# Control of ultrashort pulses in nonlinear dispersive media

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## Kurzfassung

### Manipulation von ultrakurzen Lichtimpulsen in nichtlinearen dispersiven Medien

Die Eigenschaften von Laserlicht können durch die Interaktion von optischen Impulsen mit Materie kontrolliert und manipuliert werden. Die vorliegende Arbeit befasst sich mit der Kontrolle ultrakurzer Impulse durch Propagationseffekte in nichtlinearen optischen Fasern und während der Plasmafilamentation. Der besondere Schwerpunkt dieser Arbeit liegt auf Propagationsdynamiken, welche auf Eigenschaften lokalisierter Strukturen basieren, die durch die nichtlineare Schrödingergleichung beschrieben werden und zur Erzeugung eines Superkontinuums führen.

Zuerst wird die Wechselwirkung von Solitonen mit dispersiven Wellen untersucht, deren Gruppengeschwindigkeiten angepasst sind. Es wird gezeigt, dass auf dieser Grundlage eine innovative Methode zur rein optischen Kontrolle in nichtlinearen dispersiven Medien entwickelt werden kann. Der zugrunde liegende Mechanismus zeigt interessante Analogien zu anderen Phänomenen in der Physik, wie Monsterwellen in der Ozeanografie oder Ereignishorizonte in der Kosmologie. Das Ausnutzen dieser gänzlich neuen Methode erlaubt es, erhebliche Einschränkungen in der Erzeugung hochkohärenter Superkontinua sowie der Komprimierung auf Ein-Zyklus-Impulse zu überwinden. Darüber hinaus erlaubt das Konzept des faser-optischen Ereignishorizontes die Konstruktion eines rein optischen Transistors, welches ein langersehntes Ziel in optischen Technologien darstellt. Insbesondere ermöglicht der beschriebene Transistor das Schalten eines starken Impulses durch einen wesentlich schwächeren und erfüllt auch eine Reihe sonstiger Anforderungen an einen praktischen Transistor.

Schließlich wird der Mechanismus, der hinter der Filament-Selbstkomprimierung steckt, detailliert beschrieben, der die Dominanz gekoppelter räumlicher Effekte während der Plasmapropagation offenbart. Die resultierende Wechselwirkung zwischen den Brechungsindex-Effekten verläuft unter Plasmabeteiligung und auch instantaner Kerrbeteiligung. Letzteres weist ein Saturierungsverhalten auf, dessen Ursprung in einer nicht standardisierten theoretischen Beschreibung erläutert wird, welches die Möglichkeit einer dissipationsfreien Filamentformation impliziert, die keine Ionizationseffekte erfordert.

**Schlagworte:** Ultraschnelle Prozesse in Fasern, Pulskomprimierung, Filament Propagation

## Abstract

### Control of ultrashort light pulses in nonlinear dispersive media

The properties of laser light can be controlled and manipulated when an optical pulse is induced to interact with matter. This thesis discusses the generation and control of ultrashort pulses by propagation effects in nonlinear optical fibers and during plasma filamentation. The particular focus of this work is on propagation dynamics related to properties of localized structures that are described by the nonlinear Schrödinger equation and result in supercontinuum generation.

Firstly, the interaction of solitons with group-velocity-matched dispersive waves was investigated and shown to allow the development of an innovative method for all-optical control in nonlinear dispersive media. The underlying mechanism shows intriguing analogies to other phenomena in physics, such as rogue waves in oceanography or event horizons in cosmology. Exploitation of this completely new concept may enable to overcome significant limitations in generating highly coherent supercontinua and in single-cycle pulse compression. Moreover, the fiber-optical event horizon concept allows building an all-optical transistor, which represents a long-sought goal in optical technologies. Specifically, the discussed optical transistor enables switching of a strong pulse by a much weaker one and fulfills a series of other requirements for a practical transistor.

Finally, the mechanism behind filament self-compression is described in detail, revealing a dominance of intertwined spatial effects during plasma propagation. The resulting interplay of refractive index effects involves plasma contributions as well as instantaneous Kerr contributions. The latter may show a saturation behavior, the origin of which is discussed in a non-standard theoretical description, implying the possibility of dissipation-less filament formation without requiring ionization effects.

**Key words:** ultrafast processes in fibers, pulse compression, filament propagation

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# List of Publications

This work is a compendium based on the following publications that are referred to in the text as [D1-D26].

For each work [D1-D14] reported in Chapter **2** and **3**, the author conceived the original idea and supervised the whole projects throughout. The publications [D15-D26] presented in Chapter **4** were the result of an experiment-theory project with Günter Steinmeyer, who conceived the idea. The author headed the theoretical part of this project.

In all works the author participated substantially in theoretical investigations, interpreting results, and writing the manuscripts.

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# Chapter 1

# Introduction

Since the advent of laser sources, nonlinear optics has evolved into a major research area in its own right, and many new phenomena have been discovered that pertain solely to the nature of coherent light-matter interaction [1]. Ranging from parametric amplification to high-harmonic generation, these phenomena have not only improved our fundamental understanding of optical physics, but have also revolutionized its applications, e.g., in nonlinear spectroscopy or high-speed communications systems.

A particularly interesting situation arises when an ultrashort optical pulse is sent into a nonlinear medium. The characteristics of the laser source become more crucial for the induced light-matter interaction. Even if one and the same material is used, varying regimes of light-matter interaction may be observed, with laser wavelength and pulse duration as the main parameters. Pulse duration plays a key role here, creating an ever increasing demand for shorter optical pulses.

At present, ultrashort pulses can be produced that contain a few cycles [2] or even only a single cycle of the electric field [3–7]. As few-cycle pulses cannot be directly provided by a laser, nonlinear optical processes offer various ways for wavelength conversion, using external manipulation [8, 9]. The interaction with a medium may be suitably used for tailoring multicolor field transients; this method of spectral shaping has been frequently and successfully used for ultrafast spectroscopy. Ultrabroad spectral bandwidths, however, may induce substantially more complex interaction scenarios and display an interplay of different physical effects that cannot be easily adapted to produce a short pulse. Considering the example of an event horizon scenario described below, it is therefore necessary to fully understand these complex phenomena before even thinking of exploiting them. Generally speaking, one of the most fascinating and outstanding examples of such a light-matter interaction scenario is the generation of octave-spanning broadband spectra in photonic crystal fibers [10–12]. With the advent of microstructured fibers, generation of such supercontinua became possible at nanojoule pulse energies [13]. While supercontinua had been observed before with amplified laser sources, it was highly surprising to see multi-octave broadening at the level of oscillator pulses. Such spectra revolutionized frequency metrology [14, 15] (Nobel Prize 2005) and have been used in spectroscopy, optical communications [16], and optical tomography [17, 18].

Nevertheless, the dynamics in this supercontinuum process are highly complicated, and different scenarios have been observed, but the main mechanisms behind this behavior can be reduced to effects described by the one-dimensional nonlinear Schrödinger equation. Closed solutions of this equation, e.g., solitons [19–23] or periodic solutions that absorb and release their energy into a continuous background, known as Akhmediev-breathers [24–27], play a key role in understanding the supercontinuum generation process. Soliton fission [28] is regarded as the main mechanism behind this remarkable spectral broadening process.

When a higher-order soliton is launched into a fiber, one observes the fission of this soliton into a series of fundamental solitons accompanied by the generation of phase-matched radiation in the normal dispersion regime. The solitons are then subsequently red-shifted. The underlying mechanisms are related to basic soliton effects, such as emission of Cherenkov radiation due to higher-order dispersion [29] and a soliton frequency shift induced by the Raman effect [30]. While these dynamics appear complex enough, even more complicated dynamics have been observed, and the supercontinua may vary greatly in their characteristics, in particular with regard to coherence properties. Therefore, despite octave-spanning supercontinua being nowadays routinely generated, the underlying mechanism of their generation is still far from being fully understood, especially concerning the basic principle of soliton fission [31] and modulation instability induced dynamics [32].

In the supercontinuum scenario, a strong sensitivity towards noise on the quantum level was already recognized early on. Yet, the main effect responsible for this extreme sensitivity and its root in the inherent modulation instability of the system [33–36] had originally not been taken into account in the description of the broadening mechanism. The fundamental mechanisms involved in the supercontinuum process and the particular role of the modulation instability have recently raised interest, as the system exhibits unexpected analogies to two phenomena in seemingly remote and unrelated areas of physics, namely cosmology and oceanography. The latter analogy is to rogue waves, i.e., waves of unexpected amplitude that completely defy any prediction based on Gaussian statistics [39]. As one possible origin, solutions induced by modulation instability, e.g., Akhmediev-breathers, Kuznetsov-Ma solitons [40, 41], and Peregrine solitons [42, 43] have been found to be the universal mechanism that may explain or at least substantially contribute to the formation of such rogue waves [44]. It is striking that these solutions of the Nonlinear Schrödinger equation evolve from an unsuspicious, low-amplitude waveform into a sudden short-lived spike, similar to the perceived behavior of an ocean rogue wave. In turn, the analogy to rogue waves appears to provide some guidance for understanding the complex behavior in other nonlinear wave systems [45–47].

There are further links to other areas of physics, such as turbulence [48] and, probably even more surprising, energy trapping by a gravitation force [49]. This unexpectedly rich variety of dynamical effects in the supercontinuum generation turns the fairly straightforward optical pulse propagation in a nonlinear fiber into a perfect experimental test bed for investigations of much more difficult-to-access systems. While these analogies are certainly fascinating all by themselves, the aspect of useful application has often been neglected in previous literature. In this work, some possibly ground-breaking exploitations of the analogies are demonstrated, including the concept of an all-optical transistor that overcomes the severe restrictions of all previously demonstrated concepts for all-optical switching.

The major result of this work is a new, strong, and efficient light-light interaction phenomenon, which is related to interaction of solitons with group-velocity-matched dispersive radiation. As peak intensities are relatively low, this mechanism was often disregarded in previous research. Some pioneering insights have been obtained by the work of Skryabin and Yulin [12, 50], who demonstrated a frequency shift of the soliton resulting from this interaction scenario. This specific interaction between solitons and dispersive waves has later been observed in the soliton fission supercontinuum generation [51]. This thesis now shows that this effect, combined with soliton shaping properties, may be exploited to control light pulses in many ways. The scheme described represents a new mechanism to overcome fundamental limitations that exist in the generation of pedestal-free ultrashort pulses in the single-cycle regime. Additionally, supercontinuum generation may be obtained over the whole transparency region of a medium with a high degree of coherence. Moreover, the scheme is demonstrated to fulfill the most demanding requirements for an all-optical transistor, a long-sought goal in optical technology.

At higher intensities, spatial as well as ionization effects have to be taken into account. In this regime, one observes completely different propagation dynamics, which can nevertheless be exploited for the generation of supercontinua or ultrashort pulses. One such example is the filament self-compression process [52–55]. The manipulation of pulse properties, both in the spatial and temporal domain, involves a highly complex interplay between cumulative effects from plasma contributions to the refractive index, instantaneous Kerr contributions, and spatial confinement of the laser beam [56]. This interplay of a large number of nonlinear effects in the filamentation process makes it difficult to isolate the main physical mechanism behind the pulse compression process. Moreover, a controversy on the exact nature of the filamentation process has recently arisen [57–59]. In particular, a decisive role of the higher-order Kerr effect was claimed for the propagation dynamics in filaments. This proposal is a fascinating thought as it would enable dissipation-less filament formation, i.e., enable filaments to extend forever. Ionization effects would then only play a minor role. This controversy has remained an open question up to now. This question has been addressed in this thesis following a new approach based on Kramers-Kronig relations, which, in turn, rely on causality. In fact, the higher-order Kerr effect plays an underestimated role in the near-infrared, but probably more importantly, these effects appear to completely take over in the mid-infrared.

This work is structured as follows: supercontinuum generation in a photonic crystal fiber is investigated in detail in Chapter **2**, with a focus on the interplay between the soliton fission process and the dynamics induced by modulation instability. Chapter **3** addresses the interplay between group-velocity-matched dispersive waves and solitons, and deals with possibilities to realize a strong light-light interaction mechanism. In addition to using an all-optical manipulation of pulses, a scheme for the generation of supercontinua with remarkable coherence properties and for direct adjustable pulse compression in the few-cycle regime is proposed. In Chapter **4**, the investigations are extended to include propagation dynamics in filamentation. The main mechanism behind filament self-compression is outlined and the controversy with regard to Kerr-saturation is discussed.

# Chapter 2

# Supercontinuum generation in nonlinear fibers

In this chapter supercontinuum generation in nonlinear dispersive fibers, such as microstructure or tapered fibers, is investigated. The capability of adjusting the linear and nonlinear properties of the fiber enables a direct control of the characteristics of the supercontinua.

## 2.1 Propagation equations, modeling and numerical schemes

In addition to being realizable in simple experiments, nonlinear fiber supercontinua have the advantage that their theoretical description may be reduced to a one-dimensional problem based on the nonlinear Schrödinger equation. The integrable nonlinear Schrödinger equation has exact closed solutions, and a majority of the dynamics observed in the supercontinuum is described by properties of these closed solutions and their dependence on perturbations. For an accurate modelling and numerical investigation, one has to resolve the dynamics not only on short propagation distances but also on ultrashort timescales below the femtosecond range, which ,in turn, is a challenge for the numerical schemes.

The standard method to study single mode pulse propagation in nonlinear fibers is the generalized nonlinear Schrödinger equation (GNLSE) derived from the Maxwell wave equation under the slowly varying envelope assumption [23, D1]. Higher-order linear and nonlinear effects, namely higher-oder dispersion, self-steepening, Raman scattering, or third harmonic generation can easily be included in this equation, allowing a detailed investigation of the different effects. However, the GNLSE cannot be used to describe correctly few-cycle pulse propagation. A more accurate model is given by the unidirectional Maxwell equation [28], a propagation equation directly for the electric field, but in this case third harmonic generation is inherently included in the equation and cannot be separated from the Kerr nonlinearity.

In order to advance beyond these restriction, a novel propagation model developed by Amiranashvili [60, 61] is used. This model is based on the propagation equation for the analytical signal and accurately describes interactions of ultrashort few-cycle pulses beyond the envelope approximation. The description of the optical field is also equivalent to using the forward Maxwell equation yet with the benefit of a clear separation from third harmonic generation. In addition, this approach correctly models nonlinear processes between waves of different frequencies [D2, D3].

In the following, a de-aliased pseudospectral method originating from computational fluid dynamics [62] is used for the numerical work. The conventional split-step Fourier approach either requires very small step-sizes or lacks precision when applied to a few-cycle optical pulse and relatively long propagation distance lest the conservation of integrals of motions be impaired. A Runge-Kutta integration scheme of eighth-order with adaptive step-size control for the integration of the linear and nonlinear part in the frequency domain allows calculations in a very efficient and accurate manner. Details about the numerical method can be found in Ref. [D1].

Special efforts were made towards the exclusion of effects that solely exist in the model or in the numerical scheme. Therefore, the main results have been independently reproduced with the unidirectional Maxwell equation, the unidirectional propagation equation for the analytical signal, and the GNLSE. In addition, corresponding test calculations were performed with a conventional split-step method.

## 2.2 Soliton Fission and Modulation Instability

Reference [13] showed generation of a supercontinuum spanning from 400 to 1,500 nm by injection of a nanojoule-energy 100-fs pulses close to the zero dispersion wavelength of the photonics crystal fiber. The surprising point was that a spectrum with a width exceeding two octaves was generated for relatively low intensities and long pulse durations which cannot be explained by the effect of self-phase modulation. A theoretical exploration of this phenomenon [28] revealed the fission of a higher-order soliton into redshifted fundamental solitons and blueshifted nonsolitonic radiation as the main spectral broadening mechanism. In this process, a key feature is the instability of solitons due to third-order dispersion accompanied by the generation of Cherenkov radiation [29]. Experimental evidence of supercontinuum generation by soliton fission followed directly afterwards, see Ref. [63]. Further experimental and theoretical investigations show that the phenomenology of supercontinuum generation is due to the interplay of many nonlinear effects [10], and characteristics of output spectra are critically changing with input pulse parameters. The scenario is rich and cannot be fully described by higher-soliton fission only.

In applications, the broad spectral width and brightness of the supercontinuum are required, but also a high degree of spectral coherence or low-noise properties are needed, because intensity or phase fluctuations ultimately limit the precision and sensitivity of any measurement. As discussed in [64–66], the primary source of coherence degradation is caused by noise-induced fluctuations and sensitivity to input pulse noise. Modulation instability (MI) is always inherently present in the nonlinear Schrödinger equation for pulses injected into the anomalous dispersion regime [33–36], being able to initiate Akhmediev-breather solutions [25, 37, 38]. Both, soliton fission and MI can lead to highly complicated propagation dynamics, and not all scenarios resulting from their interaction have been understood so far.

In Ref. [D4] it is demonstrated that there are parameter regions where the overall observed behavior of supercontinuum generation is primarily determined by MI, leading to spectra with bandwidths and shapes in the anomalous dispersion regime similar to spectra obtained by soliton fission. The impact of higher-order effects, such as higher-order dispersion, Raman-scattering or self-steepening has been investigated on MI-induced dynamics. It becomes apparent that higher-order dispersion plays also an important role in the MI-induced supercontinuum generation although the instability itself does not depend on dispersion coefficients of odd orders. Third-order dispersion has a strong influence on the whole propagation dynamics, leading to an asymmetric transfer of energy towards the blue or red side of the spectrum, depending on the sign of the third-order dispersion coefficient. This symmetry-breaking dynamics in the MI-induced spectrum has recently been demonstrated experimentally [67, 68]. Before these investigations, third-order dispersion has generally been considered unimportant for the MI. A strong effect may also result from fourth-order dispersion despite its relative small value. An injection of a pulse into the normal dispersion regime with a negative fourth-order coefficient is unstable against the MI. A supercontinuum may then be created in the same way as in the anomalous dispersion regime, which is a phenomenon that has not been been taken into account before. The experimental results in [69] and [70] are verified in terms of quantity and quality, respectively. Usually, the parameter regime for which solely MI-induced supercontinuum generation is observed corresponds to pulses in the range of picosecond, yet soliton dynamics may also completely be suppressed in the sub-picosecond regime at high peak intensities. However, there are parameter regions, where both effects appear at the same time.

A more detailed analysis of the interplay between soliton fission and MI is given in Ref. [D5]. Soliton fission dominates in the case of low input power, and short pulses (in the sub-100 fs range), but the MI is always present. For high input power there is always an interplay between MI and soliton fission, which leads to a degradation of the coherence of the SC. In the soliton fission dominating regime, the highest degree of coherence is given at the beginning of the higher-order soliton propagation, where a major part of the SC is excited by the higher-order soliton compression before the fission process sets in. In this way, efficient pulse compression into the sub-10 fs regime has been achieved [71].

One important point to note is that the overall behavior in the MI-induced dynamics and the soliton fission process can be described already by the nonlinear Schrödinger equation with some perturbation. Possible SC scenarios on the basis of variable strengths of MI and soliton fission have been revealed in Ref. [D1]. The interplay between these two mechanism is still not fully understood, and recent investigations focus on fundamental aspects of the soliton ejection mechanism. In Ref. [31] the N-soliton fission process in the presence of third-order dispersion is described by the so-called Newton's cradle mechanism. In Ref. [32] the possibility of direct ejection of an ensemble of fundamental solitons from MI-initiated Akhmediev breather solutions has been demonstrated when the Raman effect is taken into account. The whole scenario and especially the MI-induced dynamics have attracted increased general interest in the context of rogue waves, a phenomenon that will be discussed in Section 3.3.

In the standard soliton fission process a higher-order soliton is injected into a fiber close to the zero dispersion point to transfer energy to phase-matched frequency components in the normal dispersion regime. In Ref. [D6] the idea of reverting this mechanism is pursued. A pulse close to the zero dispersion regime is injected into the normal dispersion regime. The pulse parameters have to be chosen in such a way as to make the steepening at the leading edge strong enough, in order to provide an overlap of the broadened spectrum with the corresponding phase-matched component in the anomalous dispersion regime. Energy may then be efficiently transfered in the anomalous dispersion regime to create a soliton. Depending on the amount of the transferred energy, higher-order solitons can be excited, leading successively to the standard SC generation process by soliton fission. It is illustrated that the overall behavior is mainly determined by the dispersion profile. The possibility of the excitation of resonant radiation in the anomalous dispersion regime by pumping in the normal dispersion regime has been demonstrated in recent experiments [72]. This opens a possibility to further exploit the soliton fission process, e.g., to induce a SC also in regimes in materials where the anomalous dispersion range is not directly accessible by the commonly produced laser frequencies. This principle has very recently been used for the generation of three-octave spanning supercontinua over the mid-infrared regime in a chalcogenide fiber [73]. However, this effect can also be detrimental in direct applications, e.g., in the generation of ultrashort pulses for data-communication systems, as will be demonstrated in the next section.

## 2.3 Pulse compression limit in the normal dispersion regime

High-repetition-rate optical pulse trains for ultrahigh-speed optical time-divison multiplexed communication systems require stable femtosecond optical pulse sources in the 1550-nm range. Since low-jitter pulses, as they are directly obtainable from typical semiconductor laser-based pulse sources, are still limited to approximately 1 ps in duration, an external compression scheme must be employed to generate a femtosecond optical pulse train with gigahertz repetition rate [74, 75]. An effective standard method for pulse compression is the nonlinear pulse propagation in a fiber with normal group-velocity dispersion followed by an anomalous dispersive medium [76]. The key step here is to take advantage of the ability of spectral broadening by self-phase modulation and the Raman effect. In this regime the sensitivity to input noise is reduced, and stable spectra can be achieved without spectral modulation or fluctuations, resulting from complicated or non-deterministic temporal pulse splitting. The spectral broadening is, however, strongly reduced due to the input power in comparison to the soliton fission process. For obtaining a high spectral broadening, it appears essential that the process be operated in regimes with low normal dispersion values. It seems well known that this compression scheme also suffers from third-order dispersion, and it is believed that a compensation of the third-order dispersion in external process will permit the delivery of clean pulses.

In Ref. [D7] a fundamental limit to the compression scheme due to third-order dispersion induced pulse breaking has been presented. In an optimal compression scheme, the combined action of normal dispersion and self-phase modulation results in a broadened parabolic pulse shape with almost linear frequency chirp across it, which is ideal for a subsequent pulse compression. For low input peak powers, the higher-order terms are negligible, and the compression is close to optimal. The contribution of third-order dispersion becomes more important with increasing bandwidth. The pulse shape experiences an asymmetric temporal development with an enhanced transfer of power from the trailing portion of the pulse to the leading one. Even though the pulse is distorted by third-order dispersion and even though there is a strong deviation from the ideal parabolic pulse shape, the pulse is efficiently compressed in the fiber, which displays the linearity of the chirp. However, the spectral broadening causes an overlap to the anomalous dispersion regime. Reaching a phased-matched component in the anomalous dispersion regime,the peak intensity at the front of the pulse is strongly increased, leading to a temporal pulse splitting and the separation of a fundamental soliton. The chirp shows a discontinuity, and the whole spectrum can no longer be used for a compression. Once the power is increased, the splitting occurs at shorter propagation distances.

In experiments in cooperation with the Heinrich-Hertz-Institute in Berlin, the described limit for an ultimate break down of the compression scheme has been verified. The spectral characterization of the pulses were obtained with an optical spectrum analyzer, and the technique of frequency-resolved optical gating (FROG) [77] has been used to characterize the intensity and the frequency chirp of the pulses.

The dependence of the appearance of the pulse splitting on the fiber and pulse parameters has been investigated in Ref. [D8]. The focus of the latter work was on the limitations of the standard telecommunication systems to explore the possibility to generate pulse trains for the transmission of data in the Terabit/s regime.

## 2.4 Extreme events in supercontinuum generation

The concept of rogue waves arises from a mysterious and potentially calamitous phenomenon in oceanic surfaces [78–81]. The appearance of rare but extremely powerful optical waves in nonlinear fiber supercontinua [82–84] provided a surprising laboratory analogy of rogue waves. These laboratory experiments opened up new possibilities to investigate this phenomenon observed in oceans worldwide. Characteristic signatures of ocean rogue waves may also be found in a variety of different classical and quantum systems. Beyond optics, analogies have been shown for matter waves [85], superfluidity [86], filaments [87], financial mathematics [88], and other fields. The concept of rogue waves has now evolved into an autonomous topic in science [45, 46], in particular as the dramatic concentration of energy into giant waves exhibits a great potential for various applications [89]. There is mounting evidence that rogue waves are actually commonplace in a variety of different physical settings. A set of defining criteria for rogue waves has been advanced [90], which is general enough to be applicable to a wide class of systems:

i) The amplitude of a rogue wave is at least twice the average amplitude [91].

ii) The event is localized and unpredictable in the sense that the wave seems to "appear from nowhere and disappear without a trace" [92].

iii) The statistical distribution of the wave crests reveals a non-Gaussian heavy tail, i.e., extreme events are significantly more frequent than typically anticipated.

Beyond these criteria, an underlying modulation instability is considered to be connected to the formation of rogue waves. Modulation instabilities require dispersion and nonlinearity of the propagation speed, i.e., exactly those conditions that have been identified for rogue-wave supporting systems.

Substantial progress has been made in understanding the mechanisms behind rogue waves (for a review, see [45] and [46]). A number of different theories have been proposed for different experimental conditions, in particular in the optical analogy of rogue waves [44, 47]. Currently, most explanations follow one of the two alternatives: solitons or breathers. The former involves soliton fission and selective Raman shifting of the largest solitons toward the long-wavelength side of the spectrum [84, 93–95]. The latter is based on the dynamics of particular analytical solutions on a backgroud of the basic nonlinear Schrödinger equation, known as Akhmediev breathers [89, 96], Kuznetsov-Ma solitons [40], or the Peregrine soliton [43]. They appear due to the MI [44] and can be observed in different systems. Moreover, they seem to be promising candidates for describing hydrodynamical and general rogue waves, particularly with regard to describing the formation process without the

Raman term, which has no oceanic equivalent.

A completely different way to create intermittent giant waves in a SC is presented in Ref. [D9]. These extreme events exhibit all the signatures of rogue waves. The scheme is based on enhanced nonlinear interaction between fundamental solitons and background radiation, leading to a strong shaping of the soliton. A strong increase of its peak intensity followed by its collapse is induced. The peak intensity of the giant soliton may achieve intensities more than ten times higher than the solitons that do not interact with the background. To demonstrate the third criterion for rogue waves, a total of 4000 realizations of supercontinua is generated, using different noise seeds. The statistics received displays a typical characteristic heavy-tailed figure-L shape for rare but extreme events, which fits very well to a Weibull distribution. The data are obtained without spectral filtering of the time series.

The main mechanism behind the appearance of extreme events in this scenario is a scattering process between solitons and dispersive waves, which has been previously referred to as a reflection from the soliton. The wave reflection process originates from fluid dynamics known as wave blocking [97] and requires only a few basic conditions to be met. The approach essentially only presupposes a nonlinear Schrödinger-type scenario, with a reactive nonlinearity and a concave dispersion profile and does not presuppose any special nonlinear effects unique to optical systems. This minimal set of requirements can be expected to exist also in a wide class of physical systems. One important point is that this class of rogue waves are also based on exact solutions of an integrable nonlinear wave equation, which reflects the importance of closed solutions in nonlinear systems. It is demonstrated that giant solitons can be created in a purely deterministic way, beyond appearing during the highly complex supercontinuum generation process.

In order to investigate the difference to other nonlinear interaction types and energy transferring scenarios given by the optical fiber supercontinuum, the influence of higher-order effects has been studied [D2, D10] as well as different possible SC generation process (see section 2). It has been verified that the interaction of a soliton with background radiation may lead to giant solitons, without any soliton-soliton or another interaction mechanism. As filtering [98–100] obviously plays an important role for the heavy-tailed probability of rogue waves, separate statistics have been extracted from the simulation results. The analysis clearly reveals deviation from the Gaussian distribution, but the heavy tail behavior of the dispersive waves differs from that of the solitons. In [94], it has been observed that collisions between solitons create giant dispersive waves. Here the dispersive waves with high peak powers must not be attributed solely to soliton-soliton collisions.

A focus in the investigations was set on the energy and photon number transfer in this nonlinear process. This gives a clear definition of the interaction process that is revealed to represent also an ubiquitous wave phenomenon: the concept of an event horizon [101, 102]. This connection directly links the presented mechanism to other fields in physics, where analogue systems for event horizon have been discussed like, e.g., filamentation [103], matter waves [104], or hydrodynamics [105, 106]. The main underlying interaction of solitons with dispersive waves has originally been observed in a supercontinuum in Ref. [51] in combination with the Raman effect, counteracting against the acceleration process. Also in this case, the mechanism may create a rogue wave [107]. An attracting force between two solitons is realized by the interaction with dispersive waves, leading to a fusion of the solitons. Works related to accelerated solitons in optics can be found in Refs [108–111].

# Chapter 3

# All-optical manipulation of light

Manipulating light with light has been an active area of research for several decades. Besides a possible realization of an optical transistor, which is a long sought goal in technology [112], all-optical controlling represents a topic concerning fundamental properties of light-light and light-matter interaction. The interaction between optical pulses is achieved by their common interaction with some material medium and is strongly limited due its strength, which is generally very weak. In comparison with electrons in media, it is difficult to confine, store or control photons. Photons are not affected by voltage or any potential energy, so that the kinetic energy of an optical pulse cannot be changed easily. Up to now no interaction mechanism between light pulses in optical media is known [112] that would be strong enough to control a light pulse in an efficient manner comparable to the control mechanisms of electrons in media. However, recently a more profound study of the propagation of solitons in nonlinear optical fibers has led to unexpected analogies with other areas of physics, exhibiting new possibilities for strong light interaction, as shown in the chapter before, related to the concept of event horizons. In the optical analogy a blocking event horizon is established by a refractive index barrier by means of the familiar cross-phase modulation (XPM) [23]. The basic idea behind this interaction process is that an intense light pulse traveling down a nonlinear optical fiber creates a propagating front at which the propagation speed changes abruptly. When a co-propagating second pulse with nearly identical group velocity approaches that front, this pulse does not pass through the other pulse but is reflected. In optics this kind of XPM process is also observed in the optical push broom effect [113, 114], in collision processes between beams [115] or pulses with a moving inhomogeneity [116].

It will be shown below that all-optical reflection between two pulses at a blocking horizon can be used to manipulate ultrashort pulses in a versatile manner. The main idea is to use the frequency shifts in combination with soliton properties for efficient manipulation.

## 3.1 All-optical transistor

There is a growing trend to process data in optical networks directly using optical methods, avoiding electronic processing wherever possible. Yet despite the numerous functionalities that can now be implemented all-optically as, e.g., optical switching or routing, it appears virtually impossible to accomplish the most basic active electronic component - the transistor - in a satisfactory way. This is readily understandable, as photons do not interact directly but only via nonlinear optical effects in matter. This kind of optical interaction is much weaker than direct electrostatic interaction between electrons. As a consequence, it is much more difficult to build a photonic transistor. However, many concepts for optical transistors have been suggested and demonstrated. Nonlinear resonators have been extensively explored [117, 118], the optical Kerr effect (intensity-dependent nonlinear increase of the refractive index) has been exploited in many different ways, and optical switching has been shown using single molecules [119]. While all these advances certainly do have their virtues, they often fail to fulfil straightforward criteria for a practical transistor.

As a consequence of these and other shortcomings, strict criteria have been defined that are considered mandatory for a practical all-optical switching device [112]:

- Cascadability. The output of one stage must be adequate to drive the input of the next stage. In optics, the output and input wavelengths, beam and pulse shapes should be compatible.
- Fan-out. The output of one stage must be sufficient to drive the inputs of at least two subsequent stages (fan-out or signal gain of at least two). Stimulated emission gain, however, is not required. It is sufficient that small input power changes result in larger output power changes.
- Logic-level restoration. The quality of the logic signal is restored lest degradations in signal quality propagate through the system, in other words, the signal is “cleaned up” at each stage. For optics, we must consider restoring beam quality and/or pulse quality as well as signal-level ranges.
- Input/output isolation. We do not want signals reflected back into the output to behave as if they were input signals, as this makes system design very difficult. Transistors provide this isolation, but the microscopic physics of nonlinear optical processes and stimulated emission typically does not. A device with separate input and output would be ideal.

At this stage of the research, not a single published concept complies with the full set of specifications. In particular, nearly every optical transistor proposed so far requires a much stronger pulse to switch a weaker one, or it does not provide any pulse restoration possibility.

In Ref. [D11] it is shown that a reflection of an optical pulse at a refractive index barrier induced by the Kerr perturbation of a co-moving intense pulse provides an unprecedented potential to control the properties of that pulse in an all-optical way. The main idea is to exploit the frequency shift induced on both pulses by this kind of interaction as described in the chapter above. As it is mandated that an intense pulse be controlled by a much weaker pulse, an already marginal frequency shift of the intense pulse may lead frequency shift of the intense pulse. To this end, a soliton is injected into a spectral range of the dispersion profile where the dispersion values vary greatly. Given the rather small frequency shift of the soliton, dramatic effects on the output soliton shape can be realized.

The frequency shift of the soliton depends on the properties of the reflected weak dispersive wave. The dispersion profile determines the direction towards smaller or higher dispersion values. For a demonstration of the transistor principle, fluoride glass has been chosen. This medium exhibits a dispersion profile with one zero dispersion wavelength and enables widely separated frequency combinations of the soliton and the dispersive wave. In this experiment, the soliton was injected into the mid-infrared at a frequency of 0.6 PHz and the dispersive wave close to the group-velocity-matched frequency component in the normal dispersion at 1.8 PHz. With a faster or slower dispersive wave, a reflection process can be realised with either the leading or trailing edge of the soliton. The widely separated frequency combination excludes spectral overlap of the both pulses, allowing a reflection process independent of other four-wave mixing processes.

The collision process between soliton and dispersive wave causes frequency shifts of both collision partners into opposite directions. If the collision appears at the leading edge of the soliton, the soliton is shifted into the blue, i.e., towards the zero-dispersion wavelength. This shift therefore effectively lowers the group-velocity dispersion experienced by the soliton. Considering that the energy of a soliton is connected to the peak power and the dispersion value, the decrease of the dispersion cannot be compensated by a reduction of the energy, as the soliton energy slightly increases. Consequently, adiabatic reshaping forces the peak intensity to grow massively, depending on the variation of dispersion: the stronger the frequency shift, the stronger the dispersion value change. The frequency shift is also accompanied by a change of the group velocity of the soliton. In the case of collision at the leading edge the soliton frequency is shifted to higher values accompanied by an acceleration of the soliton. The dispersive wave is shifted toward lower frequencies, which means an increase of its velocity for the parabolic group-index profile given for dispersion profiles with a zero-dispersion wavelength. It has to be emphasized, that the photon numbers in the dispersive wave and the soliton are individually conserved, and that the energy change of the soliton is given by its frequency shift, which is shown explicitly in [D2]. The reflection of a faster dispersive wave at the trailing edge leads to an inverted behavior. In the latter case both pulses are decelerated, with a reduction of the peak intensity of the soliton. In this way, the peak intensity of the soliton can be continuously increased or decreased by the interaction with an almost group-velocity matched dispersive wave.

Effective performance of the proposed scheme is achieved over a wide range of parameters. The reflection process represents a robust mechanism and is also observed under impact of Raman scattering [51, 120, 121]. Considering deceleration effects induced by the soliton self-frequency shift [30], an increase of group-velocity mismatching with propagation distance is observed, nevertheless leaving the fundamental Kerr-type scattering process mostly untouched. A detailed analysis of the influence of Raman deceleration on frequency shifts can be found in [D2]. This effect is deliberately excluded here in order to isolate the chief effect for the observed switching behavior without the necessity of including dissipative mechanisms.

A careful adjustment of properties of the weak dispersive wave enables to enhance their effective interaction such that their center frequencies either strongly repel or attract each other, resulting in perfectly efficient mutually induced frequency shifts. In the simplest case, the optical switching action is encoded in this frequency shift. Ensuring a suitable dispersion profile, one can achieve strong changes in the soliton properties such as its time duration as well as its peak intensity. The overall described mechanism therefore requires three main conditions: the establishing a refractive index barrier, inducing a soliton frequency shift, and a strong change of the dispersion value for the induced frequency shift. The mechanism then fulfills all necessary criteria for a practical transistor functionality:

- Cascadability. The main pulse does not dispersively spread or break up into multiple pulses, thus the solitonic switching scheme is cascadable. The wavelengths of the controlling pulse (dispersive wave) and the signal (soliton) are different, but compatible, as the entire process is invertible and enables cascading and logical processing.

- Fan-out. In the presented example, a strong pulse can be switched by a 6 - 7 times lower energetic pulse, clearly distinguishing this method from previously proposed optical transistors.

- Logic-level restoration. Operating with solitons as signals has the advantage that a nonexact fundamental soliton is changed into an exact soliton while propagating in the fiber. A degradation of the signal from an exact fundamental soliton can be tolerated up to 50% [23].
- Input-output isolation. Input and output pulses can easily be separated, thus filtered out easily.

There is currently no other proposal for an optical transistor that fulfills all these four criteria, but the proposed scheme offers additional benefits. Switching between the on- and off-state can also be easily realized by switching between two soliton states. The switching time is very fast, as it depends directly on the propagation lengths and the signal durations, in contrast to resonant optical effects with extremely long switching times. In the presented example the signal is in the sub-100fs and the propagation in the cm range. For a photonic crystal fiber the signal pulse width can be reduced to few-cycle regime and the propagation length to the sub-mm range. It seems appealing to investigate the use of other materials, e.g., silicon waveguides on a chip, as this promises to shrink the required waveguide lengths.

Recent experiments using a micro-structured optical fiber have confirmed the up- and down-conversion of the frequency of an ultrashort optical pulse through reflection at either the leading or the trailing edge of the fundamental soliton [122]. The whole scheme has now very recently successfully been demonstrated experimentally by Tartara [123], including the frequency shift of the soliton and concomitant pulse shaping.

## 3.2 Adjustable pulse compression into the few-cycle regime

The generation of ultrashort pulses in the single-cycle regime has advanced for a variety of wavelength regimes. Methods include pulse compression of Ti:sapphire oscillator and amplifier pulses [124–126], coherent synthesis of compressed pulses [127, 128], optical rectification [129, 130], attosecond pulse generation via high-harmonic generation [131] as well as optical parametric amplification [132, 133]. Despite the impressive spread of wavelengths, ranging from the vacuum ultraviolet into the terahertz regime, there still are apparent gaps, e.g., in the mid-infrared from $2 - 10\,\mu$m. While nonlinear optical crystals exist that offer favorable phase-matching properties and efficiency in this region [134], it is often the unavailability of convenient broadband coherent seed sources that limits parametric amplification schemes in the mid infrared.

In Ref. [D12] it is demonstrated that the scattering of a dispersive wave at the leading edge of a soliton can be further exploited for the generation of pulses in the few-cycle regime, especially in the mid-IR regime. The main precondition of our scheme is the establishment of an effective refractive index barrier between two pulses copropagating at nearly identical group velocities. For efficient manipulation, it is necessary to launch the soliton into a spectral range with a strong third-order dispersion. In this proposal for an all-optical transistor, only a short interaction of a soliton with a weak dispersive wave suffices to more than double the intensity of the soliton. This increase of peak intensity is accompanied by a corresponding pulse shortening. To receive higher compression factors, stronger variations of the dispersion values have to be possible in relation to the frequency shift. However, an effective refractive index barrier is only created for a fairly small spectral range close to the group-velocity matching condition. New frequency components of dispersive waves have to be provided for an adequate frequency combination with the new soliton frequency. Longer interaction by generating new frequency components on the basis of self-phase modulation of the dispersive wave can be realized [D12]. A careful adjustment of the intensity of the dispersive wave and the initial time delay between the soliton and dispersive wave can be used to create a background of radiation, which enables a continuous acceleration of the soliton. The accompanying effective change of dispersion leads to strong temporal compression of the soliton and spectral broadening.

This novel adjustable adiabatic soliton compression scheme is presented for an example of a microstructured endlessly single mode (ESM) fiber [135] and that of a ZBLAN fiber [136]. The possibility of compression down to the single-cycle regime is shown for both fibers. The compressed pulses correspond to fundamental solitons and are pedestal-free. They are achieved directly in one stage, without requiring an external compensation scheme. We also indicate the ultimate limitations of our scheme, which are dictated by the dispersion properties of the fiber and the requirement of fundamental soliton propagation. The ESM fiber, which consists of fused silica, becomes highly absorbing above $2.5\mu m$, limiting the range of soliton propagation on the long wavelength side and the zero-dispersion wavelength on the short wavelength side. A growing overlap of the soliton spectrum with these boundaries leads to a loss of soliton energy. Depending on the amount of this detrimental overlap, the compressed few-cycle soliton may even be destroyed. Better performance is possible for media with wider transparency regions, allowing soliton propagation at wavelengths widely separated from the zero-dispersion wavelength. Fluoride glasses such as ZBLAN, e.g., exhibit high transmission well into the mid-infrared range, which enables multi-octave separated frequency combinations to travel at equal group velocity.

To investigate the viability of our approach as a source of few-cycle and single-cycle pulses in the midinfrared, numerous simulations in the transmission region of the ZBLAN fiber have been performed. In the entire wavelength region of $2.55\mu m$, we observe essentially identical compression behavior, with output solitons in the sub-2-cycle regime. Higher compression factors can be achieved at broader input pulses, but restrictions toward further compression into the single-cycle regime remain unchanged. Similar results are achieved when including the Raman effect, yet requiring a more careful adaptation of the frequency combination and the initial delay.

The pulse parameters are chosen to demonstrate pulse compression into the few-cycle regime, which requires stable propagation of ultrashort pulses. The vicinity of vibrational resonances fulfills this prerequisite, i.e., the compression is not accompanied by a substantial loss of soliton energy, neither due to absorption in the mid-infrared nor the strong generation of Cherenkov radiation. In addition, the parameters of the input pulses are chosen to be realistically generated in nonlinear conversion schemes. Surmising a 4000 nm idler, a 880 nm signal, and a 720 nm pump, all necessary wavelengths can be coherently generated from broadband Ti:sapphire lasers with subsequent parametric conversion or difference-frequency generation. This scheme represents an alternative route to facilitate the generation of short coherent pulses in the infrared and mid-infrared alongside with filamentation [137, 138], difference frequency conversion [139], or soliton pulse compression [140].

Apart from material properties in the discussed schemes, the efficiency of the manipulation chiefly depends on the properties of the dispersive wave. Here the amplitude and the pulse width of the dispersive wave can conveniently be used as control parameters. As any frequency shift changes the conditions for group-velocity matching, this restriction also is immediately translated into a limitation of the whole scheme. It becomes even more stringent when the Raman-induced soliton-self-frequency shift cannot be compensated by the controlling dispersive wave anymore. In the latter case, the only way to overcome this difficulty may be a substantial increase of the dispersive wave amplitude or the launch of several dispersive waves at different frequencies [D3], which is rather difficult to realize experimentally.

To surpass the limitations of the previously proposed schemes, the influence of a chirp of the dispersive wave in this compression scheme is explored in Ref. [D13]. It is shown that the chirp can be utilized as a sensible control parameter of the acceleration and compression scheme. In particular, the impact of the chirp on the cancellation of Raman-induced soliton self-frequency shift is presented. The exact temporal frequency variation along the dispersive wave has a strong impact on group-velocity matching in the collision process. This fact offers use of a chirp as an additional control parameter. A carefully chosen chirp allows then to automatically avoid walk-off due to the varying soliton frequency. As the soliton frequency constantly increases during the entire interaction process, the frequency of the dispersive wave can also constantly be decreased by an initial chirp to prevent the collision process from stagnating early instead of generating new frequency components by self-phase modulation.

It is found that a relatively small chirp can already significantly modify the dynamics of the interaction process. In general, there are two major mechanisms influencing the dynamics, namely, one related to the phase-matching condition governing the interaction of the soliton and dispersive wave and the second one related to pure linear reshaping of the chirped dispersive wave in time. The latter mechanism is important for large input chirps and enables controlling the point where dispersive wave and soliton start to interact. The former case allows for an improvement of the soliton-dispersive wave interaction in the spectral domain. This second mechanism relies on spectral broadening of the chirped wave, and it enables matching the compression behavior to the fiber length. Specifically, maximum soliton compression can be obtained at shorter propagation distances.

Taking the soliton-self-frequency shift into account for the group-velocity matching of the dispersive wave, the first collision process has to compensate or reduce the red shift induced by the Raman effect. Upon further propagation, the induced blue-shift has to overcome the soliton-self-frequency-shift in order to obtain an effective adiabatic soliton compression. The initial parameters have to be chosen suitably to ensure that the amplitude of the radiation is sufficient to continuously induce a frequency shift of the soliton into the blue during the entire interaction process. Only the low intensity parts of the dispersive wave interact with the soliton, and the intensity and the width of the initial dispersive wave ensures that a low level background is build up by broadening the dispersive wave. It should be noted that higher intensities of the dispersive wave mostly cross the soliton with only a small part interacting. At the same time, however, the intensity of the dispersive wave at the collision point has to be high enough for compensating any counteracting deceleration induced by the Raman self-frequency shift. This condition naturally implies that the group velocities of both pulses should be not too close to each other, limiting the range of the resonant condition for the reflection process.

This kind of control described above provides an additional independent degree of freedom, enabling the modification of time and position of the first collision. In particular, the introduction of a positive chirp reduces this time period and provides longer interaction distances.

The principle of adiabatic fundamental soliton compression by a frequency shift relates to an well-known effect demonstrated for Raman induced soliton self-frequency shift along an adequate dispersion profile [141, 142]. Similar compression to few-cycle pulse widths is nowadays a useful tool in the regime of plasma induced soliton-self-frequency blue shift in hollow core fibers [143].

## 3.3 Supercontinuum generation by two pulse collision

Soliton fission and MI have been identified as the key mechanisms behind remarkably efficient SC generation processes in photonic crystal fibers (see Section 2.2). In the soliton fission process an initial high-power pulses decays into a train of fundamental solitons accompanied by generation of dispersive waves, which comes with a severe disadvantage, i.e., its poor spectral coherence properties. Despite its impressive spectral coverage, the optical field often proves incompressible in the temporal domain. This loss of spectral coherence shapes out as highly irregular pulse trains that do not reproduce from shot to shot. In this situation, temporal compression requires adaptive dispersion control with MHz update rates. Moreover, spectral broadening in the anomalous dispersion regime makes SC generation highly susceptible to laser noise as the latter is always amplified in the inherent MI. Therefore, although octave-spanning SC generation is routine nowadays, there is still room for improvement. Low spectral coherence can certainly be avoided in the normal dispersion regime, where both soliton fission and MI are suppressed. Complicated pulse shapes stemming from nondeterministic temporal pulse splitting do not appear, which suitably avoids spectrally varying modulations. However, now the spectral broadening is mainly induced by self-phase modulation and the Raman effect, enabling comparatively modest spectral broadening. This seemingly unavoidable tradeoff between broadening efficiency and loss of coherence describes the fundamental dilemma of fiber-based supercontinuum generation.Therefore, it appears appealing to combine the enormous spectral coverage of soliton-based SC sources with the superior coherence properties in the normal-dispersion regime.

It has already shown that in the anomalous dispersion regime a fundamental soliton can be compressed into the few-cycle regime, leading to a spectral broadening over the whole anomalous dispersion regime of the given fiber. In Ref. [D14] it is presented that this soliton compression represents a new scheme for SC generation in combination with suitable frequency conversion due to the reflection of dispersive wave at the edge. Besides the possibility to generate different spectral coverage ranges, favorable coherence properties can be achieved, and a negligible influence of input noise is demonstrated. The resulting SC covers more than an octave.

The interaction of an accelerated fundamental soliton with a group-velocity matched background radiation additionally exhibits newly generated frequency components in the normal dispersion regime that stem from the reflection of the dispersive wave at the propagation front. The spectrum in the normal dispersion regime consists of three different parts: (i) the spectrum of the initial dispersive wave, which is not reflected and passes the soliton. This part experiences only minor broadening by self-phase modulation. (ii) Reflected dispersive wave portions. Upon propagation, nonlinear interaction accelerates the soliton, effectively feeding the interaction zone with a continuous supply of dispersive wave segments. As the frequency of the soliton increases, any of these interactions with DW segments creates new frequencies. This effect then eventually fills the entire spectral range between the dispersive wave and the zero dispersion frequency. (iii) Frequency components of the soliton that overlap the zero dispersion frequency and transfer energy to the normal dispersion regime.

It is important to note that this scheme is markedly different from the previous SC generation scenario. The soliton fission process as a generation mechanism is completely avoided, and Raman scattering is not a key factor either. There is also difference between this scheme and other two-color pumping schemes where third harmonic generation is responsible for the extension of the SC to shorter wavelengths [144]. The model here allows separate consideration of third harmonic generation, and actually only marginal affects by third harmonic generation are observed. In particular, there are only minor differences when we change the relative phase between the two input pumps. Moreover, the scheme solely exploits four-wave mixing processes between two input pulses. This segregation prevents the problems of de-coherence seen in the traditional SC scheme. The spectral broadening avoids nondeterministic temporal pulse splitting, thus translating into spectral modulation and fluctuations. Also, the scheme does not exhibit a strong susceptibility to noise in the anomalous dispersion regime.

To demonstrate the superior coherence properties of the scheme, the modulus of the complex degree of first-order coherence have been calculated at each wavelength as a measure for the SC phase stability [145]. The degree of coherence with and without the contribution of the Raman effect and third harmonic generation indicates the expected sensitivity toward noise, with near-unity values promising perfect compressibility of SC spectra. In all cases, there is no appreciable coherence degradation within the bandwidth of approximately 1.5 octaves. With the Raman effect, a stable SC is enabled when the self-frequency shift is sufficiently compensated by interaction with the DW, and we also observe degradation of the coherence with further propagation for that case. The nearly perfect coherence is slightly corrupted by contribution of the third harmonic soliton pump wavelength, which overlaps with frequency components of the dispersive waves.

In order to demonstrate the possibilities for manipulating the SC characteristics [D3], several initial frequency combinations between the soliton and the dispersive wave have been chosen. The obtainable width of the SC is chiefly determined by the separation of the two initial frequencies enabling optimization of the spectral width. An adjustment of the amplitude of the DW may serve to fill the gap between the two input wavelengths, demonstrating a further advantage of the scheme. For a fixed frequency combination, the spectral width can be adjusted by the DW energy contents, and the SC can be tailored in different ways. It is also possible to excite only a part of the spectrum between the two pump wavelengths with high brightness in the normal dispersion regime. Peak power, the pulse width of the dispersive wave, or the time delay between the DW and the soliton can be used as control parameters. More importantly, one can optimize the spectral bandwidth simply by choosing a suitable input frequency pair. In the case of fused silica a spectral bandwidth exceeding 2.5 octaves can be generated throughout almost the whole transparency region of the given fiber. In contrast to the SC by soliton fission, there is no saturation of spectral broadening.

It has also been explicitly demonstrated how nearly the same spectral broadening can be achieved when the Raman effect is included. The properties of the dispersive wave may readily serve to pre-compensate the Raman-induced soliton self-frequency shift. The compensation of the soliton self-frequency shift becomes increasingly difficult for any further exploitation of the bandwidth between the two initial frequencies. One possibility to overcome this obstacle is to use the scheme in a cascaded way, by injecting two dispersive waves into the fiber at different frequencies and different time delays. This expands the duration of effective nonlinear interaction of background radiation with the soliton, enabling the excitation of the maximal possible spectral bandwidth defined by the transparency region of the medium.

# Chapter 4

# Filamentation

In this chapter the investigations are extended to generation of ultrashort pulses by controlled propagation dynamics including spatial and ionization effects with a focus on optical filaments in noble gases.

## 4.1 Self-compression in filamentation

Optical filaments are typically defined as dynamic structures of light with an intense core, which is able to propagate over extended distances much larger than the typical diffraction length while maintaining a narrow beam size without help of any external guiding mechanism. Filament formation is ruled by two counteracting nonlinear optical mechanisms. One of these effects is self-focusing, which causes a beam collapse for sufficiently high powers. This effect is typically arrested by plasma formation, a second effect, which defocuses optical radiation.

Direct pulse self-compression in a filament without any dispersion compensation scheme has been first observed in Ref. [53]. The observed compression does not require any guiding structures such as fibers or hollow fibers and is therefore not limited by a damage threshold. Self-guiding is realized by interacting nonlinear effects in the filament. For certain initial conditions, the on-axis temporal profile of the pulse is shortened. Presupposing the usual mechanism behind filamentary compression, nonlinear spectral broadening and dispersive pulse shaping processes need to be the driving forces of this temporal shortening. As no external compression scheme for the compensation of the induced chirp is necessary, the induced chirp has to be compensated by another effect, which has to be present inherently in the filamentation propagation. This behavior is observed in all noble gases, which exhibit low dispersion values in the normal dispersion regime. In particular, negative dispersion may result only from plasma generated by photoionization. The intensities within filaments are sufficiently high to create a dilute plasma via multiphoton or tunneling ionization processes. In this description, the pulse is subject to spectral broadening accompanied by additional positive group-delay dispersion. This dispersion is accumulated by the spectral phase of the pulse, which is compensated by a source of negative group-delay coming from the plasma contributions to the refractive index. Self-compression has been analyzed before as a purely temporal phenomenon [54]. However, another mechanism is presented here for pulse compression in filamentation, which is chiefly of spatial nature, in stark contrast to any previous method of pulse compression.

In Ref. [D15, D16, D17] it is demonstrated that competing nonlinear optical effects act on femtosecond laser pulses propagating in a self-generated light filament, giving rise to pronounced radial beam deformation. The analysis has identified spatially induced temporal break-up as a first step for efficient on-axis compression of an isolated pulse. In this case, the leading break-up portion is eventually observed to diffract out and reduce its intensity, while the trailing pulse can maintain its peak intensity. A subsequent stage, dominated by diffraction and Kerr nonlinearity, serves to further compress the emerging isolated pulse, and it may give rise to almost tenfold on-axis pulse compression. The main driver behind this complex scenario is a dynamic interplay among radial effects: diffraction, Kerr-type self-focusing, and plasma defocusing. The dominance of spatial effects clearly indicates the unavoidability of a pronounced radial beam deformation structure of self-compressed pulses. The frequently observed pedestals in this method are identified as remainders of the suppressed leading pulse from the original split-up. The analysis also indicates that lower pulse energies $<1$ mJ, which require more nonlinear gases or higher pressures, will see an increased influence of dispersive coupling, which can eventually render pulse self-compression difficult to achieve. Higher energies, however, may not involve such limitation, opening the prospect to improve few-cycle pulse self-compression schemes in the future.

Self-compression in filamentations is ultimately constricted by parameter fluctuations of the input wave. At high compression ratios, it becomes increasingly difficult to maintain control of the waveforms. In Ref. [D18] an alternative approach is suggested toward efficient exploitation and control of highly nonlinear wave-shaping mechanisms as described above. Rather than trying to confine input parameters in an increasingly narrow range, it appears much more promising to relax these constraints in order to prevent input noise from strongly affecting the output waveform. Realistic parameter regimes have been revealed that enable a cascaded application of the waveform-shaping effect, e.g., in order to compress optical pulses or to concentrate energy. This cascaded method has been supported by experiments at the Max Born Institute in Berlin.

Further experimental investigations in cooperation with the DESY in Hamburg and Max-Born Institute in Berlin have been performed, verifying the pulse breaking mechanism for filament self-compression. In Ref [D19] the compression of pulses with more than 100 fs input pulse duration from a 10 Hz laser system is demonstrated, with a compression factor of 3.3 resulting in output pulse durations of 35 fs. The investigations substantially widen the range of applicability of this compression method, enabling self-compression of pulsed laser sources that neither exhibit extremely low pulse-to-pulse energy fluctuations nor a particularly clean beam profile. Numerical investigations have been adapted to the underlying experimental conditions, e.g., the role of controlled beam clipping with an adjustable aperture, revealing the exact same mechanisms at work as at shorter input pulse durations.

It has been argued that cell windows may play a decisive role in the self-compression mechanism. As such windows have to be used for media other than air, their presence is often unavoidable, yet they present a sudden nonadiabatic change in dispersion and nonlinearity, which should lead to a destruction of the temporal and spatial integrity of the light bullets generated in the self-compression mechanism. Experiments at the Max-Born Institute in Berlin prove that there is, in fact, a self-healing mechanism that helps to overcome the potentially destructive consequences of the cell windows. A comparison with a windowless cell shows that the presence of this mechanism is an important prerequisite for the exploitation of self-compression effects in windowed cells filled with inert gases. The experimental observation has been supported by numerical investigation [D20].

The pulse splitting dynamics along the femtosecond filament has recently been observed and demonstrated experimentally in Ref. [D21]. The fundamental pulse experiences a significant self-shortening during the propagation leading to pulse durations of 5.3 fs, corresponding to sub-3 cycles. It was possible to achieve a compression factor of eight in a single filamentary stage. A direct comparison of the nonlinear dynamics during filamentation between the experimental observation and numerical simulations shows excellent qualitative and quantitative agreement with the theoretical modelling.

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## 4.2 Saturation of the optical Kerr effect

The main description of how a filament is formed follows the idea of the interplay between Kerr nonlinearity and ionization effects, leading to a competition between self-focusing and Plasma defocusing. However, this fundamental concept has been questioned recently by measurements [57, 146–148] of nonlinearly induced birefringence, indicating a strong influence of higher-order nonlinearities to the extent that filament formation is explained in the complete absence of plasma formation. There is a controversial discussion about the results [58, 59, 149, 150], as they would in fact mean a paradigm shift in explaining femtosecond filamentation [58].

An independent and previously unreported approach towards computing Kerr saturation is provided in Ref. [D22]. The approach is based on a Kramers-Kronig (KK) transform [151] of optical absorption derived from Keldysh theory [152]. The results support the experimental results in Ref. [57, 146], showing that the saturation of the Kerr effect cannot be explained by including the next higher-order coefficient alone. Instead, similar to the transition from third-harmonic generation to high-harmonic generation, many coefficients start to act simultaneously. As a single-parameter theory, depending only on the ionization energy of the respective atom, the employed model provides estimates on the nonlinear refractive index that clearly confirm the importance of the higher-order Kerr coefficients for filament stabilization. Nevertheless, the assumptions of perturbative nonlinear optics are expected to hold as long as the intensity does not exceed the validity of the multi-photon ionization regime. Beyond that regime, a perturbative expansion of the ionization rate provided by Perelomov-Popov-Terent'ev (PPT) [153, 154] ceases to exist. The findings strongly suggest a saturation mechanism to be included in future models of filament formation.

In Ref. [D20, D24] the approach based on a Kramers-Kronig transform of multiphoton absorption rates to compute the nonlinear refractive index values of noble gases is extended. Requiring only knowledge of the ionization energy of the gas, the full spectral dependence of the nonlinear refractive index coefficient can be computed, including the expected sign change beyond the two-photon resonance. Moreover, the formalism also allows for computing higher-order intensity-dependent contributions to the refractive index, and enables a comparison of the theoretical results to the measurements in Ref. [57, 146] showing agreement within reasonable accuracy with measured data. The dispersion of the refractive index coefficient for all noble gases has been provided. A detailed benchmark indicated excellent agreement of 10% to 20% including chemical reference data. Assessing the expected sign change above the two-photon resonance accurately, it was possible to predict refractive index coefficient data in the ultraviolet more reliably. Further investigations of the full dispersion of the saturation behavior proved the convergence of the perturbational treatment down to Keldysh parameters close to unity. The dependence of the Kerr saturation on wavelength corroborates the existence of two different filamentation scenarios. In the visible and ultraviolet, plasma formation is expected to arrest the collapse of the beam profile induced by self-focusing favoring the well-established plasma clamping regime. However, this longstanding conceptual picture sets the course towards a novel scenario at longer wavelengths. Here the influence of the higher-order Kerr effect dominates, and the arrest of the collapse can be also induced by the higher-order Kerr effect.

A further extension of the formalism for predicting the onset of significant higher-order Kerr effect contributions can be found in Ref. [D23], where the method is applied to solid dielectric materials. So far, only isolated reports on high-order nonlinearities in solid materials exist; see, e.g., [155]. High harmonics and multiphoton absorption effects are typically only discussed in the context of optical damage induced by femtosecond pulses [156]. To shed some light on the possible role of the higher-order Kerr efffect in dielectric solids, several proven models for multiphoton absorption have been applied, calculating the nonlinear refractive index via Kramers-Kronig transform as well as the plasma contribution predicted by the Drude theory. Among these models is the original Keldysh theory [157], which is based on first-order perturbation theory with specially dressed wave functions including the effect of the external electric field. Moreover, a similar model of Brandi and de Araujo [158] based on an S-matrix approach is used and, finally, the second-order perturbation theories of Wherrett [159] and Sheik-Bahae et al. [160]. The role of the higher-order Kerr effect contributions in solids at 800 nm appears significantly less pronounced than reported for the noble gases. In the near infrared, therefore, the appearance of the higher-order Kerr effect in solids goes hand in hand with plasma formation. However, the simulations also indicate reduced plasma effects when significantly larger number of photons is required to reach the bandgap. In the mid-infrared in crystalline solids, filamentation may appear without dissipative multiphoton absorption effects [161]. Nevertheless, the higher-order Kerr effect appears to have a subtle and often underestimated role in nonlinear optics.

## 4.3 Extreme spatio-temporal events in multiple filamentation

There is a particularly rich variety of optical systems that exhibit rogue events [46], e.g., supercontinuum generation in nonlinear optical fiber propagation (see Chapter II Section 2). Similar extreme events have been observed in the temporal dynamics of single filaments [162]. Here the dynamics are also described by a propagation equation with the nonlinear Schrödinger equation as an essential part. The system bears a dependence of propagation velocity on both wave number and wave amplitude, giving rise to linear optical diffraction and dispersion on the one hand, and to the nonlinear optical Kerr effect on the other hand. These two major effects contribute to the formation of multiple filament strings [33, 56, 163] in the transverse plane of the beam. Especially, the modulation instability, which is regarded as one of the main drivers behind rogue wave formation, exits also in the spatial domain. The spatial modulation instability causes the spatially homogeneous intensity profile to break up into one or several highly localized filament strings above a critical power. This two-dimensional localization appears to be similar to the formation of solitons in the one-dimensional system, yet also relies on clamping effects due to multiphoton ionization and resulting plasma formation. Using much higher input powers, highly dynamic scenarios with hundreds of parallel plasma channels can be realised exhibiting highly complex interaction scenarios. Consequently filament formation can be regarded as a further test bed for investigating of the phenomenon of rogue waves, as the system allows also higher-dimensional effects for the frequent observation of rogue events in a few-second timescale requiring rather modest observation conditions. In particular, filaments are also accessible by small-scale numerical simulations.

The emergence of extreme events in a two-dimensional optical system is demonstrated experimentally and theoretically [D26]. The experiments have been performed at the Max-Born Institute. The multifilament scenario exhibits near-exponential probability density functions, with extreme events exceeding the significant wave height by more than a factor of 10. The extreme events are isolated in space and in time. The macroscopic origin of these heavy-tail statistics observed in experiments is shown to be local refractive index variations inside the nonlinear medium, induced by multiphoton absorption and subsequent plasma thermalization. In fact, the observed rogue wave dynamics appears to be completely unrelated to a noise-amplification process induced by input beam fluctuations. Given that the system is highly nonlinear, one expects an effect of even the smallest fluctuations in the input profile, potentially giving rise to dramatic fluctuations of the resulting patterns from shot to shot. While such noise amplification from initial Gaussian fluctuations into an L-shaped distribution is certainly possible, we actually find different mechanisms at work, in contrast to previous theoretical predictions and expectations drawn from 1D rogue waves.

Numerical simulations deliver a tangible picture for the appearance of rogue waves in this two-dimensional system, indicating an interference of neighboring filaments as the origin of this phenomenon. In this scenario, a four-wave mixing-type nonlinearity plays an important role in steering the individual filaments into each other. In repeated calculations it is observed that only those strings merge that constructively interfere and that are in close proximity. The merger of the two filaments is unstable and always follows a characteristic pattern, with the strings exiting the merger event being oriented perpendicularly to the input plane. If otherwise undisturbed, the two filament strings recollide and remain in an aggregated breather state afterwards, which effectively combines the energy of two individual filament strings into one. In the simulations, however, such behavior is typically terminated after only one cycle due to an interaction with the other neighboring filament strings. In order to establish the role of mergers in the formation of rogue wave events, a statistical analysis of the energy contained in the individual filament strings has been performed. All these merging events occupy the extreme-value tail of the energy statistics, and the analysis reveals an L-shaped distribution of energies as seen in the experiments.

While all the discussed characteristics of rogue wave formation, namely interference and collisions of individual waves, a four-wave mixing type nonlinearity, breathers, and a modulation instability, have already been discussed either for the one-dimensional nonlinear fiber scenario or for hydrodynamic rogue waves, their joint appearance in one system appears to be previously unreported. Moreover, extreme events emerge in the two-dimensional system due to turbulence and are not caused by nonlinear amplification of input noise on the beam profiles. The absence of noise amplification of the observable, i.e., the influence of intrinsic noise further sets this investigation apart from one-dimensional propagation experiments.

# Chapter 5

# Summary

## 5.1 Conclusions

The main goal of this work is the generation and control of ultrashort pulses by propagation effects in nonlinear dispersive media. Two systems, namely, nonlinear fiber propagation and filament propagation, have been considered. A focus has been applied on dynamics that can be described by equations basing the nonlinear Schrödinger equation.

Concerning the manipulation of light pulses in nonlinear fiber, the mechanisms to generate ultra-wide supercontinua have been analyzed quantitatively and qualitatively. A non-standard and highly accurate computational algorithm has been developed for the numerical investigations, capable of modeling the propagation dynamics of the electric field. The impact of the modulation instability and the soliton fission process on the dynamics have been demonstrated for different parameter regimes. With regard to applications of supercontinua for pulse compression, limitations of the individual methods have been revealed.

One of the most important achievements in this work concerns the interaction of solitons with group-velocity-matched dispersive waves, and how it can be exploited to efficiently manipulate optical pulses. A completely new scheme for an all-optical control of ultrashort pulses has been demonstrated. The method has been applied to a range of problems that remained unresolved or had been addressed by other schemes only under strong limitations:

- an all-optical transistor, a long-sought goal in optics. All necessary criteria for practical realization can be fulfilled.
- generation of supercontinua in photonic crystal fibers over several octaves with a high degree of coherence and without the modulation instability or pulse splitting, e.g., as mandated by the soliton fission process.
- adjustable pulse compression into the few-cycle and single-cycle regime. The compression is realized directly in one stage. Substantial efficiencies can be achieved for pulses with center frequencies in the mid-infrared, a regime that is difficult to achieve for few-cycle pulses.

It is important to note that the whole scheme does not rely on exotic effects but is based on well-known effects of nonlinear optics due to cross-phase modulation and soliton properties. The underlying group-velocity-matched cross-phase modulation represents the key idea for the concept of an optical analogue of an event horizon. The entire manipulation scheme can be described by the nonlinear Schrödinger equation, emphasising the universal character of interaction phenomenon and the schemes potential to be used in different systems. In particular, it has been shown that optical event horizons are build up naturally in the generation of a supercontinuum when fundamental solitons interact with background radiation. This interaction may lead to extreme waves that fulfill all rogue wave criteria.

Concerning the generation of ultra-short pulses in filament propagation, a clear picture of the filament self-compression is provided. Other than commonly perceived, the analysis identified plasma-induced pulse splitting, which results in a split-isolation cycle as the main driver behind the temporal pulse compression process. Conditions for optimal compression have been presented as well as a further improvement of the scheme by initiating a cascaded version, allowing the generation of pulses with durations in the few-cycle regime.

In the framework of this thesis, a new theoretical approach have been provided for the prediction of the magnitude of higher-order nonlinear susceptibilities in order to shed light on the controversy of filament propagation, which is not a result of plasma formation. The findings qualitatively confirmed the higher-order Kerr saturation effect and showed perfect agreement with recent experimental results. The investigation was then extended to solids. While the role of Kerr saturation appear less pronounced in the near infrared range, this phenomenon appeared to be completely missed out before and appears to play an important role in the mid-infrared range.

Finally, as the inherent spatio-temporal modulation instability in filament propagation is sensitive to noise, rogue waves have been detected in the fluence patterns of laser-driven multi-filamentation and became part of the studies in this work. Here a category of rogue waves is observed that prove to be different from the one occurring in the supercontinuum generation in fibers. Rare but extreme events have been identified as mergers of filament strings. Atmospheric turbulence as a possible microscopic driver mechanism for the rogue events has been identified as a decisive mechanism in inducing these mergers.

## 5.2 Outlook

Some of the results presented in this work have been verified in experiments in the meantime. The mechanisms behind filament self-compression [D19, D21] and fundamental limitations in fiber pulse compression [D7] were demonstrated in cooperation with other research institutions. Knowledge of the specific underlying mechanism of filament self-compression enabled the generation of few-cycle pulses in a controlled environment. The fruitful combination of experiments and numerical simulations gives reason to expect the possibility to generate even shorter pulses using these established methods. Other results were observed by independent parties. The strong impact of modulation instability on fiber-supercontinuum generation is nowadays beyond dispute. The possibility to extend supercontinua by initiating a soliton fission process with a pump pulse in the normal dispersion regime [73] has also been confirmed in recent experiments. This method represents a promising tool to further exploit the soliton fission process by transferring it to other input wavelengths and materials.

The concept of resonant radiation becomes more and more important as the spectra of few-cycle pulses can easily overlap dispersion regimes that are widely separated. The dynamics are then strongly influenced by the energy transfer at the time of transition from the anomalous to the normal dispersion regime or vice versa. This has far-reaching consequences for the physics of few-cycle pulse propagation, in particular single-cycle pulse propagation. We have already shown that there are stringent restrictions on further compression and the envelope soliton concept will break down as also observed in Ref. [164]. This gives rise to the question of what happens to the soliton fission process and the modulation instability in the few-cycle regime. The behavior of higher-order solitons in this regime is still a mystery. The same holds for the modulation instability. In Ref. [165], unexpected few-cycle sub-structures of an ultrashort pulse are observed that seem to result from the modulation instability.

As short laser pulses can nowadays be generated in the mid-infrared regime, the generation of dispersive waves becomes interesting in plasma filament propagation as well. The injection of high intensities into the anomalous dispersion regime of a bulk medium leads to the generation of extremely short pulses, accompanied by the generation of resonant radiation. Additional temporal effects due to the dispersion properties start to play a significant role in the filament propagation, but no clear picture has been provided as yet.

Understanding propagation properties of few-cycle and single pulses is the challenge we need to address now. New pulse manipulation mechanisms have become highly necessary as the schemes have to be capable of processing few-cycle characteristics. This cannot be realized by any electronic device. All-optical control schemes are more appropriate. In this work a new scheme has been proposed showing great potential for ultrashort pulses. At the time of writing this thesis, an experimental verification of the main aspects of the idea has been published [123]. The entire scheme is still in its infancy, but the different control possibilities proposed are coming closer to being experimentally realized. Several investigations by other groups on the same phenomenon can now be found [108–111, 166]. In addition to its relevance to optical science, all-optical reflection between two pulses and its analogy to a blocking event horizon has attracted heightened interest very recently [167]. The simple realization of the concept in fiber-optics may be used to investigate phenomena as the Hawking radiation [103, 168, 169], negative frequencies [170], or black body emission [171]. Further links to other areas in physics can be expected. The investigation of propagation and interaction effects of few-cycle pulses represents an interesting topic not only for the development of future technologies but also for understanding fundamental nonlinear physical wave mechanisms.

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