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Editorial

Supercontinuum generation

Lasers light a rainbow

Supercontinuum generation – a physical phenomenon leading to a dramatic spectral broadening of laser pulses propagating through a nonlinear medium – was first demonstrated by Alfano and Shapiro in the early 1970s [1]. Nowadays, more than three decades later, supercontinuum generation is still one of the most exciting topics in laser physics and nonlinear optics, the area where the high-field science in the most amazing way meets the physics of low-energy unamplified ultrashort pulses. Many interesting and physically important aspects have been added to the strong-field chapter of supercontinuum-generation story in the past few years, as laser pulses were becoming shorter and shorter and more and more intense. The rapid technical and conceptual progress in microstructure fibers has recently resulted in the appearance of a whole family of fibers, such as microstructure, photonic-crystal, holey, and tapered fibers, capable of generating supercontinuum emission with unamplified, nano- and even subnanojoule femtosecond pulses, leading to revolutionary changes in frequency metrology and opening new horizons in ultrafast science, short-pulse control, as well as spectroscopic and biomedical applications. The rainbow of colors produced by a laser beam (Fig. 1) became an optical instrument and a practical tool.

As a physical phenomenon, supercontinuum generation involves the whole catalog of classical nonlinear-optical effects, such as self- and cross-phase modulation, four-wave mixing, stimulated Raman scattering, and many others, which add up together to produce emission with extremely broad spectra, sometimes spanning over a couple of octaves. A detailed understanding of the properties of the supercontinuum is crucial for assessing the possibilities of using this broadband emission for spectroscopic, metrological, biomedical, and pulse-compression purposes. This is why many equally accurate and elegant measurements have been carried out recently on the supercontinuum produced in both strong and weak fields and much work is now in progress.

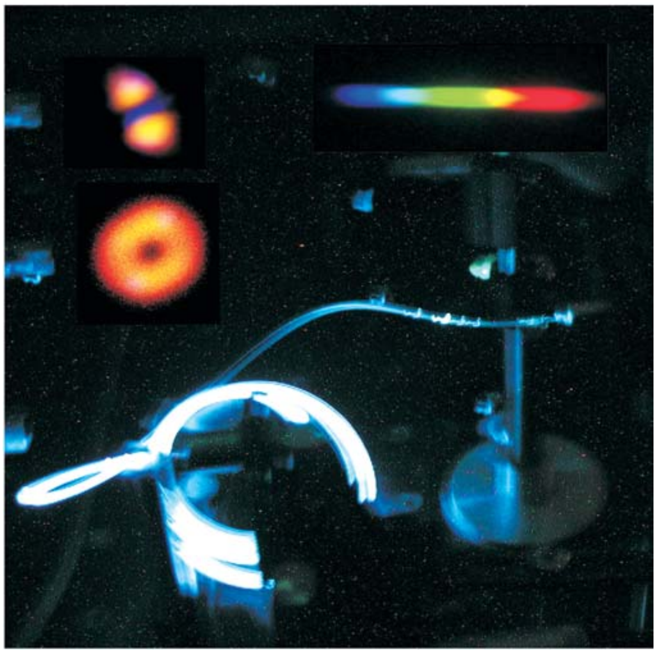

FIGURE 1 A laser lights a rainbow. Supercontinuum generation in a fused silica microstructure fiber using unamplified subnanojoule Ti:sapphire laser pulses (M.V. Lomonosov Moscow State University). The spatially dispersed spectrum and spectrally filtered spatial modes of supercontinuum emission from a microstructure fiber are also shown

This special issue of *Applied Physics B: Lasers and Optics*, focused on supercontinuum generation, is intended to highlight the latest achievements in this field and to stimulate research in this important area of optical physics. The papers published in this issue address the most important fundamental and applied aspects of supercontinuum generation using a broad variety of supercontinuum-generating materials and structures, including microstructure, tapered, Raman, and dispersion-shifted fibers, plasmas induced by high-intensity laser pulses in the atmospheric air and water, bulk fused silica, glasses, and various solutions.

Supercontinuum generation with high-intensity ultrashort laser pulses

Supercontinuum generation is one of the most intriguing and spectacular phenomena accompanying the propagation of high-intensity ultrashort laser pulses through gases, liquids and solids. Supercontinuum emission produced under these conditions is promising for optical-diagnostics and sensing applications as an ultrabroadband radiation source and is interesting from the viewpoint of fundamental research, as it involves a broad variety of perturbative and nonperturbative nonlinear-optical effects.

The opening paper by **Kandidov et al.** [2] provides a comprehensive overview of the physical mechanisms behind supercontinuum generation by high-power femtosecond laser pulses and emphasizes the role of spatiotemporal light field localization effects in supercontinuum generation. These effects accompany the filamentation of high-power laser beams, propagating in various media, such as water or atmospheric air, facilitating the spectral superbroadening of femtosecond laser pulses.

The spectral evolution of supercontinuum emission in a filament producted by an ultrashort intense laser pulse in fused silica is also analyzed both experimentally and theoretically by **Xiaojun Fang and Kobayashi** [3]. The physical scenario of supercontinuum generation is identified in this work, based on the quantitative agreement between the experimental results and numerical simulations.

New insights into supercontinuum generation with terawatt laser pulses experiencing self-focusing in a rare gas are provided by **Nishioka and Ueda** [4], who also present the results of their measurements of spatial, spectral, and temporal characteristics of supercontinua stretching from the VUV to the IR range. **Aközbek et al.** [5] have shown that third-harmonic generation may play an important role in supercontinuum generation by intense femtosecond IR laser pulses focused in air. During the filamentation process, the third harmonic pulse may generate a broad continuum, which can overlap with the continuum produced by the fundamental pulse, extending the supercontinuum spectrum further into the UV.

The paper by **Kolesik et al.** [6] presents a comprehensive model and computer simulations of supercontinuum generation in bulk media, including water and atmospheric air as representative and practically important cases of condensed and gas media. Analysis carried out in this work shows that, along with intensity clamping and plasma-induced frequency blue shift, linear chromatic dispersion plays an important role in supercontinuum generation, determining the spectral extent of supercontinuum emission.

Fiber strategies and technologies of supercontinuum generation

Several efficient and practical methods of supercontinuum generation and broadband emission have been demonstrated in recent years using microstructure, tapered, Raman, and dispersion-shifted fibers, gases, and condensed-phase materials. As supercontinuum emission becomes a practical source for frequency metrology, spectroscopy, remote sensing, and ultrafast photonics, strategies and technologies of supercontinuum generation are being adapted to specific applications.

Sorokin et al. [7] provide an experimental comparison of supercontinuum-generation strategies based on spectral broadening mechanisms in a Kerr-lens mode-locked Cr^{4+}:YAG laser and in tapered silica fibers. This study shows that both approaches allow coherent smooth spectra with a bandwidth up to 400 nm to be generated, as required for optical coherence tomography and other applications.

The strategy of supercontinuum generation demonstrated by **Prabhu et al.** [8] involves using a P-doped continuous wave Raman fiber laser, a 350-m single-mode fiber, and a 50% feedback fiber Bragg grating at 1483.4 nm. This approach allows the generation of a high efficiency supercontinuum stretching from 1434 to 1527 nm and centered at 1483.4 nm with an average output power of 2.1 W, spectral intensity of 22.3 mW/nm, and nonlinear conversion efficiency of 94%.

Nicholson et al. [9] discuss supercontinuum generation in highly nonlinear, dispersion shifted fibers at 1550 nm using both pulsed and continuous-wave laser radiation. An octave-spanning supercontinuum is demonstrated in this work with a few meters of highly nonlinear, dispersion-shifted fiber and a femtosecond erbium fiber laser. Continuum emission with a bandwidth exceeding 247 nm is produced in a kilometer-length nonlinear fiber pumped by a continuous-wave Raman fiber laser.

Petrov et al. [10] report a broad continuum generation in GeO_2-doped silica fibers using femtosecond and picosecond pulses. Over 0.5 W of average power in a broadband picosecond continuum is generated in this work within the near-infrared part of the spectrum from 800 to 1500 nm.

Husakou et al. [11] theoretically analyze the nonlinear propagation of femtosecond pulses and supercontinuum generation in photonic crystal fibers made of glasses with high nonlinear refractive indices. For specifically designed photonic crystal fibers with two zerodispersion wavelengths, supercontinuum generation due to non-solitonic radiation emitted by the solitons both into the shorter and into the longer wavelength sides is predicted.

Town et al. [12] generate supercontinuum emission by pumping a short segment of a randomly microstructured air-silica optical fiber with a Q-switched Nd:YAG laser. The specific features of supercontinuum generation by long, nanosecond pulses propagating through such a random-microstructure fiber are studied.

Supercontinuum metrology

Measurement of parameters of supercontinuum emission is the key to understand the physics behind supercontinuum generation and to find the ways to control this phenomenon. Because of a very broad spectral range typically covered by supercontinuum emission and a complicated temporal structure, supercontinuum metrology often requires instrumentally and conceptually new approaches. These problems are addressed in several papers of this special issue.

Qiang Cao et al. [13] present the results of intensity and phase measurements for a supercontinuum generated in a microstructure fiber. Cross-correlation frequency-resolved optical gating (XFROG) is used in this paper to measure the spectral intensity and the phase of the output supercontinnum. The results of these measurements reveal the temporal pulse break up and soliton fission, which are identified as dominant initial spectral broadening processes underlying supercontinuum generation in microstructure fibers.

Teipel et al. [14] characterize the supercontinuum emission generated by femtosecond laser pulses in tapered fibers, showing the dependence of supercontinuum parameters on the fiber taper waist length and waist diameter, as well as on the pulse duration, spectrum, and power. XFROG traces of light pulses propagating through tapered fibers presented in this paper confirm the soliton-splitting scenario of supercontinuum generation in the anomalous dispersion regime.

Weigand et al. [15] present the results of their measurements of spectral and temporal characteristics of supercontinuum pulses propagating through monodisperse scattering media consisting of sub-wavelength-sized particles using a broadbandwidth XFROG technique. These measurements reveal interesting phase relations between the spectral components of the ballistic component of supercontinuum emission.

McFerran and Luiten [16] report their observation of oscillations in the spectra of supercontinuum emission. The bandwidth of supercontinuum emission produced in a photonic-crystal fiber varied in these experiments from zero up to about one octave.

Coherence and noise in supercontinuum generation

Coherence and noise properties of supercontinuum emission are of crucial importance for numerous applications of supercontinua, including frequency metrology, optical coherence tomography, interferometry, and coherent spectroscopy. Several papers in this special issue address these important aspects of supercontinuum generation.

Zeylikovich and Alfano [17] present the results of their experimental studies of the temporal coherence of supercontinuum emission produced in a pyrex glass plate. The design of a supercontinuum source for coherence applications, manipulating the amplitudes and phases of optical frequency components within supercontinuum pulses, is also proposed in this paper.

Corwin et al. [18] examine fundamental amplitude noise limitations on supercontinuum spectra generated in microstructure fibers. The relative intensity noise of supercontinuum emission is measured in this work as a function of wavelength across the supercontinuum over a wide range of input pulse parameters, and the results of these experiments are explained by numerical simulations based on a generalized stochastic nonlinear Schrödinger equation.

Ames et al. [19] investigate excessive noise generation during spectral broadening in a microstructure fiber. This noise is manifested as an increase in the noise background in the radio-frequency spectrum of the photocurrent from a photodetector illuminated by the pulse train from a laser oscillator. The results of experimental studies are interpreted in terms of a quantum model for studying excess noise generation of broadband pulses in optical fibers based on the nonlinear Schrödinger equation.

Corsi et al. [20] report collinear generation of supercontinuum emission in bulk materials by phase-locked intense laser pulses. These experiments show that the mutual phase coherence of the pump pulses at the input of the medium is transferred to the supercontinuum pulses at the output.

Frequency conversion and spectral transformation of ultrashort pulses

Supercontinuum-generating materials and structures provide high efficiencies of frequency conversion and spectral transformation of ultrashort laser pulses, often suggesting an attractive alternative to nonlinear-optical crystals. Some of the strategies for efficient frequency conversion and spectral transformation of ultrashort pulses are outlined in this special issue.

The paper by **Price et al.** [21] demonstrates the potential of microstructure fibers for UV generation. Spectra of supercontinuum emission generated in pure silica holey fibers in this work extend to 300 nm in the UV, offering much promise for spectroscopic applications.

Akimov et al. [22] explore different strategies of supercontinuum generation in microstructure fibers with submicron-diameter cores surrounding a larger central fiber core. Such a multiple-core microstructure-fiber design not only allows the total energy of supercontinuum emission to be increased, but also offers a practical way of fabricating microstructure-integrated bundles of small-core high-index-step fibers with very large lengths.

The paper by **Tartara et al.** [23] is focused on blue light and infrared continuum generation by soliton fission in a microstructure fiber. With 190-fs high-intensity pulses at the input of a microstructure fiber, the output spectrum observed in this work consisted of a broad infrared supercontinuum and very intense blue peak, containing up to 24% of the input power.

Fedotov et al. [24] use supercontinuum-generating microstructure fibers to achieve a high efficiency of nonlinear-optical frequency conversion and spectral transformation of ultrashort pulses. Pump-depleting conversion of 800-nm radiation to the spectral range around 500 nm is demonstrated in this work by phase-matching the parametric four-wave mixing process for 80-fs Ti:sapphire-laser pulses.

Control of supercontinuum generation

Supercontinuum emission with controlled parameters would be an ideal tool for numerous practical applications. However, this goal is not easy to achieve because of complicated physical scenarios of supercontinuum generation involving an intricate combination of many nonlinear-optical processes.

The paper by **Kalashnikov et al.** [25] demonstrates that polarization and spectral properties of supercontinuum generation in photonic-crystal fibers can be controlled by using dual pulses of laser radiation and with polarization techniques. This work shows, in particular, that the interactions of dual pulses in a photonic-crystal fiber, enhanced by Raman processes, results in an additional broadening of supercontinuum spectra. **Srivastava and Goswami** [26] present several interesting experimental examples of efficient polarization control of supercontinuum generation in various materials.

Theoretical analysis presented by **Spanner et al.** [27] demonstrates the potential of pump-probe strategies for controlled supercontinuum generation in nonlinear media. Optimization of a strong pump and a weak probe pulse at the input of the medium, as shown in this paper, opens the ways to efficiently control the supercontinuum phases at the output.

Ultrashort pulses and ultrafast optics

Extremely broad spectra produced as a result of supercontinuum generation are attractive for the generation of ultrashort pulses. Many problems related to the complicated spectral phase of supercontinuum emission, as well as dispersion and propagation effects have to be solved, though, to make supercontinuum emission a competitive source of ultrashort pulses.

Bandrauk et al. [28] provide an attosecond perspective on supercontinuum generation, discussing the possibility of controlling continuum harmonic generation with attosecond pulses. The superposition of femtosecond and attosecond pulses, as shown in this work, results in broad spectra of high-order harmonics with a large continuum near the cutoff, thus offering a way of creating a new source of X-ray attosecond pulses.

The paper by **Sokolov** [29] shows that molecular modulation can produce ultrabroad spectrum of infrared, visible, and ultraviolet light. This technique relies on adiabatic preparation of highly coherent molecular vibrations or rotations in large ensembles of molecules. Such a light source, as shown in this paper, can be used to synthesize sub-cycle and non-sinusoidal light pulses, which are perfectly synchronized with the molecular oscillations in the given molecular system.

Shpolyanskiy et al. [30] present an interesting theoretical approach to the description of supercontinuum generation with ultrashort light pulses. Their analysis is illustrated by examples of supercontinuum generation in hollow waveguides and microstructure fibers.

Spectroscopic, lidar, and optical-memory applications of supercontinuum emission

Due to its broad spectral band and coherence properties, supercontinuum emission is an attractive source for spectroscopic, biomedical, and frequency-metrology applications. Impressive progress has also been achieved recently in the creation of a supercontinuum based infrared lidar for the remote sensing and pollution monitoring of the atmosphere.

Méjean et al. [31] demonstrate lidar applications of supercontinuum emission. Lidar signals were obtained in this work in the near-infrared range using the supercontinuum generated by a unique terawatt femtosecond laser facility. The signal at up to 4 km altitude was collected within the wavelength range of 1–1.7 μm using a 2-m astronomical telescope. This work also demonstrates a tenfold enhancement of the infrared signal backscattered from the atmosphere compared to the expectations based on previously measured laboratory spectra.

The paper by **Juodkazis et al.** [32] is devoted to optical-memory applications of supercontinuum emission. Optically induced dielectric breakdown of glass is considered as a mechanism of data storage in this work. White light continuum generated from previously damaged sites, serving as recorded memory bits, is used to readout the data stored in a 3D sample.

The paper by **Naumov et al.** [33] is focused on methodological issues related to the applications of broadband and supercontinuum chirped pulses in time-resolved spectroscopy of ultrafast processes. The spectral and temporal resolution of chirped-pulse wave-mixing and pump–probe techniques are examined in this work, and single-shot multidimensional wavemixing techniques using broadband and supercontinuum chirped pulses are discussed.

Concluding remarks

In my opinion, the material of this special issue is in many respects very representative, giving a clear idea of the state of the art in the area of supercontinuum generation, giving an adequate coverage of both conceptual and technological aspects. This would have been, of course, completely impossible without prominent scientists in the field of supercontinuum generation who contributed to this special issue. It is my pleasure to express my sincere gratitude to all the contributors to this special issue. I would like to thank Professor Frank Träger, Editor-in-Chief of *Applied Physics B: Lasers and Optics*, for supporting and promoting the idea of this special issue and for his kind help and timely advice at all the stages of this work. Last, but not least, many thanks to Frau Daniela Schiller for managing and coordinating everything so efficiently, for making the work on this project smooth and pleasant.

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