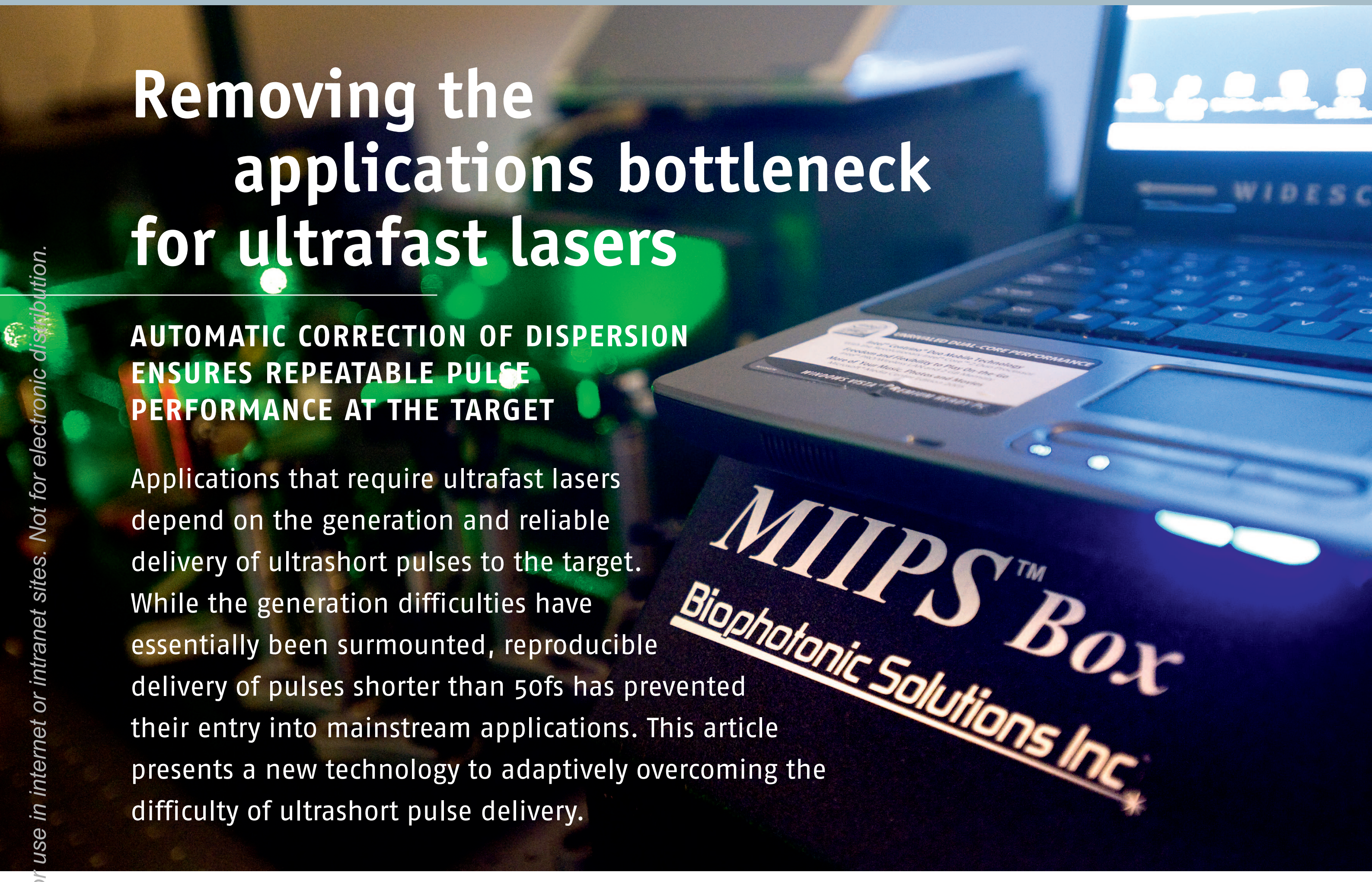


Removing the applications bottleneck for ultrafast lasers

AUTOMATIC CORRECTION OF DISPERSION ENSURES REPEATABLE PULSE PERFORMANCE AT THE TARGET

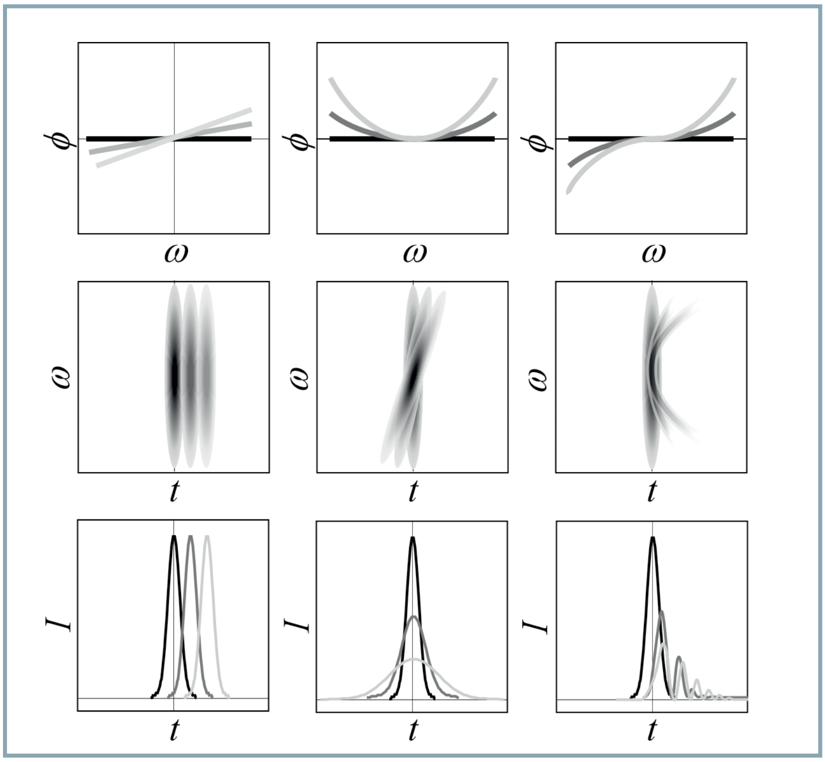
Applications that require ultrafast lasers depend on the generation and reliable delivery of ultrashort pulses to the target. While the generation difficulties have essentially been surmounted, reproducible delivery of pulses shorter than 50fs has prevented their entry into mainstream applications. This article presents a new technology to adaptively overcoming the difficulty of ultrashort pulse delivery.

MARCOS DANTUS

The number of patent applications that include ultrafast lasers is growing exponentially given the versatility of these sources. The promise of greatly improved machining, imaging, communications, sensing, processing, dentistry and even surgery depend on reliable and affordable ultrafast lasers.

Until now, generation of short pulses has always depended on extraordinarily gifted individuals at institutions. For example, there was a 10 year gap between the first demonstration of 6 fs pulses by Shank and coworkers and the time when this achievement was reproduced elsewhere. While significant progress has taken place, the delivery of sub-50 fs pulses to a target still requires an experienced scientist. This dependence on highly qualified personnel represents a bottleneck in the entry of ultrafast lasers into mainstream applications.

The problem with ultrashort pulse delivery is the dispersion caused by optical elements such as mirrors, lenses and even by air. For example, a 10 fs laser



1 The effect of different spectral phase functions on ultrafast laser pulses. The first row introduces different amounts of linear, quadratic and cubic phase as a function of frequency (from left to right). The second and third rows represent the same pulses in frequency-time and intensity-time diagrams, respectively

pulse centered at 800 nm is broadened to 15 fs after propagating through only 0.8 mm of glass, 1.1 mm of quartz, 1.6 mm of water or 2 m of air. This implies a 50 percent or greater loss of efficiency for most applications. A number of methods have therefore been introduced to compensate for linear chirp such as prisms, gratings, and chirped mirrors. Their effectiveness is limited by their inability to correct higher-order dispersion and they cannot be easily modified to accommodate changes in the optical setup. Some optics, such as dielectric mirrors, can broaden a pulse by an order of magnitude even after a single bounce.

Automated dispersion correction

The new trend in ultrafast laser research is automated measurement and correction of both linear and nonlinear chirp. The first fully integrated method for measuring and correcting spectral dispersion, known as MIIPS (multiphoton intrapulse interference phase scan), was invented in the Dantus Research Group [1]. The technology was transferred from the lab into a commercial product by Biophotonic Solutions. In 2006, Coherent licensed the MIIPS technology and introduced the Silhouette pulse shaper.

MIIPS employs the dependence of nonlinear optical signal on spectral phase, as is the case, for example, for sum frequency generation. It has been said that MIIPS technology is to ultrafast lasers what the electronic fuel injection is to the automotive engine. The electronic fuel injection significantly increases engine performance, especially as it adapts to a wide range of temperatures and altitudes. In a similar fashion, MIIPS technology adaptively corrects for dispersion of ultrafast laser pulses ensuring optimal performance at the target even after changing the optics or optical path.

CONTACT

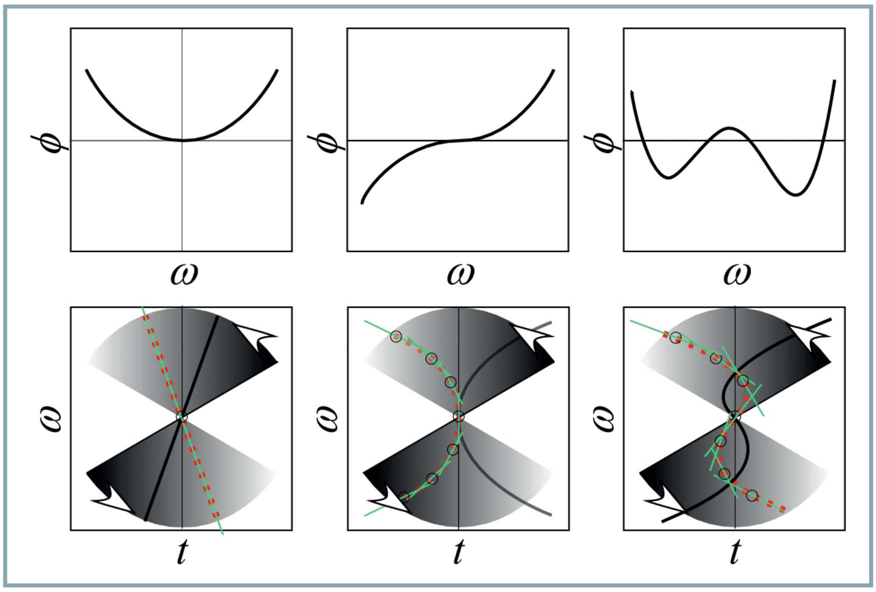
Biophotonic Solutions, Inc.
East Lansing, MI 48823, USA
Tel. +1 517 580 4075
www.biophotonicsolutions.com

Approach

MIIPS uses a pulse shaper that allows the independent control of the phase for every wavelength within the bandwidth of the pulse. The objective is to employ a calibrated phase to measure the unknown phase distortions.

Introducing a linear phase as a function of frequency is equivalent to a time delay of the pulse, as illustrated schematically by the first column in Figure 1. When the phase depends quadratically on frequency (middle column in Figure 1), the lower frequencies are advanced to arrive earlier in time while the higher ones are delayed to arrive later in time, resulting in chirped pulses (pulses for which the instantaneous carrier frequency changes as a function of time) as illustrated in the second column. This case corresponds to linear dispersion or group velocity dispersion (GVD). A phase that depends on the frequency cubed has a retarding or advancing effect on frequencies that is proportional to frequency squared (right hand column in Figure 1). This case, also known as quadratic dispersion or quadratic chirp, causes the pulse to rise monotonously and fairly quickly but then decay with some oscillations caused by interference between low and high frequencies which are both delayed to later times (for positive quadratic chirp).

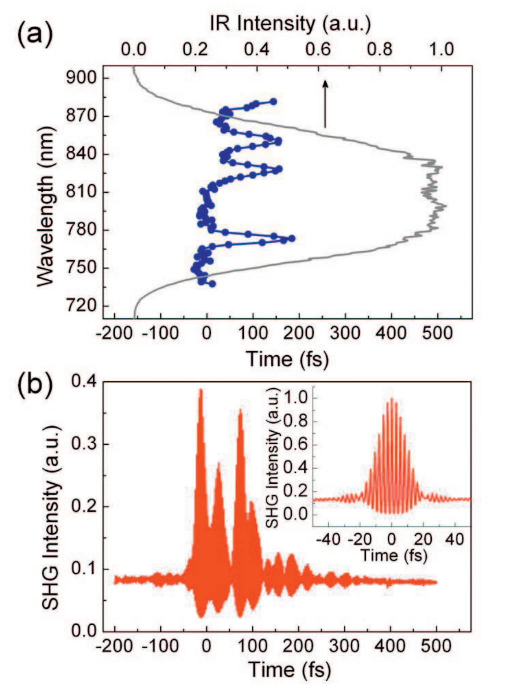
During a MIIPS scan, a reference phase, such as the quadratic phase $\beta\cdot(\omega-\omega_c)^2$, shown in the second column in Figure 1, is scanned from negative to positive values of coefficient β. This scan sweeps the frequency-time space and reveals the complimentary local phase needed to cancel curvatures in the spectral phase of the pulse. The effect of such a MIIPS scan is schematically represented in Figure 2. Mathematically, the goal is to find the points at which the dispersion being measured is compensated by the dispersion being introduced by the pulse shaper.



2 Schematic representation of a MIIPS measurement. The top row shows the spectral phase as a function of frequency. The second row represents the same phase as above in the frequency-time domain (heavy black line). The shaded area is the frequency-time space swept by scanning a quadratic phase function $f_{ref}(\omega)=\beta\cdot(\omega-\omega_c)^2$ from positive to negative values of β. For every measured point (small circle), the chirp introduced by the pulse shaper cancels the local dispersion of the pulse (slope)

When the phase $\phi(\omega)$ is quadratic, it corresponds to a straight line in the frequency-time plot (first column), therefore one slope value corrects dispersion at all frequencies. The time-frequency representation of a cubic phase is a parabola (second column), that is, the delay has a quadratic dependence on frequency. In this case, the dispersion (slope in the frequency-time plot) changes for different frequencies as shown in the second column of Figure 2. MIIPS can measure arbitrary phase functions. In the third column, one such arbitrary phase is shown.

Compensation of phase distortion



3 Measurement and compensation of the phase distortions introduced by a broadband dielectric mirror that has Gires–Tournois-like interferences. (a) Group delay spectrum measured for 45° incidence angle, after a single bounce off the mirror. The grey solid line maps the laser spectrum. (b) An interferometric cross correlation of the pulse after the broadband dielectric mirror. In the MIIPS scan, the phase distortions are compensated by introducing the complementary phase and bandwidth limited pulses (shown in the inset) are obtained

Bandwidth-limited pulse generation

Once the phase distortions in a pulse are measured, the MIIPS system can introduce a complementary function so that the residual dispersion is zero, thus obtaining bandwidth-limited pulses. The pulse shaper also permits arbitrary pulse synthesis to control (enhance or suppress) nonlinear optical processes or to design complex pulse sequences in the time and frequency domain.

Experimentally the MIIPS measurement does not require moving parts or time-delay scans. As the reference phase is scanned by the pulse shaper, the spectrum of a nonlinear optical process such as second harmonic generation (SHG) is measured. When the reference phase cancels locally the curvature of the phase being measured, then the intensity of the SHG is highest.

There are several advantages of the MIIPS technology. The pulse can be measured with interferometric accuracy at the target, whereby the user has the option of not only measuring but also eliminating the phase distortions. The system is easy to setup, with no need for beam splitters or delay lines, and the method is compatible with any laser wavelength provided there is a nonlinear optical signal to be detected. Finally, the phase measurement is direct, without a retrieval algorithm and delivers results in only a short frame of time.

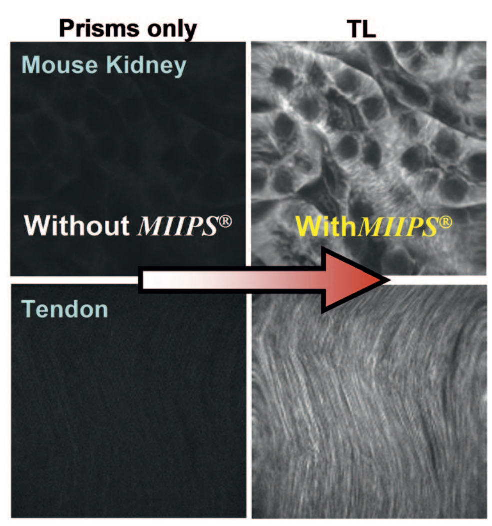
Unprecedented results

The MIIPS technology enables applications using the shortest laser pulses available. For example, pulses at the output of a hollow waveguide were compressed to 4.6 fs in minutes [2].

More impressive is the measurement and correction for phase distortions introduced by particularly bad dielectric mirrors, as shown in Figure 3. The figure shows the phase distortions introduced by the mirror; the pulse is shown before and after compensation for high-order dispersion [3]. The cross correlation and autocorrelation measurements shown were obtained using a phase-only, multiple independent comb shaping method [4].

The MIIPS technology is so accurate that it is valuable for performing dispersion measurements of optical materials. For example, the dispersion of distilled water was measured to be 24.76 ± 0.13 fs^2/mm at 800 nm, one of the most accurate measurements available in the literature [5].

One of the applications where MIIPS provides a clear advantage over simple prism compression is biomedical imaging. With a MIIPS enabled pulse shaper it is possible to perform two-photon microscopy with pulses as short as 10 fs, even when using high numerical aperture objectives. This capability is demonstrated in Figure 4, where images of kidney and tendon tissues obtained with and without MIIPS are shown. MIIPS corrects the high order dispersion and provides the most efficient, damage-free sample excitation. The same laser intensity was used to obtain all four images while the signal increase generated through MIIPS is approximately a factor of eight. The MIIPS enabled pulse shapers can even be used to tailor the excitation pulses depending on the tissue being imaged and its leading cause of damage. An image of melanoma tissue obtained with 13.5 fs pulses is shown in Figure 5. Correcting high-order dispersion from microscope objectives is also useful for ultra-



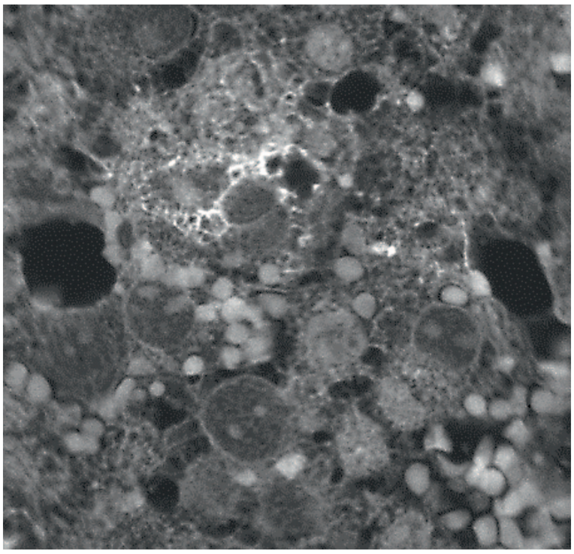
4 Two-photon fluorescence of stained mouse kidney and SHG imaging of rat tendon using 12 fs laser pulses corrected for linear dispersion using a pair of prisms and corrected for high-order dispersion using MIIPS. The scanned beam is focused with a water-immersion Zeiss LD C-Apochromat 40x/1.1 NA. The image size is about 100 x 100 µm²

fast laser machining and surface processing applications.

Amplified ~30 fs pulses can generate peak intensities exceeding 1015 W/cm^2. These extremely high fields ionize any material in their path. Recently, one such system incorporating a MIIPS devise was used to perform protein sequencing [6]. The laser pulses were directed into a commercial mass spectrometer where the protein ions were cleaved by the intense field. Of particular importance was that this method is capable of cleaving the strongest chemical bonds while maintaining the weaker bonds, which are usually associated with modifications indicative of disease, intact.

Biophotonic Solutions has worked with a number of research laboratories and laser companies to customize devices for specific lasers and applications. Three types of MIIPS-enabled systems are currently available. The smallest device, designed for OEM applications, is housed in a 15 cm cube and offers 128 pixel resolution. This system can handle most commercial laser systems, and is ideally suited for pulse compression of amplified ultrafast lasers. When the unit is installed between the oscillator and the amplifier, it allows delivery of amplified bandwidth-limited pulses at the target without loss of power.

The top of the line system offers phase and amplitude control over 640 spectral channels. This unit is best suited for compressing supercontinuum sources or for designing trains of pulses, which offer certain advantages for machining applications. Every one of the systems comes with the push-button MIIPS technology for automated pulse compression at the target.



5 Autofluorescence/SHG imaging of human melanoma xenograft tumor (unstained), injected sub-cutaneously in a mouse. Transform-limited 13.5 fs laser pulses, with the average laser power of 5 mW (repetition rate 87 MHz, 810 nm), are used. The scanned beam is focused with a water-immersion Zeiss LD C-Apochromat 40x/1.1 NA. The image size is about 150 x 150 µm^2

Summary

Taking advantage of one of the most accurate means to measure phase distortions, and the long experience of working with sub-5 fs pulses, Biophotonic Solutions is introducing this year a line of MIIPS-certified ultrafast laser optics. Each of the optics being offered (mirrors and nonlinear optical crystals) is individually tested and certified compatible with ultrashort laser pulses. This eliminates the possibility of a single optical element ruining the train of pulses.

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AUTHOR

Dr. MARCOS DANTUS is a University Distinguished Professor in the Department of Chemistry and the Department of Physics and Astronomy at Michigan State University. He is also the President and founder of Biophotonic Solutions.