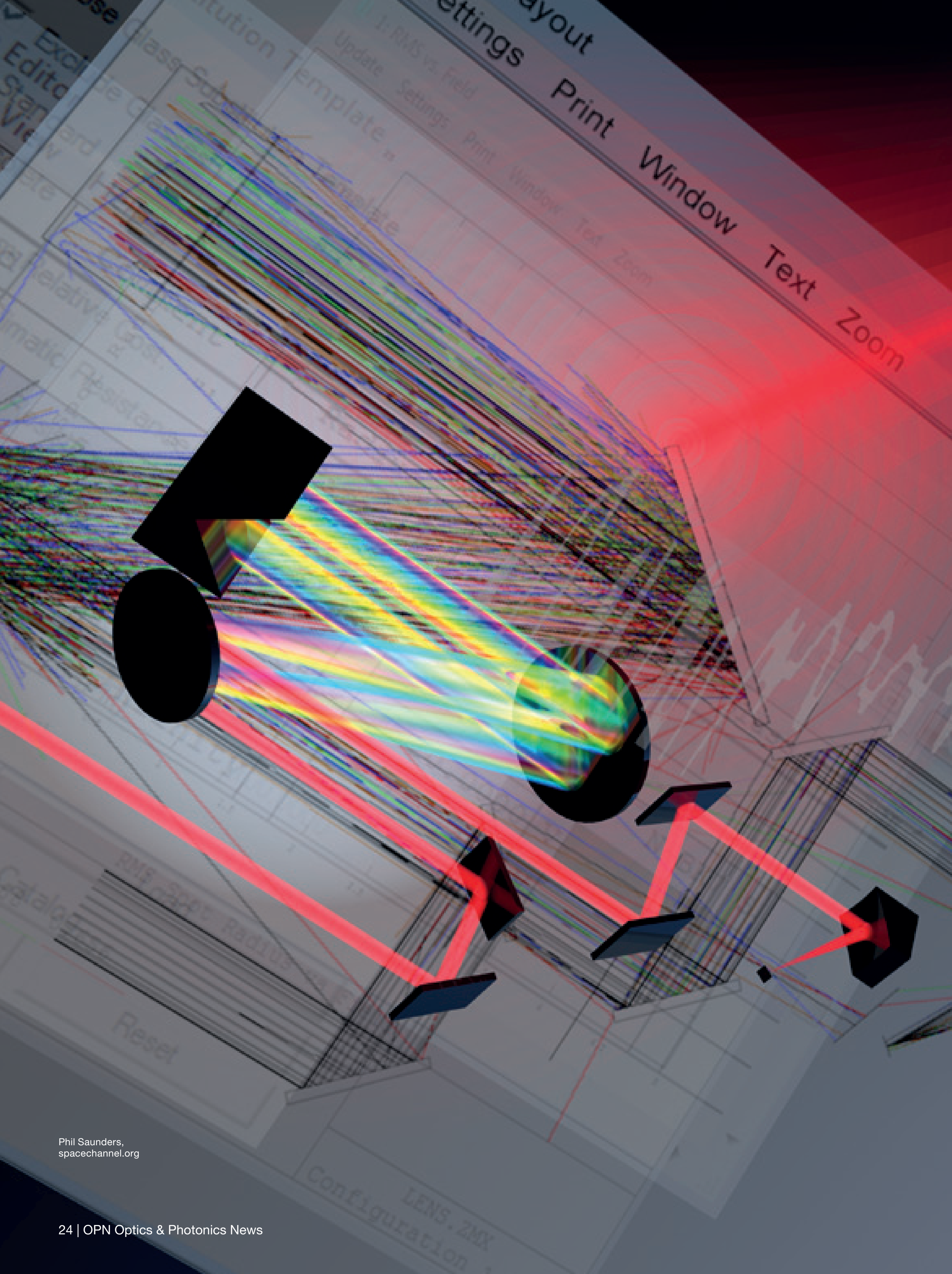

Phil Saunders, spacechannel.org

Computers at Work on Ultrafast Laser Design

Catalin V. Filip

Ultrafast lasers have evolved so quickly in the last decade that engineers have only recently incorporated computer technology into their design. Today, new computer programs could provide increased precision and performance for ultrafast lasers used in medical applications, micromachining and scientific research.

Power and speed: In the world of lasers, these are two qualities in big demand. Today's lasers are nearly 10^{12} times more powerful than they were 50 years ago. This amazing progress is the result of simultaneously increasing pulse energy and reducing pulse duration.

The first attempts at directly amplifying picosecond (ps) and femtosecond (fs) ultrashort laser pulses proved to be disastrous because the electric field intensifies so much that it changes the structure of the material it propagates through. This reaction feeds back onto the laser pulse phase and creates

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self-phase modulation. Although not dangerous by itself, self-phase modulation predicts the appearance of self-focusing, which damages the laser optics. In order to increase the peak power of today's ultrafast lasers, it is essential that engineers reduce or control self-phase modulation.

Computer-aided design and modeling, which has yet to make its grand entrance into the field of ultrafast lasers, could provide engineers with the tools to reduce self-phase modulation. This would greatly expand the utility of ultrafast lasers in applications such as multiphoton imaging, laser micromachining of both absorptive and transparent media and the generation of attosecond pulses or nonlinear optics.

CPA: An early solution to self-focusing

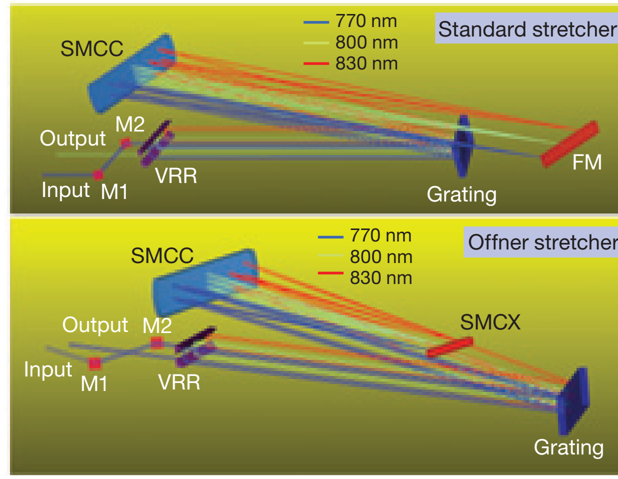
Donna Strickland and Gerard Mourou demonstrated a simple solution to self-focusing in their 1985 *Optics Communications* paper. They started with a ps oscillator pulse that was purposely stretched in time within an optical fiber to reduce its peak power. The 300-ps stretched pulse was further amplified and then compressed in a standard two-grating compressor to produce 2-ps pulses with 1 mJ of energy. The technique was dubbed chirped-pulse amplification (CPA). Since then, significant technological progress—such as the introduction of the titanium-sapphire (Ti:S) material—has brought the pulse duration down to less than 10 fs and the energy up to tens or even hundreds of joules. Scientists at Lawrence Livermore National Laboratory, U.S.A., achieved a record level of peak power (1.1 petawatt) in 1999, and researchers involved in several ongoing projects, including the Extreme Light Infrastructure project in Europe, are planning to generate a peak power beyond 100 petawatt.

Dispersion management—how the pulse is being stretched, amplified and compressed—is the key element in a CPA system. In order to achieve high levels of amplification, one must stretch seed oscillator pulses as much as possible. However, the more they are stretched, the more difficult it is to compress the amplified pulses back to their original width or near their transform-limited duration. The fidelity of the stretch-compression scheme becomes the quintessential part of all CPA systems.

Scientists have constructed a variety of schemes to stretch and compress laser pulses. Very long optical fibers, due to their dispersive capabilities, were initially used as stretchers. Later, the use of spatially dispersive optical elements based on diffraction gratings became widespread because they can stretch optical pulses more than fibers. Researchers stretched pulses quasi-linearly in time both in a positive (red colors first) and a negative (blue colors first) dispersion way using lenses, gratings, spherical mirrors, parabolic mirrors, etalons, etc. The compressor designs have been very diverse, ranging from grating arrangements to bulk material and chirped mirrors.

With such a wide variety of dispersive elements and schemes at their disposal, scientists began paying attention to the stretching ratio and the residual phase of the compressed pulses. The former is defined as the ratio between the duration of the stretched pulse and the duration of the oscillator pulse. More energy can be amplified if this factor is large. The latter is used to show how good the compression process will be. A residual phase near zero guarantees a good, compressed pulse. The residual phase is also used in conjunction with the time-bandwidth product to characterize the duration of the compressed pulse.

[Grating-based optical stretchers]



Optical 3-D layout and beam propagation for two optical stretchers using Zemax. M1, M2 and FM are folding mirrors, SMCC is a concave spherical (or parabolic) mirror, SMCX is a convex spherical mirror and VRR is a vertical retro reflector. These layouts are necessary for accurate dispersion calculations.

Grating stretchers and compressors

The diffractive grating proved to be the most successful dispersive element used in CPA systems because it helped achieve compressed pulses with good quality and large stretching ratios. In 1969, Treacy showed how a two-grating assembly can compress a positively chirped pulse. The grating stretcher was developed much later by Martinez in 1987. Martinez realized that a telescope placed among the gratings of a compressor will effectively reverse the dispersion sign. The simple but ingenious work by these scientists helped define the path for modern ultrafast amplifier technology.

Today, almost any CPA system that produces more than 1 mJ/pulse uses diffraction gratings in its design, both in the stretcher and the compressor. Initially, following Martinez's work, any stretcher design was regarded as the exact opposite of a compressor, including those with lens telescopes. Later, experimental studies pointed out the limitations of refractive stretcher designs due to aberrations and additional dispersion factors introduced by the glass. Reflective stretcher designs were quickly developed after that.

The stretcher of a kHz repetition rate Ti:S CPA laser is considered the industry standard. Its telescope is made of

Since stretcher designs are diverse, 3-D computer modeling is needed to pinpoint which one is the most appropriate for the task.

one spherical (or parabolic) mirror and a flat mirror. The stretching ratio is as high as 10,000 and its footprint is roughly 1 × 4 square feet. This stretcher works better than a lens-telescope stretcher and is used to amplify 40-fs pulses. Below 40 fs, the dispersion characteristics of the stretcher need to be calculated very precisely because even its smallest aberrations become important.

Computer programs calculate dispersion

How do we accurately calculate the dispersion of a relatively complex 3-D optical system where the rays bounce back and forth many times between components? The most accurate way is with the help of a commercial, well-tested 3-D ray tracing computer program such as Zemax, CodeV, Oslo or Fred. This method is more precise when compared to previously used analytical calculations and 2-D ray tracing computations.

The exact optical path can be calculated for any wavelength within the interval of interest, for any of the three modules that form a CPA laser: the stretcher, the amplifier material and the compressor. The stretcher is the hardest to calculate because of the multiple passes between its components. The dispersion of the amplifier material is easy to compute because the laser is usually made of well-characterized glasses, sapphires and/or other crystals. The compressor is also straightforward to study because exact analytical formulas for their measurement already exist. A perfectly aligned compressor is, in fact, a fantastic resource for anyone who wants to benchmark a ray tracing program in order to avoid potential errors. Once the optical path is known anywhere in the CPA system, the laser designer can calculate the stretching ratio, residual phase and shape of the compressed pulse.

Accurate dispersion calculations are priceless

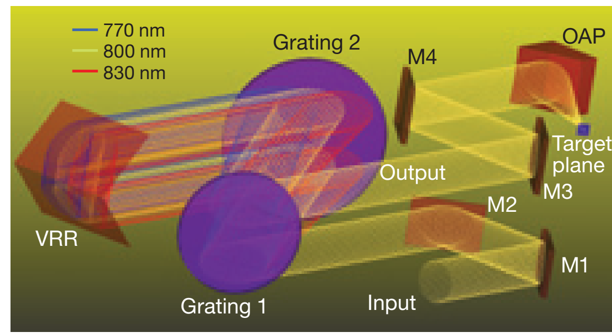
Let's have a closer look at a special CPA system, the optical parametric CPA (OPCPA). An OPCPA's laser pulse is amplified in a nonlinear crystal by as much as 10,000 to 100,000 times. Two or more crystals can be used sequentially to further increase the amplification. Since these crystals are usually thin, they don't introduce significant dispersion. Therefore, the designer of the OPCPA just needs to make sure the compressor is compensated by the stretcher exactly. In other words, the stretcher is an exact opposite of the compressor. Since stretcher designs are diverse, 3-D computer modeling is needed to pinpoint which one is the most appropriate for the task. For OPCPAs, studies show that an Offner-type stretcher made of a concave and a convex spherical mirror is the best match for the compressor.

Other CPA designs introduce significant dispersion by amplifying material such as a regenerative amplifier with intracavity polarizers, Pockels cells and gain media. The total length of the material could add up to 1 to 2 m, and in this case, a complete analysis including the stretcher, compressor and the amplifier is necessary. Any combination of grating groove densities, curvatures, distances and incidence angles—both in the stretcher and the compressor—could result in the best dispersion compensation case. The most important thing to know is the dispersion characteristics of all the CPA laser system components. This can only be achieved by using a computerized 3-D ray tracing model.

Misalignment in CPA lasers

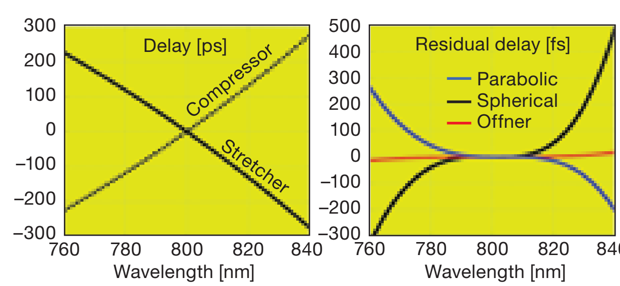
Computerized 3-D optical simulations can also study laser misalignment. The typical causes for misalignment are

[Standard dual grating compressor]



Optical 3-D layout of a compressor with the off-axis parabola (OAP) used to focus the beam. M1 to M4 are folding mirrors and VRR is the vertical retro reflector.

[Dispersion calculation result]



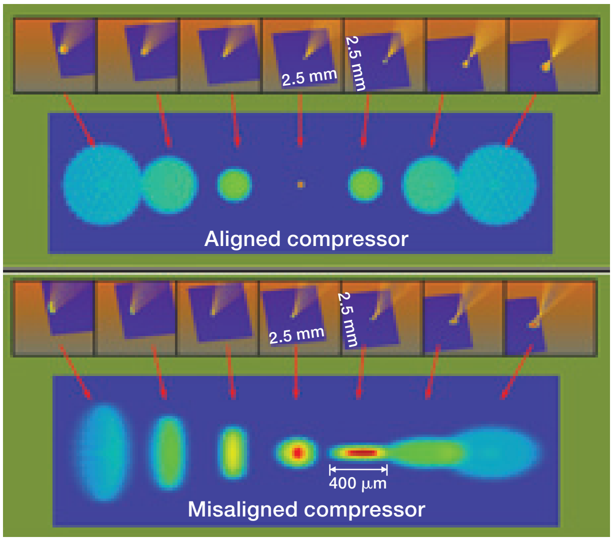
(Left) The delay introduced by one compressor and three stretchers. The stretcher delay curves appear as one because there are extremely small differences between them. (Right) The residual delay from summing the compressor and the stretcher delay curves. The Offner stretcher is almost exactly opposite of the compressor because the residual delay is almost zero from 760 nm to 840 nm.

mechanical stress, temperature variations, vibrations, shocks and chemical instability of the adhesives that are used to glue the optics in their mounts. A CPA system is more sensitive to misalignment compared to other lasers because of the unique relationship between beam pointing and dispersion. The most sensitive CPA lasers are the free-space systems, with all-fiber lasers being less sensitive to misalignment.

For a free-space CPA laser, the beam pointing variations into the stretcher and compressor will affect the dispersion balance—which changes the pulse duration. It is also possible that some components in the stretcher and the compressor will also become misaligned; this will also change the pulse duration. Dispersion-wise, some of these components are more important than others, and sometimes misalignment in one direction does more damage than misalignment in another. It is very important to identify such critical optics in CPA systems that strive for extreme beam pointing and pulse duration stability under adverse environmental conditions.

Misalignment can also be a big problem for a scientific research laser. The following example is based on a high-end laser: a 100 TW, Ti:S CPA system generating sub-30 fs pulses in a 50-mm beam. We will assume the laser uses a two-grating compressor that is perfectly aligned in air. Suppose a compressed pulse is focused on to the target by an off-axis parabola (OAP). In this instance, one can achieve a diffraction-limited spot size near 5 µm.

[Compressor alignment study]



(Top) Final focus images obtained with Zemax ray tracing of an ultrafast laser. A 2.5 mm^2 square detector screen is scanned across the focus produced by an F/3.6 off-axis parabola. The compressor is perfectly aligned. The spot is diffraction-limited and pictured in the middle as a dot. (Bottom) Similar images appear if the compressor is misaligned by a 0.05 degree rotation of the 2nd grating in the plane of dispersion.

However, the experiment is performed in a vacuum. The bending and pulling of the entire vacuum chamber under the atmospheric pressure will determine minuscule movements of the compressor optics. If the second grating happens to rotate in the plane of dispersion by only 0.05 degrees—less than 1 mrad—the diffraction-limited spot will transform into an aberrated spot. The beam pointing, dispersion balance, pulse duration, spot size and ultimately the laser pulse intensity in the focal spot will change.

By using a ray-tracing computer program, the laser engineer can calculate the magnitude of these changes and, based on the results, recommend solutions—for example, a stiffer mechanical design for the vacuum chamber. Mechanical behavior of the optic holders in a vacuum chamber can be predicted quite accurately with commercially available finite element analysis software packages even before the chamber is built. Other solutions may be investigated with the ray-tracing program, such as compensating with the vertical retro-reflector and/or the OAP, or by changing the beam pointing into the compressor.

Stray light: some want it, some don't

Scattered light—or stray light—is present in all lasers, but it is of particular interest in high-energy systems. It is generated by the laser's optics and follows beam paths other than those for which the laser was designed. Lenses are known for producing "back reflections" from their surfaces. Although the reflections are very weak, the stray light could cause damage if it is focused on the surface of another optic in the laser. Computer models built in the nonsequential ray-tracing mode are very useful in determining the most appropriate curvatures and positions of lenses and telescopes relative to each other. The simple solution is to rotate a lens to avoid back reflections to other optics. For a high-end ultrafast laser, however, one has to use a ray-tracing program to estimate the implications of such a small angle rotation on the final laser spot size and pulse duration.

Scattered light can be both a saint and a demon. Many simple, industrial CPA lasers are being used for tasks that do not require compressed pulses with high temporal contrast. The stray light that bounces off the stretcher and compressor gratings at almost any angle can be visualized with an infrared viewer. This allows for a fast and easy alignment check that is greatly appreciated by laser engineers and technicians.

For cutting-edge scientific systems, however, scattered light poses a grand challenge and possibly a fundamental limitation. This problem is usually related to the light that is scattered from the compressor grating surfaces. The mechanism is simple: the stretched pulse hits the first grating and a very tiny part of it will scatter. A similar process is reproduced on the second grating, and then again on the subsequent hits after the pulse is sent back by the vertical retro reflector.

Scattered light will end up at the intended target either earlier or later than the compressed pulse because it does not follow a compressible path, thus contributing to the generation of a temporal pedestal. The spatial contrast worsens because

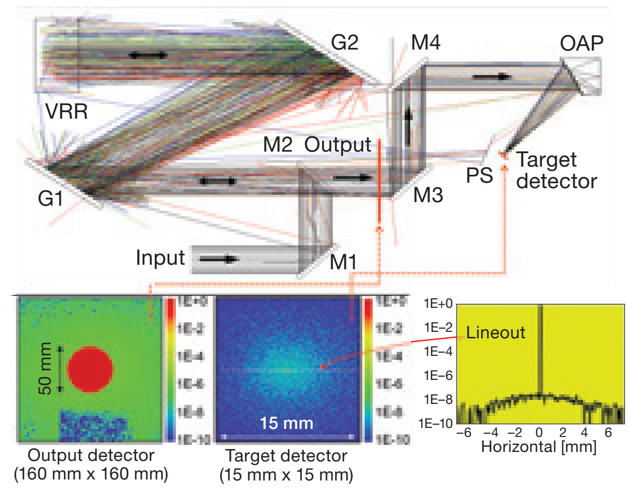
Optical CAD programs are now being integrated with mechanical programs, together with finite element analysis capabilities to ensure highly accurate manufacturing of laser components.

part of the scattered light will travel at slightly different angles than the compressing-path beam and it will be focused around the final spot. No matter how “clean” the stretched pulse is, some temporal and spatial background will be generated by the stray light in the compressor.

The amount of energy contained solely in the stray light that ends on the target could exceed 0.01percent of the incident energy. If the laser output is, for example, near 100 J, the stray light could contain as much as 10 mJ. If we assume that half of this light will reach the target before the main pulse and half after, that is still more than enough energy to vaporize the target material and create a pre-plasma. The consequence is simply that the experiment performed in this way is different than what was intended and no clear scientific conclusion can be reached.

One solution to this problem is to manufacture gratings that scatter less light. Researchers have made progress with holographic gratings that exhibit superior performance over ruled ones. Multilayer dielectric coatings appear to scatter less than bare gold coatings. The scattering angle and characteristics also depend on the groove density and substrate material, as well as the manufacturing process. How would laser engineers take into account all these options and find the best solution? They should first characterize the scattering in a small experimental setup. Then, the resulting data can be entered into a ray-tracing computer program that can analyze various compressor designs without actually having to build one.

[Compressor-generated stray light]



(Top) Top view of a two-grating compressor showing stray light rays. The stray light scattered on the gratings is at the level of a polished glass surface. PS is a protective screen used to block the stray light coming from the left. (Bottom, left) The image recorded by a detector placed in the output beam. The shadow at the bottom of the image is given by M2. (Center) The image recorded by a detector placed in the final focus (target) plane. (Right) The lineout of the light distribution of the target detector. The stray light could produce a pre-plasma in high-energy, solid-target experiments.

Computer screen to production

Ultrafast lasers are composed of many parts, sometimes hundreds of them. Each component needs to perform perfectly: If one piece fails, the entire laser fails. This all-or-nothing phenomenon was well understood in the mid-1960s when the first mechanical computer-aided design (CAD) programs were built for automotive and aerospace companies such as General Motors and Lockheed Martin. Progress is being made on CAD programs for laser design, but there is still a good amount of work to do.

Optical CAD programs are now being integrated with mechanical programs, together with finite element analysis capabilities, to ensure highly accurate manufacturing of laser components. Some of the traditional CAD programs can now trace rays and work with free-form or user-defined optical surfaces.

For now, data are quickly exchanged between optical, mechanical and analysis modules. Once fully integrated modules are perfected, optical engineers will be able to find the best design, save time and money and avoid errors by using them individually. Hopefully, a decade from now, engineers can use one CAD program that incorporates all three modules to manufacture flawless lasers directly from the computer screen.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory, U.S.A., under contract DE-AC52-07NA27344.

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ONLINE EXTRA: Visit www.osa-opn.org for short video examples of a compressor and stretcher ray tracings in Zemax, as well as a focal-spot compressor misalignment study.

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