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Real-time measurements, rare events and photon economics

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Abstract. Rogue events otherwise known as outliers and black swans are singular, rare, events that carry dramatic impact. They appear in seemingly unconnected systems in the form of oceanic rogue waves, stock market crashes, evolution, and communication systems. Attempts to understand the underlying dynamics of such complex systems that lead to spectacular and often cataclysmic outcomes have been frustrated by the scarcity of events, resulting in insufficient statistical data, and by the inability to perform experiments under controlled conditions. Extreme rare events also occur in ultrafast physical sciences where it is possible to collect large data sets, even for rare events, in a short time period. The knowledge gained from observing rare events in ultrafast systems may provide valuable insight into extreme value phenomena that occur over a much slower timescale and that have a closer connection with human experience. One solution is a real-time ultrafast instrument that is capable of capturing singular and randomly occurring non-repetitive events. The time stretch technology developed during the past 13 years is providing a powerful tool box for reaching this goal. This paper reviews this technology and discusses its use in capturing rogue events in electronic signals, spectroscopy, and imaging. We show an example in nonlinear optics where it was possible to capture rare and random solitons whose unusual statistical distribution resemble those observed in financial markets. The ability to observe the true spectrum of each event in real time has led to important insight in understanding the underlying process, which in turn has made it possible to control soliton generation leading to improvement in the coherence of supercontinuum light. We also show a new class of fast imagers which are being considered for early detection of cancer because of their potential ability to detect rare diseased cells (so called rogue cells) in a large population of healthy cells.

1 Introduction

Rare or rogue events, also known as extreme value events, black swans or outliers, are singular occurrences in a random phenomenon that carry a large impact. They occur in a number of diverse fields and are believed to be a characteristic of complex systems. Interestingly, the best known examples are not in physical sciences, but rather in finance and socioeconomics, where recent books by Taleb [1] Gladwell [2] and Anderson [3] have become best sellers. Nevertheless,

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extreme rare events are also observed in technology and science experiments, for example, as occurrences of rare solitons in nonlinear optics [4–8]; as power-law behavior observed in statistical distribution of Raman amplified pulses in silicon [9]; as errors in data communication [10,11] and in medicine as rogue cells that are forerunners of metastatic cancer, the disease stage that is responsible for 90% of mortalities [12,13].

A distinct feature of complex systems that harbor rare, but extreme value events is that history is of little use for predicting the future. In other words, traditional techniques, such as simple extrapolation to the future from the recent history, or more sophisticated techniques such as maximum likelihood, known popularly as the GARCH model in the world of finance [14], are of limited use [1,15]. This fact is vividly apparent in the behavior of the best known example of a complex system, the stock market.

Traditional predictive models fail [1,13] because they rely on the some measure of standard deviation, referred to as "volatility" in the financial world, that is derived from past data. The fundamental assumption in such models is that the random process can be described by a well-behaved distribution function such as a Gaussian ("Normal"). More sophisticated models may attempt to include the effect of extreme events and non-Gaussian statistics by the log-Normal function as a simple example of a skewed distribution. Of course, the assumption that a random phenomenon conforms to Gaussian distribution is not without solid foundations. Mathematically, its justification is offered by the Central Limit Theorem, and physically, by the fact that a Gaussian distribution maximizes the entropy. However, these descriptions apply to a system at equilibrium; while on the other hand, systems in real world are not always at equilibrium. Even in systems at equilibrium, extreme value distributions can arise by the action of a highly nonlinear system response to an input that has a Gaussian (normal) distribution. Given that both basic ingredients, noise and nonlinearity, exist in optical devices, extreme value optical phenomena can be amusingly called "photon economics".

In sharp contrast with the Gaussian distribution, which is symmetric and has a well-defined center, extreme events arise in highly skewed probability distributions that are characterized by a long tail extending significantly beyond that of the Gaussian distribution. Therefore, they are generally highly skewed power-law functions that are characterized by a "heavy-tail" or "fat tail". Because of the shape, extreme value distributions are also referred to "L-shaped" distributions. Unlike the Gaussian, they allow events much larger than the average to occur. In other words, the probability or the risk of occurrence of extreme events is much higher than that predicted by the Gaussian distribution. Because of the highly skewed shape, a fat tail distribution cannot be conveniently described by its first two moments, the mean and the variance.

Despite extensive research and the fascination surrounding them, extreme value behavior and their underlying physics remain mysterious in most cases. This stems from the complexity of the systems that harbor such behavior, but also because of the lack of sufficient and reliable data, making it difficult to develop and test models. Due to the low probability of their occurrence, it is generally difficult or impossible to collect enough data to characterize the system with a high degree of statistical accuracy. Another reason is that rare extreme events appear in environments where it is impossible to perform experiments under controlled conditions preventing test and validation of models. Such difficulties are self evident for the case of oceanic rogue waves and natural disasters such as earthquakes. To be sure, controlled experiments are of course equally unachievable in socioeconomic and financial systems, where such "experiments" are legally and ethically prohibited.

Fortunately, ultrafast optical or electronic phenomena provide an opportunity. These processes occur on short timescales, so it is possible to collect sufficiently large data sets in a short time, even for rare events. Equally important, in most cases such phenomena can be studied in table top experiments where system parameters can be identified and varied in a controlled and reproducible fashion. Using such data, one can develop models that not only provide clues to why and how extreme value events occur, but also provide insight into taming and harvesting them. At the same time, there are mathematical and physical connections underlying extreme events in optics and electronics with extreme events in other fields of physical and social science. Therefore, the knowledge gained from ultrafast events may be helpful in understanding extreme behavior that occur over a much slower timescale and that have a closer connection with human experience.

The focus of this paper is to explain the limitations of traditional instruments and to describe a series of real-time instruments that we have developed that are well suited for the capture and study of rare optical and electronic events. To the extent possible, these techniques are presented in the context of applications in studying of rare extreme events that have both scientific and practical significance.

Rare events are difficult to capture, in particular when they occur over an exceedingly minute time interval. While the study of such phenomenon holds promise for understanding and harvesting the potential of complex systems, it also poses daunting technological obstacles. The predicament is best described by the popular adage "detecting a needle in a haystack." In fact, the problem is more challenging than this proverbial statement suggests. The events of interest occur over a very short timescale, requiring an instrument with fine time resolution. At the same time, since the time of occurrence is not known, the instrument must be able to capture the signal continuously – in real-time. This is in sharp contrast with conventional sampling scopes. Although they boast high time resolution, they operate in equivalent-time, in other words, they have very low real-time bandwidth. These instruments can capture fast events as long as the event is repetitive; however, they have slow update rates with a long dead-time between measurements. Additionally, to achieve sufficient sensitivity, "sampling" instruments usually perform time-averaged measurements, which wash out rapid changes.

The simple fact that extreme events occur rarely requires the recording instrument to capture continuously and over long time intervals (long relative to the time scale of the event). Therefore, the type of instruments needed must simultaneously achieve fine time resolution, continuous (real-time) capture, and long record length, while maintaining high sensitivity.

While the path to creating such instruments harbors many challenges, the biggest obstacle stems from a fundamental tradeoff between real-time bandwidth and noise. Most detection systems are limited by the thermal noise of the detector and the front end electronic circuitry. Thermal noise (as well as shot noise) increase linearly with bandwidth, which results in the well known reduction of sensitivity in high speed detection. In the case of an optical signal, optical amplification prior to optoelectronic detection raises the signal above the thermal noise floor and hence improves the detection sensitivity. Amplification does introduce additional noise (produced by amplification of the device's spontaneous emission); however the strategy works when the system is thermal noise limited. High speed real-time instruments that are reviewed here make use of this approach to overcome the fundamental tradeoff between noise and bandwidth, and allow real-time detection of fast rare events, such as rare events in communication networks and complex systems. We point out that the utility of these types of instruments is not limited to study of fast events. An important application may prove to be in high throughput screening applications such as the search for rogue cancer cells among a large population of healthy cells in blood and tissue [16].

This technique maps the optical spectrum into an amplitude modulated time domain waveform, and allows the waveform to be slowed down in time such that it can be captured by an analog-to-digital converter. It allows the optical spectra, and the information that is encoded in it, to be recovered by sampling the time domain waveform using a real-time electronic digitizer. An early demonstration where the spectrum of acetylene was mapped into a temporal waveform and measured electronically is shown in Figure 1. In addition to absorption spectroscopy shown here, it has also been used for fast real time capture of stimulated Raman spectra [22] (Fig. 2). In this paper, we refer to this method as Time Stretch Fourier transform. It allows fast real time recovery of the any information that has been mapped onto the spectrum of a broadband (continuum) optical pulse. It forms the basis of a class of fast real time instruments, including wideband analog-to-digital converters, spectrometers, and imaging systems. These systems perform a two step process (Fig. 3). In the first step, the information to be captured is stamped onto the spectrum of a broadband optical pulse. The information can be a fast (wideband) electrical waveform such as that in a communication network or radar system, the spectral signature of a material or process, or a spatial image. In the second step, the spectrum, and hence the information, is slowed down and mapped onto a time-domain waveform whose amplitude modulation mirrors the spectrum. It is then digitized using an electronic digitizer such as a digital oscilloscope. These systems can capture fast events in real-time because the timescale of the information is slowed down in the analog domain, and also because they

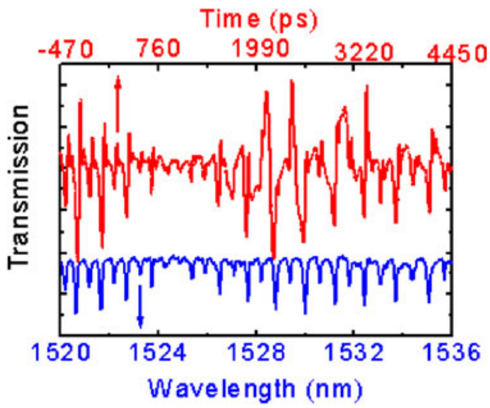

Fig. 1. Upper trace shows the absorption spectrum of acetylene capture using time stretch dispersive Fourier transform spectrometer [17]. The top horizontal axis shows the time scale. The lower trace and horizontal axis show the same spectrum captured with a conventional grating based optical spectrometer. One can readily see that all the absorption lines appear as notches in the temporal waveform. The spikes in the temporal waveform are due to the ringing of the high speed photodetector/amplifier circuit. The time stretch dispersive Fourier transform can acquire the spectrum in real time with subpicosecond shutter speed and a frame rate of 100's of MHz to a few GHz. The ultimate frame rate is limited by the bandwidth of the real-time digitizer.

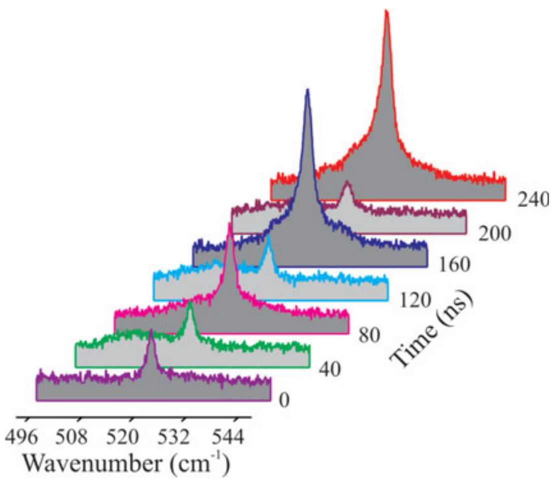

Fig. 2. A time-varying stimulated Raman signal from a silicon sample, measured in a real-time continuous measurement [18]. Every 40 ns, a new spectral snapshot was acquired (frame rate of 25 MHz).

eliminate the need for traditional spectrometers. Our effort for creating fast real time instruments began with analog-to-digital converters that achieve large real-time bandwidth by slowing down fast electronic waveforms using a dispersive analog fiber optic link [19,17,21] and evolved into spectroscopy [22,23,18,25] and imaging [16,24].

2 Slowing down the event and mapping spectrum into time using the Time Stretch Fourier Transform

The Time Stretch Fourier transform can be used to perform optical spectroscopy in real time without repetitive measurements [17,21–27]. The technique employs group-velocity dispersion to chirp a pulsed optical signal so that its spectrum can be measured directly in time with

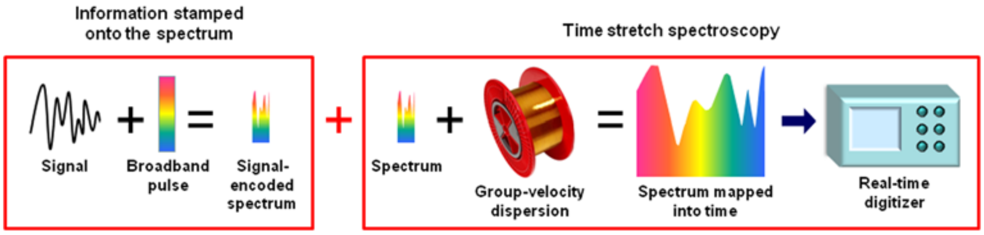

Fig. 3. Generalized description of time stretch instruments. The instruments perform a two step process. First, the signal (information) is stamped onto the spectrum of a femtosecond, broadband) optical pulse. In the second step the spectrum is measured in real-time by mapping it into an intensity modulated optical waveform that is detected by a fast photodiode and then digitized with a real-time digitizer (for example a digital oscilloscope). A number of instruments with record real-time speed have been demonstrated with this technique. These include analog-to-digital converters [17,19,21] spectrometers [18,22,23] and imaging cameras [16,24].

a photodetector and an oscilloscope. This technique relies on the property that the temporal envelope of a signal assumes the shape of its spectrum when sufficiently dispersed, resulting in a one-to-one mapping of the optical frequency into time: $\omega_{opt} = t/\beta_2 L$, where the scale factor, $\beta_2 L$, in the denominator is the total group-velocity dispersion (β_2 is the GVD per unit length of the dispersive medium and L is the length of the dispersion element) [22]. This expression can be obtained by considering that group velocity dispersion causes a relative phase shift of $\exp(i\beta_2 L\omega^2/2)$ at each spectral component, ω, and performing a Fourier transform of the resulting spectrum. Here we assume the impact of higher (than 2^{nd}) order dispersion on the temporal shape is negligible. These relations are valid in the stationary phase approximation which requires the amount of total group-velocity dispersion to be large [18]. The impact of higher order dispersion (β_3, $\beta_4, \ldots$) terms, as well as spectral resolution, can also be obtained using the same procedure [28].

It is important to note that in addition to converting the spectrum to time, this technique allows the user to select the time scale of the signal. By choosing a sufficient amount of dispersion, $\beta_2 L$, the time domain waveform, mimicking the optical spectrum, can be slowed down to the point that it can be captured by a real-time digitizer.

The primary issue in the time stretch Fourier transform is the loss in the dispersion element. Although low-loss dispersive fiber is readily available at 1550 nm for telecommunications, such fibers have high loss at other wavelengths of interest, namely the visible, near- and mid-IR bands. Even at 1550 nm, fiber losses can become appreciable when high dispersion is needed. In general, these losses are an issue because large dispersion goes hand-in-hand with optical loss. By increasing the optical path length, a resonant cavity can be used to create a more compact device, but it does not improve the dispersion per unit loss and also restricts the optical bandwidth. Furthermore, regardless of the application and even in the absence of losses, the act of dispersing a signal reduces its peak power level, degrading the signal-to-noise ratio. In a real-time measurement, signal averaging is not possible and, thus, a signal can only be dispersed so much before it falls beneath the single-shot noise floor. Fortunately, internal amplification can be stimulated inside the dispersive device to beat the dispersion-loss trade-off and facilitate real-time measurements [19,22,23]. In other words, it is possible to simultaneously use the medium's linear dispersion and one of its nonlinear properties – Raman gain – to overcome the dispersion-loss limitation. During the wavelength-time mapping process, broadband distributed Raman amplification can be implemented within the dispersive medium to keep signals above the measurement noise floor (and away from high power levels that could cause nonlinear distortion) (Figure 4). This method is known as the *amplified dispersive Fourier transform* [23]. The distributed nature of the Raman amplification provides better dynamic range than if discrete amplifiers were used, a fact that is utilized in optical networks [29].

Figure 5 shows a demonstration of the benefit provided by distributed amplification. In this example, a broadband incoherent pump source was employed to generate Raman amplification of the signal within the dispersive fiber, avoiding the need to have multiple lasers to produce

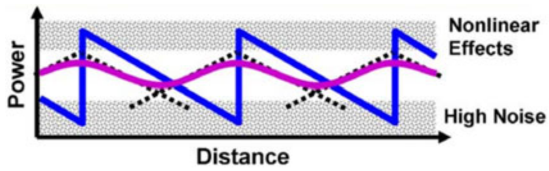

Fig. 4. Illustration of the benefit of distributed Raman amplification. Distributed amplification keeps the signal at a relatively constant level (purple). In contrast, with discrete amplification the signal level (blue) may drop into the high noise regime and abruptly rise to a high level where nonlinear effects can distort the signal.

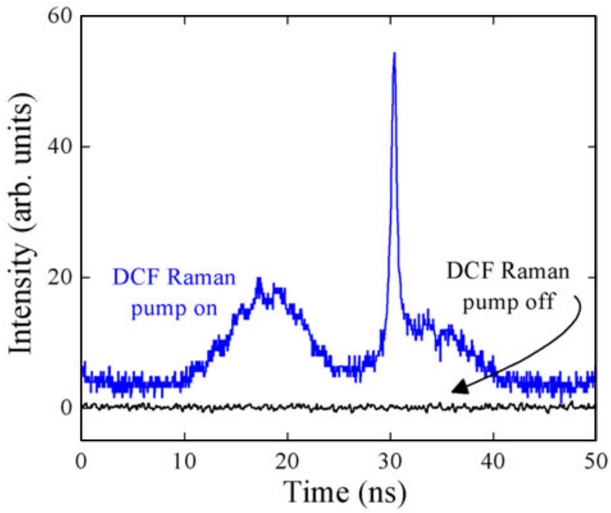

Fig. 5. Real-time measurement of stimulated Raman spectrum using amplified time stretch Fourier transform. Broadband pump light is coupled into the dispersive fiber along with the signal to produce distributed Raman amplification of the signal as it simultaneously travels through a group velocity dispersive element. The amplification raises the signal, which is otherwise invisible, well above the measurement noise floor [18].

a broadband gain response. The signal was combined with the ASE pump and amplified by the Raman gain of dispersion compensating fiber while being simultaneously dispersed. The amplification raises the weak signal above the noise floor of the detector.

Discrete optical amplification offers an alternative possibility but traditional optical amplifiers are generally only available for a limited number of restricted wavelength bands, while distributed Raman amplifiers are not fundamentally tethered to specific wavelengths, but can operate wherever suitable Raman pumps and fibers are available. In addition, a distributed amplification process provides optimal management of the signal-to-noise ratio, as the signal is always maintained at a relatively constant level. Compared to parametric amplification techniques, such as four wave mixing, Raman gain has the advantage of not requiring phase matching, which would be difficult to maintain over the large bandwidth of the continuum pulse.

Incoherent pumping can also be used to produce a useful amplified wavelength-time transformation if the noise floor of the detector or digitizer is the limiting factor for the measurement [22]. The advantage of this approach is that a single broadband source of intense incoherent light, such as amplified spontaneous emission (ASE) from a fiber amplifier or superluminescent diode, can be used to produce uniform Raman gain in lieu of multiple pump lasers.

Although amplification does mitigate the dispersion-loss trade-off, it is still desirable to reduce the dispersion requirement to minimize loss and the burden on the distributed amplification process. Unfortunately, the spectral shape becomes highly distorted in the time domain when too little dispersion is used. The near-field spectral profile is also distorted, particularly when the spectrum contains multiple features in close proximity (Figure 6) [30]. Normally, the

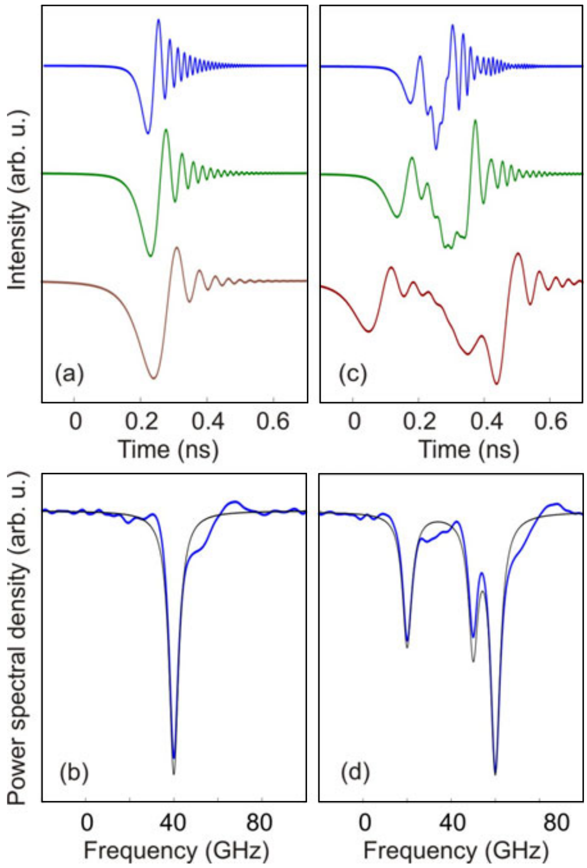

Fig. 6. (a) Simulated Near-field waveforms from one absorption line (5 GHz width) after dispersion with −300 ps/nm (blue), −600 ps/nm (green), and −1200 ps/nm (red). (b) Reconstruction of spectral line by temporal GS algorithm (blue); actual spectrum (black). (c) Near-field waveforms from three close 5 GHz absorption lines after dispersion with −300 ps/nm (blue), −600 ps/nm (green), and −1200 ps/nm (red). (d) Reconstructed spectrum of the three lines; actual spectrum (black) [30]. Frequency axis offset is arbitrary.

true spectral profile cannot be obtained from a time-domain measurement in the near field. Distortion ripples arise because the signal's constituent wavelength components do not have the proper amplitudes and phases to sum to the original pulse profile, and have not been separated enough in time to avoid interference effects.

If optical phase information were available in addition to the time-domain amplitude data, one could obtain the spectrum by computing the Fourier transform. We have recently demonstrated that two independent time-domain near-field measurements can be used to recover the optical phase using a time-domain analog of the Gerchberg-Saxton (GS) algorithm [30]. Once phase information has been obtained, the spectral profile can be readily determined (Figure 6). The GS algorithm was previously employed to retrieve the phase of a spatial image based on two intensity measurements. The GS algorithm has also been applied in photonic time-stretch ADC to improve SNR [31,32]. Recovery algorithms are also employed for optical phase retrieval in frequency-resolved optical gating (FROG), a well-known technique designed for ultrashort pulse characterization [33]. In the present situation, a time-domain recovery algorithm is suitable for obtaining the temporal phase in the dispersive Fourier transform using measurements with two different dispersive values in the temporal near field. The recovery algorithm operates by iteratively selecting an optical phase that is consistent with two independent (amplitude) measurements of the dispersed signal. This approach reduces the amount of dispersion required for the time stretch Fourier transform. It is important to note that ultimately the spectral resolution will be limited by the comb line spacing of the optical source, just as it is in any measurement, and is not diminished in the near-field.

In an experimental demonstration of the near-field phase recovery algorithm in spectroscopy, the GS algorithm was applied to the measurements obtained with two dispersive elements, producing a recovered spectrum that compares well with that obtained from a conventional spectrometer [30]. Operating in the near field means that the signal is stretched less, so its bandwidth may exceed the maximum bandwidth of at the digitizer. One solution to this predicament is the photonic time-stretch analog-to-digital converter, which offers much greater bandwidth than conventional digitizers, and useful dynamic range. The photonic time-stretch ADC requires dispersive elements itself; however, it operates at 1550 nm and, therefore, allows us to shift the dispersive burden away from problematic wavelengths. In other words, we can use this method to place the major burden of dispersive element at 1550 nm regardless of the signal wavelength. Presently, the 1550nm wavelength band is technologically preferred for implementing the time stretch Fourier transform because of the availability of low loss dispersive fibers that have been developed by the telecommunication industry.

Independent of the near-field reconstruction approach, one can also shift the dispersive burden away from problematic wavelengths by employing optical frequency conversion techniques to transfer the signal to the 1550 nm band. For example, visible and near-IR signals can be down-converted to the telecommunications band using difference frequency generation. Once converted to this portion of the spectrum, one can readily apply low-loss dispersive fibers, fiber amplifiers, distributed Raman amplification, and various fiber-based passive components to disperse and manipulate the signal as desired. The potential drawback in this method is the need for a relatively narrowband, high-power pump source to drive the nonlinear frequency conversion with appreciable efficiency. However, with suitable nonlinear media, reasonable efficiencies are realistically achievable. This technique provides an advantage when the losses of the dispersive fiber at the initial signal wavelength exceed the loss of wavelength conversion to 1550 nm.

3 Fast real-time measurements of optical rogue events

Real-time spectroscopy is a powerful tool for studying dynamic chemical and physical systems. Unfortunately, conventional spectrometers are relatively slow, and do not permit time-resolved measurements. On the other hand, conventional pump-probe techniques offer extremely fine temporal resolution, but rely on repetitive excitation to reconstruct the underlying dynamics. The time stretch Fourier transform permits spectra to be acquired in real-time as described above. In one demonstration, distributed amplification within the dispersive element was used to achieve an extraordinary −11.76 ns/nm "loss-less" dispersive element [19] (Fig. 7). This dispersive element would have caused approximately 60 dB of attenuation, but with amplification it became essentially transparent [23]. By removing the loss-limitation in dispersive optical fiber, high spectral resolution can be achieved. Using this method, many thousands of sequential snapshots of the spectrum can be rapidly recorded in real time, providing a "movie" of fast dynamic physical and chemical processes.

Real-time measurements have the potential to reveal new phenomena that are not readily observable with time-averaged techniques. For example, in another line of research, the wavelength-time mapping performed with the time stretch Fourier transform has proven useful for the detection of rare and random solitons known as optical rogue waves (Fig. 8). These rare broadband pulses can arise during supercontinuum generation by stochastic enhancement of spectral broadening. As described above, conventional measurement methods are not suited to capture a large number of ultrafast events (in the search for rare extreme spectra) within a fast pulse series [4]. The wavelength-time transformation permits real-time detection of multiple sample points within a single ultrashort rogue event, and provides spectral information. As such, it was instrumental in providing a clear identification of optical rogue waves when they were initially reported. On the other hand, once the process has been identified and modeled, full spectral characterization is not necessarily needed to simply detect events with large spectral content. Extreme spectra can be identified by the energy in their redshifted spectral tails,

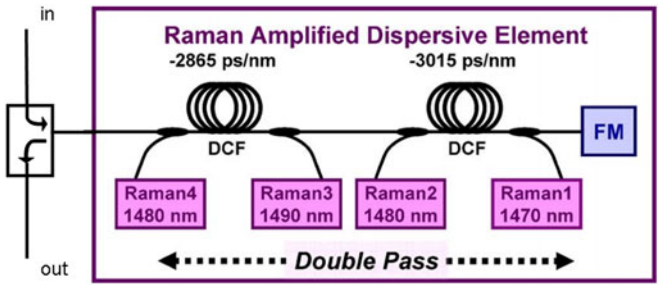

Fig. 7. Amplified time stretch Fourier transformer. A "loss-less" group velocity dispersive element generating −11.76 ps/nm dispersion is realized using distributed Raman amplification within dispersion compensating fiber [18,21,25]. A Faraday mirror (FM) reflects the signal to double-pass the signal through the amplified dispersive element. An optical circulator delivers near-transform-limited pulses to the dispersive element and routes the reflected portion to the sample. A, B, C, and D illustrate the signal content at different steps.

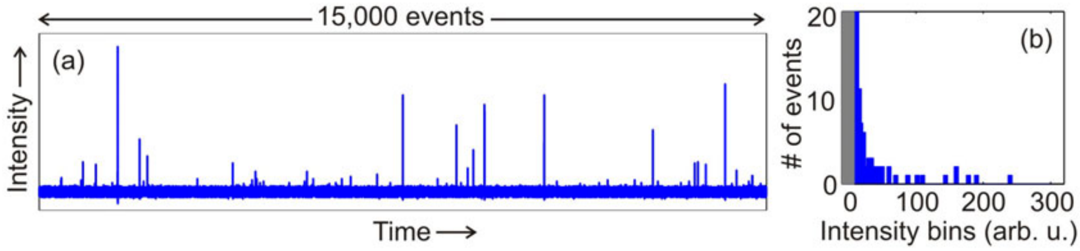

Fig. 8. Experimental observation of optical rogue waves in supercontinuum generation (a) Single-shot time trace containing approximately 15,000 pulses and histogram. The rare events reach intensities of at least 30–40 times greater than the average value [4].

obtained by using an optical filter to reject the short wavelength portion and integrating the remaining tail [4,5]. This parameter can also be measured for each pulse using a suitably chosen wavelength filter (designed to pass only wavelengths far from the pump), a photodetector, and a real-time ADC, but it does not provide the full time evolution of the complete pulse spectrum.

Pulse-to-pulse fluctuations generally go unnoticed when the pulse spectra are measured with conventional spectrometers, and spectral fluctuations often lead to smooth spectral profiles when many SC pulses are averaged together. As such, rare events, which have physical significance, would generally go unnoticed. An analysis of optical rogue waves has shown that they are correlated with a random surplus in a particular noise component able to seed modulation instability. This finding has shown a means to enhance and stabilize supercontinuum generation with a seed field [34,35]. Stimulated supercontinuum generation has a reduced input power threshold and can produce white light with greatly enhanced amplitude and phase stability (Figure 9). Pulse-resolved measurements have also shown that another form of extreme supercontinuum fluctuation, unusually narrowband pulses following left-skewed "reverse" heavy-tailed statistics, can appear by a different mechanism [36,37]. The study of these extremes has shown that spectral broadening can be frustrated by stochastic effects, an effect that can also be induced with seed pulses.

4 Fast real-time imaging with mplified time stretch Fourier transformation

4.1 Serial Time-Encoded Amplified Microscopy (STEAM)

High-speed real-time optical imaging is essential for studying rapid dynamical phenomena in a broad range of industrial and scientific applications such as shockwaves, combustion, chemical dynamics in living cells, neural activity, laser surgery, and microfluidics. High-speed imaging is indispensable in microscopy because on the micrometer scale, even slow-moving phenomena

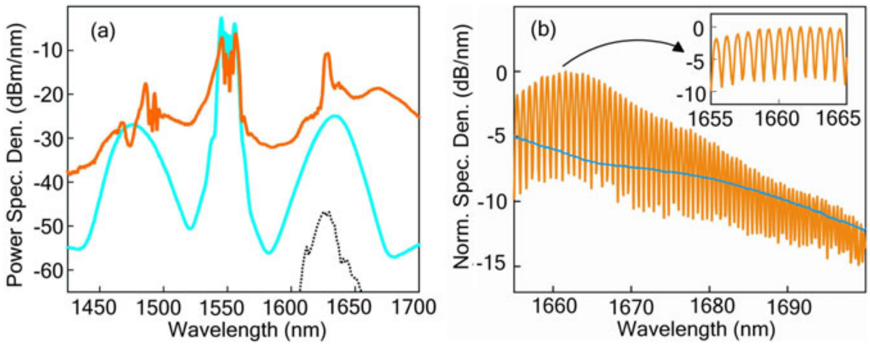

Fig. 9. (a) Stimulated SC spectrum (orange trace) and unseeded spectrum (blue trace) with same pump power; weak seed spectrum (black dotted line). (b) Measured pulse-to-pulse spectral interferograms of coherently-stimulated SC (orange trace) and spontaneous SC (blue trace) [34].

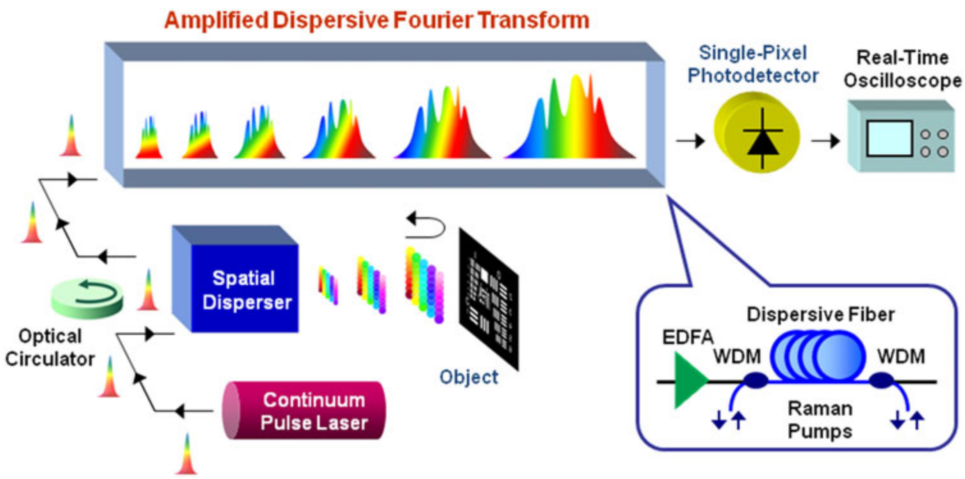

Fig. 10. Schematic of the STEAM spatial imager [16]. The basic functions of STEAM are (1) encoding the spatial information (image) of an object into a serial time-domain data stream into the spectrum of a broadband pulse, (2) serializing the image into a 1D temporal data stream, (3) amplifying the image-encoded spectrum in the optical domain during the image serialization process, (4) detecting the 1D temporal data stream with a single-pixel photodetector and digitizing the signal with a real-time oscilloscope, and (5) performing digital image processing to reconstruct the image.

require high temporal resolution due to the small field-of-view [38]. One example is the spatiotemporal study of signaling in cells and tissues, an application that require micro-second to nano-second time resolution [39]. Another important application is in the field of flow cytometry, [40–43] where high-speed cameras are needed to provide high-throughput cell characterization and detection of rare cells, such as circulating tumor cells in blood [11] that cause cancer metastasis.

The CCD and CMOS camera is the most widely deployed optical imaging technology today. It offers a spatial resolution of a few micrometers, as many as ten million pixels, and relatively low cost. Typical CCD and CMOS cameras used in consumer electronics have frame rates up to 30 Hz, although top-end versions can operate at rates on the order of 100 kHz by reducing the number of pixels. While useful for imaging of stationary or slow objects, conventional CCD and CMOS cameras have difficulty in capturing fast dynamical processes with high sensitivity at high speed [16]. This is due in part to a technological limitation – it takes time to read out the data from the sensor array. Also, there is the fundamental trade-off between sensitivity and speed; at high frame rates, fewer photons are collected during each frame. To ensure an adequate signal-to-noise ratio and to prevent a drop in sensitivity at high frame rates, the CCD

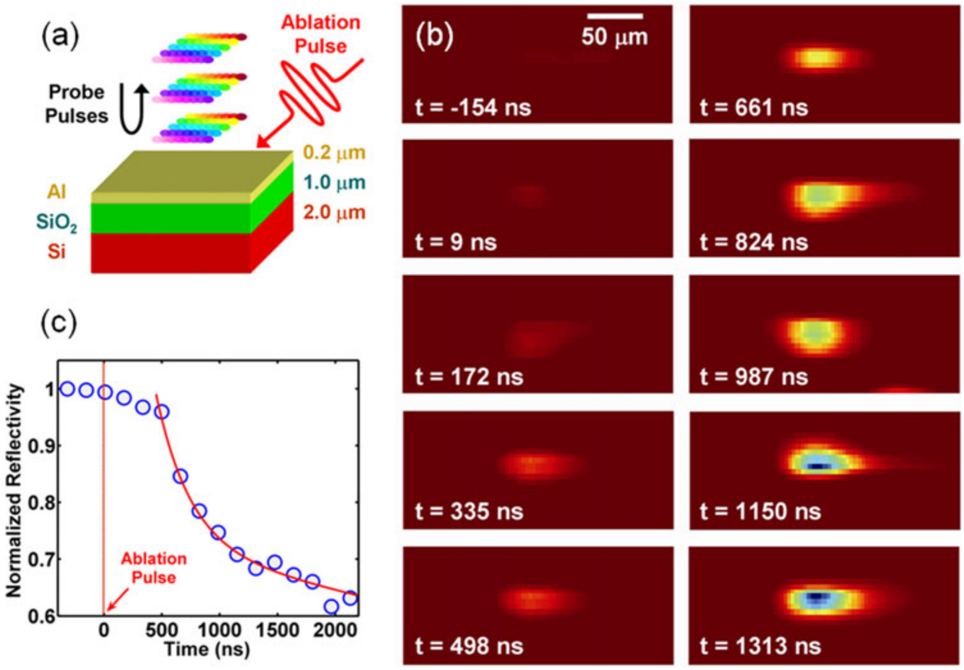

Fig. 11. The experimental block diagram, real-time STEAM images, and characterization of the laser ablation experiment [16]. (a) The schematic of the laser ablation experiment. A mid-infrared pulse laser (6 mJ pulse energy and 5 ns pulse width) is focused at an angle onto the sample with a bilayer of aluminum and silicon dioxide deposited on top of a silicon-on-insulator substrate, while STEAM pulses monitor the ablation process at normal incidence. (b) Real-time 2D images captured by the STEAM camera with the temporal resolution of 163 ns and shutter speed of 440 ps. The changes in sample surface reflectivity due to the laser-induced mass ejection are evident after the excitation pulse hits the sample at $t = 0$ ns. (c) The time-sequenced surface reflectivity change showing that the time-delay between the pulse excitation and the sudden decrease in the surface reflectivity correlates with the mass ejection process.

and CMOS camera relies on a high-power illuminator – a requirement that renders it unsuitable for microscopy, where focusing of the high-power illumination over a small field of view can cause damage to a biological sample [16]. This trade-off between sensitivity and frame rate is not unique to the CCD and CMOS camera – it impacts almost all imaging and detection systems.

In scientific applications, high-speed imaging can be achieved with the so-called time-resolved pump-probe technique, but as discussed before, these instruments do not operate in real time and hence are incapable of detecting transient events that occur randomly. An imaging technology with fast, continuous, and real-time capability is required to capture rare events. Another type of fast optical imaging is the framing streak camera that is often used for diagnostics in laser fusion, plasma radiation, and combustion. However, this imager operates in burst mode only, providing only a few (less than 10) frames [44], and hence requires the camera to be synchronized with the event that is to be captured.

The amplified dispersive Fourier transformation can be used to overcome technological and fundamental limitations of existing technologies. A new technology called serial time-encoded amplified imaging or microscopy (STEAM) [16,45] offers frame rates that are 100 – 1000 times higher than those of conventional CCD/CMOS cameras. The key feature of the STEAM camera is the mapping of the spatial information (image) of an object into an optically amplified serial time-domain data stream using amplified dispersive Fourier transformation. It captures the entire image using a single-pixel photodetector and achieves an optical image amplification of the image. The *optical image amplification*, its most important feature, eliminates the need for high-intensity illumination. Equally important, by compensating for the loss of the time

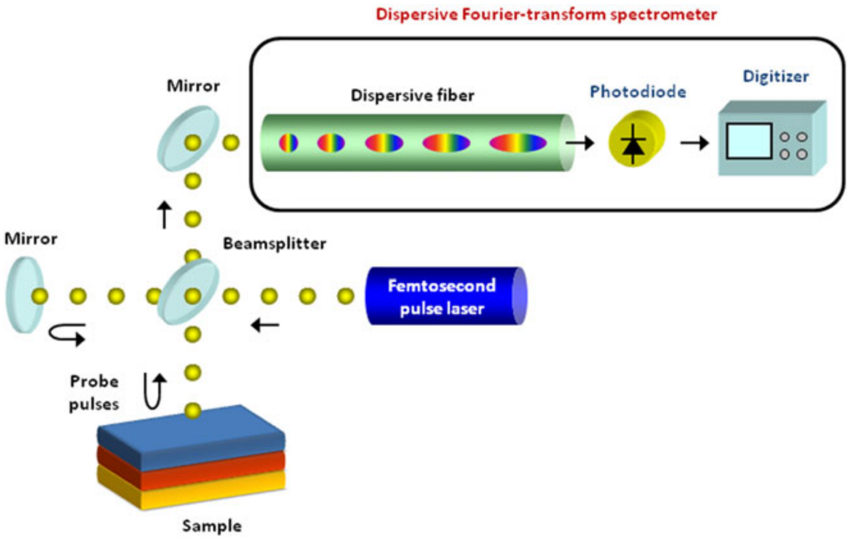

Fig. 12. Block diagram for STEAM ultrafast reflectometry, also referred to as Optical Coherent Tomography (OCT) [24].

stretch dispersive medium, it allows the fast event to be slowed down in time by a large factor so that it can be captured with a real-time electronic digitizer, such as a digital oscilloscope.

As shown in Figure 10, the basic functions of the STEAM camera are the following [16]: (1) encoding the spatial information (image) of an object into the spectrum of a broadband pulse, (2) serializing the image into a 1D temporal data stream, (3) amplifying the image-encoded spectrum in the optical domain, (4) detecting the 1D temporal data stream with a single-pixel photodetector and digitizing the signal with a real-time oscilloscope, and (5) performing digital image processing to reconstruct the image. To demonstrate the utility and application of the STEAM camera, it has been used to observe ultrafast microfluidic flow and laser ablation in real time [16] (Fig. 11).

4.2 Ultrafast optical coherence tomography

Optical coherence tomography (OCT) [46–49] is a powerful tool for capturing micrometer-resolution, tomographic images of biological tissue. The time stretch dispersive Fourier transform can also be applied to OCT to obtain high scan rates [24]. The loss of the dispersive element will necessitate high power lasers to overcome the fundamental tradeoff between speed and sensitivity. On the other hand, the amplified time stretch Fourier transformation significantly increases the axial scan rate and achieves high sensitivity without the need for high power illumination [18]. Measuring depth-encoded spectra in spectral-domain OCT with this technique avoids these issues by eliminating the diffraction grating and detector array (e.g., the CCD). These elements are replaced by a dispersive element, a single-pixel photodetector, and a high-speed digitizer as shown in Fig. 12. This simplifies the system, and more importantly, enables fast real-time image acquisition. This method also allows larger bandwidth to be used compared with swept-source OCT. As a result, frequency-domain OCT with dispersive Fourier transformation has shown scan rates on the order of 1 MHz or higher – a few orders of magnitude higher than conventional frequency-domain OCT.

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