Supercontinuum Light

Bright, broadband and spatially coherent, supercontinuum light reveals fascinating nonlinear physics and enables new applications in diverse areas of fundamental and applied science.

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1. Introduction

The many uses of laser light are so well-known that they need little introduction. The development of high brightness spatially-coherent optical radiation has enabled diverse and familiar applications in areas such as spectroscopy, communications, material processing and so on. A continual challenge, however, has been developing sources of laser light at new wavelengths, because different applications generally require lasers operating in specific regions of the electromagnetic spectrum. Whilst there has been tremendous effort to develop new laser materials to generate new wavelengths directly, there has also been extensive work using the processes of nonlinear optics to convert laser radiation from one frequency to another. The last decade has seen a veritable revolution in this field with the development and widespread use of the *fiber supercontinuum*, a truly remarkable source of optical radiation.

A supercontinuum is usefully defined as broadband light generated from the nonlinear frequency conversion of a laser that is focused to high intensity in a dielectric medium. Most useful supercontinuum light today is generated in optical fiber, typically spanning the visible and near infrared spectral regions, and with up to several watts of average optical power. Because it is produced within the guided mode of an optical waveguide, the supercontinuum preserves the spatial coherence properties of the incident laser, and thus essentially combines the brightness and focusing properties of a laser with the broad bandwidth of a white-light incandescent bulb. This yields a unique optical source that can be considered as an essentially arbitrary-wavelength source of spatially coherent laser light [1, 2].

What makes the supercontinuum especially useful is its diversity. When combined with spectral filtering, it can be used as a narrowband yet tunable source for applications such as spectroscopy. On the other hand, when used over its full bandwidth, it finds applications in multi-wavelength microscopy, or in the encoding of information at high capacity using multiple data channels at different wavelengths. Generating a supercontinuum in the laboratory is simple enough to be carried out by undergraduates, and there is a burgeoning commercial market for supercontinuum sources in imaging and microscopy where the ability to focus tightly allows diffraction-limited spatial resolution. Yet although it is easy to generate a supercontinuum in the lab, understanding its physics is more difficult, as it requires knowledge of concepts from nonlinear and ultrafast fiber optics that are somewhat specialized [3]. In this article, we present an introduction to this fascinating field of optical science, reviewing briefly how and why the field developed so quickly in the last ten years, describing the essential physical ideas, and pointing out new applications and current fields of research.

2. Immediate impact

The physics of supercontinuum generation is based on inducing a broadband electronic polarization in a dielectric medium using an intense light pulse from a high power laser. As a rule of thumb the magnitude of such a nonlinear polarization and thus the supercontinuum bandwidth scales with the pump pulse power. Since the highest peak powers of lasers are usually associated with the production of ultrashort picosecond and femtosecond pulses, supercontinuum generation typically using pulsed pumping. However, this isn't a strictly necessary requirement, and intense continuous laser sources can also be used.

Supercontinuum light was first observed in the late 1960s by focusing pulsed lasers into bulk crystals and glasses, and this was followed by experiments in other media including liquids and gases, and optical fiber [4,5]. It was the observation of a white light supercontinuum using a new type of photonic crystal fiber in 1999, however, that revolutionized the field [6]. This was because the particular properties of this type of fiber (extreme light confinement and specifically engineered dispersion) enabled supercontinuum generation using low energy pulses from widespread tabletop femtosecond laser sources. Before this development, supercontinuum generation required relatively large and complex experimental setups, which significantly impeded its uptake as a useful technology. A typical experimental observation of a femtosecond laser-generated supercontinuum is shown in Figure 1.

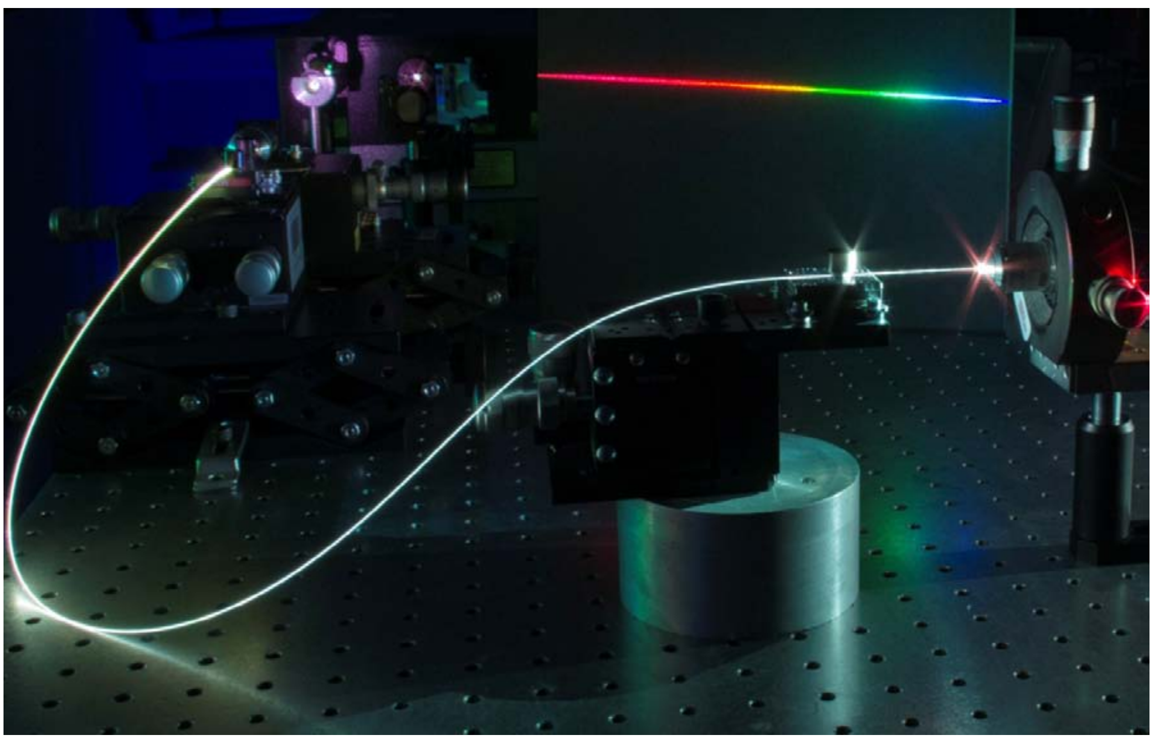
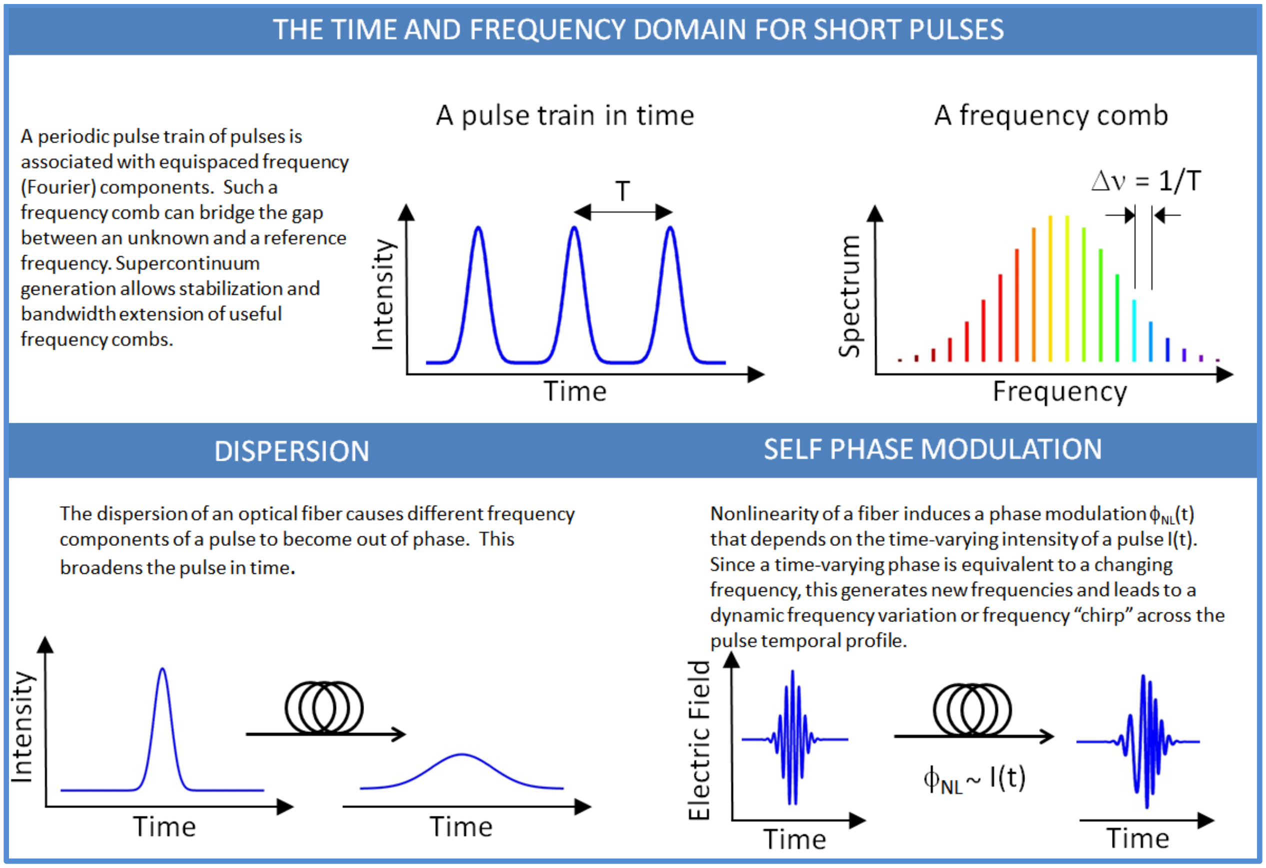


Figure 1. Injection of 800 nm (invisible) femtosecond pulses into an optical fiber (from the coupler on the left) leads to dramatic frequency conversion and the generation of a white light supercontinuum which is dispersed using a diffraction grating onto a screen. Note that although we see only the visible portion of the spectrum in this photo, the supercontinuum actually extends from below 400 nm into the infrared beyond 1500 nm. The fact that we are able to create a collimated line focus of the diffracted spectrum is because the spatial focusing properties of the pump laser are preserved during the spectral broadening process in the fiber.

This experimental simplicity rapidly attracted enormous interest, both from the nonlinear optics community who wanted to probe the underlying physics, but also – and at first sight surprisingly – from the optical metrology community who applied the supercontinuum to precision measurements of optical frequencies [7-9]. In fact, the supercontinuum played a central role in the development of the stabilized frequency comb which was a component of the 2005 Nobel Prize in physics. We will return to the details of the supercontinuum generation process below, but it is worthwhile pausing to briefly consider this immediate application in frequency measurement.

The precise measurement of optical frequencies impacts on fundamental areas of physics such as the search for slow changes in the fundamental constants, as well as on applications using frequency references in communications and navigation. To measure an unknown optical frequency, we compare it with one known more precisely. This technique was initially developed using room-size frequency chains starting from a stable microwave reference linked to a cesium atomic clock, and subsequently generating exactly known higher frequencies up to the optical regime via a number of other intermediate oscillators. In the late 1990s, however, it was realized that this technique could be greatly simplified using an optical frequency comb generated from a mode-locked laser. The optical spectrum associated with the pulses emitted by a mode-locked laser is not continuous, but consists of a comb of discrete lines exactly separated by the repetition rate at which the pulses are emitted (see Box) that can be used as a "frequency ruler" to bridge a gap between two unknown frequencies under the laser pulse bandwidth.

A limiting problem with the frequency comb, however, arises because the absolute position of the comb lines from a mode-locked laser is generally unknown. However, if the laser is used to generate a supercontinuum that spans over an octave in frequency, the position of the comb lines can be stabilized with reference to an atomic clock through two relatively straightforward radio frequency measurements: one of the pulse repetition frequency, and another derived from the measured interval between the fundamental pulse frequency and its second harmonic [4]. And at the same time, the extended bandwidth of the supercontinuum allows much more flexibility in bridging frequency intervals. Once the supercontinuum was applied in this way for comb stabilization, the field of frequency metrology was revolutionized virtually overnight. Frequency combs now enable the measurement of optical frequencies to better than 1 part in 10^{15}, rivaling the best atomic clocks in their stability [9].



Box: Some basic concepts of ultrafast nonlinear fiber optics

3. Nonlinear ultrafast optics

This is all very well, but what actually causes the continuous spectral broadening in the first place? This is not evident at first sight because, although the basic principles of nonlinear optics are widely known, the familiar processes of optical harmonic generation involve the conversion of particular monochromatic frequency to *discrete* doubled or tripled frequencies at shorter wavelengths [10]. The physics of supercontinuum generation, however, is very different because it depends on how an input optical field that already spans quite a broad bandwidth (e.g. from a short pulse) interacts with a dielectric medium to generate a *continuum* of new frequency components. This is the field of *nonlinear ultrafast fiber optics* [3].

Before discussing nonlinearity, however, it is easier to first review how linear propagation affects a short pulse of light. The linear optical properties of a material are of course determined by the refractive index, but for the case of a broad bandwidth incident pulse, there can be a very large variation of refractive index with wavelength across the pulse bandwidth. This dispersion results in the different frequency components of the broadband spectrum becoming out of phase, which results in the broadening of the temporal pulse envelope with propagation (see Box).

In addition, the intensity of an ultrashort pulse can be so high that the refractive index itself can be modified by the incident pulse in a way that is proportional to the incident intensity, sometimes referred to as the optical Kerr effect. This nonlinear refractive index causes a time-dependent phase shift that depends on the time-dependent pulse intensity. This *self-phase modulation* across the temporal pulse generates the new frequency components and a temporally varying instantaneous frequency (or "chirp") such that the lower-frequencies are on the pulse leading edge and higher frequencies on the pulse trailing edge (see Box).

Self-phase modulation will occur when light is focused into any dielectric material, but the effects of diffraction in a bulk medium will always limit the distance over which light is intense enough to stimulate this nonlinear frequency generation. This highlights why optical fiber is such an important platform for nonlinear frequency conversion: the fact that light is guided over long distances within a small cross-sectional area means that effects such as self-phase modulation can be observed at much lower power in fiber than in bulk materials, and can accumulate with propagation.

4. Supercontinuum and Solitons

Explaining fiber supercontinuum generation in terms of only self-phase modulation, however, is an oversimplification. The rich physics of the supercontinuum really arises from the interaction between the nonlinear effect of self-phase modulation and the linear dispersion. In particular, we discussed above how nonlinearity leads to a dynamic frequency variation of the carrier wave under the envelope of a propagating pulse, with the Box showing how this results in the generation of new red-shifted components on the pulse leading edge and blue-shifted components on the trailing edge. But now the effect of the linear dispersion makes things interesting! This is because – depending on properties of the fiber used and the wavelength of the pump pulses – dispersion will either increase the temporal separation between these red and blue components causing the pulse to spread in time ("normal dispersion"), or can cancel it altogether and induce stabilization of the pulse in the form of an optical soliton ("anomalous dispersion") [3].

The concepts of soliton physics are essential to obtain a correct physical picture of the supercontinuum. Solitons are localized nonlinear structures that have fascinated physicists since their fortuitous discovery in the 19th century on canals [11], and soliton effects have now been identified in a very wide range of physical systems [12] and of course optical fiber waveguides [13]. However, although the most well-known class of optical soliton is the invariant *fundamental soliton*, there also exists a class of *higher-order soliton* where the interactions of self-phase modulation and dispersion lead to a periodically evolving (but regular) temporal and spectral evolution. These generic examples of soliton evolution are shown in Figure 2(a) and (b).

Ideal periodic solitons, however, are essentially impossible to see in practice because of perturbations to the fiber dispersive and nonlinear responses that break the symmetry of the evolution. In this case, the higher-order soliton undergoes a remarkable process known as *soliton fission*, where the initial pulse splits into a train of individual fundamental soliton pulses which then undergo further nonlinear and dispersive propagation. Of course, the same perturbations that may induce higher-order soliton breakup can also affect the ejected fundamental solitons, and this is in fact the key to understanding the extension of the supercontinuum bandwidth. For each ejected soliton, the effect of higher-order dispersion results in a resonant transfer of energy to shorter wavelengths whilst the effect of Raman scattering within the bandwidth of each soliton leads to a continuous self-frequency shift to longer wavelengths [2].

Understanding these two processes in full mathematical detail is very complex, but their effects on the pulse breakup in both the time and frequency domain can be readily seen from numerical modeling. This is shown in Fig. 2(c). The left figure shows the process of soliton fission, induced by realistic dispersion and Raman perturbations in fiber, to be compared to the ideal case of higher-order soliton evolution in Fig. 2(b). The right figure shows the spectral evolution of the supercontinuum, labeling the frequency shifting Raman soliton and the dispersive wave generated early in the evolution. For the case of sub-100 fs pulses, all these different processes occur deterministically such that each injected pulse generates an identical supercontinuum at the fiber output. This can lead to octave-spanning optical spectra with extremely high stability allowing their use in precision frequency measurement where the phase stability of the supercontinuum can be preserved over 100s of THz [7-9].

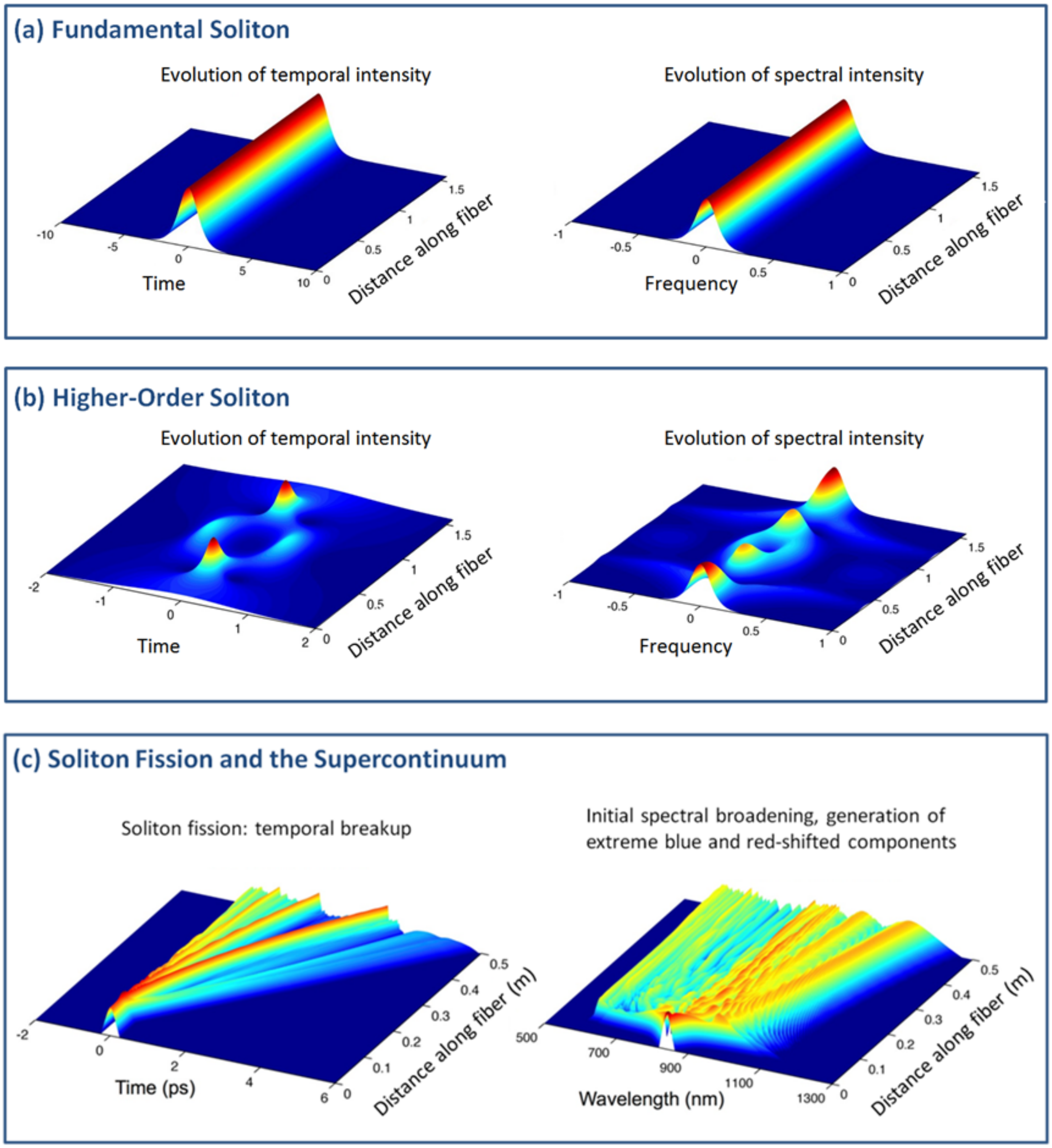


Figure 2. Numerical modeling of soliton dynamics and supercontinuum generation, showing the temporal and spectral intensity of an evolving pulse in an optical fiber [3, 13]. Color coding shows normalized intensity (blue: zero background; red: highest intensity). (a) shows the ideal invariant evolution of a fundamental soliton with perfect balance between nonlinearity and dispersion. At higher intensity it is possible as in (b) to see regular and periodic evolution of a higher-order soliton in both time and frequency. In (a) and (b) we plot normalized time, frequency, and distance coordinates. In (c) we plot realistic simulations including higher-order dispersion that breaks the initial periodic

evolution and induces temporal soliton fission and the appearance of distinct temporal and spectral structure. Parameters for (c) are similar to those used in Dudley, Coen & Genty [2].

5. Supercontinuum and Instabilities

The generation of noise-free supercontinuum as described above generally occurs using sub-100 fs pulses. When longer pulses are used, the initial phase of evolution does not show deterministic higher-order soliton dynamics, but there is rather a noise-driven process known as *modulation instability* that excites the symmetric generation of frequency sidebands, introducing a strong temporal modulation on an input pulse [3]. Remarkably, after this initial growth from noise, the modulated field still evolves to resemble a train of fundamental optical solitons and we see the same forms of frequency shifting dynamics as described above. But the fact that the initial seed is noise-driven means that the characteristics of these emerging solitons are random and thus there is no phase stability from shot to shot.

With regard to this unstable form of supercontinuum generation, an extremely surprising link has also been made between supercontinuum noise and the emergence of the infamous giant "rogue waves" on the surface of the ocean [14]. In fact, ocean wave group propagation and light propagation in fibers have much physics in common: wave propagation is dispersive in both systems and the speed of a wave group on the ocean, like the speed of an optical pulse, depends on its amplitude. In the case of light propagation in fibers, noise during the SC generation process with long pump pulses can behave like an "optical wind" which can trigger the appearance of a small number of short-lived waves with extremely large amplitude. The appreciation of this analogy has essentially opened up a new and extremely active research area using optical systems to study nonlinear wave shaping, confirming theoretical predictions from the hydrodynamics literature from over 25 years [15]. It has been particularly gratifying to see how experiments in optics generating rogue waves are motivating studies in wave tanks to generate similar waves in the hydrodynamic environment [16]. This is a particularly exciting and fast developing area of research, as it touches equally on turbulence, Bose-Einstein condensation, soft-condensed matter physics, nonlinear acoustics etc.

6. Applications

Because of the ability to dispersion-engineer optical fibers, it is possible to fabricate optical waveguides that are suitable for supercontinuum generation using a wide range of pump laser sources. This allows the generation of radiation from supercontinuum light spanning a remarkable range from the ultraviolet near 200 nm to the infrared over 4 μm. A survey of available supercontinuum sources using different types of pump is presented in Figure 3**.** Here we show the power spectral density obtained in each case and we also indicate the spectral bandwidth generated. It is clear that virtually any laser source with sufficient power can be used to generate a supercontinuum but it is also worth noting that only the results obtained using femtosecond pulses would possess high stability and be suitable for the most demanding applications in frequency metrology. On the other hand, unstable supercontinuum spectra also find many applications where time-averaged measurements are important such as imaging and spectroscopy.

One cannot stress enough the impact that new developments in optical fibers have had on this field [17]. Prior to the nonlinearity and dispersion-engineering possibilities of fiber invented in the 1990s, generating broadband supercontinuum was an extremely expensive technology, requiring complex lasers and large laboratory facilities. Also building on advances in available pump sources, the supercontinuum has become an extremely affordable (and sometimes very compact) technology, which has naturally led to the development of a very wide range of applications.

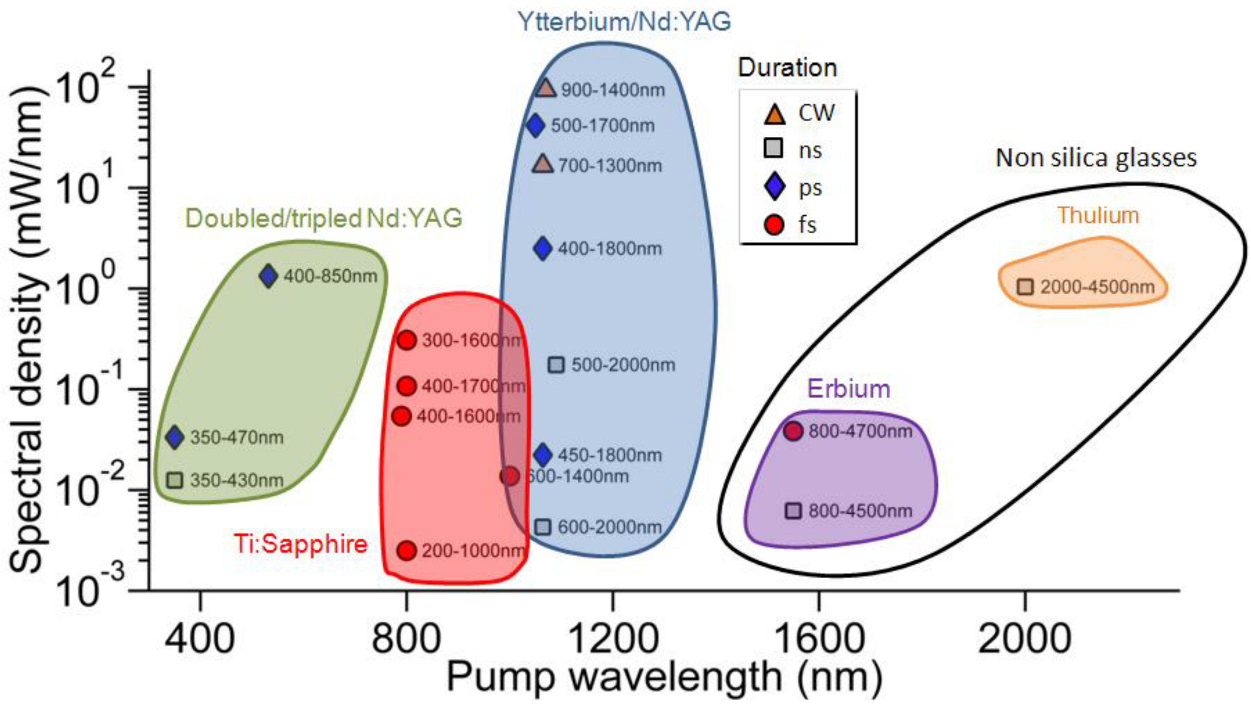


Figure 3. A survey of different supercontinuum sources as a function of different pump lasers. Ytterbium, Erbium and Thulium are fiber laser sources, whereas Nd:YAG and Ti:Sapphire are solid-state lasers. All results using pump sources below 1200 nm were obtained using silica-based fiber as the supercontinuum generation medium.

Areas where supercontinuum sources are finding significant commercial success include spectroscopy and microscopy, where the high brightness and large bandwidth have greatly increased the achievable resolution compared to that obtained with traditional lamps or LED sources. For example, in confocal microscopy, the broad bandwidth allows essentially arbitrary tuning of excitation wavelengths to perfectly match fluorophores. The result is optimal excitation of the fluorescent dyes with minimal cross-excitation, reducing the requirement for laser power, and increased viability for long live cell experiments. Supercontinuum sources have also found applications in STED microscopy [18], an advanced super-resolution technique allowing imaging at below the diffraction limit. STED is an acronym standing for Stimulated Emission Depletion Microscopy and is based on using dual wavelength excitation to deplete specific regions of the sample while leaving a sub-diffraction limit center focal spot active to emit fluorescence. There are also many potential novel applications in biomedical diagnostics; the combined broad bandwidth and local frequency precision of the supercontinuum as a spectroscopic tool has led to important advances in the demonstration of medical testing using breath analysis; this is a truly fascinating area of research.

One of the more surprising applications of frequency comb technology is its use to improve the accuracy and stability of wavelength calibration of astrophysical spectrographs by as much as two orders of magnitude [9]. Such “astro-combs” have represented a major advance in the resolution of astrophysical Doppler shifts, the basis for the discovery of exo-planets. If this technique is confirmed and widely adopted, it will be a truly remarkable example of how fundamental research in one field can find completely unexpected applications in another.

7. Brighter Future

Supercontinuum generation involves the interaction between a number of different nonlinear effects and the intrinsic linear dispersion of the fiber waveguide. Although its basic physics is well understood, the richness of the underlying nonlinear dynamics provides ongoing challenges for theory and modeling, and continues to throw up surprises.

The ability to generate supercontinuum with a compact tabletop system has reduced the power demands for nonlinear frequency conversion, leading to new technological developments, commercial success, and major contributions in many different fields of science. The optical supercontinuum appears as a common factor in many breakthrough experiments that have combined ideas and researchers from diverse domains from guided wave optics, to laser source development, nanophotonics, materials science and biology. As new materials continue to become available, and laser pump sources become more widely available, the supercontinuum can be expected to continue to find new applications, and one can only express the wish that some of them will be as unexpected and as exciting as the many that we have seen to date.

Acknowledgements

The authors thank Roy Taylor for important comments concerning Figure 3. Figure 1 was taken at the laboratories of JMD by B. Wetzel. JMD thanks the European Research Council (MULTIWAVE) and GG thanks the Academy of Finland for financial support.

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