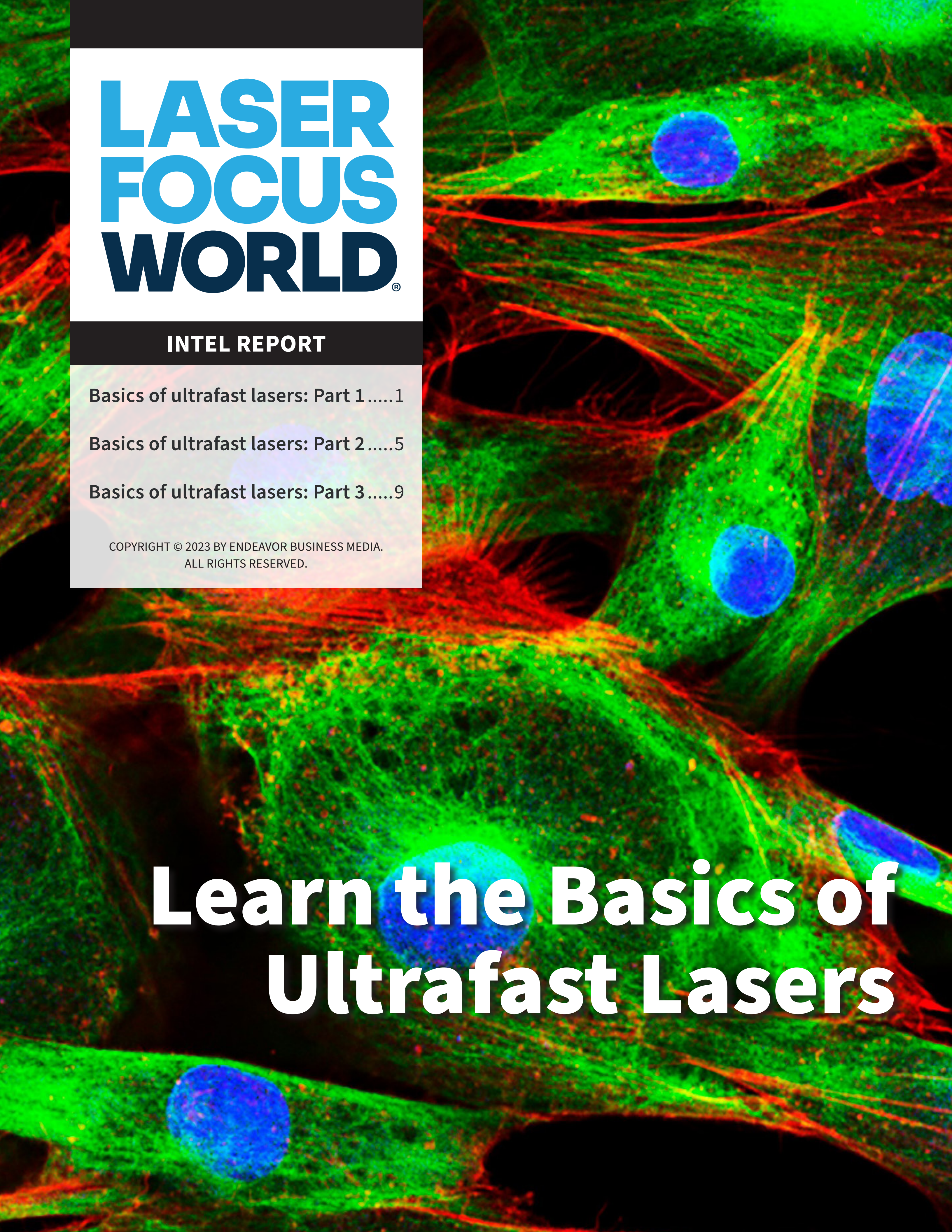
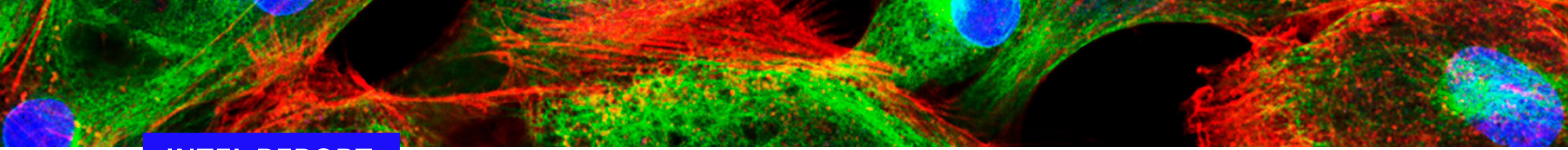


LASER FOCUS WORLD

INTEL REPORT

Learn the Basics of Ultrafast Lasers



INTEL REPORT

Basics of ultrafast lasers: Part 1

OLIVIA WHEELER

Imagine gazing out your window on a sunny spring afternoon. As you admire the green trees and blossoming flowers, you see a small blur dart past. You follow the motion until the blur finally pauses, and you realize it is a beautiful hummingbird—the first of the season! You pull out your phone to capture this beacon of warmer weather in a photo for your social media, only to startle the hummingbird with the sound of the capture button. A photo that once held the promise of many “likes” is now a giant blur across your screen.

Similar frustrations motivated the development of ultrafast lasers within the scientific community. Instead of capturing a fluttering hummingbird, these lasers with pulse durations on the order of femtoseconds to picoseconds (10^{-15}–10^{-12} seconds) are used to capture events like molecular vibrations,[1] electronic motion,[2] and even quantum phenomena.[3] At timescales of one millionth of a billionth of a second, ultrafast lasers continue to expand our access to fundamental physical phenomena, as well as revolutionize industrial processes.

Unique features of ultrafast lasers

Thanks to their ultrashort pulse durations, ultrafast lasers possess key features that distinguish them from longer pulse or continuous-wave (CW) lasers. Generating such a short pulse requires a broad spectral bandwidth. The minimum bandwidth to generate a pulse of a particular duration depends on the pulse shape and the central wavelength. In general, this relationship is described by the time-bandwidth product (TBP), which arises from the uncertainty principle. For a Gaussian pulse, the TBP is given by:

$$TBP_{Gaussian} = \Delta\tau\Delta\nu \approx 0.441$$

where $\Delta\tau$ is the temporal duration of the pulse and $\Delta\nu$ is the frequency bandwidth.[4] Fundamentally, this equation says there must be a reciprocal relationship between spectral bandwidth and pulse duration—as the pulse gets shorter, the bandwidth required to generate it gets wider. Figure 1 demonstrates the minimum bandwidth required to support a variety of pulse durations.

Beyond broad spectral bandwidths, incredibly high peak powers are another consequence of ultrashort pulse durations. For context, let’s examine the difference

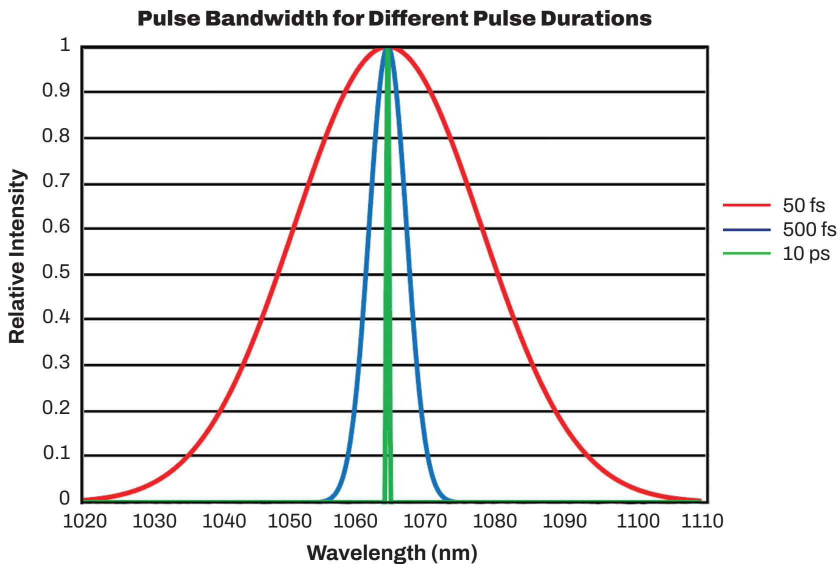
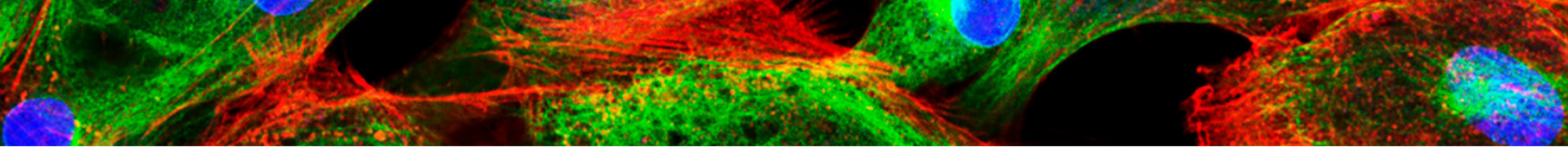


FIGURE 1. The minimum spectral bandwidths required to support 10 ps (green), 500 fs (blue), and 50 fs (red) laser pulses.



in the peak power output of a 10 W CW laser vs. that of a 10 W ultrafast laser with 150 fs pulses and a repetition rate of 80 MHz—properties common for many commercially available ultrafast laser sources.

In the case of the CW laser, its average power and peak power are the same: the laser always emits 10 W, or 10 J/s. In the case of the ultrafast laser, the average power is still 10 W, equal to that of the CW laser. The difference between these two sources is the ultrafast laser is emitting that 10 W of average power over only a small fraction of time. Figure 2 demonstrates the difference between average power and peak power.

For the ultrafast laser, that 10 W is distributed across the 80 million pulses emitted each second, according to the repetition rate. At first glance, the sub-microjoule pulse energy of this laser may seem miniscule. But if we account for this energy being squeezed into only 150 fs of time, we arrive at a massive peak power of over 800,000 W for this laser, which is more than four orders of magnitude greater than the average power. While such enormously high peak powers and broad spectral bandwidths have made ultrafast lasers useful for a wide variety of application spaces, these features also give rise to some of their unique technical challenges.

Technical challenges of ultrafast lasers

Broad spectral bandwidths, incredibly high peak powers, and ultrashort pulse durations of ultrafast laser pulses must be considered and properly managed when applying an ultrafast laser to your project or process. Typically, the simplest of these is managing the broad spectral output of your laser. If you have mostly worked with CW or longer pulsed lasers in the past, your inventory of optical components may not reflect or transmit the entire bandwidth of your ultrafast laser pulse. The good news is many suppliers keep these needs in mind when designing ultrafast laser optics, so it is quite easy to source mirrors, lenses, and other optical components that sufficiently cover the bandwidth of ultrafast lasers.

The laser damage threshold (LDT) of optical components is another important distinction between ultrafast and other lasers that can pose a challenge for ultrafast laser users (see Fig. 3). When sourcing optical components for nanosecond lasers, it is common to see laser damage thresholds on the order of 5–10 J/cm^2. For ultrafast optics, values this large are practically unheard

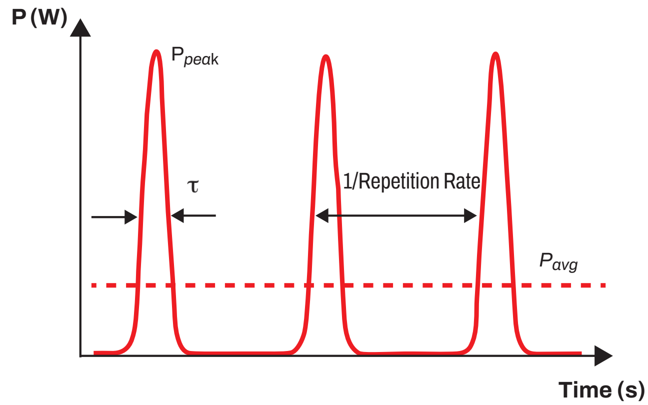
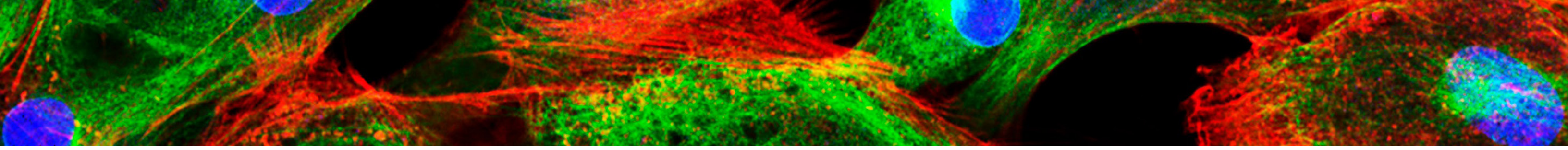


FIGURE 2. A depiction of average power, P_{avg}, and peak power, P_{peak}, for a laser with pulse duration, t, and a particular repetition rate.

of; you are more likely to see LDT values < 1 J/cm^2, typically closer to 0.3 J/cm^2. This dramatic difference in LDT values across different laser pulse durations reflects the different mechanisms for laser damage at play.

For nanosecond lasers or even longer pulses, the predominant damage mechanism is thermal in nature. In these cases, the material is absorbing incident photons and heating up, which can result in deformation of the lattice. Effects like thermal expansion, lattice strain, cracking, and melting are common outcomes for thermal pathways of laser damage.[5] In the case of ultrafast lasers, the duration of the pulse itself is actually faster than the timescale of heat transfer into the surrounding material lattice. Instead, the high peak powers of ultrafast lasers shift the damage mechanism toward more nonlinear pathways, such as multiphoton absorption and ionization.[6] For these same reasons, one cannot scale the LDT rating for nanosecond pulses down for ultrafast pulses. As a result, the most appropriate



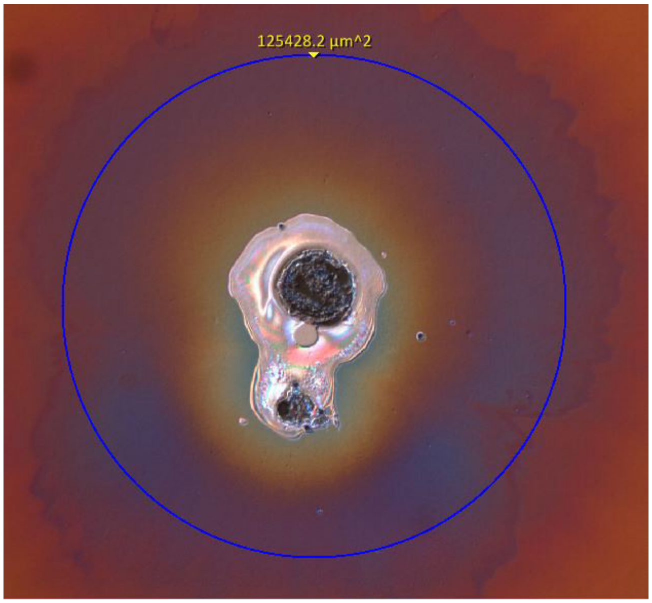


FIGURE 3. Laser-induced damage to optical surfaces can decrease the performance of laser systems, render them useless, and even be dangerous. Damage mechanisms of ultrafast lasers differ significantly from those of conventional lasers because of their short pulse durations.

optic for your particular application is one with a sufficiently high LDT rating obtained under the same conditions (laser wavelength, pulse duration, repetition rate, etc.) it will experience in your application.

One of the most difficult technical challenges associated with ultrafast lasers is maintaining the ultrashort pulse duration provided by your laser. Ultrashort pulses are highly susceptible to temporal distortion, which worsens as the pulse duration gets shorter. Though your laser may emit a 50 fs pulse, relaying this pulse to a target position using mirrors and lenses, or even just passing it through air, has the potential to temporally broaden your ultrafast pulse.

In the ultrafast community, we quantify this temporal distortion as group delay dispersion (GDD). GDD is a frequency-dependent value that, for a given material, scales linearly with thickness. Transmissive optical components like windows, lenses, and objectives normally apply positive GDD so your once-compressed pulse may emerge from the transmissive optical component with a longer duration than initially emitted by your laser.

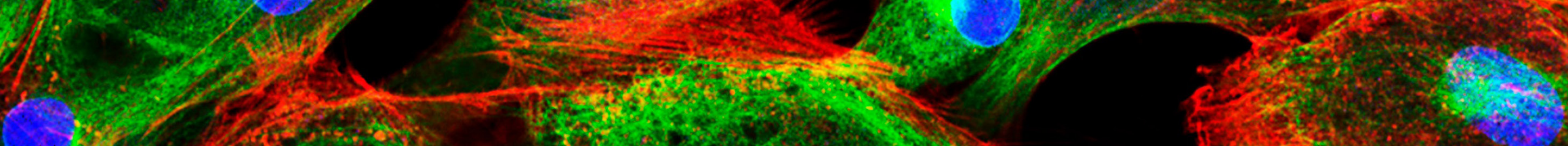
For longer pulses, such as nanosecond and even picosecond pulse durations, GDD is not a major concern. In the case of femtosecond pulses, however, even 10 mm of N-BK7 in the path of your laser beam can broaden a 50 fs pulse centered at 800 nm by over 12%. This is roughly equivalent to having two windows or filters in the path of your beam. Because of this tendency toward temporal distortion, it is recommended to use specialized ultrafast optics that impart minimal to no additional GDD and decrease the chances of an elongated pulse duration.

Ultrafast laser applications

The ultrashort pulse durations and high peak powers of ultrafast lasers provide benefits to a wide variety of applications, including:

Spectroscopy. Since the inception of the ultrafast laser, its application in spectroscopy has been ubiquitous. By decreasing the pulse duration down to femtosecond timescales, dynamic processes in physics, chemistry, and biology were suddenly observable.[7] The advent of ultrafast lasers has provided access to atomic motions—improving our understanding of fundamental processes ranging from molecular vibrations and dissociation all the way to energy transfer in photosynthetic proteins.[8]

Biological imaging. The very high peak powers of ultrafast lasers support nonlinear processes that can improve the resolution of biological imaging, such as in the case of multiphoton microscopy. In these studies, it is necessary to overlap two photons in both space and time to generate the nonlinear signal from the biological medium or fluorescent target. This nonlinear mechanism improves the imaging resolution by substantially reducing the signal background that plagues studies conducted with single photon processes.[9] Figure 4 demonstrates how this reduced background can result in higher resolution.



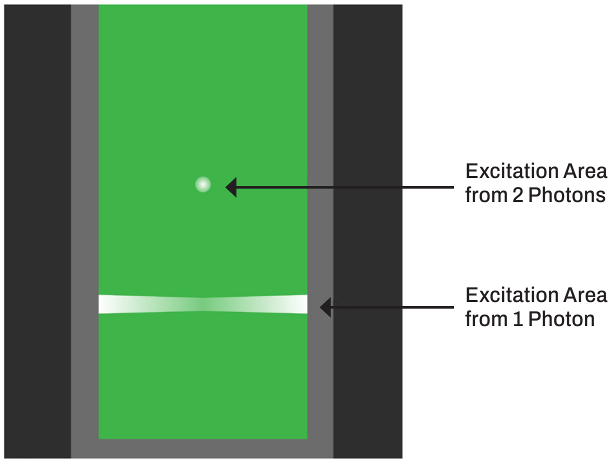


FIGURE 4. A depiction of the signal location for two-photon (top) and single-photon (bottom) microscopy studies. The overlap of two photons produces signal from a smaller focal volume, while the single-photon signal is plagued by background signal from outside the focal plane. This prevents phototoxicity and minimizes damage to the sample.

Laser materials processing. Ultrafast lasers have revolutionized the laser micromachining and materials processing worlds because of their ultrashort pulse durations. As mentioned in the context of LDT, the duration of the ultrafast laser pulse itself is faster than the time scale of thermal diffusion into a material's lattice. As compared to nanosecond pulsed lasers, this means an ultrafast laser produces a much smaller heat-affected zone, resulting in lower kerf loss and more precise machining.[10] This principle extends to the medical field as well, where the increased precision of ultrafast lasers cuts is routinely used to decrease damage to surrounding tissues and improve the patient experience.[11]

Future of ultrafast lasers: shorter pulses

As research into the applications of ultrafast lasers continues, so too does development of new and improved ultrafast laser sources. To gain insight into even faster physical processes, many researchers are turning their attention to the generation of attosecond pulses—pulses on the order of 10^{-18} seconds in the extreme ultraviolet radiation (XUV) spectral region.

Studies to track electronic motion are already being conducted using these even shorter ultrafast pulses, and the field of attosecond science continues to improve our understanding of electronic structure and quantum mechanics.[12] While integration of XUV attosecond pulses into industrial processes has not yet gained major traction, continued research and advancements in this field will almost certainly propel this technology out of the lab and onto the manufacturing floor, as has been the case with femtosecond and picosecond laser sources.

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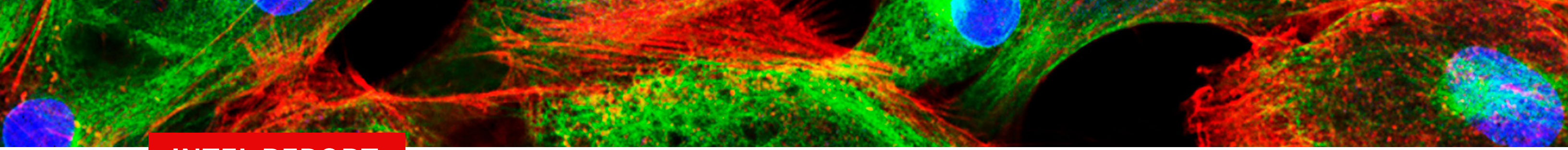

INTEL REPORT

Basics of ultrafast lasers: Part 2

OLIVIA WHEELER

In recent years, ultrafast lasers have successfully transitioned from extremely sensitive behemoths relegated to the research laboratory into compact, reliable sources suitable for integration in industrial processes. With their integration into such a wide variety of application spaces—everything from medical procedures to commercial electronics manufacturing—users from a wide variety of backgrounds now routinely operate ultrafast lasers.

Because of the unique properties of ultrafast lasers, it can be difficult for new users to know the best practices in the field. This article offers advice for using ultrafast lasers—including how to select the best optical components, an introduction to dispersion and temporal distortion, and when you should consider pulse compression.

Selecting ultrafast optical components

The technical challenges associated with ultrafast lasers can create difficulties when selecting the proper optical components for your application. The required spectral coverage, laser damage threshold (LDT), and dispersion specifications may be foreign to users accustomed to continuous-wave (CW) or longer-duration pulsed lasers.

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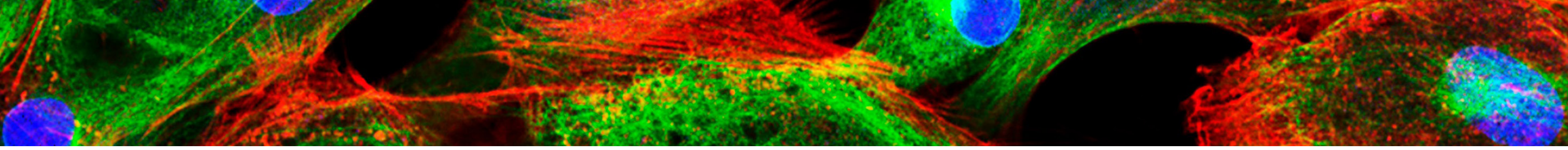


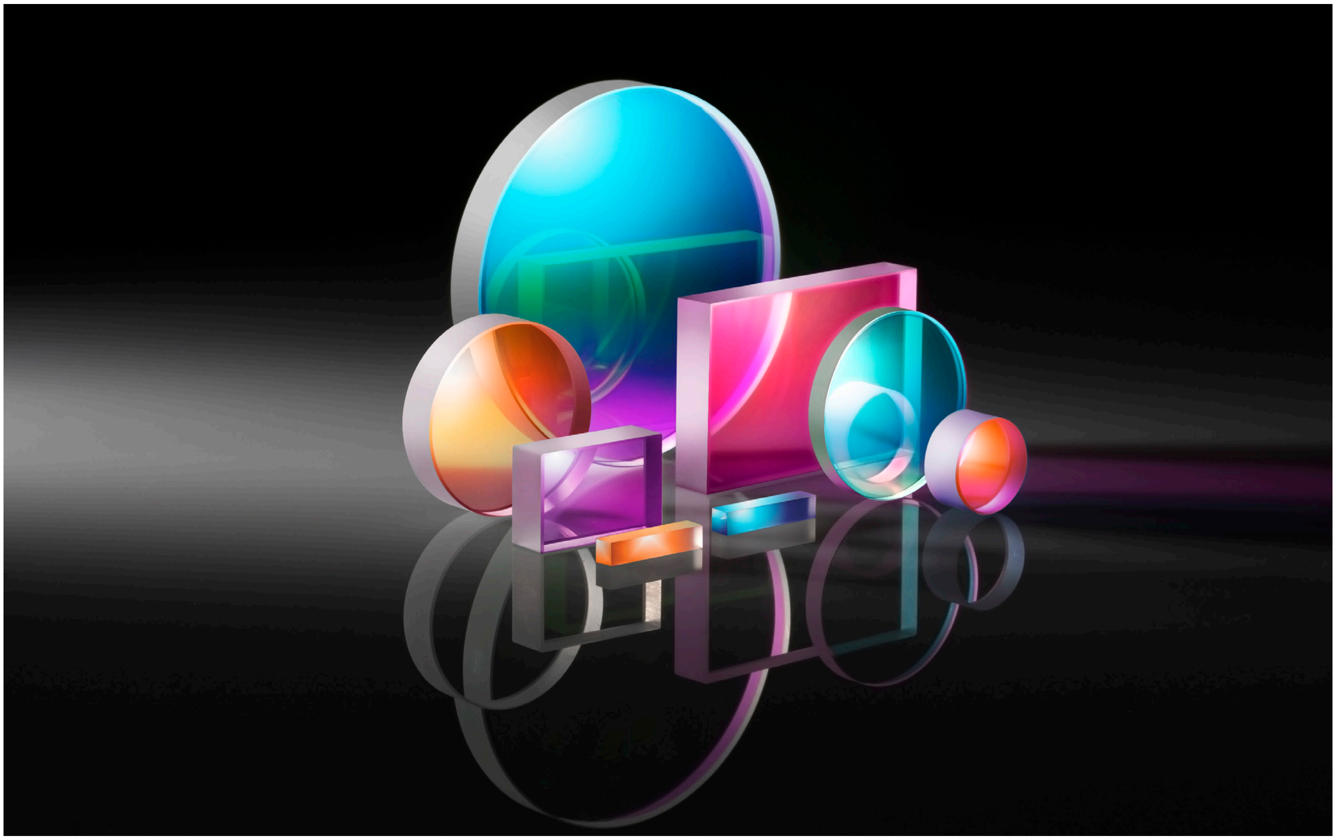
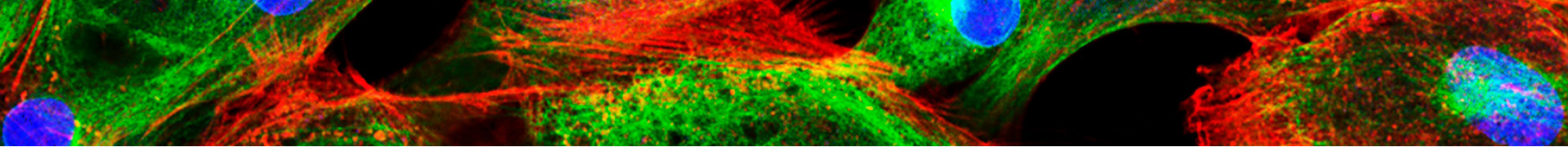


FIGURE 1. Ultrafast laser optics require low-loss coatings over their application waveband like other types of laser optics, but they have unique dispersion requirements to minimize pulse broadening. *(Courtesy of Edmund Optics)*

As discussed in Part 1 of this series (see www.laserfocusworld.com/14291054), generating an ultrafast laser pulse requires a broad spectral bandwidth. To illustrate this point, a Gaussian laser pulse centered at 1030 nm with 150 fs duration would require a minimum spectral bandwidth of more than 10 nm at full width at half maximum (FWHM). In contrast, the typical spectral linewidth of Nd:YAG (1064 nm) laser sources with nanosecond pulses is less than 1 nm. As a result, ultrafast laser users should ensure their optical components are sufficiently reflective or transmissive across their entire bandwidth to avoid unintended spectral (and temporal) distortion. Fortunately, most standard highly reflective or antireflective coatings are designed to operate at an appreciable bandwidth, which makes sourcing optical components for use with your ultrafast laser less frustrating (see Fig. 1).

While the coating you select for your optical component may reflect or transmit the entire bandwidth of your ultrafast laser pulse, it does not mean the optic is designed to withstand the enormous peak power associated with these short pulses. Because long-pulse or CW lasers have dominated the commercial laser market for so long, it is common to see LDT ratings determined with nanosecond or CW laser sources. Unfortunately, it is impossible to scale these LDT ratings down to the ultrafast regime because the mechanisms for damage are entirely different across these orders of magnitude in pulse duration (see Fig. 2).

In the most ideal case, you will be able to select an optical component with a suitable LDT rating determined under conditions as close as possible to your own operating conditions. In practice, it is likely the LDT rating for a given optic will not be determined for your exact



conditions. In these situations, it is best to reach out to your optical component supplier for guidance about which optic is the best choice for your application.

Introduction to group delay dispersion (GDD)

Perhaps the most difficult challenge with using ultrafast lasers is maintaining the ultrafast pulse duration. As pulse durations get shorter, the possibility of temporal distortion grows. Without diving into the mathematics that underpin this phenomenon, we can conceptualize why this is true by considering the frequency-dependence of the refractive index for a given material.

Imagine that our broadband ultrafast laser pulse is travelling through a particular medium with normal dispersion, meaning lower-frequency (longer-wavelength) components travel faster than higher-frequency (shorter-wavelength) components. As our pulse travels through this material, the colors in our pulse will continue to stretch further and further apart in time.

For shorter pulse durations, and therefore broader bandwidths, this effect is further exaggerated and can lead to significant temporal distortion of our pulse. In most cases, it is convenient for us to examine this effect via the factor known as group delay dispersion (GDD), which is also known as second order dispersion. Higher-order dispersion terms may also affect the temporal profile of your ultrafast laser pulse. In practice, however, it is often sufficient to examine the impact of GDD.

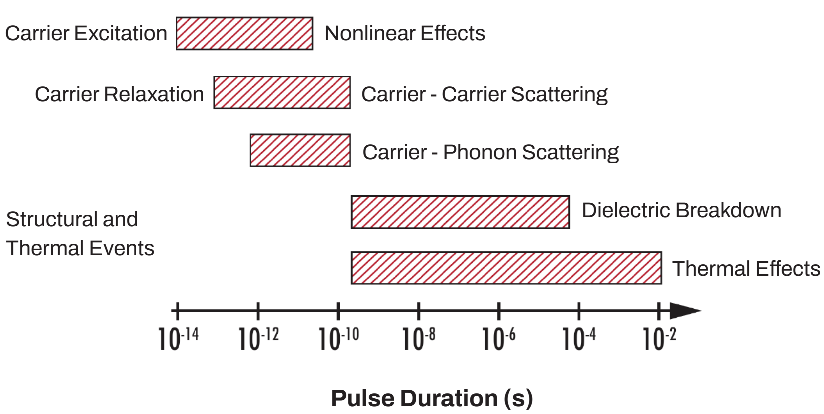


FIGURE 2. Mechanisms for laser-induced damage for different pulse durations. *(Courtesy of Edmund Optics)*

The impact of GDD on your pulse duration depends on several factors, including the input pulse duration (τ_{input}), center frequency (or wavelength), and the material through which your pulse propagates. Temporal stretching due to GDD is governed by:

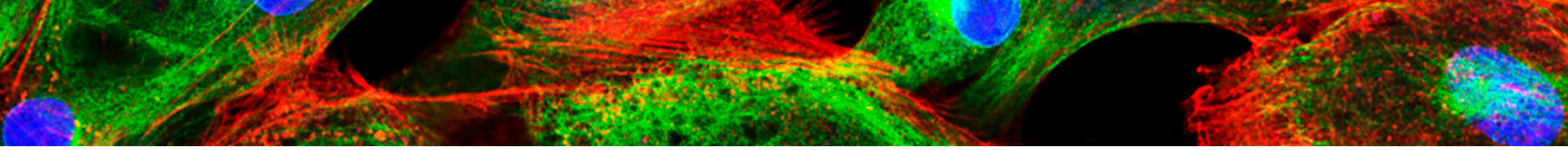
$$\tau_{output}=\tau_{input}\sqrt{1+(4\ln(2)\frac{GDD}{\tau^2_{input}}}$$

From this equation, it is clear that shorter pulse durations will be more substantially broadened as compared to longer input pulses for the same amount of GDD. This explains why we never discuss GDD in the context of nanosecond or even picosecond pulses. For context, it would take 20,000 fs^2 of GDD to broaden a 1 ps pulse by only 0.2%. We show in just a moment that this would be equivalent to propagating your 1030 nm pulse through more than 1 m of fused silica.

Because the refractive index of a material depends on the frequency of light, so too does the value of GDD. When selecting transmissive or refractive optics to use with your ultrafast laser pulse, it is often recommended to use fused silica, as this has one of the lowest GDD values in the visible and near-infrared (near-IR) spectral regions. For example, propagating your pulse through 1 mm of fused silica will generate ~19 fs^2 of GDD at 1030 nm,[1] but 1 mm of SF11 optical glass will generate more than 125 fs^2 at the same wavelength.[2] Refractive index databases, such as refractiveindex.info, are exceedingly helpful in determining which material is the best choice for your optical components, as well as how much GDD you are accumulating in your beam path.

Pulse (re)compression

For most ultrafast laser applications, it is rare that your



pulse accumulates no GDD along your beam path. Even some reflective optics, particularly broadband dielectric mirrors, can impart some non-zero value of GDD. The question then becomes: when is it necessary to (re)compress my laser pulse? While it is impossible to provide hard and fast guidelines for every situation, an example calculation can help to demonstrate some best practices.

Let's imagine we are performing a multiphoton microscopy experiment. The beam path may look similar to the one shown in Figure 3.

For the purposes of calculating pulse elongation, a first order approximation may be obtained by summing the GDD contribution of all elements within the system before the laser reaches the specimen. In this schematic, let's assume the major contributors will be the beam expander, the dichroic filter, and the objective. We will disregard the scanner mirrors, since they are typically made from low GDD metallic coatings. After identifying major contributors, we should collect the GDD contributions of all components. If our pulse is centered at 1030 nm, this system could easily contribute more than 600 fs^2 of GDD.

Whether or not we should recompress our pulse depends on the input pulse duration and the needs of our application. If we started with a 150 fs pulse, these optics would negligibly affect our pulse duration. If we were conducting fundamental studies and needed time resolution on the order of 10 fs, however, this amount of GDD would stretch our pulse to about 167 fs. In the latter case, we would need to recompress (see Fig. 4). Of course,

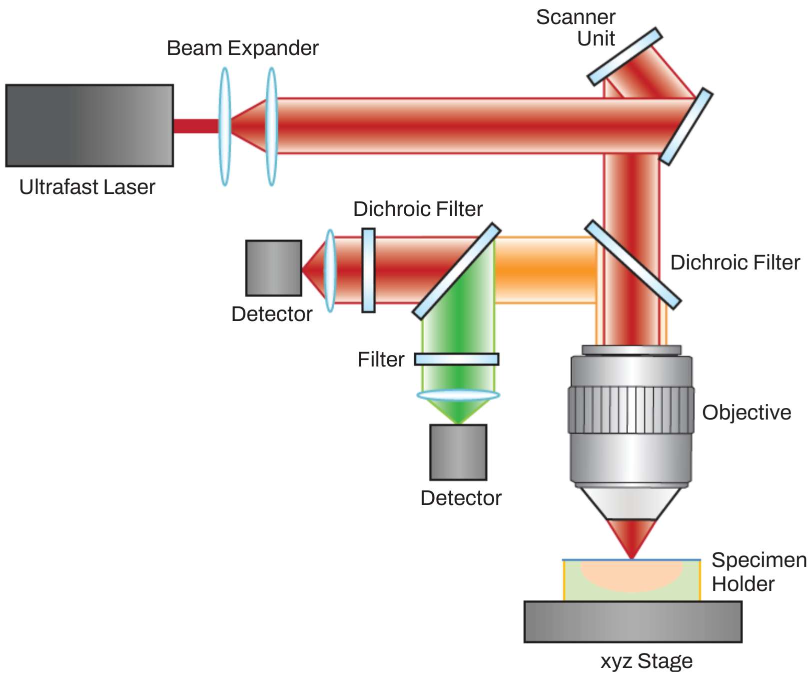


FIGURE 3. An example schematic of the beam path in a multiphoton microscopy experiment. *(Courtesy of Edmund Optics)*

these details heavily depend on your beam path and application. For assistance with choosing the best optical components for your pulse duration, contact your optical components supplier.

As ultrafast lasers are integrated into a wider variety of application spaces, more users are facing the technical challenges posed by their broad spectral bandwidths, ultrahigh peak powers, and ultrashort pulse durations. No matter the application, ultrafast laser users can follow these practical guidelines to deliver their ultrafast laser pulse to the target material without decreasing their spectral coverage, distorting their temporal profile, or damaging optical components along the way.

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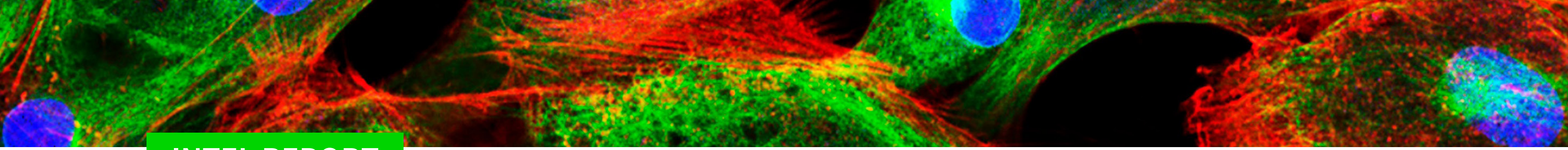


INTEL REPORT

Basics of ultrafast lasers: Part 3

OLIVIA WHEELER

Parts one and two of this three-part series focused on the unique features of ultrafast lasers and the basics of selecting the right optical components for an ultrafast laser system.[1, 2] Now, we will dive into how and when to (re)compress ultrafast laser pulses. The short pulse durations of ultrafast lasers naturally have broader bandwidths than conventional laser pulses. The positive dispersion of most optical media causes the ultrafast pulses to then broaden temporarily, reducing system performance. A variety of techniques can be used to mitigate these effects and compress the pulse back to its desired pulse duration, a few of which will be highlighted in this article.

Signs that pulses need to be compressed

Blurry images in ultrafast imaging applications like multiphoton microscopy indicate that pulses may be stretching temporally (see Fig. 1). In ultrafast laser machining, pulse stretching can lead to less-accurate cuts and less precision. It is the short durations and high peak

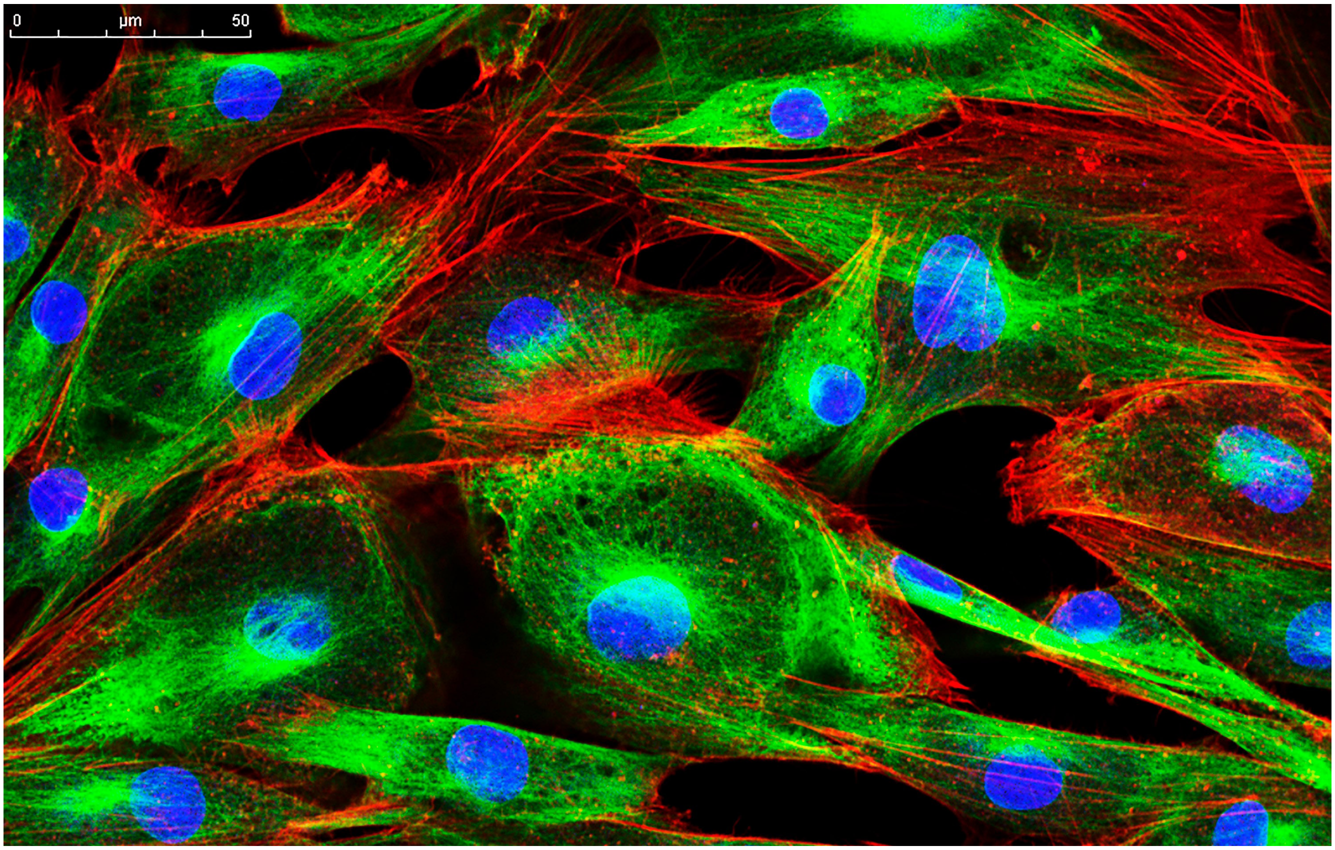
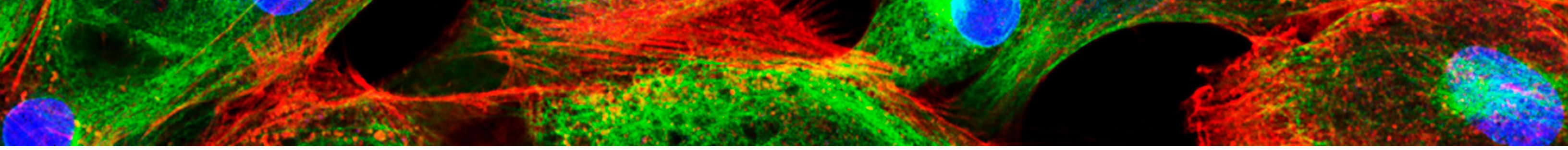


FIGURE 1. Multiphoton, or nonlinear, microscopy, uses ultrafast laser sources for capturing high-resolution three-dimensional (3D) images with reduced photobleaching and phototoxicity compared to traditional confocal microscopy techniques. However, pulse spreading can make multiphoton microscopy images like this one become blurry. *(Courtesy of Edmund Optics)*



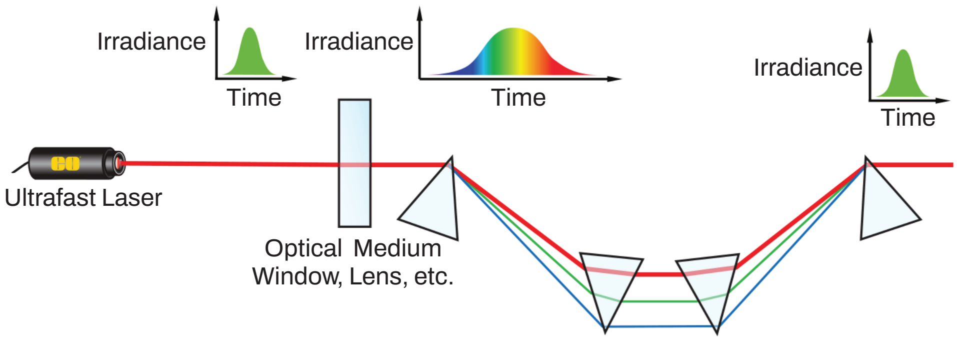


FIGURE 2. While prisms and gratings can be used for pulse compression, they face disadvantages compared to highly dispersive mirrors. *(Courtesy of Edmund Optics)*

powers of ultrafast pulses that lead to their advantages in both of these applications. Elongating the pulses lowers the probability of multiphoton interactions, which reduces the efficiency of your ultrafast process.

When and how should I compress pulses?

To examine when and how to compress your laser pulse, consider these key questions:

How variable is your system? Can you easily swap in different components to your system? Will you perform different processes or experiments that require different optical configurations? This influences which components are best for your solution.

How sensitive is your process to pulse duration variations? Are pulse durations within a 5 fs accuracy required? Or is 100 fs accuracy sufficient? The less variation allowed, the more flexibility and tunability is required from your pulse compression solution.

What's your ideal pulse duration, and what's your starting pulse duration? If you're working with pulse durations on the order of hundreds of femtoseconds, you can typically use several transmissive optical components before noticing an effect on pulse duration. This is not the case for someone using a significantly shorter pulse, perhaps on the order of 5 to 10 fs. Furthermore, if you start with a 100 fs pulse but want to compress it down to 5 fs, extra steps are involved that are beyond the scope of the pulse compressing strategies discussed in this article.

What other optics are in your beam path? How much group delay dispersion is there? The temporal distortion of the pulse due to dispersion is quantified by group delay dispersion (GDD). GDD is a frequency-dependent value that, for a given material, scales linearly with thickness. Transmissive optical components like windows, lenses, and objectives normally apply positive GDD, so that your once-compressed pulse may emerge from the transmissive optical component with a longer duration than was initially emitted by your laser. Having a rough sense of the magnitude of GDD present in your system can make your selection of pulse recompression strategy quite straightforward.

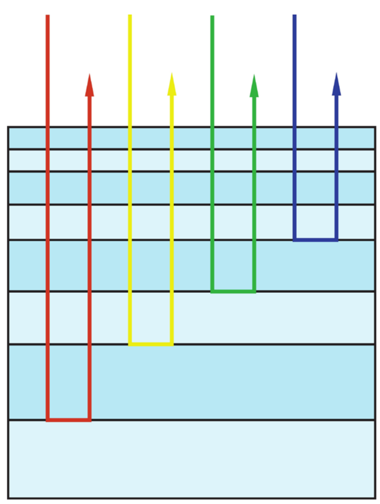
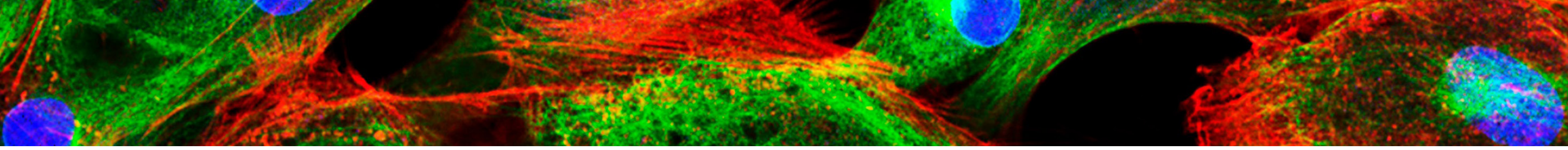


FIGURE 3. The variable layer thickness, combined with strategic choice of coating materials, causes chirped mirrors to apply negative dispersion to an incoming pulse. *(Courtesy of Edmund Optics)*

Pulse compression methods

Prisms/grating compressors. Prisms compress ultrafast pulses by applying a frequency-dependent delay to frequency components of the pulse via the difference in refractive index of the prism material (see Fig. 2). This optical path difference aligns the different wavelengths of the pulse in time. Grating compressors work in a similar way, but rely on diffraction rather than refraction to re-compress the pulse.



Advantages:

- Continuously tunable via variables like distance between elements, amount of material insertion, and groove density.
- Can accommodate very large bandwidths.
- Good for adjusting very, very short pulses.

Disadvantages:

- Difficult for beginners to align.
- Apply higher order dispersion, which can further distort a pulse's temporal profile.
- Can easily create separate frequency components of the pulse in space (known as "spatial chirp").

Pulse compressing mirrors: Chirped mirrors. Chirped mirrors function by creating a wavelength-dependent penetration depth into the coating of the mirror (see Fig. 3). Similar to the operation of prism or grating compressors, the effect delays some wavelengths relative to others. In the case of chirped mirrors, this effect arises because some wavelengths travel deeper into the coating. All wavelengths end up emerging from the coating at the same time, at which point the pulse gets recompressed. Chirped mirrors are typically characterized by high GDD oscillations, so they must be used in pairs to get a semi-flat GDD response.

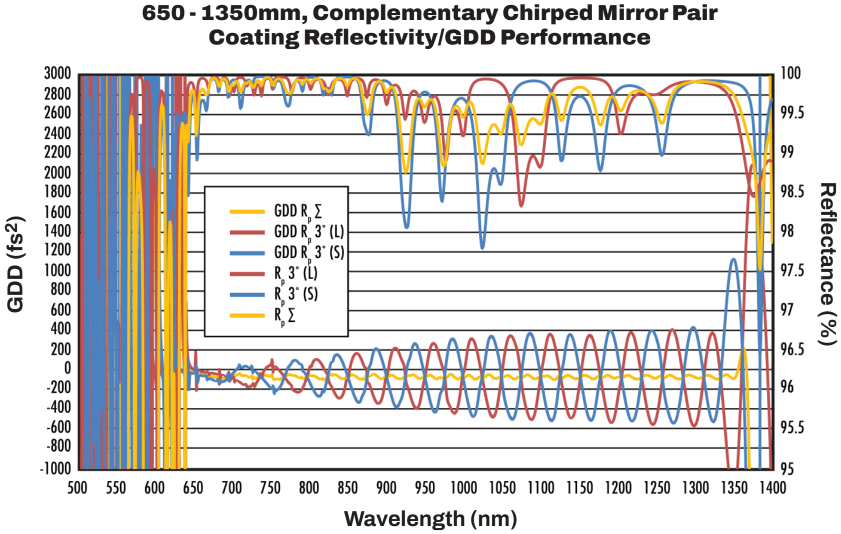


FIGURE 4. The high-magnitude GDD oscillations in these ultrabroadband chirped mirrors are offset by using the "L" and "S" components in concert to achieve the combined response, "Σ". *(Courtesy of Edmund Optics)*

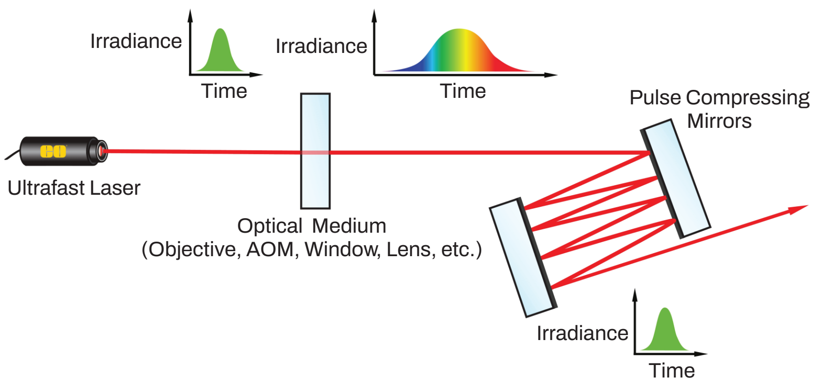


FIGURE 5. Highly dispersive mirrors are powerful tools for introducing negative dispersion, canceling out the positive dispersion experienced by ultrafast laser pulses as they transmit through optical media. *(Courtesy of Edmund Optics)*

Advantages:

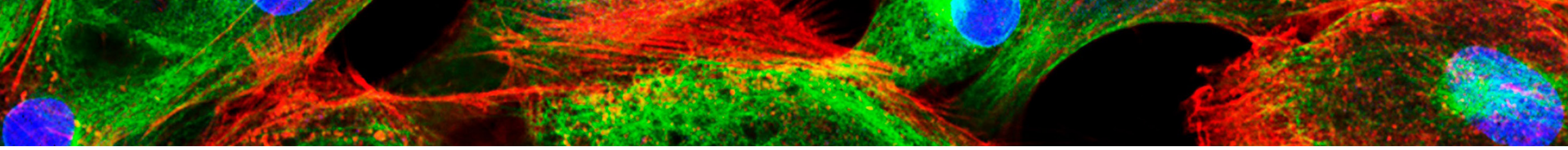
- Broad bandwidths possible.
- Typically have small angles of incidence, which makes it easy to reflect many times between the two mirrors in the chirped mirror pair.
- Easy to align relative to prisms and gratings.

Disadvantages:

- Provides only integral steps of GDD, which are not continuously tunable.
- Need to use in a complementary pair due to GDD oscillations.
- Limited in application by their specified bandwidth.
- Typically feature smaller values of GDD than other methods.

For example, a chirped mirror pair would be a good option if you need to compensate for a small amount of GDD in your system, or if you switch between different setups (such as between a Ti:sapphire and Yb-doped laser). Figure 4 contains some example characteristics of a complementary-chirped mirror pair.

Pulse compressing mirrors: Highly dispersive mirrors. Highly dispersive mirrors combine the



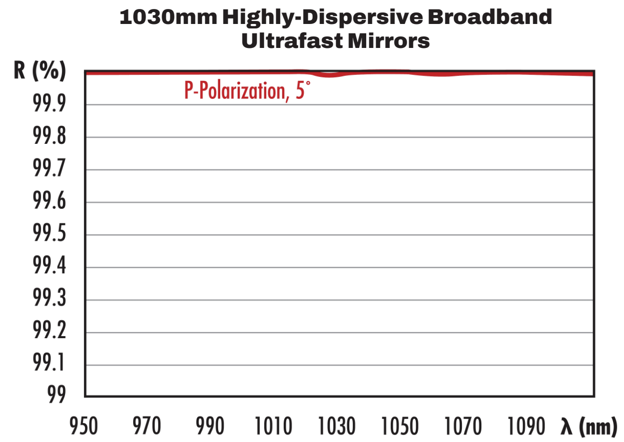


FIGURE 6. In addition to negative dispersion for ultrafast pulse compression, highly dispersive mirrors provide high reflectivities to maximize throughput. *(Courtesy of Edmund Optics)*

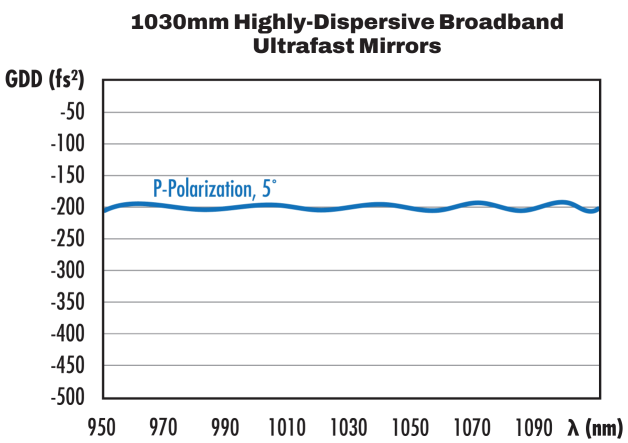


FIGURE 7. Ultrafast highly dispersive mirrors offer negative GDD with a high magnitude and far less wavelength-dependent oscillation than chirped mirrors. *(Courtesy of Edmund Optics)*

frequency-dependent penetration depth of chirped mirrors with a multiresonance effect to produce larger magnitudes of GDD with fewer oscillations. While the bandwidths addressed by highly dispersive mirrors may be somewhat narrower than other methods, many highly dispersive mirror designs are able to achieve very high reflectivity across their specified bandwidth (see Fig. 5).

Advantages:

- Able to achieve high magnitudes of GDD.
- Typically feature small angles of incidence for many reflections between multiple mirrors.
- Easy to align compared to prisms and gratings.
- Do not need to use in pairs.
- Typically feature high reflectivity, creating less power loss throughout your optical path.

Disadvantages:

- Provides only integral steps of GDD that are not continuously tunable.
- Limited by their specified bandwidth.

Highly dispersive mirrors are great options if you need to compensate for a decent amount of GDD in a fixed system. Sample reflectivity and GDD curves for a highly dispersive mirror are shown in Figures 6 and 7.

The decision of when and how to recompress ultrafast laser pulses is heavily application-dependent, but a basic knowledge of different methods and their advantages/disadvantages gives you a head start. Discuss your specific application with your optical component supplier for guidance to determine the best pulse-compressing method for your system.

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