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Introduction and history

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With the invention of the laser (Maiman 1960), rapid technological development of Q-switching (McClung and Hellwarth 1962) and mode locking techniques (Mocker and Collins 1965, DeMaria et al. 1966) allowed the achievement of the shortest, controllable, man-made pulse durations, and, consequently, for even modest pulse energies, unprecedented optical peak powers were achievable with ever-decreasing pulse durations, establishing a trend which continues to the present day. The enormous optical field strengths generated at the focal point of a pulsed laser ensured that the corresponding electronic polarization response of a transparent medium was nonlinear, in that higher order terms of the expansion describing the polarization needed to be considered despite the then insignificance of the magnitude of the second and third order susceptibilities and as a consequence ushered in the era of nonlinear optics. The first nonlinear optical process to be reported was second harmonic generation (Franken et al. 1961), which although observable, is of little importance in relation to the subject matter of this book, supercontinuum generation in optical fibres. However, this was followed by reports of frequency mixing (Bass et al. 1962) and parametric generation (Giordmaine and Miller 1965, Akhmanov et al. 1965). Essential for supercontinuum generation are the processes that result from the third order nonlinear term (Maker and Terhune 1965). In addition to third harmonic generation (New and Ward 1967), again extensively observed but of little importance in supercontinuum generation, these third order processes include the optical Kerr effect or intensity dependent refractive index (Maker et al. 1964), self-focusing (Askaryan 1962, Shen and Shaham 1965), four-wave mixing (Carman et al. 1966), stimulated Brillouin scattering (Chiao et al. 1964) and stimulated Raman scattering (Woodbury and Ng 1962, Eckhardt et al. 1962), all theoretically proposed and experimentally characterized within a few years of the development of the laser and clearly illustrating the richness of the field in those early days.

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Researchers were well aware of the processes leading to self-focusing instabilities and spectral broadening in early laser driven systems (Brewer and Lifsitz 1966), with these causing damage to laser rods and primarily looked upon as deleterious effects rather than as a resource. However, as early as 1964, Jones and Stoicheff utilized a nominal "continuum" generated via anti-Stokes scattering in liquid to probe the Raman absorption spectra of other organic species in an effective nanosecond time scale transient absorption experiment. Although the continuum utilized was only a few nanometres wide, it did illustrate the principle of nonlinear spectrally broadened sources applied to spectroscopic measurement. Of course, this was not a new technique; Kirchoff and Bunsen (1860) in their systematic investigations of line reversal in the alkali and alkali earth elements in the nineteenth century had utilized a continuum or "white light" source, however, all measurements were time integrated. Significant spectral broadening of Q-switched ruby lasers in self-focused filaments in carbon disulphide cells was also later reported (Ueda and Shimoda 1967, Brewer 1967) and based on experimental observation, Shimizu (1967) theoretically demonstrated that the spectral broadening and observed interference was due to self phase modulation arising from the intensity dependent refractive index.

In 1969, Alfano and Shapiro undertook a series of measurements to characterize self phase modulation in crystals and glasses using picosecond pulse excitation from a frequency doubled Nd: glass laser (Alfano and Shapiro, 1970a). However, it should be noted that the role of self phase modulation in glass leading to spectral broadening and a linear frequency chirp had been identified by Treacy (1968), who had used a pair of diffraction gratings to directly compress to sub-picosecond durations the 10 nm, 4 ps chirped pulses from a passively mode locked Nd:glass laser. Despite the earlier results reporting spectral broadening in a variety of liquid, crystal and glass samples, the first report of "supercontinuum generation" is widely recognized as Alfano and Shapiro (1970b), recording spectral coverage from 400 nm to 700 nm, a "white light" source, in a borosilicate glass sample pumped by GW picosecond pulses from a frequency doubled Nd: glass laser. Alfano and Shapiro immediately recognized the importance of this unique source in transient absorption measurements, subsequently deploying it in undertaking the first spectroscopic measurements in the picosecond domain of Raman absorption spectra (Alfano and Shapiro 1970c). Throughout the 1970s and 1980s the technique of focusing amplified picosecond and femtosecond pulses (Shank et al. 1979, Knox et al. 1984), primarily from dye laser sources, into liquid filled cells or jets generated white light continua, with self phase modulation identified as the major contributing effect (Fork et al. 1983), that were extensively used in time resolved spectroscopy. It is interesting to note that over the first two decades of research the phenomenon was most commonly referred to as frequency broadening, anomalous frequency broadening or white light generation. A simple reference to any bibliography search engine reveals that the first use of "supercontinuum" to describe the process was in 1980 by Gersten et al. of the Alfano group.

Time resolved spectroscopy remained the principal application of the various sources. However, the technology remained very much in the basic research laboratories primarily because of the quite extensive nature of the experimental configurations. The physics, technology and applications of these first generation supercontinuum sources are best reviewed in Alfano's seminal text *The Supercontinuum Laser Source* (1989).

Driven by the potential application in telecommunications, the development of low loss, single mode optical fibre in the 1970s provided the platform for a new field of study – nonlinear fibre optics. The advantage of fibre over bulk is very clear, despite the exceedingly low nonlinear coefficient of silica, simply by considering the many orders of magnitude improvement ($\sim 10^7$–10^8) in interaction length achieved through propagation over the loss length of a single mode fibre compared to the achievable confocal interaction length of lens coupling to a bulk medium. The interaction in a single mode fibre also allowed more control over the nonlinear process by eliminating the problems of self-focusing and filamentation that were often necessary to observe nonlinearity in bulk media but which also led to irreproducibility of results and quite frequently damage.

Stimulated Raman scattering was the first nonlinear effect reported using the enhancement offered by a carbon disulphide liquid-filled hollow core fibre (Ippen 1970), a concept that once again has come into vogue with the availability of air core photonic band gap fibre. A similar experimental configuration was also used to make the first observation of self phase modulation in an optical fibre (Ippen et al. 1974). With the availability of conventional low loss fibres, however, all the principal nonlinear effects that had previously been observed in bulk materials were rapidly characterized and reported, but, and importantly, at much lower power levels. These included stimulated Raman scattering (Stolen at al. 1972), stimulated Brillouin scattering (Ippen and Stolen 1972), the optical Kerr effect (Stolen and Ashkin 1973), four-wave mixing (Stolen et al. 1974) and self phase modulation (Stolen and Lin 1978), all of which can play important roles in supercontinuum generation in fibres.

A key nonlinear process and a vital component in supercontinuum generation was proposed by Hasegawa and Tappert in 1973 arising through the balance of self phase modulation and anomalous dispersion. Optical soliton generation had to wait a further seven years before it was unambiguously demonstrated and characterized in a series of classic experiments by Mollenauer (Mollenauer et al. 1980, 1983; Mollenauer and Gordon 2006). The long delay between theoretical prediction and experimental realization was a result of the technological challenges involved in developing an appropriate source of transform-limited picosecond pulses in the anomalous dispersion regime, i.e. at wavelengths greater than 1.27 μm for conventional silica-based fibres. The early experiments relied on launching pulses with power and transform limited spectral characteristics to match the fundamental soliton requirements of the particular fibre. It is known, however, that a pulse with any reasonable shape will evolve into a soliton (Hasegawa and Kodama 1981). In such a case, the energy not required to establish the soliton appears as a dispersive wave and this again is an important process in the supercontinuum generation process. It is interesting to note that in the early reports of supercontinuum generation utilizing single pass cascaded Raman generation and prior to the first reports of optical soliton pulse realization, solitons most certainly were generated as evidenced by the continua in the spectral region above 1.3 μm (Cohen and Lin 1978, Lin et al. 1978). Pulses generated in what is now designated the soliton Raman continuum were detector limited and if autocorrelations traces had been taken, the signature of sub-picosecond soliton generation, without doubt, would have been recorded.

Another nonlinear process closely related to soliton generation, resulting from the interplay of the intensity dependent refractive index and anomalous dispersion is modulational instability, which was first proposed in 1980 by Hasegawa and Brinkman and is an important effect in the initiation of supercontinuum generation particularly under cw or long pulse pumping in the region of low dispersion. Many nonlinear systems exhibit such an instability leading to modulation of the steady state, for example in plasmas (Hasegawa 1970) or in fluids (Benjamin and Feir 1967) and was first observed in optical fibre by Tai et al. (1986a), where the generated picosecond modulations appeared on an effective cw background of 100 ps pump pulses. In conventional fibre, the unavailability of adequately powered cw sources at suitable wavelengths above 1.3 μm inhibited observation with true cw excitation until reported by Itoh et al. in 1989 using 1.319 μm from a cw Nd: YAG laser in 5 km of a silica fibre with a fluoride doped depressed cladding.

The modulational instability process can be envisaged as a four-wave mixing process phase matched through self phase modulation, where exponential growth of the Stokes and anti-Stokes sidebands takes place at the expense of two photons from the pump. Modulation instability is, most commonly, self-starting from noise at the frequency separation of the maximum of the gain (Hasegawa and Brinkman 1980). However, it is possible to initiate the process by seeding with an additional signal at a frequency separation from the pump lying within the gain window. This process of induced modulational instability was initially proposed by Hasegawa in 1984 and was experimentally verified by Tai et al. (1986b). This mechanism introduces a control to the modulational instability process that allows manipulation and enhancement of the supercontinuum generation process. As will be discussed below for long pulse and cw pumping, supercontinuum generation processes are dominated by soliton Raman effects that proceed via modulational instability (Gouveia-Neto et al. 1989a) and by seeding the modulational instability process via Raman amplification of the sidebands, enhanced spectral coverage of the continuum associated with cleaner pulses and reduced pedestal components is achieved (Gouveia-Neto et al. 1988a).

Cross phase modulation, which is inherent in the Raman generation process (Gersten et al. 1980, Schadt and Jaskorzynska 1987) can also be used to induce modulational instability on weak signals in the anomalously dispersive regime and is particularly effective when the signal is group velocity matched with a pump in the normal dispersive regime (Gouveia-Neto et al. 1988b).

For supercontinuum generation in the anomalously dispersive regime, in addition to soliton effects, the Raman process contributes in several ways to the formation. Vysloukh and Serkin first proposed the use of the stimulated Raman process for soliton generation (Vysloukh and Serkin 1983, 1984) and the technique was first experimentally demonstrated by Dianov et al. (1985). As well as demonstrating a soliton Raman continuum, for the first time, this latter paper also describes for the first time the important mechanism of Raman self-interaction of the generated femtosecond solitons to account for the continuous extension of the Stokes continuum with propagation or increased pump power. This mechanism was later rediscovered and renamed the soliton self-frequency shift (Mitschke and Mollenauer 1986, Gordon 1986). Throughout the 1980s and early 1990s the Dianov group undertook an immense catalogue of work, both experimental and theoretical (Serkin 1987a,b, Grudinin et al. 1987, Golovchenko et al. 1987a, 1987b) investigating the generation, propagation, stability and decay of femtosecond soliton structures in fibres. This definitive work laid a foundation for the understanding of the mechanisms contributing to supercontinuum generation in fibres. However, much of this seminal work has quite often been overlooked or perhaps translations of the original Soviet texts were unavailable to researchers. As these are too numerous to list, reference should be made to those listed above and the review text *Nonlinear Effects in Optical Fibres* (Dianov et al. 1989a).

The decay of high order solitons launched in the region of minimum dispersion was primarily investigated as a route for extreme pulse compression (Mollenauer et al. 1980, Grudinin et al. 1987, Tai and Tomita 1986a, 1986b, Gouveia-Neto et al. 1987a, 1988c, Beaud et al. 1987), although naturally the process was also accompanied by substantial spectral broadening. Perturbations to high order solitons in the region of minimum dispersion caused by the effects of higher order dispersion (Vysloukh 1983, Wai et al. 1986) lead to instability and soliton fragmentation into its numerous constituent fundamental solitons. In fact, high order solitons are extremely susceptible to any external perturbation, such as from Raman gain

(Tai et al., 1988) or other self-effects, rapidly decaying into their various coloured solitons (Golovchenko et al. 1985, 1987a, 1987b), which in recent years has been renamed soliton fission.

Launched around the region of the minimum dispersion, Wai et al. in 1987 theoretically predicted that solitons would emerge from pulses of any arbitrary shape and amplitude. It was also shown that with increased amplitude at launch, the solitons would frequency down shift with increasing amplitude and that the central frequency of the dispersive wave component would correspondingly increase. These theoretical predictions were experimentally verified by Gouveia-Neto et al. (1988d). Beaud et al. (1987) had earlier investigated the decay of high order solitons launched near the zero dispersion and experimentally characterized the trapping of dispersive waves by femtosecond solitons. As the solitons experienced the soliton self-frequency shift on propagating over increasing fibre length, the trapped dispersive wave correspondingly shifted to shorter wavelengths. The authors clearly identified the mechanism and demonstrated the essential group velocity matching to maintain the process. This too is an essential ingredient in the short wavelength extension of both pulsed and cw pumped supercontinuum generation.

Following the characterization of the basic nonlinear processes in fibre as described above, Lin and Stolen reported the first continuum generation in fibre in 1976. Pumped by various nanosecond pulsed dye lasers, the continua extend from 392 nm to 685 nm, depending on pump wavelength, but were typically 100 nm to 200 nm broad. The high Raman gain coefficient in the visible accompanied by self phase modulation, spectrally broadened the cascaded Raman orders into a continuum and the application of such versatile pulsed sources to spectroscopy was clearly identified by the authors. Extension of the technique into the infrared followed, using Q-switched and Q-switched and mode locked Nd:YAG lasers as the pump (Cohen and Lin 1978, Lin et al. 1978) generating the familiar, distinct, cascaded Raman orders in the normal dispersion regime, and a soliton Raman continuum in the region of anomalous dispersion of the fibres which were hundreds of metres in length. In these early systems utilizing pump wavelengths around 1 μm and dispersion zero wavelengths greater than 1.3 μm, four-wave mixing processes were inefficiently phase matched and wavelength generation below the pump was orders of magnitude less intense than the Stokes Raman dominated contributions. However, by utilizing higher order mode propagation to phase matching, short wavelength generation enhancement was possible (Stolen 1975, Sasaki and Ohmori 1983).

The role of sum frequency generation between the pump radiation and long wavelength generated Stokes radiation was also recognized (Fuji et al. 1980) in the contribution to the short wavelength in the blue/green components of a supercontinuum, generated in a few metres of fibre, that extended from 300 nm to 2100 nm pumped by the 100 kW pulses from a Q-switched and mode locked Nd:YAG laser in a conventional early experimental configuration.

The importance of pumping in the region of low anomalous dispersion was also demonstrated (Washio et al. 1980) through the use of a Q-switched and mode locked Nd:YAG laser operating at 1.34 μm, such that the generated supercontinua exhibited the smooth spectral profile of a soliton Raman continuum instead of the more recognizable signature of discrete cascaded lines obtained in the normal dispersion regime. However, the mechanism for the smooth spectrum was not alluded to since soliton generation was in its infancy and it would also be several years before soliton Raman effects would be theoretically proposed and demonstrated (Vysloukh and Serkin 1983, Dianov et al. 1985). The efficiency of the Raman generated continuum and reduction of the required pump power with increasing fibre length was noted together with the highly efficient four-wave mixing in the region of the zero dispersion.

Early investigations were also carried out on continuum enhancement in multimode fibre in the region of low dispersion using dual pump wavelengths, a technique that would later be examined particularly in relation to seeded modulational instability in single mode fibre. It was shown (Nakazawa and Tokuda 1983) that the presence of the 1.34 μm component of a Nd:YAG laser gave rise to four-wave mixing with the 1.32 μm component pump which spectrally enhanced the generated supercontinuum compared to the discrete cascaded Raman orders obtained when pumping solely with the latter wavelength. The dual pump technique also led to a reduction in pump power for supercontinuum generation.

The early 1980s saw improved understanding of the processes contributing to supercontinuum generation and it was realized that self phase modulation alone could not account for the extent of the generated spectral broadening at a given pump power. Grigoryants et al. (1982) using nanosecond pumping of a multimode fibre demonstrated that it was essential to consider four-wave mixing as an important contribution to the continuum generation process, in addition to the role of sub-nanosecond pulse spiking within the envelope of their pump pulse. They also observed that a better understanding of supercontinuum generation would be gained by considering stochastic spontaneous oscillations and while the effects of noise on supercontinuum generation and soliton evolution dynamics have been considered in the intervening twenty-five years, it is still an important field of study even to the time of writing (Solli et al. 2007, Dudley et al. 2008).

By the mid-1980s research volume on supercontinuum generation was declining. However, as mentioned above, interest was still maintained in spectral broadening in fibres primarily as a result of extreme pulse compression through soliton effects. It had been shown (Mollenauer et al. 1980, 1983) that the breathing of high order solitons led to pulse compression and for solitons of order N, an optimum compression ratio of $4.1N$ was achievable. For low soliton orders and relatively long, picosecond input pulse durations the breathing solitons recovered their input durations following compression. However, for input pulses of high soliton order, extreme pulse compression led to femtosecond pulse durations (Tai and Tomita 1986b) in optimized fibre lengths. This technique was used to produce pulses of 18 femtoseconds, four optical cycles at 1.32 μm, with an associated self phase modulated dominated spectrum extending more than 200 nm, from 1200 nm to 1400 nm (Gouveia-Neto et al. 1988c). On propagation beyond the optimum compression length, perturbations, primarily arising from higher order effects such as self Raman interaction or higher order dispersion (Golovchenko et al. 1987a, Kodama and Hasegawa 1987) led to fragmentation of the high order soliton into its constituent or various "coloured" solitons which was later termed soliton "fission" (Hermann et al. 2002). This soliton compression, fragmentation and spectral shifting is an important mechanism contributing to the long wavelength extension of supercontinuum generation.

Following the theoretical prediction and experimental realization of broad band continua based on soliton Raman effects (Vysloukh and Serkin 1983, 1984, Dianov et al. 1985) the latter part of the decade saw extensive investigations of this mechanism for broad band generation using a variety of pump laser sources and pump pulse durations (Gouveia-Neto et al. 1987b, Grudinin et al. 1987, Vodop'yanov et al. 1987, Islam et al. 1989a). Many of these systems were pumped by pulses with durations in excess of 100 picoseconds and also laid the foundations for high average power supercontinuum generation with average output powers in some cases in the watt regime. Where the pump wavelength was in the region of normal dispersion the generated spectra exhibited the classic cascaded Raman orders up to the region of anomalous dispersion where soliton effects dominated and a continuum was formed. Pumping in the region of anomalous dispersion using a Nd:YAG laser operating at 1.32 μm, Gouveia-Neto et al. 1987b identified that modulational instability initiated the process and that the generated spectrum contained many fundamental solitons formed randomly in time from the Raman amplification of noise structures, which also gave rise to the characteristic smooth spectral profile. Multisoliton collisions in the presence of Raman gain were also shown to play a very important role in the wavelength extension of the continuum (Islam et al. 1989b). The spectral and temporal evolution of the continuum from modulational instability was characterized (Gouveia-Neto et al. 1989a) and it was also demonstrated (Gouveia-Neto et al. 1988a) that by Raman amplification of a seeded modulational instability signal the continuum could be generated at substantially lower overall pump power levels and the autocorrelations of the temporal signature demonstrated shorter pulses and lower pedestals indicative of fewer yet more powerful solitons within the continuum.

The soliton Raman continuum provided a source of widely tunable ultrashort pulses and the technique of spectral selection to provide such sources was patented as early as 1988 (Taylor et al.), however, since these Raman schemes are based on the evolution from noise signatures they are not appropriate for sources where low temporal jitter is essential (Keller et al. 1989). By the early 1990s, however, supercontinuum generation for source applications in wavelength division multiplexed systems was intensively investigated. Initially demonstrated by Morioka et al. (1993), a mode locked Nd:YLF laser producing 7.6 ps pulses was used to generate a relatively narrow supercontinuum extending from 1224 nm to 1394 nm in a 450 m long polarization maintaining fibre and from which 100 wavelength channels on a 1.9 nm spacing were selected using a periodic birefringent filter. The demands placed upon the spectral extent of the source for this application are somewhat less than usual, lying within the second and third telecommunications windows, however, it is important that the spectrum remains relatively flat over the required wavelength of operation and that the noise induced jitter of each channel is substantially less than the time window of the receiver. The role of amplified spontaneous emission or noise perturbing the amplitude and carrier frequency of a fundamental soliton, giving rise to jitter, has been well documented (Gordon and Haus 1986) as well as the elegant, yet simple, technique of spectral filtering, the sliding-guiding filter (Mollenauer et al. 1992), to minimize or negate the effect of jitter. Similarly, the Nakazawa group at NTT laboratories actively investigated the role of modulational instability or noise on high order solitons and demonstrated that spectral filtering in the region of the maximum modulational instability gave rise to improved supercontinuum stability (Kubota et al. 1999). The supercontinuum source was simplified through the use of an all-fibre amplified Er fibre laser and the nearly penalty-free transmission of 6.3 Gbit/s pulse trains was demonstrated (Morioka et al. 1994). The technique was developed extensively throughout the latter part of the decade with up to 1021 channels (Collings et al. 2000) being spectrally selected from the moderately broad continua and total transmission rates of 1 Tbit/s (10 channels at 100 Gbit/s) over 40 km (Morioka et al. 1996), while by employing distributed Raman amplification a 10 GHz repetition rate supercontinuum with an average power in excess of 1 W was generated (Lewis et al. 1998). To date, however, although successfully demonstrated in the laboratory the technique has not been implemented in the field.

Various techniques were used in order to develop spectrally flat continua with low temporal jitter for the wavelength division multiplexed application, although the demand on spectral coverage was quite modest since application was effectively limited to the Er gain bandwidth. Tapered fibres were employed (Mori et al. 1997, Okuno et al. 1998) where the fibres exhibited a dispersion flattened profile and the group velocity dispersion decreased along the length of the fibre, anomalous at input and normal at the output. The flattened third order dispersion inhibited break up of the short pulse solitons, while the adiabatic nature of the dispersion decreasing profile gave rise to soliton pulse compression, with associated spectral broadening and these highly compressed, high peak power pulses generate a self phase modulated dominated spectral broadening in the normal dispersion regime. On propagation through the region of nominal zero dispersion, the generation of very high order solitons leads to spectral and temporal instability. The enhancement of supercontinuum generation in a tapered, dispersion-decreasing fibre had been initially reported by Lou et al. (1997). However, the concept of the dispersion-decreasing fibre had been first proposed by Tajima (1987) to compensate for fibre loss and allow enhanced soliton transmission distances. Its application in the adiabatic compression of solitons was first proposed by Dianov et al. (1989b) and theoretically expanded and experimentally verified by Mamyshev et al. (1991). With extensive development of the technique for soliton pulse compression, particularly from sinusoidal beat signals in the early 1990s (Chernikov et al. 1992, 1993), for high bit rate generation, it was shown that the dispersion-decreasing fibre could be effectively broken up into its individual nonlinear and dispersive elements (Chernikov et al. 1994a) and controlled in a comb-like dispersion profiled multi-element fibre or more simply as a step-like dispersion-decreasing profiled fibre consisting of several segments (Chernikov et al. 1994b). The step-like dispersion profile was later reintroduced (Travers et al. 2005a) for the control of the phase matching conditions required for enhanced short wavelength generation for supercontinuum in photonic crystal fibres.

Increased stability in supercontinuum generation for WDM application was also achieved simply by pumping in the normal dispersion regime (Takushima et al. 1998), hence avoiding problems with soliton instability, or with solitons but by using short fibre lengths (Nowak et al. 1999) and consequently high powers, such that the high order solitons rapidly compress in the optimized length, and hence spectrally expand (Tai and Tomita 1986a, 1986b, Gouveia-Neto et al.1988c), while the spectrum is extracted before instability and soliton fission into various coloured solitons that would take place with further fibre propagation. Nowak et al. also employed a two-step dispersion-decreasing profiled fibre configuration. Through using tapers with relatively short (∼30 mm) and long waists (∼100 mm) manufactured through heating and stretching in a hydrogen flame, Birks et al. (2000) generated spectra that extended over two octaves from 370 nm to 1545 nm pumped by an unamplified 100 fs pulse length Ti:sapphire laser, with average power around 400 mW.

By the end of the 1990s the processes contributing to supercontinuum generation in fibres were well established and improved theoretical modelling (Gross and Manassah 1992) of these allowed similarly improved agreement between predicted performance and experimental observation. Although the principal thrust