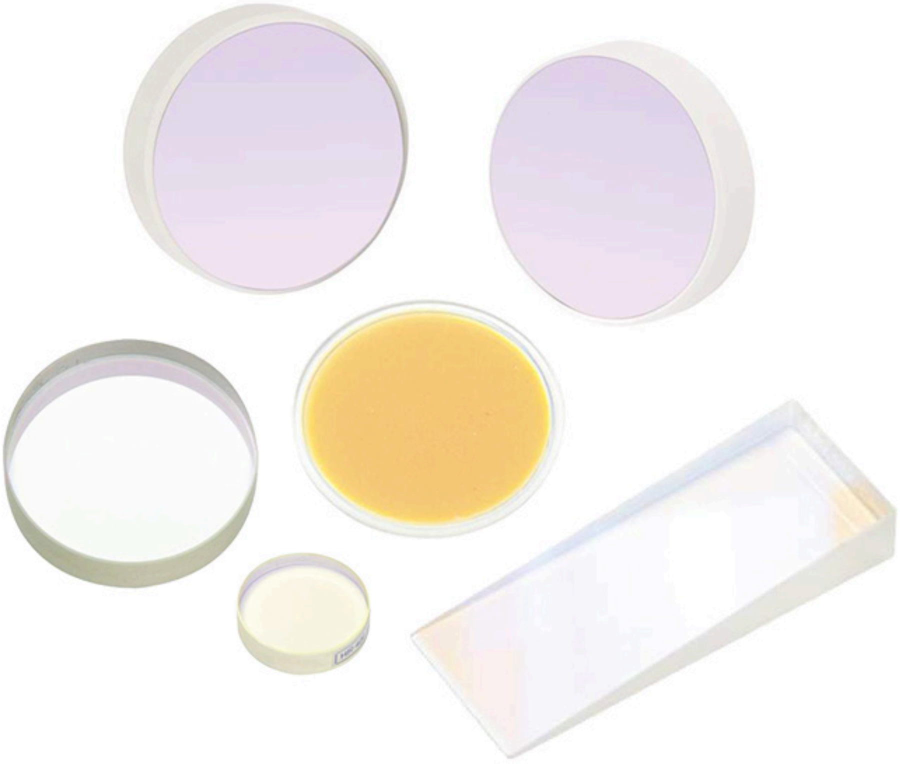
Ultrafast Laser Optics:

Balancing Costs with Successful Outcomes



Ultrafast Laser Optics: Balancing Costs with Successful Outcomes

Maintaining high operational value while minimizing system costs is a constant challenge in the technology industry. This is particularly true for advanced research and manufacturing systems that employ laser light for purposes such as analysis, sensing and fabrication.

The good news is that the cost of lasers has decreased over time to the point where more common lasers can be purchased at a more cost-effective price, regardless of their power output. This simplifies the choices for optics in many laser applications, as the use of a higher power laser can compensate for lower quality optics. However, this is not the case for ultrafast laser applications where success or failure is highly dependent upon high-quality, specialty lasers and optical components.

Lasers chosen for cutting-edge applications must produce coherent light with precise, application-specific characteristics. The parameters that define these characteristics include:

- Pulse width and shape
- Peak pulse energy
- Spectral bandwidth
- Wavelength
- Average power
- Beam size
- Polarization

The properties of ultrafast laser light at the target are strongly affected by phenomena such as dispersion within the optical path. This is why ultrafast laser selection requires careful consideration of the optical properties of the reflective and refractive components in the optical path to the target.

In this white paper, we explore the “false economy” provided by lower quality, lower cost optic components and its impact on the ultimate success or failure of research experiments and other ultrafast laser applications.

The False Economy of Lower Cost Optics

While the prices for ultrafast lasers have been dramatically reduced in recent years, the costs remain significant, especially for research applications where funding may be limited. If a researcher has invested most of the available funding into the laser system of an analysis, sensing or fabrication system, there may be a strong temptation to opt for less expensive optics to complete the laser light delivery subsystem. This is almost always a detrimental choice for ultrafast laser applications.

Components in the optical path that have poor optical characteristics will degrade many critical quality parameters of the laser light delivered to the target. Moreover, the erosion of the laser light quality in ultrafast laser systems is often subtle and not easily detected without dedicated specialty instrumentation such as spectrum, power or pulse width analyzers.

When inexpensive optics are used in an ultrafast laser system, the laser light pulse most often suffers from dispersive effects. Dispersion of the laser light pulse as it passes through the optical train results in:

1. The pulse at the target being much longer than expected and/or distorted.
2. The need for dispersion compensation that requires the addition of an optical compressor toward the end of the optical path.

Lengthening or distortion of the laser light pulse can have serious negative impacts for research experiments and other applications. For example, peak power is a critical laser parameter in applications such as nonlinear optical investigations. It is directly and proportionately affected by an increase in the duration of the laser light pulse. A laser pulse length that changes from 20 fs to 30 fs duration – easily the case when using non-specialized optics – produces an approximate 30% decrease in the peak power of the pulse at the target.

This, in turn, produces concomitant changes in the results of measurements or manufacturing processes using the laser system. If a corrective dispersive mirror solution cannot be implemented in the optical path, optical pulse compressors (Figure 1) can be employed. However, optical compressors are expensive and are composed of optical components that can be challenging to align. They also produce additional power losses in the optical path (prism compressors normally account for 30-40% loss) and they may fail to compensate for higher order dispersion effects.

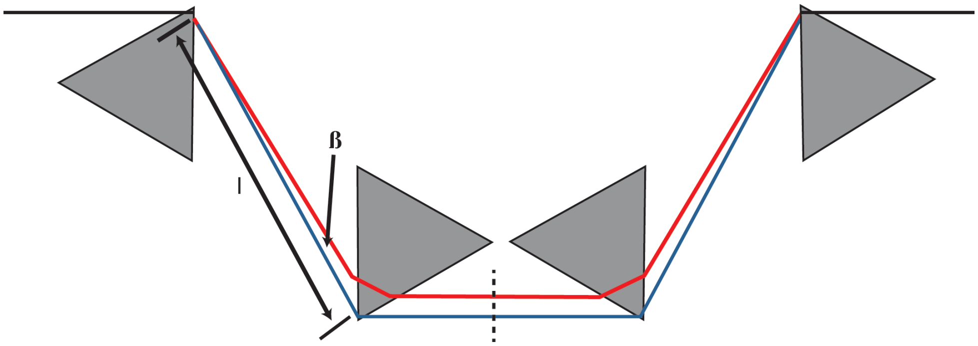


Figure 1. This is an example of a prism optical pulse compressor. A four-prism set up is difficult to align and will induce additional power loss [1].

Inexpensive optics can create dispersion in the optical path for ultrafast systems that require compensation for best performance. Dispersion can be avoided by using specially designed optical components that may be more expensive in the short term, but create more successful outcomes overall.

Why It's Different for Ultrafast Lasers

While more common laser costs have decreased overall, laser costs for cutting-edge applications remain high. We're talking about cutting-edge applications that require lasers with specialty properties which are not normally required for standard nanosecond applications.

This may include extremely high power or ultrafast (pico- and femto-second) laser light pulses. Pricing typically scales with increasing energy and/or shorter pulses.

As well, delivering the shortest pulse width with the highest fluence at the target is critical in most ultrafast laser applications. Many femtosecond applications require specialty optics that compensate for dispersion within the optical path by compressing the light pulse just before the target.

Much of the cost for ultrafast, laser-based systems is invested in the laser and the optics. That's why it's important to make strategic, application-specific choices for the laser and optical components to produce the greatest operational value – while simultaneously minimizing system costs.

Understanding Critical Specifications for Ultrafast Laser Optics

Specially designed optics can keep dispersion in check, eliminating the need for costly, difficult-to-align optical compressors. When selecting such specialty optics, it is important to consider certain critical specifications for use in ultrafast laser systems:

1. **Wavelength bandwidth:** Ultrafast laser systems may require optics that perform well over a large wavelength range. Specialty optics should not exhibit dispersion and distortion over the tunability range of ultrafast lasers such as the Spectra-Physics Mai Tai® Laser, which can be wavelength tuned from 690 to 1040 nm. Inexpensive coatings on optical components can exhibit unwanted effects such as reflection power loss or distortion over the full spectral range.
2. **Pulse Width:** The laser light pulse width produced by an ultrafast laser is an important parameter; it can determine how deeply the light pulse probes tissue and the clarity of an image in Raman spectroscopy applications. When employing ultrafast lasers with extremely short pulse widths (such as the Spectra-Physics Rainbow™ 2 laser, which has near transform-limited sub-6 femtosecond pulse widths), it is important to ensure that the coatings on all optical components in the system are optimized for ultrafast lasers. If not, the pulse can experience significant distortion. Dispersion can be quantified as either Group Velocity Dispersion (GVD) or Group Delay Dispersion (GDD) where GDD is simply GVD in a medium of length L. Dielectric coatings not optimized for Group Delay Dispersion (GDD) will expand the pulse width as shown in figure 2.

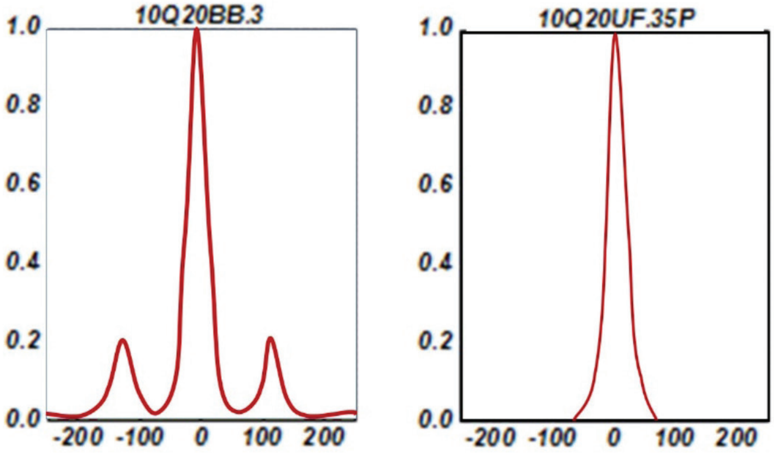


Figure 2. Autocorrelation on 60 nm/20fs pulse, 800nm center wavelength, reflected off standard dielectric mirror (left) and off an ultrafast optimized mirror (right)

The two graphs in Figure 2 clearly demonstrate the distortion that occurs when an ultrashort pulse is reflected by a standard dielectric mirror (left) as compared to the same pulse reflected by a mirror optimized for use with an ultrafast laser (right).

3. **Scratch-Dig:** This parameter characterizes the light scatter losses throughout an optical system. When there is light scatter in a system, the optical power reaching the target is significantly reduced. An optical train with a low scratch-dig figure can also produce wavefront degradation. High quality lenses or mirrors suitable for ultrafast laser systems typically specify a scratch-dig value of 10-5.

4. **Flatness:** The wavefront flatness of plano-optics (mirrors) is an important specification, especially for imaging systems. Plano-optics with specifications greater than the standard 1/10 wave flatness may exhibit unacceptable image distortions. This wavefront flatness specification applies equally to applications in which high intensity is required (i.e., attosecond pulse generation), since poor wavefront quality degrades the focus of the beam, reducing the intensity at the focal spot.

Component Selection for Ultrafast Laser Optical Systems

Reflective Optics

It's important to note that any of the reflective optics discussed in this section may be used; however, the unique needs of your particular application should be carefully considered in the decision process.

A typical ultrafast laser optics configuration may have, in addition to polarizing and focusing elements, at least 10 reflective mirrors between the laser light source and the target. The high number of mirrors makes it imperative that the specific reflectivity of the mirrors be maximized since any optical losses due to reflection are cumulative and these losses reduce the optical power at the target.

It is important to consider that standard metallic mirrors such as gold or silver work well in the ultrafast regime only so long as the protective over-coat is designed for ultrafast laser system use. A bare metal coating has minimal GDD because the light does not penetrate deeply into the metal before being reflected, thereby minimizing dispersion. However, bare metals are not recommended because of degradation over time.

Most metallic mirrors have dielectric over-coats for environmental protection and reflectivity enhancement; however, improper design of these coatings may significantly distort the GDD at certain wavelengths within the high reflectance range.

Also, metallic mirrors typically have poor reflectivity at specific wavelengths as compared to dielectric coatings. Ultimately, the use of a dielectric or metallic mirror with no GDD specifications risks distortion of the pulse or reduced broadband reflectivity within the optical train.

As a model, consider some different options shown here for a mirror optimized for 800 nm laser light pulses in an ultrafast spectroscopy experiment. The different mirrors in this list are rated from "OK" to "Best" for this application.

Ultimately, the investment made depends upon your particular application and needs.

1) Newport 10D20ER.2 standard silver coated mirror, one-inch diameter, 1/10 wave flatness, 15-5 scratch dig, reflectivity R = 93-96% at 800 nm, no specification for GVD – Lowest cost: OK.
https://www.newport.com/p/10D20ER.2
2) Newport FemtoOptics™ femtosecond optimized silver mirrors, one-inch diameter, 1/10 wave flatness, 10-5 scratch dig, reflectivity R = 99% at 800 nm, GVD less than 5 fs^2 – Low to intermediate cost: GOOD.
https://www.newport.com/p/10B20EAG.1

3) Newport 10B20UF.25 low GVD ultrafast mirror, one-inch diameter, 1/10 wave flatness, 15-5 scratch dig, reflectivity R > 99% at 800 nm, near zero GVD at 800 nm – Intermediate to higher cost: BETTER.

   - Even though the reflectivity is similar to #2, this is an all dielectric coating, so this mirror will wear longer.
   https://www.newport.com/p/10B20UF.25

4) Newport 10Q20UF.55P ultrafast broadband turning mirror, one-inch diameter, 1/10 wave flatness, 20-10 scratch dig, Reflectivity $R_p > 99.6\%$, near zero GVD – Higher cost: BEST,

   - This mirror is ideal for the Spectra-Physics Mai Tai® or Insight® lasers which can be tuned to the whole spectrum (690 – 1040 nm, 680 – 1300 nm).
   https://www.newport.com/p/10Q20UF.55P

Legend:

R = absolute reflectivity, typically at normal angle of incidence

R_p = reflectivity of P-polarized light, typically at 45° angle of incidence

Choosing the best optics for an ultrafast laser application can be a challenging proposition. The choices made for the ultrafast laser, particularly for the optical components, will be critical for determining the success or failure of research experiments and other ultrafast laser applications.

It is always prudent to take the time to understand the optical requirements of the application and to study the specifications of the optics selected to meet these specifications prior to purchasing the system components. The least expensive choice may not always be the most cost-effective or technologically suitable one, resulting in higher costs – and more failures – in the long run.

References

[1] Technology and Applications Center, Newport Corporation, “Application Note: Prism Compressor for Ultrashort aser Pulses,” [Online]. Available: https://www.newport.com/medias/sys_master/images/images/h25/h7f/8797242818590/Prism-Compressor-for-Ultrashort-Laser-Pulses-App-Note-29.pdf. [Accessed 5 September 2017].

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