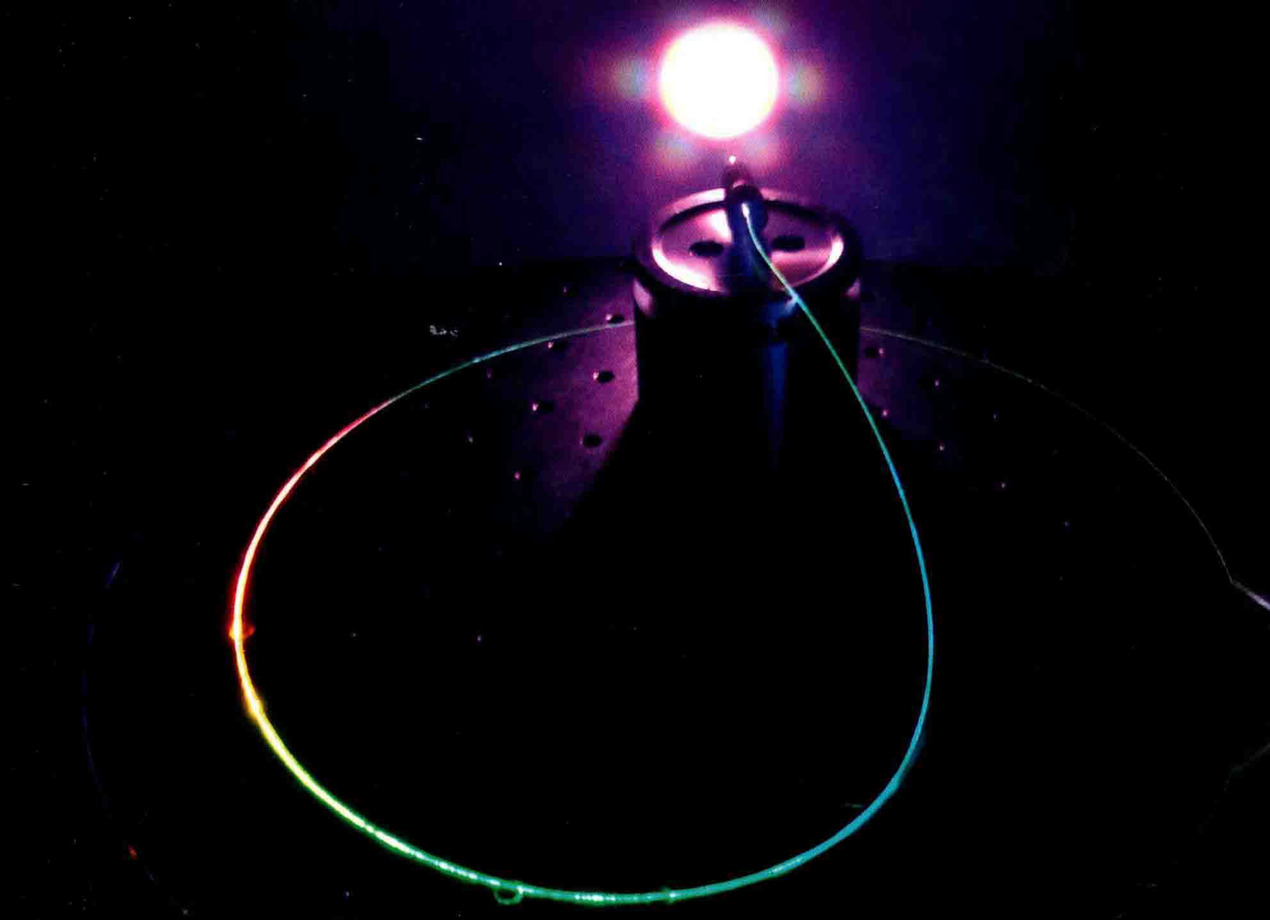

Supercontinuum Generation *in Optical Fibers*

Edited by

J. M. Dudley and J. R. Taylor

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SUPERCONTINUUM GENERATION IN OPTICAL FIBERS

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SUPERCONTINUUM GENERATION IN OPTICAL FIBERS

The optical fiber based supercontinuum source has recently become a significant scientific and commercial success, with applications ranging from frequency comb production to advanced medical imaging. This unique book explains the theory of fiber supercontinuum broadening, describes the diverse operational regimes and indicates principal areas of applications, making it an indispensable guide for researchers and graduate students.

With contributions from major figures and groups who have pioneered research in this field, the book describes the historical development of the subject, provides a background to the associated nonlinear optical processes, treats the generation mechanisms from continuous wave to femtosecond pulse pump regimes and highlights several important applications. A full discussion of numerical methods and comprehensive computer code are also provided, enabling readers to confidently predict and model supercontinuum generation characteristics under realistic conditions.

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Preface

Spectral broadening and the generation of new frequency components is an inherent feature of nonlinear optics, and has been studied in both bulk media and optical fiber waveguides since the 1960s. However, it was not until the early 1970s that the mechanism was widely applied to provide an extended "white-light" source for time resolved spectroscopy, which was later coined "a supercontinuum" by the Alfano group. Subsequent developments in the late 1970s in low-loss optical fibers with conventional structures for telecommunications led to the introduction of fiber as an ideal platform for supercontinuum generation. At the same time, the development of optical soliton physics throughout the late 1980s and early 1990s laid the theoretical foundation and established all the experimental mechanisms required for the production of this versatile source. Despite this progress, however, extensive laboratory deployment remained inhibited by unwieldy pump sources and unreliable system integration.

The advent of photonic crystal fiber in the late 1990s, together with developments in efficient high power and short pulse fiber lasers, fuelled a revolution in the generation of ultrabroadband high brightness optical spectra through the process of supercontinuum generation. Experiments using photonic crystal fiber in 1999–2000 attracted widespread interest and excitement because of the combination of high power, high coherence and the possibility to generate spectra spanning more than an octave. Moreover, the design freedom of photonic crystal fiber allowed supercontinuum generation to be optimized to the wider range of available pump sources, and experiments reported broadband spectra covering the complete window of transmission of silica based fiber using input pulses with durations ranging from several nanoseconds to several tens of femtoseconds, as well as high power continuous wave sources. Supercontinuum generation in PCF was rapidly applied to a range of fields including optical coherence tomography, spectroscopy, and optical frequency metrology and, indeed, this latter result was explicitly cited in the award of the 2005 Nobel Prize in physics.

These results have since led to a huge research effort studying nonlinear spectral broadening in PCF, and have also renewed interest in similar nonlinear phenomena in standard optical fiber. Recent results have provided new insight into the spectral broadening mechanisms, tailored supercontinuum properties to specific applications, and extended supercontinuum generation into new fibers and waveguides using engineered dispersion profiles and/or non-silica materials. Improvements in numerical modeling techniques have also led to remarkable agreement between theoretical prediction and experimental realization.

This progress has of course been well documented in the archival literature, but researchers are now facing the problem that there is no single resource that explains the physics of fiber supercontinuum generation, describes the important properties of new fibers and waveguides, and outlines the features of supercontinuum generation relevant to specific applications. Our aim with this book is to address this problem explicitly through a series of invited papers written by experts familiar with all aspects of this field: the fundamentals and recent developments in supercontinuum generation physics, the different possibilities raised by the availability of new fibers and materials; and the diverse applications where supercontinuum sources can be used.

The book begins with two chapters describing the historical development of the field preceding a concise introduction to nonlinear fiber optics and the numerical modeling of supercontinuum generation. This is followed by a chapter providing an overview of the fiber supercontinuum generation processes under a wide range of conditions. These first four introductory chapters are aimed to ensure that the book is self-contained and accessible to advanced undergraduates and beginning doctoral students requiring a broad introduction to the field. The most significant technical content of the book appears in the subsequent chapters where various aspects of fiber waveguide properties and fiber supercontinuum processes are described in detail by researchers who have been responsible for seminal contributions to the field.

At this point it is perhaps appropriate to add a short word about citing the work in this book. Books and monographs sometimes develop the tendency to become general references that are cited in lieu of the original literature. Whilst this can sometimes be useful, it can also sometimes be detrimental in hiding the contributions of primary journal papers and the original authors. As a solution to this problem, we wish to suggest that readers please take due care that they do not forget to cite the primary literature where appropriate. When material is described both in the primary literature and in this book, there is of course the possibility to cite both.

In closing, we wish to say that we have been very fortunate in being able to include chapters from pioneering and leading research groups from across the world, and we are very grateful to all contributors for their agreement, their effort and their patience. We hope that this book and the excellent contributions that we have been lucky enough to solicit from our colleagues will allow professionals to develop their research even further, and students to enter this field more effectively.

Contents

1
Introduction and history

J. R. Taylor

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

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

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

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

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

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

A key nonlinear process and a vital component in supercontinuum generation was proposed by Hasegawa and Tappert in 1973 arising through the balance of self phase modulation and anomalous dispersion. Optical soliton generation had to wait a further seven years before it was unambiguously demonstrated and characterized in a series of classic experiments by Mollenauer (Mollenauer et al. 1980, 1983; Mollenauer and Gordon 2006). The long delay between theoretical prediction and experimental realization was a result of the technological challenges involved in