Chapter 11
Current Applications of Supercontinuum Light

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1 Introduction

Since the first observation of supercontinuum (SC) light in 1970 by Alfano and Shapiro (1970), numerous applications have emerged. The first application of SC was in inverse Raman scattering (Alfano and Shapiro, 1971) and later for time-resolved laser spectroscopy of liquids and solids. In the previous edition of the book published in 2006, Dorsinville et al. (2006) reviewed many supercontinuum light applications of time resolved absorption spectroscopy (in the areas of solid state physics, chemistry, and biology), time resolved excitation spectroscopy (in the areas of coherent anti-Stokes Raman scattering, and Raman induced Phase conjugation), as well as optical pulse compression. Dorsinville et al. also explored future applications in ranging, imaging, optical computational switches, atmospheric remote sensing, kinetics of nonlinearities in solids, and optical fiber measurements. This chapter does not focus on these previously reviewed topics. Interested readers can refer to the second edition of the book published in 2006.

As there are newer and ever growing applications of the supercontinuum light source, the aim of this chapter is to review some of its recent applications in the past 10 years. This include recent advances in creating exotic supercontinuum complex light modes for which new applications are now emerging in super-resolution microscopy, particle manipulation, astrophysics, and other emerging areas. The chapter also includes how the SC light source has been used in precision optical frequency metrology such as the development of the most accurate optical clocks,

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spectroscopy, microscopy, and imaging. One of the major applications of supercontinuum light is in the area of optical communications, and a chapter is dedicated to it in this edition (Chapter 10). We also provide updated references on some of the topics published by Dorsinville et al. in previous edition of the book to give the readers a flavor of how some of the past applications of SC light have evolved into its more recent applications. On a final note, we highlight studies of an optical analog to astrophysical phenomenon such as the event horizon and Hawking radiation which occurs in the cosmos. Although such study is not a direct application of SC light, many concepts used to describe supercontinuum light are used in the description of optical analogs of this astrophysical phenomenon.

It is impossible to review all the exciting recent advances in the application of supercontinuum light, and so we have selected some of the recent work that reflects the interest of the authors. We apologize if your work is not mentioned in this chapter.

1.1 Basic Properties of Supercontinuum Light

Some of the previous chapters in this book discuss many of the properties of supercontinuum light in great detail. Nevertheless, we feel that it is important to briefly highlight some of its basic properties that have enabled many of the latest modern applications of this light source.

As is noted in many of the early chapters, there is often more than one nonlinear process responsible for the generation of supercontinuum light. In optically transparent solids, the SC process starts with self phase modulation (SPM). This is a process where a material experiences an intensity dependent change in refractive index, which modulates the phase of light in the material. Afterwards, many other nonlinear processes such as cross phase modulation, four wave mixing, Raman processes, soliton self frequency shifting, etc. causes further broadening in the frequency spectra. While the first observation of supercontinuum light was in solids and liquids, most modern applications of supercontinuum light in the last 10 years have relied on the use of optical fibers such as single mode fibers and microstructured fibers (Dudley et al., 2006) as well as microchips or waveguides (Leo et al., 2015; Lau et al., 2014; Gattass et al., 2014) for its generation.

The main properties of supercontinuum light that have been exploited in modern applications are:

1. It has a broad frequency bandwidth, often extending more than an octave, i.e., the frequency span of the input laser frequency is broadened to more than twice the input center laser frequency. Typically the SC spans from 400 nm to 2500 nm.
2. Low power can be used to obtain broadband supercontinuum light. In fact, supercontinuum light has been generated with tens to hundreds of milliwatt average power using continuous wave lasers (Del'Haye et al., 2007; Herr et al.,

2012) and pulsed lasers. It is common to use pulsed lasers in optical fibers to generate supercontinuum light, especially those involving precision spectroscopy and metrology.
3. The light source has very high spectral brightness, especially when it is generated with a high peak power pulsed laser source, and
4. The light source has high spatial coherence (Bellini and Hänsch, 2000) in order to see spatial interference effects, while keeping a relatively low temporal coherence.

While discussing the specific applications of supercontinuum light, the particular property that has enabled each of these applications will be briefly highlighted. For an in-depth discussion of these characteristics of supercontinuum light, see the previous chapters.

2 Complex Light Modes with Supercontinuum Light

An example of a complex mode of light is an optical vortex. These modes are interesting because they can be designed to possess orbital angular momentum (OAM) (Andrews and Babiker, 2012; Andrews, 2011; Franke-Arnold et al., 2008; Torres et al., 2011; Yao and Padgett, 2011) and spatial vector polarization. OAM light differs from the usual spin angular momentum (SAM) of light as it is not limited to angular momentum values of $\hbar$ or $-\hbar$ as in right circular polarization or left circular polarization, but the OAM can be designed to be any integer value of $\hbar$. The OAM of light is a spatial characteristic of the optical beam profile. A prominent feature of an optical vortex is the presence of a singularity in the middle of the beam which is the result of the beam having a helical phase structure. On propagation into the diffraction far field, the point singularity forms a large dark center, namely a vortex core. This transverse beam profile resembles a donut, and sometimes called a donut beam. Optical vortices have cylindrical symmetry, and therefore its optical spatial profile in the far field is conveniently described in the Laguerre–Gaussian basis. For this reason, they are also often called "Laguerre–Gaussian" beams, or "LG" modes for short. An example of the optical field in the LG basis is below:

$$E(r,\phi,z) = E_0\left(\frac{r\sqrt{2}}{w(z)}\right)^{|l|}\frac{w_0}{w(z)}Exp\left[-\frac{r^2}{w(z)^2}\right]Exp\left[-i\frac{kr^2}{2R(z)}\right]$$
$$Exp\left[-i(2p+l+1)ArcTan\left[\frac{z}{z_R}\right]\right]Exp[-ikz]Exp[-il\phi]L_{\mathrm{p}}^{l}(r,z)$$

Here E_0, r, w_0, $w(z)$, and $R(z)$ are the amplitude, radius, beam waist, beam waist as a function of distance, and radius of curvature term, respectively. k, z, p, l are the wave vector, propagation distance, radial index, and winding number (or azimuthal index), respectively. L_{p}^{l} is the generalized Laguerre polynomial. Optical vortices

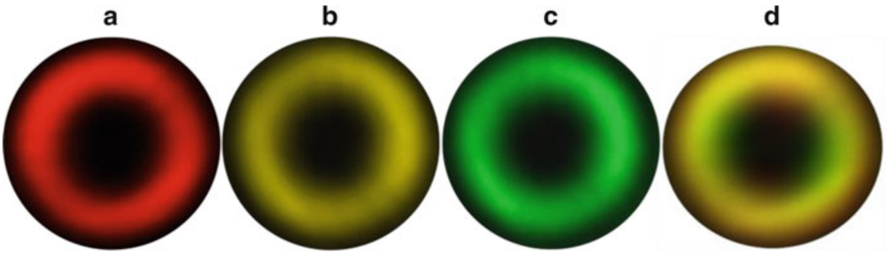

Fig. 11.1 Optical vortices from a single supercontinuum laser source (Rumala et al., 2013): (**a**) red vortex, (**b**) yellow vortex, (**c**) green vortex, (**d**) multi-color vortex

can either be a scalar vortex or a vector vortex. A scalar vortex has uniform polarization with helical phase structure, while a vector vortex (Zhan, 2009) has a polarization modulation about the circumference of the beam. Because of the polarization modulation about the circumference of the beam, vector vortices are sometimes referred to as polarization singularities (Figure 11.1).

One of the advances in the last 10 years that have come out of this research area is the combination of optical vortices with supercontinuum light to form either supercontinuum scalar vortices (Yue et al., 2012; Sztul et al., 2006; Neshev et al., 2010; Anderson et al., 2012) or supercontinuum vector vortices (Tokizane et al., 2009; Fadeyeva et al., 2010; Rumala et al., 2013, 2014; Murakami et al., 2013; Mawet et al., 2010). These supercontinuum light optical vortices are emerging as a useful tool in making compact setups for super-resolution microscopy such as stimulated emission depletion (STED) microscopy (Auksorius et al., 2008; Wildanger et al., 2008), in particle trapping and micro-manipulation (Morris et al., 2008; Guillon et al., 2008; Fischer et al., 2006; Wright et al., 2008), in better understanding the rotational Doppler effect (Lavery et al., 2014), in coronagraphs to search for distant planets (Murakami et al., 2013; Swartzlander, 2005; Mawet et al., 2010), and as a potential tool for optical communication (Rumala et al., 2013, 2014). All of these applications derive from (a) The high peak power, high spectral brightness, large spectral broadness, and high spatial coherence of supercontinuum light, as well as (b) the OAM contained in the light beam, optical singularity in the middle of the beam, and the beam's complex topology and shape.

2.1 *Ultrahigh-Resolution Microscope: Stimulated Emission Depletion (STED) Microscopy*

STED microscopy is a noninvasive molecular imaging method that uses light in the far field to gain resolution beyond the diffraction limit (Hell and Wichmann, 1994). It is therefore referred to as one of the super resolution microscopy techniques, and Stefan Hell was recognized with the 2014 Nobel Prize in Chemistry for the development of STED microscopy. In STED microscopy, the sample is stained with a fluorophore where one laser beam excites the sample in a diffraction limited spot, and a second laser beam, namely the STED beam forms a donut and it is co-aligned with the spot. The purpose of the STED beam is to de-excite the sample through stimulated emission such that it depletes the excited state of the sample. The excitation and de-excitation generally happens within a few picoseconds of each other, with the STED beam tuned towards the red (lower frequency) of the emission spectrum. In order to beat the diffraction limit, the STED donut beam effectively narrows the point spread function to smaller than the diffraction limit. It is for this reason that the final samples are super-resolved.

The use of a supercontinuum light source combined with an optical vortex to create the donut beam has significantly simplified and reduced the cost of a conventional STED experimental set up (Auksorius et al., 2008; Wildanger et al., 2008). This is because the supercontinuum light is a spectrally broadband light source with high laser power such that the same beam can excite and de-excite the sample. Furthermore, the optical vortex in the broadband supercontinuum STED beam serves to create the donut beam to effectively narrow the point spread function and subsequently obtain sub-diffraction limited resolution. For example, with yellow light at around 570 nm, it is now routine to obtain imaging resolution of samples on the order of 57 nm. In fact, resolutions down to 15–20 nm has been achieved using this technique.

2.2 *Rotational Doppler Effect*

These supercontinuum complex light modes have also formed special tools in understanding the rotational Doppler shift of light (Lavery et al., 2014). This shift is analogous to the usual longitudinal Doppler effect where light propagating towards a quantum object such as an atom experiences a blue shift, while light propagating away from the quantum object experiences a red frequency shift in the observed light frequency. In the case of the rotational Doppler effect, all colors of light experiences the same frequency shift, and therefore it is wavelength independent. The OAM of light forms a natural basis for studying the rotational Doppler shift of light. Here the frequency shift, $\Delta\omega$, is equal to the product of the angular rotational frequency or angular speed, $\mathbf{\Omega}$, of object, and illuminating light containing OAM, $\mathbf{l}$. That is, $\Delta\omega = \mathbf{\Omega}\,\mathbf{l}$.

This effect is expected to be useful in determining rotation speeds of a mechanical platform that is rotating. Supercontinuum light was important in showing that the rotational Doppler shift is independent of wavelength as it is a spectrally broadband laser source and has high peak power to observe ample scattering off the rotating object. In the experiment, light is simply reflected off the surface of the rotating platform, and the light is collected by the detector in the OAM basis. The back scattered light from the spinning surface is Fourier transformed to give a power spectrum for which the peak modulation frequency can be measured. The frequency shift is used to quantify the angular velocity of the rotating object.

2.3 Particle Trapping and Micromanipulation

Particle trapping by optical fields involves the confinement of particles by light's optical potential, and manipulating the dynamics of the particle by changing properties of the optical field (i.e., wavelength, intensity, beam size, beam shape, etc.). Most often, the particle manipulated are on the micron or submicron scale, and therefore researchers refer to this as "micromanipulation" of the particles. Examples of these particles include atoms, molecules, dielectric micron scale particles, and many others. These particles have been confined along the longitudinal optical field of a Gaussian laser beam as well as in a Laguerre–Gaussian optical mode made of a single color. When particles are trapped in longitudinal fields, the particle experiences a harmonic potential which confines the particle. On the other hand, when the particles are trapped in an optical donut mode, the presence of OAM, causes the particle to revolve about the singular point inside a toroidal-like potential. A recent advance in the last 10 years is the extension of these traps to use broadband light beams, such as supercontinuum light to trap (Guillon et al., 2008) and manipulate the particle in a donut optical mode (Morris et al., 2008; Fischer et al., 2006; Wright et al., 2008). Here, the supercontinuum light provides the confining potential, and the OAM light in the donut mode causes the particle to revolve about the singular point. It has been shown that even when these toroidal traps are made with supercontinuum light, their dependence on OAM, and radius scales similarly to traps made with single color light (Wright et al., 2008).

2.4 Optical Vortex Coronagraphs

In astrophysics, one of the goals is to look into the heavens for earth-like planets that can support life. This includes the search of exosolar planets (or exoplanet for short). These are planets that revolve around their own star as opposed to the sun, which is the earth's star. A problem often encountered in the search for exoplanets is that the light coming from the planet is expected to be 10^7 times less intense than its star light in the infrared region of the spectrum, or 10^{10} times less intense when looking in the visible region of the spectrum (Swartzlander et al., 2008). The vortex coronagraph (Murakami et al., 2013; Swartzlander, 2005; Mawet et al., 2010) is a device based on contrast imaging used to eliminate extraneous star light when searching for exoplanets. The vortex coronagraph are theoretically close to ideal because of its high throughput from the earth-like habitable planet, high angular resolution, and the device could be designed to be broadband to accommodate light from different regions of the spectrum. Either a vector vortex or scalar vortex could be used for this endeavor. Before actually going on to search for exoplanets these coronagraphs need to be tested in the laboratory. A supercontinuum light source serves as a tool to mimic the star light coming from outer space during the laboratory testing of the device (Mawet et al., 2010).

2.5 Optical Communication

The transmission of information using light has formed the cornerstone in modern communication systems. The use of optical fibers has advanced this capability in insurmountable ways through optical networks and interconnects. The techniques to transmit information have involved multiplexing and demultiplexing techniques of light beams at different wavelengths as a way to encode and decode information in a light beam. In the past 10 years, these techniques have been extended to include optical vortices in free space and optical fibers at different optical wavelengths. Optical vortices provides an additional degree of freedom to increase the information carrying capacity of a light beam. Most recently, researchers have started thinking of ways to implement similar techniques with supercontinuum light as it could be engineered to contain several frequency channels, and combining it with optical vortices (Rumala et al., 2013, 2014). In this case, there will be more degrees of freedom for encoding and decoding of light beams to include not just the optical wavelength, but also to include the polarization, and topology of the optical vortex beam. Chapter 10 provides an in-depth discussion of supercontinuum wavelength division multiplexing (WDM). A proposal on combining supercontinuum WDM with mode division multiplexing (MDM), and polarization division multiplexing (PDM) is discussed in Refs. Rumala et al. (2013, 2014) to further increase the information capacity of light.

3 Optical Clocks, Frequency Comb Technology, and Attosecond Technology

3.1 Optical Clocks and Frequency Comb

The measure of frequency has formed the corner stone of modern measurements. It is from this measurement that the standards of time and length are obtained. Furthermore, frequency measurements have facilitated the definition of many of our fundamental constants that engineers and physicist use in designing and building systems to enhance our daily lives. From our modern day GPS system to navigation from one part of the globe to another, the measure of time is a crucial element for precise movement. The world's most precise time keepers are atomic clocks (Poli et al., 2013; Ludlow et al., 2014). They are already approaching accuracies of 10^{-18} (Rosenband et al., 2008; Hinkley et al., 2013; Bloom et al., 2014), an accuracy that makes it possible to start probing the standard model, a model that defines the fundamental laws of nature, in table top experiments. These fundamental laws include testing of the time variation of fundamental constants (e.g., hyperfine constant, gravitational constants), measuring the gravitational red shift, as well as in the realization of the standards for time, frequency, and length. Central to obtaining this precision are methods developed to measure the frequency of light at an ever more precise level. This is because a clock is only as accurate as the counter used to measure the number of cycles or oscillations in a given time period.

One of the modern technologies at the heart of precise frequency measurements is the frequency comb. As the name implies, it is light with evenly spaced intensity spikes in the frequency domain, such that it resembles a comb. The frequency comb has formed a revolution in modern optical metrology, spectroscopy and it is already finding its way in the study of astrophysical phenomenon (Chang et al., 2010; Steinmetz et al., 2008) and optical communication (Chitgarha et al., 2014; Pfeifle et al., 2014). These applications are made possible because (1) It can form an ultrastable and ultraprecise frequency counter for frequency standards without the need for an external reference to an atomic or molecular transition, (2) It forms a bridge between the previous microwave standards as defined by the cesium atomic clock[1] (Diddams et al., 2000a), and the more newly defined modern optical clock which are in the optical region of spectrum (Diddams et al., 2000b), and (3) It is relatively compact (e.g., fit on a 1 m^2 bread board) compared to previous frequency synthesizers that can fill a whole laboratory room (Evenson et al., 1972). For this achievement, the 2005 Nobel prize in physics was awarded to John Hall and Theodor Hansch for precision optical metrology, including the development of the frequency combs.

In the development of frequency combs, supercontinuum light has been one of the enabling technologies for increasing the frequency bandwidth to include more comb lines so that it spans an octave and beyond while keeping the system compact (Jones et al., 2000). This is because supercontinuum light has a very wide bandwidth and has very high spatial coherence to observe white light interference (Bellini and Hänsch, 2000). In addition, the device used to generate the SC light source are relatively small. For example, an optical fiber of a few meters or less are needed to generate supercontinuum light. In fact, one of the recent advances in the last 10 years is the demonstration of micron-scale devices that generates either only supercontinuum light (Leo et al., 2015; Lau et al., 2014; Gattass et al., 2014), or generates both supercontinuum light and frequency combs (Del'Haye et al., 2007; Herr et al., 2012; Papp et al., 2014).

The conventional way of generating frequency combs starts with a mode locked laser producing evenly spaced pulses of light in time. The spectrum of the train of pulses gives a frequency comb in frequency space. This basic idea of evenly spaced combs was known shortly after the pulsed laser was developed. The big breakthrough came in the development of methods to determine the absolute frequencies of the comb lines without the need for an external frequency reference, as well as extending the bandwidth of comb lines (Jones et al., 2000). This is a feat in which supercontinuum light played an important role, and thus enabled the frequency comb to become much more wide spread (Cundiff and Ye, 2003; Ye and Cundiff,

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[1] The cesium clock has been used to define the standard for time since 1967, and its atomic transition frequency is in the microwave region of the spectrum.

2005; Udem et al., 2002). While many of the papers on frequency combs do not explicitly mention supercontinuum light, they do mention self phase modulation as the primary mechanism to extend the bandwidth of the comb lines. In this sense, supercontinuum light has been an enabling technology in the development of frequency combs. The main characteristics of supercontinuum light that has had an impact on comb generation is the presence of broad spectra often extending over an octave, ability to generate this broad spectra with low powers, and the high spatial coherence of the transverse intensity profile (Bellini and Hänsch, 2000). This has been particularly useful in the mechanism to broaden the frequency range of the comb lines, and ultimately enabled it to serve as a self-frequency reference.

3.2 Attosecond Technology

Supercontinuum light has been produced over an even broader region of the spectrum (from the X-rays to infrared) through the process of high harmonic generation in a gas jet. In this case, the ultrawide frequency bandwidths are used in the generation of attosecond pulses (Popmintchev et al., 1287, 2010; Chini et al., 2014). These are pulses with very narrow pulse width of order 10^{-18} s. A basic understanding of attosecond pulse generation comes from Fourier analysis of the frequency spectra. That is, the inverse Fourier transform of a very wide frequency spectrum will give a very narrow pulse. Such ultrashort pulses is expected to find application in studying various processes that occur on very short time scales. It also serves as a good way for generating X-rays which are used in spectroscopy of gasses. For more technical details on attosecond pulse generation and extreme ultraviolet generation, see Chapter 9.

4 High-Resolution Microscope and Spectroscopy

In addition to the STED microscope which has enabled one of the best resolutions in imaging (surpassing the diffraction limit) in the far field, there are a number of other techniques that have been used to image and perform spectroscopy on biological and nonbiological samples. They include multiplex Coherent Anti-Stokes Raman scattering (CARs) microscopy (Kano and Hamaguchi, 2005a,b, 2006; Kee and Cicerone, 2004a,b; Leproux et al., 1871; Mandon et al., 2008), Two-Dimensional Electronic spectroscopy (Tekavec et al., 2009; Krebs et al., 2013; Harel et al., 2011; Spokoyny and Harel, 2014), Impulsive Stimulated Raman (ISR) spectroscopy (Silvestri et al., 1985; Ruhman et al., 1987; Fragnito et al., 1989; Weiner et al., 1990, 1991; Fujiyoshi et al., 2003; Kukura et al., 2007; Polli et al., 2010; Liebel and Kukura, 2013; Kahan et al., 2007), Confocal microscopy (Chiu et al., 2012; Shi et al., 2004; Hubbard et al., 2010; Lindfors et al., 2004), and Optical Coherence Tomography (OCT) (Drexler et al., 1999; Wang et al., 2003, 2005; Drexler, 2004; Ishida et al., 2011; Kieu et al., 2011; Humbert et al., 2006). Supercontinuum light has been an enabling technology in many of these microscopy and spectroscopy techniques, including probing superconductors (Gadermaier et al., 2014). As there have been a number of advances in this area in the past 10 years, updated references has been included in this section for multiplex CARS microscopy, optical coherence microscopy, and confocal microscopy which was briefly mentioned in the last edition of book. Some of the newer applications of supercontinuum light in the past 10 years has been in two-dimensional electronic spectroscopy in order to understand efficient energy transfer and light harvesting phenomenon such as photosynthesis. Furthermore, some more newer applications include the use of near infrared (NIR) supercontinuum light to obtain images through biological tissue.

4.1 Multiplex CARs Imaging and Spectroscopy

In standard CARs microscopy, the Raman shift is determined from one vibrational mode to obtain a single color image of the sample. The Raman shift is the difference between the pump and stokes waves. In multiplexed CARS, several vibrational modes are excited to obtain multicolored images. A particular advantage is that supercontinuum light provides an effective way of producing the broadband light for efficient imaging of biological samples, with added benefits of compactness, robustness, stability, and cost compared to optical parametric oscillators or other methods that rely on a delay time between the pump and stokes pulses. For example, in recent years, multiplexed CARs has yielded micrometer level resolutions (Kano and Hamaguchi, 2006) of yeast cells. Not only have biological samples been measured, but atmospheric gasses such as acetylene, ammonia, and other molecules have been measured using this technique (Mandon et al., 2008).

4.2 Two-Dimensional Electronic Spectroscopy

Two-dimensional spectroscopy is a powerful frequency resolved technique for studying energy and charge transfer, wave packet motion, and other ultrafast dynamical processes (Tekavec et al., 2009; Krebs et al., 2013; Harel et al., 2011; Spokoyny and Harel, 2014). As such it has been used to unravel the vibration coupling in various complex molecules such as protein folding, and the inner workings of complex chromophores such as light harvesting complexes and the photosynthetic reaction centers, chiral dimers, and other areas. In two-dimensional electronic spectroscopy, a 2D spectral pump-probe map is created with the probe wavelengths on one axis, and the pump wavelengths on the other axis. From this map, time dynamics of the system can be extracted through a Fourier relationship. With conventional laser sources there is a limited bandwidth, which complicates the analysis. The supercontinuum laser source provides ultrawide laser bandwidth for this application, as well as great tunability over different wavelengths to resolve distinct features in the spectra, and ultimately study the dynamics of various processes.

4.3 Impulsive Stimulated Raman Spectroscopy (ISR)

Impulsive Stimulated Raman (ISR) spectroscopy pioneered by Ippen, Nelson and Weiner (Silvestri et al., 1985; Ruhman et al., 1987; Fragnito et al., 1989; Weiner et al., 1990, 1991; Fujiyoshi et al., 2003; Kukura et al., 2007; Polli et al., 2010; Liebel and Kukura, 2013; Kahan et al., 2007) takes advantage of the swift driving force that a short pulse exerts on a Raman active vibration mode, in order to study ultrafast chemical dynamics. It has the benefit of providing high time resolution compared to other techniques such as CARS, femtosecond (fs) pump-probe infrared spectroscopy, and femtosecond (fs) infrared vibration spectroscopy. The time resolutions of ISR is generally less than 50 fs in the vibrational frequency range between 0 and 1,300 cm^{-1}. The other techniques tend to have much lower time resolutions (greater than 50 fs and could be up to 1 ps). The ISR spectroscopy technique, however, does not have good signal to noise ratio, and tends to work better with the low frequency modes (Kukura et al., 2007). The early work in the field used picosecond (ps) pulses to excite and probe the ISR signal. With the advent of shorter pulses such as femtosecond pulses, the time resolution has been improved. In particular, an ultrafast femtosecond pulse can have a sufficiently wide range of frequencies to excite vibrational states (i.e.10 fs pulse has a frequency bandwidth of approximately 1500 cm^{-1} which covers the vibrational bands in electronic states). Some of the molecules that ISR has been used to study include organic compounds like Coumarin 6 (Polli et al., 2010) and β-carotene (Liebel and Kukura, 2013), proteins like bacteriorhodopsin (Kahan et al., 2007), and molecular crystals like α-perylene (Weiner et al., 1991). Many of these molecules could have several hundred degrees of freedom. For example bacteriorhodopsin which is a relatively simple molecule could have up to 300 degrees of freedom. Nevertheless, the ISR methods can be used to study it, and achieve high time resolution.

One of the recent advances in the past 10 years is the use of the supercontinuum light source as a probe in impulsive Stimulated Raman spectroscopy (Polli et al., 2010; Liebel and Kukura, 2013). The main advantage of the supercontinuum light source is that it reduces the experimental complexity while improving the time resolution towards the limit of the pump pulse duration. It also covers multiple absorption and emission bands, with minimized laser noise on the detector and good background subtraction. Thus, the signal to noise ratio is improved. In one of the most recent studies, the supercontinuum light source enabled probing the electronic states of an organic compound, β-carotene. This is made possible by the broadband supercontinuum probe pulse, which covered a wide frequency range, including the ISR pulse and excited state transition for which the vibrational spectra of excited electronic states was recorded (Liebel and Kukura, 2013).

4.4 Confocal Microscopy

Confocal microscopes has been used in a number of different disciplines, including biology, chemistry, and material science. Similar to a STED microscope, an aperture characterizes the point spread function to obtain the resolution of the sample. In fact the STED microscope is a variation of the confocal microscope, but STED microscopes beat the diffraction limit by using a much smaller point spread function as defined by donut beam to increase resolution. Recent advances in the conventional confocal microscopes have been to obtain depth information while increasing resolution by making use of supercontinuum light (Chiu et al., 2012; Shi et al., 2004; Hubbard et al., 2010; Lindfors et al., 2004).

4.5 Optical Coherence Tomography (OCT)

Optical Coherence Tomography (Drexler et al., 1999; Wang et al., 2003, 2005; Drexler, 2004; Ishida et al., 2011; Kieu et al., 2011; Humbert et al., 2006) has been another very successful method for obtaining three dimensional images in a highly scattering medium to ascertain micrometer level resolution. This topic has been briefly discussed in the previous edition of the book. The low temporal coherence of the light source, intense, and ultrawide bandwidth of the light source makes the supercontinuum light source particularly attractive for this application. In the last 10 years, some of the recent advances have been to extend this technique to the infrared region of the spectrum at 1.7 μm where there is low water absorption (Ishida et al., 2011). Furthermore, all reflective optical components has helped in suppressing chromatic dispersion to enable even higher resolutions of biological samples (Kieu et al., 2011).

4.6 Near Infrared Imaging of Tissue

Most recently, the supercontinuum light source in the near infrared (NIR) has been used to image tissue by transmitting light through it. While using this method to image tissue, it is important to reduce scattering because scattering causes blurring of the image. Also, it is important to reduce absorption of collagen, elastin, lipids, hemoglobin, and deoxyhemoglobin which occurs in the near infrared region of the spectrum. Penetration depths of images carrying ballistic light through turbid media are determined by scattering and absorption (Wang et al., 1991, 1993; Yoo and Alfano, 1990). Light in the first optical window (from 650 nm to 950 nm), known as the therapeutic window (Anderson and Parrish, 1981) has minimum absorption of light by water molecules and by oxygenated and deoxygenated hemoglobin.

The first NIR window is conventionally used for imaging abnormalities in tissue and photo-therapy, where the imaging light was collected by silicon based detectors.

With the advent of new detectors such as detectors made out of the indium gallium arsenide (InGaAs) (for wavelengths up to 1,700 nm) and indium antimonide (InSb) (for wavelengths longer than 1,700 nm), images can be obtained at much longer NIR wavelengths of light. Most recently, it was shown that there are three NIR windows suitable for imaging more deeply into tissue (Sordillo et al., 2014). In this study, optical images of black wire in tissue were obtained using an InGaAs camera detector. A halogen lamp is typically used to obtain images at longer NIR wavelengths in the second optical window (1,100–1,350 nm) and third optical window (from 1,600 nm to 1,870 nm). The latter is called Golden Window. Total attenuation lengths of light through these tissue samples are calculated and found that longer attenuation lengths are located in the second and third NIR optical windows. At longer NIR wavelengths, image quality is increased due to less scattering from the inverse wavelength power dependence ($1/\lambda^n$ where $n \geq 1$). Longer NIR wavelengths in the second (1,100–1,350 nm) and third (1,600–1,870 nm) NIR windows are used to penetrate more deeply into tissue media and produce high quality images. A limitation of the halogen lamps is its low power, therefore it contains less ballistic photons for very deep tissue imaging. Brain transmission zones were measured by Shi et al. to show Golden Window is best for deep penetration.

Using the NIR supercontinuum (SC) laser light source with wavelengths in the second and third NIR optical windows, images of tissue are obtained (Sordillo et al., 2015). With a greater number of ballistic photons due to its high power, the SC laser source provides ballistic imaging and offers a more intense light source than the conventional lamp source that was previously used. The SC ballistic beam can have penetration depths of up to 10 mm through tissue, and can be used to image lesions in areas such as the breast tissue and prostrate tissue. The SC is an ideal light source for deep tissue imaging for optical mammography.

5 Optical Event Horizon

When a massive star collapse it experiences an immense gravitational pull thus forming a black hole. It was postulated that nothing can escape a black hole, not even light. As light travels towards a black hole, the point which light is lost forever, and still observed is referred to as the event horizon. In 1974, Stephen Hawkins predicted that close to the event horizon which forms the boundary where light is trapped in the black hole and observed, there is a weak emission of black body radiation. This radiation is referred to as Hawking radiation (Hawking, 1974). While this prediction is significant, this radiation is too weak and virtually impossible to detect. In fact, Hawking radiation is expected to be significantly weaker than the cosmic microwave background. In an effort to understand black holes, and the radiation that should emanate from it, physicists have recast the problem in terms of a “white hole” which is a black hole working in reverse. Nevertheless, it must be noted that unlike black holes, white holes are expected to be too unstable to exist in the cosmos. Nonetheless, the idea of white holes creates a useful tool in making laboratory optical analogs (Philbin et al., 2008; Belgiorno et al., 2010; Webb et al., 2014) to the event horizon in order to comprehend this astrophysical phenomenon. It is important to note that even though there is an immense gravitational pull at the center of a black hole, the event horizon does not depend fundamentally on gravity, and it is for this reason that one could successfully use optical analogs in describing the event horizon.

An analogy commonly used to conceptually understand white holes is to consider water flowing downstream from a mountain top, and fish trying to swim upstream to the steep mountain top. When the fish is at the bottom of the mountain swimming in a direction opposite to the water, it moves freely. Nevertheless, once it starts swimming up the mountain, it reaches a point where it cannot swim further because the backward velocity of water is quite large compared to the forward velocity of the fish. The point between the bottom of the mountain and top of the mountain where the fish cannot swim forward is the event horizon. The point beyond the event horizon is referred to as the white hole. This analogy of water waves (Cho, 2008; Dudley and Skryabin, 2010) carries on when creating optical analogs to study the physics of white holes. In the case of optical waves, an ultrashort intense pulse in a material experiences an intensity dependent refractive index (i.e., Kerr effect) which steepens the pulse, such that a velocity gradient between the leading edge of the pulse and trailing edge of the pulse creates an event horizon at points on the leading edge and trailing edge. It turns out that there could be a weak emission of black body radiation, namely Hawking radiation from this white hole event horizon. Ultimately, the optical analog of Hawking radiation is observed by positioning the detectors appropriately from the laboratory setup where the white hole is created (Belgiorno et al., 2010). Care is taken to prevent self phase modulation which would cause broadening of the spectrum and create supercontinuum light as this may be much stronger than the “Hawking radiation” from the white hole (Belgiorno et al., 2010).

While supercontinuum light is considered detrimental (Faccio, 2012) to the creation of optical analogs for understanding white holes and event horizon, many of the concepts used in the description of supercontinuum light also plays a role in the physics of event horizons and white holes. This includes self steepening of a pulse due to the Kerr effect, four wave mixing, optical dispersion, soliton dynamics, laser pulse filamentation, Raman frequency shifting, and many others (Philbin et al., 2008; Belgiorno et al., 2010; Webb et al., 2014; Faccio, 2012). So far short pulses of light in an optical fiber (Philbin et al., 2008; Webb et al., 2014) or bulk Kerr medium (Belgiorno et al., 2010) has been used to study the physics of white holes and event horizons in the laboratory. These optical analogs provides a promising route to understanding the physics of event horizon, and ultimately observing Hawking radiation in the laboratory (Belgiorno et al., 2010), even though it has not yet been measured in the cosmos.

6 Conclusion

This chapter summarizes some of the recent applications of supercontinuum light. As seen, over the last 10 years there have been a number of new applications of supercontinuum light possessing complex light modes in superresolution STED microscopy, particle trapping, rotational Doppler effect, and the search for exoplanets. Furthermore, the SC light source shows potential for studying astrophysical phenomenon as well as for optical communications. We have also expanded on previous applications of the supercontinuum light source for optical metrology, especially in the development of the most precise frequency rulers, i.e., the frequency comb. This included the development of micron scale devices that produce both supercontinuum light and frequency combs for the most accurate optical clocks. In addition, we provide updated references to some of the recent advances of supercontinuum light in spectroscopy such as 2D electronic spectroscopy, multiplex CARs spectroscopy, near infrared imaging, and other standard microscopy and spectroscopy techniques. Finally, we discussed optical analogs to the physics of event horizon and Hawking radiation in astrophysics. Many of the concepts used to describe supercontinuum light are also used to describe the physics of the event horizon, which has not yet been observed in the cosmos.

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