CPA systems has the potential to improve their reliability ensuring well defined signals at the focal volume. By improving the focussability of the light arriving in the focal volume the peak power delivered to the focal volume might be improved by a factor of two or more cutting in half the required of pump light, cooling, aperture, etc. This significant savings can make paying the price of deformable mirrors and the cost in time and table-space more feasable.

VI. Summary and Conclusion

The rapid and sustained growth of high-field science is due in part to the widespread use of the ultra-intense lasers employing CPA technology. Continued growth in this field will require further attention to compactness and reliability, features which tend to make CPA systems more accessible to university- and institute-level research. We have outlined the theoretical limits of CPA lasers in the range of 10^{23} W/cm^2 for each cm^2 of gain aperture and noted the importance of Yb-doped materials, particularly glasses, in scaling toward those limits. The potential remains for the development of Yb-doped materials with saturation fluence on the order of 10 J/cm^2, flourescent lifetime of 0.5 ms and bandwidth for 30-fs pulses.

In addition, the advantages of exercising spatial and temporal control over the phase of high intensity pulses have been noted. The building blocks for fine measurement and control of both spatial and temporal phase exist. Frequency resolved optical gating techniques for the characterization of ultrashort pulses are well developed and new high-contrast measurement techniques can quantify prepulse energy to seven orders of magnitude. Static correction of phase in the stretcher is well established. This capability will be further refined by adaptive optics. Improvement of pulse contrast by preamplification of short pulses provides needed pulse contrast of 10^7 to 10^8. Spatial phase distortions can be measured in a single shot with resolution variable from several λ to $\lambda/100$. Potential for improving focal intensity and correcting for mild nonlinearities will make the use of deformable mirrors a key factor in tailoring ultra-intense pulses to the demands of various experiments.

Using these materials and techniques the move to the next generation of high-field lasers will not involve a move to a larger laser facility. On the contrary the next compact CPA lasers will produce important results in the broad scientific community and find applications in medicine and materials processing and other fields. Such lasers will also bring us one step closer to the limits of focused intensity.

VII. Acknowledgment

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John Nees received the B.S. degree in physics from Kansas State University, Lawrence, in 1983, and the M.S. degree in optics from the University of Rochester, in 1985.

After completing his degree work in the study of ultrafast phenomena, he continued as a Research Engineer at the Laboratory for Laser Energetics, until 1988, when he moved to the Center for Ultrafast Optical Science (CUOS), University of Michigan at Ann Arbor. His has studied ultrafast electronics and optoelectronics and is currently engaged in the development of high peak-power laser systems.

Mr. Nees is a member of the Optical Society of America.

Subrat Biswal received the B.S. degree in electrical engineering from The Johns Hopkins University, Baltimore, MD, in 1991 and the M.S. degree in electrical engineering from the University of Michigan, Ann Arbor, in 1993, and is working toward the Ph.D. degree in electrical engineering at the Center for Ultrafast Optical Science, University of Michigan.

His thesis focuses on ultrashort-pulse high-intensity and high-average-power lasers.

Frédéric Druon, photograph and biography not available at the time of publication.

Jérôme Faure received the Masters degree from Universite d'Orsay, Paris XI, France, in 1996, and also graduated from l'Ecole Superieure d'Optique.

He is currently fulfilling his military service for France at the Center for Ultrafast Optical Science (CUOS), University of Michigan at Ann Arbor, as a Research Assistant. His research is on CPA laser development. He is also interested in laser-matter interaction.

Mark Nantel received the Ph.D. degree in physics of energy from INRS-Energie et Matériaux, Université du Québec, PQ, Canada, in 1994, for his research on the effect of drive laser inhomogeneities on X-ray laser gain.

He then took a one-year position in the Jaeglé group at LSAI, Université de Paris-Sud, France, to further work on X-ray lasers and their applications. The work presented in this paper was done while he was a Research Fellow at the Centre for Ultrafast Optical Science (CUOS), University of Michigan at Ann Arbor. He was the Coordinator of the 10-Hz 100-fs laser at CUOS, and has worked on various projects, including ultrafast laser wavefront diagnostics, and contrast measurement and improvement techniques. Principally though, his main thrust at CUOS was the application of short-pulse lasers to X-ray sources, high-density plasma, and ion acceleration. He is presently a Senior Staff Scientist at Photonics Research Ontario, ON, Canada, and an Adjunct Professor of physics at the University of Toronto, Canada.

Gérard A. Mourou (M'89–SM'97–F'98), received the Ph.D. degree in physics from the Université de Paris.

He started the Ultrafast Science Group at ENSTA, France, in 1974. Three years later, he moved to the University of Rochester, becoming Director of the Ultrafast Science Group at the Laboratory for Laser Energetics. In 1988, he became a Professor in the electrical engineering department of the University of Michigan and founded the Ultrafast Science Laboratory, which became the National Science Foundation Science and Technology Center for Ultrafast Optical Science in 1991, of which he is director. In 1995, he bacame the A. D. Moore Distinguished University Professor of Electrical Engineering and Computer Science. His research groups have made many significant contributions to the field of ultrafast science, introducing a variety of powerful techniques, such as electrooptic sampling, time-resolved electron diffraction, and particularly chirped-pulse-amplification which has revolutionized the field of laser-matter interaction with high-intensity ultrashort pulses.

Prof. Mourou has received many awards, including the R. W. Wood Prize for outstanding discovery and inventions in the field of ultrafast optical science and the Harold E. Edgerton Award for the invention of the chirped-pulse amplification technique.

Akihiko Nishimura, photograph and biography not available at the time of publication.

Hiroshi Takuma, photograph and biography not available at the time of publication.

Jiro Itatani, photograph and biography not available at the time of publication.

Jean-Christophe Chanteloup, photograph and biography not available at the time of publication.

Clemens Hönninger, photograph and biography not available at the time of publication.