Femtosecond optics

Altechna

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Since the introduction of the first sub-picosecond lasers in the 1990s, the market for femtosecond optics has grownrapidly. However, it still cannot compete with longer pulse or CW laser markets. In femtosecond applications problems of conventional optics and coatings are that they either distort the temporal characteristics of the pulse, or are damaged by high peak power of the pulse. To better understand why this happens, let's look at the basics of the ultrashort world.

Though the definition sometimes varies, an **ultrashort pulse** is an electromagnetic pulse with a time duration of one picosecond (10^{-12} second) or less. Since ultrashort phenomena are too fast to be directly measured with electronic devices such events are sometimes referred to as *ultrafast* (the meaning, however, is the same).

Pulse length is inversely proportional to the optical spectrum of the laser beam therefore ultrashort pulses have a very broad spectrum, e.g. the gain bandwidth of Ti:Sapphire is 128 THz thusthe shortest pulse duration is 3.4 femtoseconds ($3.4 \cdot 10^{-15}$ seconds). Technically, such pulses are no longer the shortest artificially generated electromagnetic waves, attosecond (10-18 second)[1] pulses have already been achieved but this technology is still far from commercial use.

Chromatic dispersion

Since the optical spectrum of an ultrashort pulse is very broad, *group velocity* plays a key role in understanding how ultrashort optics work. *Group velocity* of a wave is the velocity with which the overall shape of waves' amplitudes propagates through space. It would be correct to say that *group velocity* is the velocity with which whole broad electromagnetic ultrashort pulse propagates. For free space where the refractive index is equal to one, *group velocity* is constant for all components of the pulse.

Optical materials possess a specific quality, the phase velocity of light inside the material depends on the frequency (or wavelength), and equivalently the group velocity depends on the frequency. This is called *chromatic dispersion or group-velocity dispersion (GVD)*. This means that for different wavelengths of light the refractive index inside of the material is different. Therefore, the group velocity at which light passes through the material is different for each wavelength. Figure 1 showshow refractive index depends on the wavelength of light in different glasses.

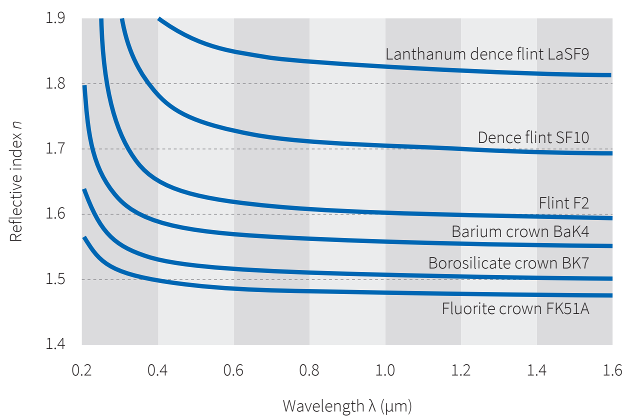

Figure 1. Refractive index as a function of wavelength for different commercially available glasses[2]

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Following from the previous, we can see that inside the material each frequency component of light travels at a different speed. This results in a spread pulse compared to the initial one emitted from the laser. *Group velocity dispersion* is sometimes called *second order dispersion* because it arises from the Taylor expansion of the wavenumber k (change in spectral phase per unit length) as a function of angular frequency ω (around some center frequency ω_0, e.g. the mean frequency of a laser pulse)[3]:

$$k(w) = k_0 + \frac{\partial k}{\partial w}(w - w_0) + \tag{1.1}$$
$$+ \frac{1}{2}\frac{\partial^2 k}{\partial w^2}(w - w_0)^2 + \frac{1}{3}\frac{\partial^3 k}{\partial w^3}(w - w_0)^3 + \ldots$$

Zero-order term of the expansion (1.1) describes a common phase shift, *first-order term* contains inverse group velocity (or group delay per unit length) and describes an overall time delay without an effect on the pulse shape, the *second-order (quadratic) term* describes the second-order dispersion or group delay dispersion (GDD) per unit length, and *the third-order (cubic) term* describes the third-order dispersion (TOD) per unit length.

Group velocity *dispersion* (GVD) and *group delay dispersion* (GDD) are interchangeable: group velocity dispersion (in units of s^2/m or fs^2/mm) is the group delay dispersion per unit length (in units of s^2 or fs^2). It follows that the GDD per unit length (in units of s^2/m or fs^2/mm) is the group velocity dispersion (GVD).Group delay dispersion can be described as the derivative of the group delay with respect to the angular frequency, or the second derivative of the change in the spectral phase[4].

$$D_2(w) = \frac{\partial T_g}{\partial w} = \frac{\partial^2 \varphi}{\partial w^2} \tag{1.2}$$

GDD is usually an **unwanted effect** because a streched ultrashort pulse will lose its two main properties: it will no longer be ultrashort and its peak power will distribute within the streched pulse (please refer to figure 2 below). Usually, the only case where pulse streching is a desired effect is in ultrashort pulse amplification, where the pulse is streched, amplified and compressed again. Amplifying an ulstrashort pulse without stretching is impossible due to high peak power, damaging theoptical components of the amplifier.

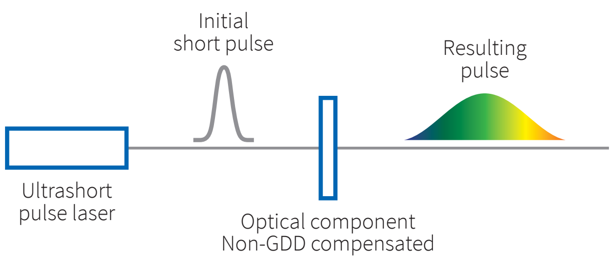

Figure 2. Schematic representation of ultrashort pulse spreading after a non-GDD compensated optical component is introduced to the setup.

Ultrafast optics – what is out there?

As mentioned at the beginning of this article, compared to longer pulse or CW, the market of femtosecond optics is not as large. Nevertheless, there are a few solutions available to help you deal with ultrashort pulses. Altechna has been working with femtosecond optics since the beginning of the company in 1996 and has shown its expertise byhelping its customers tame the sub-picosecond pulses.

In summary, applications of ultrafast optics are:

- Ultrashort pulse generation;
- Maintaining of the temporal properties of the pulse;
- Stretched pulse compensation;
- Pulse stretching.

Altechna offers products for each of these applications:

1. Ultrashort pulse generation:
   a. Yb:KYW/KGW crystals
   b. Ti:Sapphire crystals
2. Maintaining of the temporal properties of the pulse:
   a. Low GDD mirrors
   b. Ultrafast thin film polarizers
   c. Watt Pilot - Motorized Attenuator, Ultrafast Version
   d. Reflective beam expander
3. Stretched pulse compensation:
   a. Gires-Tournois Interferometer (GTI) mirrors
4. Pulse stretching:
   a. Brewster angle dispersing prisms

All of these optical components are not only designed for femtosecond pulses, but they are also optimized for high peak powers.

References

[1] T. Pfeifer et al, “Single attosecond pulse generation in the multicycle-driver regime by adding a weak second-harmonic field”, Opt. Lett., Vol. 31, Issue 7, pp. 975-977 (2006)

[2] commons.wikimedia.org/wiki/Dispersion-curve.png

[3] rp-photonics.com/chromatic_dispersion.html

[4] rp-photonics.com/group_delay_dispersion.html

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