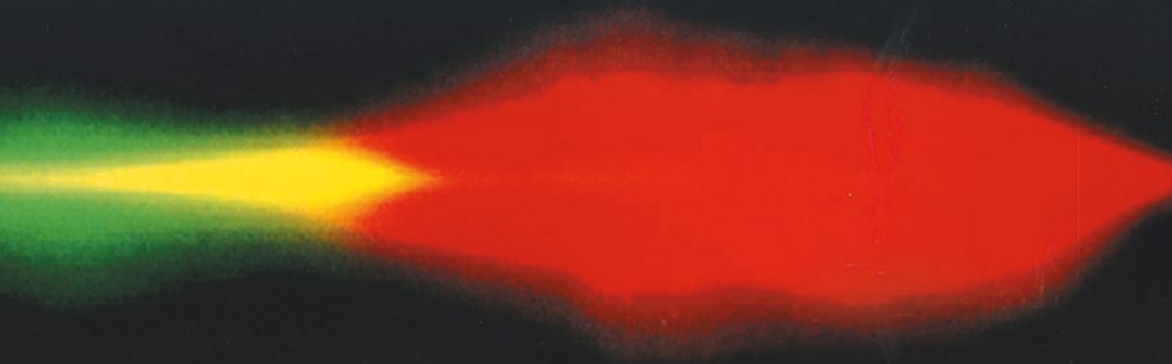
Robert R. Alfano *Editor*
Foreword by Donna Strickland

The Supercontinuum Laser Source

The Ultimate White Light

Fourth Edition



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Contents

Chapter 9
Supercontinuum in Telecom Applications

S. V. Smirnov, J. D. Ania-Castañón, S. Kobtsev, and S. K. Turitsyn

Abstract This chapter documents progress in the extensive area of supercontinuum (SC) generation research devoted to applications in telecommunications, including research into the different mechanisms of spectral broadening and their interplay, SC generation in various media and the most promising SC applications in fibre-based and free-space telecom.

Keywords Pump power · Optical fibre · Wavelength division multiplexing · Time division multiplexing · All-optical processing · Stimulate Raman scattering · Four-wave mixing · Photonic crystal fibre · Rogue wave · Orbital angular momentum

9.1 Introduction

Supercontinuum (SC) generation and spectral broadening of coherent or partially coherent light signals in optical fibres has captured much attention over the past couple of decades, fuelled by the advent of microstructured photonic crystal fibres (PCF) that can be designed for extremely high non-linear responses (Knight et al., 1996; Leong et al., 2005). Fibre-optic-based supercontinuum presents multiple practical applications both within and outside the field of optical communications (Holzwarth et al., 2000; Fedotov et al., 2000; He et al., 2002; Sanders, 2002; Hartl et al., 2001; Ivanov et al., 2001; Povazay et al., 2002; Wang et al., 2003a; Marks et al., 2002), and the interest in this phenomenon has led to an improved knowledge of the

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interplay between the different non-linear processes affecting high-power radiation evolution in optical fibre waveguides. By applying techniques such as frequency-resolved optical gating (FROG) (Kane & Trebino, 1993; Dudley et al., 2002a; Gu et al., 2002; Cao et al., 2003) and spectral-phase interferometry for direct electric-field reconstruction (SPIDER) (Iaconis & Walmsley, 1998, 1999; Anderson et al., 2000; Stibenz & Steinmeyer, 2004), researchers have been able to painstakingly analyse non-linearly broadened radiation, improve on the models used to describe the broadening process and increase our understanding of the phenomenon (Tamura et al., 2000; Appl. Phys. B **77**, No. 2–3 (2003) – Special Issue: Supercontinuum generation; Biancalana et al., 2003; Foster et al., 2004; Ranka & Gaeta, 1998; Dudley & Coen, 2002; Corwin et al., 2003a; Nikolov et al., 2003). From a purely practical point of view, the progress has also been impressive and has allowed, for example, for generation of high-power supercontinuum radiation (Cumberland et al., 2008; Chen et al., 2011; Chi et al., 2014) with spectra spanning more than one octave, and even reaching thousands of nm (Wadsworth et al., 2002; Nicholson et al., 2003a, 2004a; Takanayagi et al., 2005; Silva et al., 2012; Qin et al., 2009) in microstructured, tapered and highly non-linear fibres (HNLF). Broad supercontinua extending well into the mid-infrared region have been reported using ZBLAN HNLF fluoride fibres (Chenan et al., 2009), ZBLAN PCF (Jiang et al., 2015), chalcogenide tapered fibre (Petersen et al., 2014; Hudson et al., 2017), chalcogenide step-index fibre (Cheng et al., 2016) and silicon-on-sapphire nanowire (Singh et al., 2015).

Supercontinuum generation, first observed in 1970 by R.R. Alfano and S.L. Shapiro in bulk borosilicate glass (Alfano & Shapiro, 1970a), is an essentially non-linear phenomenon arising from synergic combination of several fundamental non-linear processes, most important of which are self-phase modulation (SPM), four-wave mixing (FWM) and stimulated Raman scattering (SRS). The interplay between different non-linear effects has a substantial impact on important SC properties such as homogeneity and coherence. These interactions between different non-linear processes are themselves determined by the pumps' spectral locations and powers and the non-linear and dispersive characteristics of the medium. In that regard, the development of PCFs offered interesting opportunities to control (to some extent) SC generation by using specially tailored fibre waveguides with desirable dispersive and non-linear properties (Reeves et al., 2003; Dudley et al., 2006). Large spectral broadening and SC in optical fibre at the telecom wavelengths was first demonstrated in (Nelson et al., 1983; Baldeck & Alfano, 1987), whereas the first application of photonic crystal fibre for SC generation was demonstrated in 1999 in (Ranka et al., 1999, 2000a).

Despite important recent advances in SC studies, and although the main mechanisms of SC generation are well understood, a number of fundamental problems are yet to be explored, and the complex interplay of intervening factors can be elusive. Hence, all-encompassing, universally valid, quantitatively precise numerical modelling for SC generation in optical fibre is yet to be fully realised. Important topics for basic research in this field have included the study of the noise and coherence properties (Dudley & Coen, 2002; Corwin et al., 2003a, b; Mori et al., 1998; Nakazawa et al., 1998; Kubota et al., 1999; Washburn & Newbury, 2004; Kelleher et al., 2012) of SC, analysis of the effect of polarisation (Proulx et al., 2003; Lehtonen et al., 2003) in the non-linear broadening process, the observation of extreme temporal events such as rogue waves (Dudley et al., 2008) or formulation of a general theory of SC generation based on wave turbulence (Barviau et al., 2009; Swiderski & Michalska, 2013), to name a few.

From an application standpoint, a healthy fraction of the current research is focused on exploitation of fibre-optically generated spectrally broadened radiation, whether in bio-medical optics, where it allows for the improvement of longitudinal resolution in optical coherence tomography by more than an order of magnitude (Hartl et al., 2001; Povazay et al., 2002; Wang et al., 2003a, b; Marks et al., 2002; Drexler et al., 1999; Fercher et al., 2003; Drexler, 2004); in optical frequency metrology, where a revolutionary breakthrough has been achieved (Holzwarth et al., 2000, 2001; Fedotov et al., 2000; He et al., 2002; Sanders, 2002; Jones et al., 2000; Diddams et al., 2000a, b, 2001; Bellini & Hänsch, 2000); or in many other areas from material science (Wang et al., 2003c) to telecommunications. Note that in some telecom applications, in contrast to the technologies mentioned above, ultra-large broadening associated with SC generation is not a desirable feature at all, and many useful applications require moderate or even minimal spectral broadening of the signal or pumping wave. The aim of this manuscript is to provide the reader with a general overview of the recent development of spectral broadening applications and SC generation in the particular area of optical communications.

9.2 Basic Physics of Optical Spectral Broadening and SC Generation in Fibres

Light radiation propagating through a non-linear medium experiences spectral broadening that can be very substantial under certain conditions. SPM—an effect caused by dependence of the refractive index on the intensity of the transmitted light (Kerr non-linearity)—has been identified in the early works on continuum generation (CG) of 4-ps-long laser pulses propagated through bulk samples of different glasses and crystals (Alfano & Shapiro, 1970a, b) as the main mechanism responsible for generation of ~50-THz-wide spectra. In a medium with Kerr non-linearity, after propagation over the distance z, an optical pulse acquires an additional phase (due to non-linear part Δn of the refractive index) that can be estimated (Agrawal, 2001) as:

$$\varphi_{NL}(z,t) = \Delta n \cdot \frac{\omega}{c} z = n_2 I(t) \cdot \frac{\omega}{c} z \tag{9.1}$$

The corresponding frequency shift then is:

$$\delta\omega(z,t) = -\frac{d}{dt}\varphi_{NL}(z,t) = -n_2\frac{dI(t)}{dt}\cdot\frac{\omega}{c}z \tag{9.2}$$

where n_2 is the non-linear refractive index of the medium, ω the carrier frequency, c the light speed in vacuum and I the power flux density. It can be seen from (9.2) that, as the optical pulse propagates, the frequency at its leading edge decreases and that at the trailing edge, conversely, increases. Spectral broadening is proportional both to the energy flux and to the propagation distance; therefore, SPM can be amplified due to self-trapping, which was reported in (Alfano & Shapiro, 1970b). When the pump power is greater or about 10 TW/cm^2, which can be reached in light filaments, free-electron plasma formation can also occur, further strengthening the effect of SPM (Bloembergen, 1973).

One of the primary inherent disadvantages of CG schemes based on bulk media (also including those based on liquids (Werncke et al., 1972; Smith et al., 1977) and gases (Corkum et al., 1986; Corkum & Rolland, 1989; François et al., 1993) as non-linear media) is a requirement of high pump powers. Typical level of power density required is around several terawatts per cm^2, thus necessitating additional amplification of laser pulses at the risk of sample damage. It became possible to relax such high pump power requirements during the next phase of SC generation studies by using optical fibres as non-linear medium (Tamura et al., 2000; Lin & Stolen, 1976; Baldeck & Alfano, 1987; Morioka et al., 1993). The required pump power was lowered, on the one hand, due to a substantially longer path of interaction between light and matter and, on the other hand, thanks to a higher localisation of radiation. Thus, for example, dispersion length for 4-ps-long Gaussian pulses at 530 nm in standard SMF-28 is about 80 m, or 5.3×10^4 times larger than the length of light filaments observed in (Alfano & Shapiro, 1970b), which amounted to about 1.5 mm. The effective area of SMF-28 at 530 nm is about 50 μm^2, which is 30–60 times smaller than the area of power concentration estimated for 5–10 light filaments having diameter of 20 μm each as observed in (Alfano & Shapiro, 1970b). Correspondingly, generation of continuum covering a significant part of the visible spectrum became possible with a peak pump power of only 1 kW (Lin & Stolen, 1976), whereas the power used to induce CG in glasses was about 200 MW (Alfano & Shapiro, 1970b).

In early experiments using optical fibres (Lin & Stolen, 1976; Baldeck & Alfano, 1987), continuum was formed by broadening and merging of separate spectral lines, generated due to SRS and FWM. Phase matching conditions for the latter were met as a result of multi-mode propagation of light through the fibre. SPM could not contribute considerably to the spectrum broadening because of low power density and comparatively long pulses (within picosecond and nanosecond range), so that the value of dI/dt in (9.2) was small compared to those typical in bulk media experiments.

In the next generation of fibre experiments on SC generation, however, SPM plays a key role again, allowing one to obtain flat spectra with good noise parameters in the normal dispersion regime. By using additional optical elements with negative second group velocity dispersion β_2, it is possible to achieve temporal compression of pump pulses as well (Fisher et al., 1969; Gouveia-Neto et al., 1987; Tomlinson et al., 1984). With this method, it was possible to generate pulses as short as 6-fs (Fork et al., 1987). Another physical mechanism of spectral broadening is based on adiabatic soliton compression in a fibre with decreasing dispersion (Tamura et al., 2000; Tamura & Nakazawa, 1998; Mori et al., 1997; Okuno et al., 1998). A relative disadvantage of this method is instability of higher-order solitons in the presence of noise, which imposes an upper limit on the pump power and, hence, on the resulting spectral width.

One can also combine these two approaches using specially designed fibres with dispersion smoothly changing along the fibre from positive to negative values (Mori et al., 1997, 2001; Okuno et al., 1998).

The most recent period of CG investigations is associated with the development of PCFs (Knight et al., 1996, 1997, 1998a, b, c; Birks et al., 1997; Broeng et al., 1998; Mogilevtsev et al., 1998; Silvestre et al., 1998). Essentially, they consist of quartz fibres sheathed in a conduit formed by two-dimensional (usually regular) array of air-filled capillaries (Zheltikov, 2000). It is pertinent to note that there are two different types of fibres called PCF. The first of them proposed in 1996 (Knight et al., 1996) has a quartz core with refractive index greater than the average refractive index of cladding formed by an array of air capillaries. The principle of light propagation in this type of fibre is similar to that in standard optical fibres where the condition $n_{core} > n_{cladding}$ is also met. Fibres of the second type introduced in 1999 (Cregan et al., 1999) have an air channel in the core, so that the inverse inequality holds: $n_{core} < n_{cladding}$. These fibres can be considered as two-dimensional crystals, and a single or several holes (capillaries) absent in the centre of the lattice can be treated as a defect. Light propagation along this type of fibre is possible due to the photon band-gap effect. One of the most important applications of the hollow-core PCF is in high-power lasers, since breakdown threshold in gases is much higher than in solids (Zheltikov, 2000), and thus special efforts are required to obtain intense SC in condensed media (Lu et al., 2014). In this paper, we will use the term PCF for fibres of the first type—guiding light through the effect of total internal reflection.

Compared to conventional optical fibres, PCF presents several significant advantages. First of all, this type of fibre gives a quite unique opportunity of dispersion control. This is possible because penetration of electro-magnetic field into the fibre cladding (and hence, its effective index of refraction) depends on the wavelength of radiation inside the fibre. As a result, the refractive index of the cladding at different wavelengths can be controlled by arranging capillaries in a certain way at the time of pulling. This technique was used to create fibres with flat dispersion profile (Ferrando et al., 1999, 2000, 2001; Reeves et al., 2002; Renversez et al., 2003; Saitoh et al., 2003; Poli et al., 2004; Saitoh & Koshiba, 2004), which allow generation of flat and wide SC spectra. In addition, one can shift the zero dispersion wavelength λ_{ZD} of PCF and produce anomalous dispersion in the visible spectral region (Knight et al., 2000; Ranka et al., 2000b). It is the latter feature that made it possible to generate SC spanning more than two octaves (Ranka et al., 2000a). Another advantage is that PCF can be designed to support only one spatial mode in a wide spectral range (Birks et al., 1997; Mogilevtsev et al., 1998) having rather small effective area of the waveguide mode.

We note also a special type of PCF called free-strand or cobweb fibre (Wadsworth et al., 2002; Apolonski et al., 2002). The quartz core of such waveguides is attached to the cladding by a cobweb-like structure of thin bridges, from which the name of the fibres comes. Since the core of cobweb fibres is almost entirely surrounded by air, the structure of these waveguides is similar to that of air-clad tapered fibres (ACTF). Continuum spectra generated in these two types of fibres under the same conditions are nearly identical (Wadsworth et al., 2002). In particular, CG spanning two octaves was observed in ACTF (Birks et al., 2000; Akimov et al., 2002). Soliton self-frequency shift of several hundred nm was also demonstrated in ACTF (Kobtsev et al., 2004) and cobweb fibres (Kobtsev et al., 2005). ACTF have some advantages such as an easier fabrication process compared to PCF, as they can be made by pulling a heated conventional single-mode fibre. On the other hand, the design freedom is limited, since there is practically only one single parameter of ACTF that can be controlled—its waist diameter, which means there are limitations on the fabrication of ACTF with the required dispersion characteristics. Besides, it is quite complicated to make long ACTF due to fragility of very thin quartz strand.

Microstructured fibres can be designed within a huge range of possible dispersive characteristics and parameters, and their non-linearity can be rather large due to a small effective area. These remarkable features call into play a plethora of non-linear mechanisms of spectral broadening in PCF that may differ depending on waveguide dispersion profile, power, wavelength and duration of pumping pulses. For example, using femtosecond pump pulses within the anomalous dispersion region, most of the authors point out a key role of soliton effects in CG (Ortigosa-Blanch et al., 2002; Genty et al., 2002; Husakou & Herrmann, 2001; Herrmann et al., 2002). The red wing of the spectrum generated under these conditions is formed due to soliton self-frequency shift (Gordon, 1986; Mitschke & Mollenauer, 1986; Reid et al., 2002), while the blue one is a result of resonant energy transfer and soliton fission. In the case when a femtosecond pump falls within the normal dispersion region, CG develops in two stages. First, the spectrum of the pumping pulse is broadened to the point of zero dispersion due to SPM and SRS, upon which soliton effects come into play (Ortigosa-Blanch et al., 2002). Parametric processes and Raman scattering are also observed to contribute to CG under these circumstances (Genty et al., 2002).

When duration of pumping pulses is within the picosecond and nanosecond domain, SPM does not affect CG significantly. Spectral broadening is usually assumed to occur as a result of SRS giving rise to a series of spectral lines, each of which, once emerged, can act as a pump source for parametric processes. Phase matching conditions can be met in this case due to proximity of the zero dispersion wavelength (Dudley et al., 2002b; Coen et al., 2001, 2002). When energy is transferred into the region of anomalous dispersion, modulation instability (MI) and soliton effects come into operation and broaden the spectrum further (Knight et al., 1996; Coen et al., 2001).

Let us illustrate in more detail the spectral broadening of femtosecond pump pulses propagating in anomalous dispersion region, this case being the most frequent in CG studies. To do this we will examine the dynamics of spectrum broadening as a function of pump power. Figure 9.1 shows simulated spectra of chirp-free 60-fs-long sech^2 pulses after passing 10 cm through a 2.3-μm-diameter ACTF waist. Pump pulse power increases from 0.5 kW for the bottom graph (Fig. 9.1a) up to 20 kW for the top graph (Fig. 9.1f). The pump pulse spectrum is shown in the bottom of Fig. 9.1 with a dotted line. Our simulations are based on the generalised nonlinear Schrödinger equation (Agrawal, 2001) which is mostly used for theoretical modelling of CG when polarisation effects can be averaged out or neglected. Continuum spectra given in Fig. 9.1 are typical for the case of a femtosecond pump; similar results can be found in numerous published papers (Dudley et al., 2002a, b; Dudley & Coen, 2002). When $P_0 = 0.5$ kW (Fig. 9.1a), the pump pulse spectrum is broadened due to SPM. As the pump peak power reaches 2.5 kW (Fig. 9.1b), a peak at the long-wavelength side of the spectrum emerges. It corresponds to an optical soliton, which experiences an increased shift of its frequency farther into IR region as the pump power grows, thus leading to further spectral broadening. Besides, in this process, the number of solitons also increases, and their spectra begin overlapping and form the red wing of the continuum spectrum. As the pump power rises, the spectrum is also broadened toward shorter wavelengths. The position of the short-wavelength spectrum edge depends on the fibre dispersion and is governed by the equality of temporal delays for long- and short-wavelength components of continuum radiation, which agrees with the model of resonant energy transfer into the short-wavelength part of the spectrum mentioned above.

Reports on observation of spectral broadening in media or with light sources never used before with the purpose of CG constituted a significant part of early papers in this field, and they did not cease to appear till now. Among these are, for example, generation of broadband continuum directly in Ti/Sa laser (Morgner et al., 1999; Bartels & Kurz, 2002), CG in fibres with continuous wave pump (Nicholson et al., 2003b; González-Herráez et al., 2003; Avdokhin et al., 2003; Abeeluck et al., 2004) and CG in new types of fibres and waveguides (Phillips et al., 2011; Zhang et al., 2006; Hsieh et al., 2007; Liao et al., 2009; Hudson et al., 2011). However, at the present phase of CG studies, papers of another sort are more common. They are dedicated to investigation of different properties of continuum radiation, such as spectral shape and width (Wadsworth et al., 2002; Mori et al., 2001; Apolonski et al., 2002; Teipel et al., 2003; Tianprateep et al., 2004; Kobtsev et al., 2003), temporal structure (Dudley et al., 2002a; Dudley & Coen, 2002; Teipel et al., 2003; Kobtsev et al., 2003; Bagaev et al., 2004; Zeller et al., 2000), polarisation (Knight et al., 1996; Apolonski et al., 2002; Kobtsev et al., 2003), noise and coherence (Tamura et al., 2000; Dudley & Coen, 2002; Bellini & Hänsch, 2000; Apolonski et al., 2002; Kobtsev & Smirnov, 2006; Demircan & Bandelow, 2007; Heidt et al., 2017), as well as to research into dependence of these properties on conditions of CG. Aside from this, a considerable number of papers seek to understand the physical mechanisms of spectral broadening (Knight et al., 1996; Dudley et al., 2002a, b; Ortigosa-Blanch et al., 2002; Genty et al., 2002; Husakou & Herrmann,

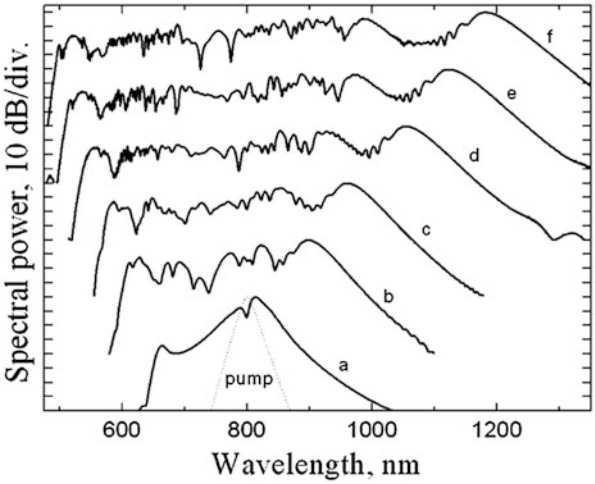

Fig. 9.1 Simulated spectra at the exit of 10-cm-long tapered fibre waist with diameter of 2.3 μm. We use 60-fs-long sech^2 pump pulses at $\lambda = 800$ nm. Pump peak power is 0.5 kW (for graph *a*), 2.5 kW (*b*), 5 kW (*c*), 10 kW (*d*), 15 kW (*e*) and 20 kW (*f*). The pump pulse spectrum is shown at the bottom with a dotted line

2001; Herrmann et al., 2002; Gaeta, 2002; Gorbach & Skryabin, 2007; Skryabin et al., 2003). The practical goal of most of these studies is to optimise continuum generation for diverse applications or even to make SC generators controllable (Kobtsev & Smirnov, 2008a; Genty et al., 2009; Cheung et al., 2011), since each application sets its own specific requirements to the SC properties. For instance, spectroscopic and some other applications require SC in different spectral areas, so that generation of mid- and near-IR SC in short waveguides of different types (Domachuk et al., 2008; Kurkov et al., 2011; Geng et al., 2012; Granzow et al., 2011; Lopez-Galmiche et al., 2016), producing ultra-broadband SC spectra (Silva et al., 2012; Qin et al., 2009), extending SC toward UV (Qin et al., 2009; Kudlinski et al., 2006; Belli et al., 2015; Jiang et al., 2015) and terahertz CG (Kim et al., 2008) and bandwidth maximising/restriction and spectral tailoring (Hu et al., 2010; Bétourné et al., 2009; Kudlinski et al., 2009) are of particular interest. Another example of contradictory requirements is related to the power level, so that both low-threshold (Hudson et al., 2011; Yeom et al., 2008) and high-power SC (Cumberland et al., 2008; Kudlinski & Mussot, 2008; Chen et al., 2010) are interesting for different applications.

As far as telecom applications are concerned, the spectral flatness and temporal parameters of continuum are of a prime importance in development of multiplexing schemes for fibre communication systems. Development of broadband Raman fibre amplifiers requires a high degree of spectral uniformity of the gain factor, and a continuum with a specific spectral profile $I(\lambda)$ can be used as a pump source to solve this problem in a cost-efficient way, avoiding multi-pump schemes.

Let's also note that optical fibre is obviously a very convenient optical medium for experimental investigations into SC generation as well as an appropriate basis for commercial SC generators. That's why the majority of recent studies deal with optical fibres, especially in what concerns telecom applications. However, there is another one very promising research area that is paid a constantly growing attention and that is expected to further gain research focus in the future, namely, on-chip (nano-photonics) SC generators. There have been a number of reports on broadband SC generation in different types of waveguides including silicon (Kuyken et al., 2011; Safioui et al., 2014; N. Singh et al., 2015, 2018; Ettabib et al., 2015), silicon nitride (Johnson et al., 2015; Epping et al., 2015) and others.

9.3 Application of Spectral Broadening and Continuum Generation in Telecom

In this section, we overview the main applications of the spectral broadening effect and SC generation in optical fibre communications. The idea of main SC applications is outlined, whereas in the next section, we will discuss preferable conditions of SC generation that should be met in order to better fulfil the requirements of SC applications in telecom.

9.3.1 Pulse Compression and Short Pulse Generation

Ultrashort optical pulses form the foundation of optical telecom systems. Information transmitted through telecom lines are encoded using amplitude and phase of such pulses. Therefore, it is essential for telecom to have reliable low-noise sources of high-quality ultrashort laser pulses, especially broadband or multi-wavelength sources. The latter can be used for simultaneous transmission of many information channels through a single optical fibre, known as wavelength division multiplexing (WDM) technology, which is the optical analogue of frequency-division multiplexing commonly used for radio transmission.

Islam et al. (1989) demonstrated application of non-linear broadening to generation of femtosecond pulses. When a fibre is pumped in the anomalous dispersion regime with a narrow-spectrum laser, modulation instability and the soliton self-frequency shift initiate a multi-soliton collision that generates a series of short, low-intensity solitons. On the other hand, non-linear temporal compression has been for a long time a well-known technique for generating ultrashort pulses (Tomlinson et al., 1984; Shank et al., 1982). In this technique, the spectrum of the signal is first non-linearly broadened, and the chirp is then eliminated by a dispersion-compensating element. Südmeyer et al. (2003) have recently demonstrated that the use of microstructured fibres, combined with a prism pair for chirp elimination, would make it possible for this method to be applied at very high power levels, obtaining a train of 33 fs pulses with peak power of 12 MW, whereas Schenkel et al. (2003) employed gas-filled hollow fibres for the broadening, together with a spatial light modulator using SPIDER measurements as a feedback signal for adaptive pulse compression and generation 3.8-fs pulses with energies up to 15 μJ.

The fundamental limits on generation of few-cycle pulses by compression of SC spectra generated in microstructured fibres have been analysed by Dudley & Coen (2004), confirming that quality of compressed pulses was closely related to spectral coherence of the SC. According to their work, a median coherence of about 0.7 could be expected to be a good benchmark for the potential compressibility of SC down to few-cycle pulses, provided compressors with sufficiently high resolution to compensate for the fine structure in the SC group delay were made available in the future.

Conversely, high-power ultrashort pulse sources obtained with techniques such as the ones explained above can be used as the input to generate ultra-broadband octave-spanning SC radiation in optical fibres, as illustrated, for example, by the works of Takanayagi et al. (2005) and Nishizawa and Goto (2001). Stretched femtosecond pulses have been used by Nicholson et al. (2004b) in the development of a high-repetition-rate, swept-wavelength Raman pump source.

9.3.2 Pulse Train Generation at High Repetition Rates

Quite a simple and convenient technique for producing an ultrashort pulse train of high repetition rate was suggested by Hasegawa (1984) and for the first time was implemented by Tai et al. (1986) as early as 1986. This technique utilises the effect of induced modulation instability, i.e., growth of initial relatively small-intensity modulation amplitude of CW radiation due to modulation instability (MI). Such spectral sideband growth is an initial stage of spectral broadening and SC generation.

Since the first demonstration, a number of groups proposed different modifications and improvements of this method (see, for instance, Dianov et al., 1989; Chernikov et al., 1993, 1994; Tadakuma et al., 2000; Pitois et al., 2002). Specifically, using numerical modelling (Dianov et al., 1989) and experiment (Chernikov et al., 1993), it was demonstrated that application of optical fibres with adiabatically decreasing dispersion or optical amplifiers allows one to produce periodic trains of non-interacting solitons. Also it was shown that optical fibres with longitudinal step dispersion profile (Chernikov et al., 1994; Tadakuma et al., 2000) allow one to obtain periodic soliton trains. Paper Pitois et al. (2002) theoretically and experimentally demonstrated that generation of regular spectral-limited Gaussian pulses is possible in passive optical fibres with longitudinally constant dispersion provided the pumping wave has optimal power.

Various groups reported generation of ultrashort pulse (USP) trains with repetition frequency in the range between 60 GHz (Chernikov et al., 1994) and 340 GHz

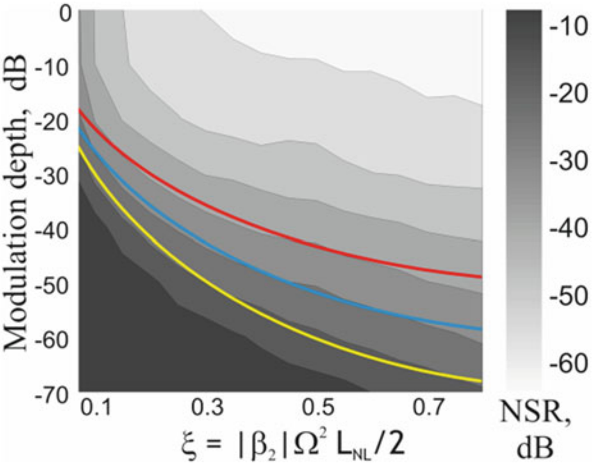

Fig. 9.2 Dependence of noise-to-signal ratio at the fibre exit on parameter ξ and modulation depth I_S/I_0

(Tai et al., 1986). Achieved relatively high USP repetition rates constrain substantially the application field of this technique, since most applications including telecom require post-processing of such pulse train by electronic means. This fact stimulates development of methods for changing and lowering pulse repetition rate attainable with this technique. For example, paper by Chernikov et al. (1993) reported pulse train generation with repetition rate of 80–120 GHz. In the past decade, USP generation with much wider range of repetition rates from 20 GHz up to 1 THz was produced (Fatome et al., 2006). As it has been shown recently (Kobtsev & Smirnov, 2008b), there is a fundamental problem preventing arbitrary low repetition frequencies with the use of induced MI, namely, noise amplification. It can be easily seen, if we consider initial modulation in terms of square of dimensionless frequency $\xi = -\beta_2 \Omega^2 L_{NL}/2 = (\Omega/\Omega_c)^2$, where $L_{NL} = (\gamma P)^{-1}$ stands for non-linear fibre length, γ is fibre non-linearity and P is power of CW pump, that Ω_c is the frequency scale introduced in (Agrawal, 2001). Figure 9.2 shows the results of NLSE-based full numerical modelling (Kobtsev & Smirnov, 2008b) for output pulse train noise-to-signal ratio (NSR) as a function of input modulation depth I_S/I_0 and modulation frequency square ξ. Note that the NSR reaches its minimum at large values of initial modulation depth (0.1 … 1) and large values of ξ (minimum is reached at $\xi = 1$, whereas the plot shows the range $0.08 < \xi < 0.8$). As the modulation depth is reduced and/or ξ is decreased, NSR worsens and reaches unity (0 dB) in the lower left part of the area plotted in Fig. 9.2, which corresponds to completely "noisy" generation mode and irregular temporal structure of the formed pulse train. This result allows estimation of the minimal pulse repetition frequency for a given NSR and explains the problem of producing pulse frequencies lower than 1 GHz using induced MI (Kobtsev & Smirnov, 2008b).

9.3.3 Multi-wavelength Optical Sources

One of the most important applications of SC to the field of telecommunications is the design of multi-wavelength sources for ultra-broadband wavelength-division-multiplexed (WDM) systems based on spectral slicing of SC generated by a single laser. As it was mentioned in the previous section, a powerful short optical pulse can be non-linearly broadened into a SC spectrum. This spectrum can then be sliced with an array of filters to create a series of WDM channels. This was the approach originally adopted by Morioka et al. (1993) using short (few ps) pulses with GHz repetition rates in dispersion-decreasing fibre (DDF) to create WDM pulsed sources, and different variations have been implemented by multiple authors (Dudley et al., 2008; Morioka et al., 1996; Tamura et al., 1996; Sotobayashi et al., 2002a; Takara et al., 2000, 2003a; Yusoff et al., 2003; Mori et al., 2003; Takada et al., 2002; Miyagawa et al., 2006; Ohara et al., 2006) ever since. In particular, a long-haul data transfer was demonstrated, including distances over 1000 km (Takara et al., 2003a).

The ultimate limit for dense packing of WDM channels in a SC generated from a pulsed source is imposed by the spectral distance between cavity modes in the original mode-locked laser. In a medium with normal dispersion, cascaded non-linear processes used to broaden the spectrum preserve the structure of cavity modes (Alfano, 1989) present in the original laser output. This makes it possible to generate an optical frequency comb, in which the separation between peaks corresponds to the microwave mode-locking frequency of the source laser, with accuracy of the order of kHz (see Sect. 9.4.3 on frequency combs). Each peak can be considered as potential transmission channel. This property was used by Takara et al. (2000) to generate more than 1000 optical frequency channels with a channel spacing of 12.5 GHz between 1500 and 1600 nm. Out of those, between 600 and 700 were demonstrated to offer SNRs and Q-Factors sufficient for 2.5 Gbit/s multi-span transmission. Following the same principle, Takara et al. (2003b) recently reported 124 nm seamless transmission of 3.13 Tbit/s, over 160 km using 313 10 Gbit/s channels spaced at 50 GHz. In their experiment, they used Raman amplification in hybrid tellurite/silica fibre for improved gain flatness. In an even more recent experiment from the same group, Ohara et al. (2005) demonstrated transmission of over 1000 channels, with a 6.25 GHz spacing, using a SC multi-carrier source. In Ref. Takada et al. (2002), supercontinuum radiation within the 1460–1620 nm range was subdivided into 4200 channels spaced 5 GHz apart, and paper by Miyagawa et al. (2006) reports the highest channel count of 10,000 with individual channels spaced at 2.5 GHz within the range of 1460–1640 nm and per-channel data rate of 1.25 Gbit/s. The conservation of coherence properties was also successfully employed by Sotobayashi et al. (2002b) to create a 3.24 Tb/s (84 channels × 40 Gbit/s) WDM source of carrier-suppressed return-to-zero (CS-RZ) pulses. By generation of SC in a normal dispersion fibre, the relative phase between adjacent pulses is preserved in different channels, allowing for the multiplication of the CS-RZ structure. More recently, but following a related approach, multi-channel coherent OFDM sources relying also on SC-generated optical frequency combs have allowed capacities of up to 32.5 Tbit/s (Hillerkuss et al., 2011, 2012).

SC WDM sources can be of great utility in more modest systems: Kartapoulos & Bouhiyate (2005), for example, studied the use of supercontinuum sources in coarse WDM applications with channel protection and concluded that in systems with a limited number of channels, the use of supercontinuum WDM sources can result in lower costs and increased reliability.

9.3.4 All-Optical Analogue-to-Digital Conversion

All-optical analogue-to-digital conversion, signal processing and switching are very promising technologies that open new horizons in ultra-high-speed data transmission by allowing one to overcome bit rate limits imposed by electronics.

In a series of recent papers (Oda et al., 2004; Oda & Maruta, 2004, 2005a), Oda et al. proposed and successfully demonstrated a novel quantisation scheme for all-optical analogue-to-digital conversion based on splicing of the non-linearly broadened spectrum of a train of short pulses by means of an arrayed waveguide grating (AWG).

By varying the power of the input pulses by means of an erbium-doped fibre amplifier (EDFA) prior to their launch into a section of dispersion-decreasing fibre (DDF), they were able to generate a series of non-linearly broadened quasi-symmetrical spectra, in which the degree of broadening was directly dependent on the amount of power injected into the fibre. The broadened spectra were then passed through an AWG providing a series of output ports set on the Stokes side of the initial signal. The number of ports that are "on" (i.e., the number of ports that transmit power above a certain threshold) for each spectrum depends on the amount of broadening and thus on the power of the input pulses. This imaginative solution, partially based on the work of Ho et al. (1997), still has to overcome some important problems, such as high average power requirements of the first prototype, but could open the door to a new generation of all-optical analogue-to-digital convertors. A later refinement (Oda & Maruta 2005b) uses a NOLM for coding of the signal after slicing. Since the proposed solution relies only on fibre non-linearity, and not on electronic devices, it can operate beyond 40 GHz.

9.3.5 TDM-to-WDM-to-TDM Conversion

Basically, there are two major approaches for combining low-speed data channels from different local networks into a single high-speed optical telecom line: multiplexing in wavelength and in time. The latter method known as time-division multiplexing (TDM) relies on synchronised switching of communication channels so that the signal from each channel is fed into the high-speed line only for a fraction of time in an alternating pattern. In contrast, information from different WDM channels is transmitted simultaneously being separated spectrally rather than temporally. Both technologies are widely used to considerably (up to several orders of magnitude) improve the transmission capacity of telecom lines. WDM-to-TDM conversion is required between low-bit-rate WDM data stream and high-bit-rate TDM data stream and vice versa (e.g., at a gateway between local-, metropolitan- and wide-area networks). All-optical multiplexing/demultiplexing schemes allow one to go beyond the present limitations of electronic gateways and thus to further increase achievable bit rates.

Sotobayashi et al. (2001, 2002a) proposed and demonstrated the concept of a photonic gateway able to perform conversion from time-division-multiplexed (TDM) signals to WDM signals and vice versa by using SC generation. Their scheme is based on combining ultrafast photonic processing in both the time and the frequency domain, using optical gating and time shifting in the time domain, combined with non-linear broadening under normal dispersion and spectral slicing.

In order to convert from TDM to WDM, the signal is first amplified and then non-linearly broadened. The spectral properties of SC generated under normal dispersion (high coherence, flat spectrum, easily equalised channel power, similar pulse width in different frequencies and relative independence of the spectrum from the input pulse characteristics) make possible generation of a series of independent channels through spectral splicing, all of them carrying the same sequence of pulses as the original signal. By time-shifting different channels and using an optical time gate with the appropriate repetition rate, it is then possible to split the information between the newly created WDM channels, effectively switching from TDM to WDM.

For the opposite conversion, the process starts by differentially time-shifting the input WDM channels, so the bits transmitted at different frequencies are all in temporal sequence. Then, non-linear broadening effectively performs superposition of all the different channels, and spectral splicing selects a single channel at the central frequency, which now contains the complete bit sequence.

The solution, of course, is not without its drawbacks. Although quite robust with respect to input pulse quality and featuring good noise performance, its response is polarisation dependent (because of the time-gating devices), and its application is limited to the return-to-zero format. It is nevertheless an excellent illustration of the possibilities that non-linear broadening has opened in terms of adding flexibility to signal manipulation.

9.3.6 Optical Fibre Characterisation

Optical fibre plays crucial role in state-of-the-art telecom industry. Besides standard SMF fibres following ITU-T G.652 recommendations, such as SMF-28, used for long-haul data transmission, there is a plethora of types of optical fibres used for amplification, dispersion compensation, optical processing, etc. In order to improve existing legacy telecom systems, new types of fibres are constantly invented with tailored dispersion and non-linearity. SC provides a convenient, quick and cost-effective way for characterisation of optical fibres in a wide spectral range. Measurements of wavelength-dependent attenuation can be made simultaneously over a wide bandwidth, and group-velocity-dispersion (GVD) measurements in conventional fibre with group delay resolutions of 0.01 ps/km in fibre lengths of up to 130 km over more than 600 nm, using SC white pulses as was demonstrated by Mori et al. (1995). GVD measurements can also be carried out in non-typical media such as tapered air-silica microstructure fibres by means of white-light interferometry with the help of broadband sources, as demonstrated by Ye et al. (2002). Spectral interferometry with a SC source was also used by Jasapara et al. (2003) to perform GVD measurements in photonic bandgap fibre. González-Herráez et al. (2003) showed that continuous-wave generated SC could be effectively used to perform accurate, long-range (>200 km) measurements of polarisation mode dispersion in fibres (see Sect. 9.4.4 for more information on CW-generated SC).

9.3.7 Frequency Combs

One of the most fascinating applications of SC generation, which has revolutionised optical frequency metrology and may potentially have impact on telecom, is frequency comb generation. An optical frequency comb is an optical spectrum showing spectral lines at fixed frequency spacing. A simple example would be the longitudinal mode structure at the output of a mode-locked cavity laser. By measuring frequency separation between laser radiation at a given frequency f and its second harmonic $2f$, the laser's absolute frequency can be determined. Hence, frequency combs can be used as "optical rulers" for high-precision spectroscopy and, by extension, for high-precision frequency or time-based metrology, achieving accuracies of one part in 10^{17} in the measurement of optical clocks (Newbury, 2011; Ye & Cundiff, 2005). In order for a frequency comb to be used for the purpose of determining absolute frequency, its spectrum must span at least a complete optical octave. The development of optical frequency combs earned Profs. John L. Hall and Theodor W. Hänsch one half of the Nobel Prize in Physics in 2005.

Non-linear broadening is the key for generation of at-least-octave-spanning optical frequency combs, and multiple different methods have been proposed and applied that go beyond the scope of this chapter. Let it be mentioned, as a typical example (Ye & Cundiff, 2005), that a stable (one allowing for multiple hours of continuous operation) frequency comb can be generated by non-linearly broadening a high-powered output pulse train from a mode-locked fs fibre laser in a single-mode HNLF. It is important that broadening in the HNLF takes place under controlled effective dispersion and that noise gain is kept sufficiently low not to spoil the spectral comb structure.

Potential applications of frequency combs in telecommunications can be grouped into two distinct groups: namely, those related to extremely precise transmission of signals and those related to transmission of high-speed optical data.

The former makes use of phase coherence and broad bandwidth of frequency combs and could theoretically and through the use of Doppler-compensated fibre links (Newbury, 2011) be used to couple optical clocks with uncertainties of one part in 10^{19}.

The latter application relies on the use of narrow-band, chip-scale frequency combs to enable highly parallel WDM or OFDM with tens or hundreds of channels, in which multi-Terabit/s rates can be achieved while symbol rates are kept low enough to stay compliant with electronics speed limitations (Hillerkuss et al., 2011, 2012; Levy et al., 2012). So far, frequency combs have been successfully applied in this type of Terabit/s optical interconnects to demonstrate 26.2 Tbit/s encoding-decoding with OFDM and up to 32.5 Tbit/s with Nyquist WDM, with net spectral efficiencies of 6.4 bits/Hz. These schemes have been demonstrated to be applicable to transmission of advanced coherent modulation formats (QPSK and dual-polarisation 16QAM signals with Nyquist pulse shaping). Gaeta et al. (2019) have overviewed recent developments and progress in the generation of the optical frequency comb in photonic-chip waveguides by using supercontinuum. The underlying physics of generating a frequency comb in microresonators exploiting Kerr effect is very similar to fibre systems. Therefore, a solid knowledge accumulated during the study of supercontinuum and solitons in nonlinear fibre-optics can be transferred to micro-resonator systems, enabling comb technology for a broad spectral range from the near-ultraviolet to the mid-infrared with numerous practical applications including and beyond telecom.

9.3.8 Orbital Angular Momentum Multiplexing

Although linear optics has a pretty long story, there is a concept that was discovered only several decades ago, namely, orbital angular momentum (OAM). Optical beams carrying OAM have a helical phase structure and attracted much attention last years. In contrast to spin angular momentum associated with photon spin that has only two possible values $\pm\hbar$ (what corresponds CW and CCW circular beam polarisations; here $\hbar$ is Planck's constant), OAM is theoretically unlimited and thus has a great potential for increasing the capacity of communication systems, either by using different OAM states as encoding basis or by employing OAM beams as information carriers for multiplexing (Gibson et al., 2004). Let's note that OAM multiplexing may be used in combination with other well-established techniques such as polarisation-division multiplexing (PDM), optical time-division multiplexing (OTDM), etc.

In particular, the group of Prof. Willner (Wang et al., 2012) reported proof-of-concept experiments demonstrating the multiplexing/demultiplexing of information-carrying OAM beams for terabit free-space data transmission, as well as data exchange between OAM beams for efficient all-optical data processing. The authors used four polarisation-multiplexed OAM beams, each carrying a 42.8 × 4 Gbit/s (4 bits per symbol) quadrature amplitude modulation (16-QAM) signal, thereby achieving a capacity of 1369.6 (42.8 × 4 × 4 × 2) Gbit/s (4 bits per symbol for the 16-QAM, with 4 OAM beams and 2 polarisation states) with a spectral efficiency of 25.6 bit/s/Hz (50 GHz grid). Two years later, the Willner's group managed to improve their first results by almost two orders of magnitude: by utilising WDM along with OAM and polarisation multiplexion, they demonstrated 100 Tbit/s free space data link (Huang et al., 2014). Let's note that OAM-carrying supercontinuum for WDM and other applications can be generated by introducing helical phase wavefront either before (Prabhakar et al., 2019) or after spectral broadening (Sztul et al., 2006; Wright et al., 2008).

OAM multiplexing can be used also for data transfer through optical fibres, as a particular case of mode-division multiplexing, with much of the transmitter and receiver technology being similar to those used for free-space communications (Willner & Liu, 2020). However, in this case, special efforts should be made in order to mitigate significant modal cross-talk that takes place in conventional optical fibres (Bozinovic et al., 2013; Richardson et al., 2013; Ndagano et al., 2015; Brunet et al., 2014).

Finally it's worth noting that OAM multiplexing can be implemented not only in optics but also in other frequency bands of electromagnetic waves, in particular, in millimeter-wave communications (Yan et al., 2014; Willner et al., 2015; Ren et al., 2017), what makes this technique very promising for future generations of cellular data networks.

9.4 Different Regimes of SC Generation

A series of major SC applications in telecom were outlined above. In our treatment, we have so far focused on applications, not paying close attention to practically important questions about conditions that should be met in order to obtain required spectral broadening and properties of generated SC. In what follows, we perform briefly such analysis, namely, we discuss the main regimes of SC generation and properties of SC generated under different conditions (including peculiarities of temporal structure, noise and coherence) as well as applicability of different supercontinua in telecom.

9.4.1 Pulse-Pumped SC

Along with spectral properties such as bandwidth and spectral power uniformity, temporal structure of SC radiation may be critical for various applications including telecom, spectroscopy, sensing, ultrashort pulse generation and others. We continue our discussion with an outline of peculiarities in temporal structure of SC radiation under different pumping conditions: pulse pumping in a fibre with normal dispersion, spectral broadening of relatively short (normally in the range of tens to hundreds of femtoseconds) and of long pulses in fibres with anomalous dispersion.

Spectral broadening of pumping pulses in the normal dispersion regime is caused mainly by the effect of self-phase modulation (SPM). Temporal radiation profile at the output from the optical fibre usually has the form of a train of isolated pulses with repetition rate equal that of the pumping pulse repetition rate (see typical results of numerical modelling (Kobtsev & Smirnov, 2007, 2008c) shown in Fig. 9.3, upper row). As a rule, such SC is highly coherent, which makes it preferable for noise-sensitive telecom applications. In most cases, such SC has comparatively narrow spectral width, usually not exceeding 100–200 nm in the telecom spectral range. However, in Ref. Heidt et al. (2011), authors managed to obtain an octave-spanning SC in all-normal dispersion PCF.

Efficiency of spectral broadening is usually considerably improved in the anomalous dispersion regime of the optical fibre due to soliton effects. In case of relatively short pumping pulses, soliton fission effect is the principal mechanism of spectral broadening during the initial stage of SC generation that leads to broadening of the pulse spectrum and its temporal decomposition into a train of sub-pulses (see Fig. 9.3, second row). This process can be regarded as the decay of a high-order soliton into a sequence of fundamental solitons. As they propagate further along the fibre, these fundamental solitons undergo a self-shift of their carrier frequency caused by the effect of stimulated Raman self-scattering, thus leading to widening of the SC spectrum. Since the multi-soliton pumping pulse decays into a train of fundamental solitons mostly because of SPM within a comparatively short stretch of fibre, noise amplification does not noticeably affect this process. As a result, the temporal profile of SC intensity in this case has the form of a regular sequence of wave packets, each of which, in its turn, consisting of a complicated non-periodic train of soliton sub-pulses with different intensity, energy and wavelength (Kobtsev & Smirnov 2004). Due to large spectral width achievable at moderate pump powers, this SC generation regime is attractive for a wide range of applications. However, for telecom tasks, the priority is not an extreme spectral width of SC (which in fact may be quite moderate, only covering data transmission bands) but perfect stability and reliability of light sources: low noise level, high coherence and spectral flatness, stable temporal profile of SC. From the viewpoint of these requirements, SC produced under pulsed pumping in normal dispersion is, as a rule, preferable for telecom applications.

A completely different picture can be seen when pumping with comparatively long (dozens of picoseconds and longer) pulses in the anomalous dispersion domain of the fibre (see Fig. 9.3, third row). Because the spectrum broadening rate caused by SPM is inversely proportional to pulse duration, soliton fission requires too long a fibre stretch, and therefore does not occur. Instead, modulation instability (MI) becomes the principal factor leading to noise amplification within two spectral bands located symmetrically with respect to the pumping line. By the time when the magnitude of amplified noise becomes comparable to that of the pumping pulse,

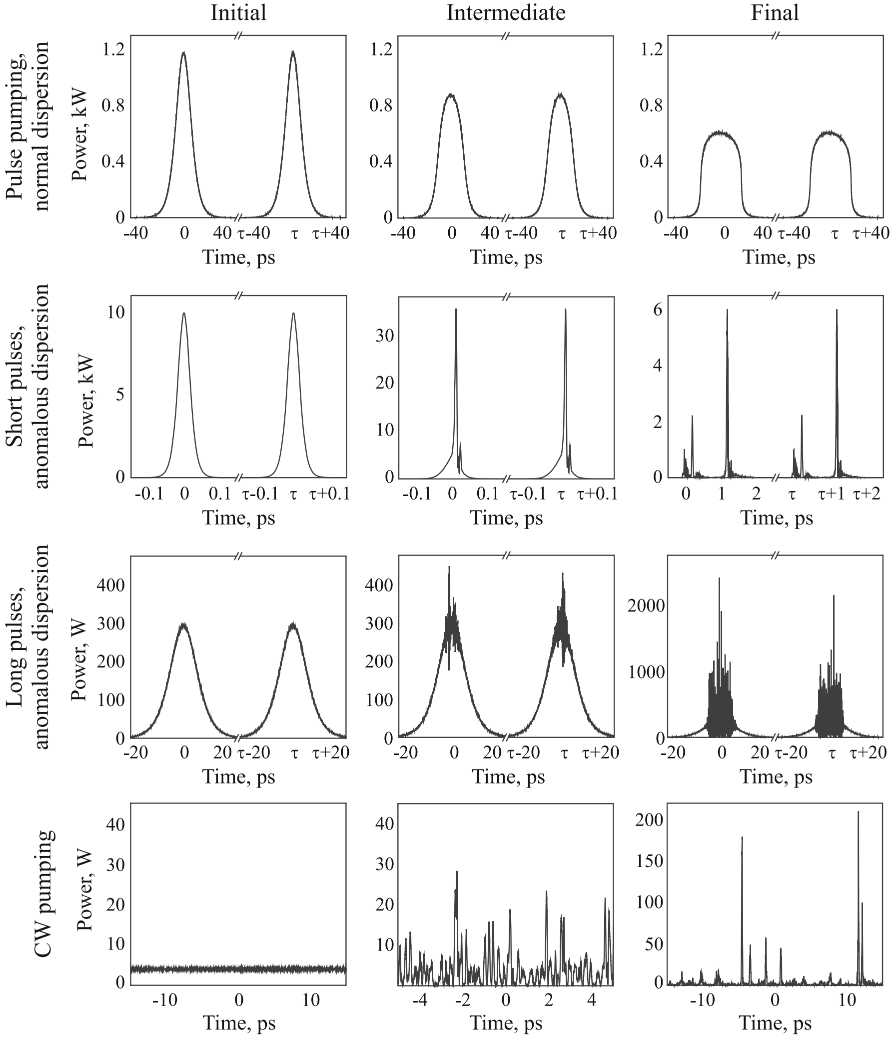

Fig. 9.3 Evolution of temporal structure of pumping radiation during SC generation under different conditions (Kobtsev & Smirnov, 2007, 2008c)

the pulse decays into a stochastic train of sub-pulses whose mean repetition rate is governed by the position of MI gain lines. Some of these sub-pulses form optical solitons experiencing self-shift of carrier frequency, thus giving rise to significant broadening of the SC spectrum. However, in contrast to the case of short pumping pulses discussed above, the energy and wavelength of these solitons are random values and exhibit considerable shot-to-shot fluctuations from one pumping pulse to another. Consequently, experimental SC spectra are much smoother and are often free from isolated soliton peaks, which happens because of averaging during data acquisition over a large number of solitons with random parameters. The temporal structure of SC radiation is formed by a train of wave packets following one another with the pump pulse repetition rate, each of them consisting of a large number (several hundred or more) sub-pulses with essentially random parameters. Such SC has low pulse-to-pulse coherence and cannot be re-compressed to a single ultrashort pulse.

In an intermediate case of pulses with sub-picosecond and picosecond durations, partially coherent pulse trains (wave packets) are formed in the optical fibre due to interplay of soliton fission effect and modulation instability, which, the latter, creates a considerable level of amplified noise. As it has been shown previously (Kobtsev & Smirnov, 2006; Dudley & Coen, 2002), the pulse-to-pulse degree of coherence reaches its maximum in the limit of short pumping pulses, and in the opposite limit of very long pulses, it approaches zero, accordingly corresponding to generation of a regular or a stochastic wave packet sequence.

9.4.2 Spectral Broadening of CW Pump

As we have shown, non-linear broadening is usually achieved by transmitting short, high-power pulses through a strongly non-linear medium. The initial modulation may lead to an increased initial bandwidth and allows the effect of SPM to act on the transmitted signal from the beginning, usually increasing the efficiency of the broadening process. On occasion, however, it can be practical to generate a wide spectrum from a conventional high-power CW source (typically a fibre laser). This possibility was illustrated in 2000 by the work of Prabhu et al. (2000), who demonstrated generation of a 100 nm SC centred at 1483.4 nm with output power of over 1 W and a weak spectral modulation of 0.11 nm, from a 1064 nm CW 8.4 W ytterbium-doped fibre laser. The broadening medium consisted of a 700 m phosphorus-doped and a 500 m Flexcor-1060 single-mode fibre that, together with a series of gratings, formed a Raman and a Brillouin cavity. The whole setup worked as a hybrid Raman/Brillouin fibre laser that produced a broad output SC spectrum. Further work in this direction was carried out by Abeeluck et al. (Nicholson et al., 2003b; Abeeluck et al., 2003), who in 2003 demonstrated generation of a broad 247 nm SC by pumping a 4.5 km HNLF with a tuneable Raman fibre laser and clearly identified modulational instability (MI) as a fundamental effect in the generation of the SC. The same authors have recently reported much broader SC generation of more than 544 nm bandwidth, with output powers of up to 3.2 W (Abeeluck et al., 2004; Fermann et al., 2000). Other groups have made interesting contributions to the use of CW to generate SC for metrological applications (González-Herráez et al., 2003). In 2008, ultra-long cavity fibre lasers (Ania-Castañón et al., 2006) were used to obtain SC generation from CW in conventional (non-PCF) fibres with a flatness of <1 dB over 180 nm, with more than 40% energy conversion efficiency, thanks to partial confinement of the pumps within the laser cavity (El-Taher et al., 2009).

The spectral broadening of CW radiation may be considered in the limit as equivalent to the broadening of extremely long pulses, so similar physical mechanisms can be considered as responsible for CW SC generation and for the spectral broadening of quite long pulses in the anomalous dispersion regime. Thus, temporal distribution of SC intensity in this case takes the shape of a stochastic train of pulses (solitons) having different (random) parameters and propagating along the fibre at different velocities (see Fig. 9.3, the bottom row). When recording the spectra of such SC in the experiment, an average over an enormous number of "random" solitons is taken, giving, as a result, a smooth spectrum without any peaks corresponding to individual solitons (Vanholsbeeck et al., 2005; Kobtsev & Smirnov, 2005). For telecom applications, CW-pumped SC may be attractive due to its smooth and adjustable spectrum (El-Taher et al., 2009). Irregular temporal structure makes such SC inapplicable as a multi-wavelength source light source for data transmission; however, there are some other telecom applications that can use irregular temporal profile as well. Thus, for example, non-linear broadening of CW can be applied to the pumps of a Raman amplifier widely used in telecom, in order to reduce its gain ripple when amplifying over a large bandwidth. The gain ripple in broadband Raman amplification can also be minimised by using a large number of pumps, but this is not always a practical solution, since it implies an increase on the complexity of the system, reducing its adaptability and increasing its cost. A Raman pump can be initially modulated and then rapidly broadened through SPM, but a more interesting possibility is to use modulational instability in the fibre to provide the initial modulation, thus considerably simplifying the design of the amplifier by using continuous wave pump lasers. This was the approach originally taken by Ellingham et al. (2002) and later followed by Chestnut & Taylor (2003) to broaden the spectra of single pumps in different sets of fibre. In the original paper by Ellingham et al., broadening performance of several non-zero dispersion-shifted fibres was evaluated at different pump input powers, and a fivefold gain ripple reduction was predicted for future dual-pump implementations. In order to maximise the effect of modulational instability, the wavelengths of the pumps must be such that they propagate through the broadening fibre in a slightly anomalous regime, close to the zero-dispersion point. Other desirable properties of the fibre include a high non-linear coefficient and a small attenuation, in order to minimise the loss of the pump power. The non-linear-broadening method was finally applied to a multi-pump Raman amplifier by Ellingham et al. (2005), using Truewave™ fibre, and increasing the 0.1-dB gain ripple bandwidth from 5 to 19 nm in an amplifier designed to provide gain in the 1565–1595 nm region.

In general, using a pulsed pump in the normal dispersion regime is preferable for SC generation in telecom applications due to much better coherence and noise properties and preserved temporal pulse structure (Heidt, 2010; Hooper et al., 2011; Nishizawa & Takayanagi, 2007).

9.4.3 Rogue Waves

When discussing peculiarities of the temporal structure of spectrally broadened radiation, it is impossible to pass over an intriguing aspect of non-linear optical science involved in supercontinuum generation, which is related to the optical analogue of oceanic rogue waves—rare events with extremely large intensity fluctuations (Solli et al., 2007, 2008; Mussot et al., 2009; Dudley et al., 2009; Erkintalo et al., 2009; Lafargue et al., 2009; Akhmediev et al., 2013; Vergeles & Turitsyn, 2011). It was shown that supercontinuum generators can be used as a simple and convenient test bed for studying the optical analogue of oceanic freak waves, since non-linear optics provides a relatively large frequency of high-intensity fluctuations and presents an opportunity of experimental studies that can be carried out with just a table-top set of equipment offering a high degree of control and rapid data acquisition.

The appearance of rogue waves can be caused by MI, which is known to have high sensitivity to the initial conditions and to exhibit emergent behaviour (Solli et al., 2007; Mussot et al., 2009; Dudley et al., 2009). Extensive studies in this area were focused on different non-linear physical systems such as optical cavities, passively mode-locked lasers and EDFA (see review Akhmediev et al., 2013) and even in linear telecom data transmission lines (Vergeles & Turitsyn, 2011) due to pulse (bit) overlapping.

9.4.4 Noise and Coherence of SC Sources

Noise and coherence properties of light sources are extremely important in telecom. Coherence loss and excess noise potentially lead to deterioration of transmitted data. Thus, obtaining high coherence and low noise operation of SC generators are of primary importance for telecom applications. Let us note that there are several different types of coherence such as spatial, temporal, pulse-to-pulse and so on. Spatial coherence of SC is usually high enough, thanks to a small effective core area of single-mode fibres used for spectral broadening. Pulse-to-pulse coherence, on the other hand, will only be high in the case of SC generated from periodic pulse trains, in which the effects leading to non-linear broadening have preserved the correlation between the electric fields of different pulses. The noise limitations (Corwin et al., 2003a) and coherence properties (Dudley & Coen, 2002) of SC spectra generated in different kinds of fibre have been studied theoretically and experimentally by multiple groups with the goal of designing the best possible SC sources. The effect of pump fluctuations in the generation of SC pulses was first studied by Mori et al. (1998), who showed that pulses were more stable when generated in dispersion-flattened decreasing-dispersion fibre (DDF). Nakazawa et al. (1998) studied degradation of coherence during SC generation in DDF, concluding that FWM phase-matched by SPM and a small anomalous dispersion in the presence of amplified spontaneous noise (i.e. modulational instability) was the main cause of the coherence loss. More recently, other studies appeared about the noise and coherence properties of SC generated in PCF and highly non-linear fibres (HNLF) (Washburn & Newbury, 2004; Gu et al., 2003). Corwin et al. (2003a, b) identified amplification of quantum-limited shot noise and spontaneous Raman scattering as the main causes of amplitude fluctuations in microstructured fibres and concluded that short input pulses were critical for generation of broad SC with low noise, whereas Dudley and Coen (2002) demonstrated that coherence degradation depended strongly on the input pulse duration and wavelength and that the effect of modulational instability in anomalous dispersion could be reduced by using short pulses.

9.5 Summary and Outlook

Research conducted over the past 20 or so years has convincingly demonstrated the possibility of efficient telecom applications relying on SC techniques, mostly in WDM and DWDM technologies using large numbers of channels (up to 10,000) with different wavelengths. However, despite this demonstration of efficiency over the entire telecommunication spectrum, these technologies have yet to be widely adopted in the industry. Most probably, the following considerations have played a role in delaying their acceptance by the industry:

1. Poor resilience. Failure of one master oscillator or an amplifier used in SC generation immediately causes interruption of data transfer in all generated channels. Separate diode lasers with different output wavelengths used to generate each channel generally provide better resilience of the data transfer system.
2. Difficulties in generation of SC with uniform radiation parameters over a broad spectral range. The output at different wavelengths may have different intensity, stability, different degree of coherence and so forth. In case of SC, not all of the channels may have identical data transmission parameters.

Still, improvements to the reliability of the components used in SC generators and the development of methods to better equalise SC radiation parameters within a broad spectral range might yet allow SC technologies to fully realise their potential and bring them into mainstream telecommunication applications. In this regard, it is worth pointing out recent advances in the generation of SC-based optical frequency combs, which have paved a promising way for applications in telecom.

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