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Invited Papers

Thermodynamic approach of supercontinuum generation

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ABSTRACT

This paper is aimed at providing an overview on recent theoretical and experimental works in which a thermodynamic description of the incoherent regime of supercontinuum generation has been formulated. On the basis of the wave turbulence theory, we show that this highly nonlinear and quasi-continuous-wave regime of supercontinuum generation is characterized by two different phenomena. (i) A process of optical wave thermalization ruled by the four-wave mixing effects: The spectral broadening inherent to supercontinuum generation is shown to result from the natural tendency of the optical field to reach its thermodynamic equilibrium state, i.e., the state of maximum nonequilibrium entropy. This approach also reveals the existence of a thermodynamic phase-matching. (ii) The generation of spectral incoherent solitons induced by the Raman effect in the low frequency part of the supercontinuum spectrum. Contrary to conventional solitons, spectral incoherent solitons do not exhibit a confinement in the space–time domain, but solely in the frequency domain. They owe their existence to the causality property underlying the Raman response function. Both phenomena of optical wave thermalization and spectral incoherent solitons are described in detail by the wave turbulence theory. In this way, we provide a unified nonequilibrium thermodynamic description of the incoherent regime of supercontinuum generation.

1. Introduction

The phenomenon of supercontinuum generation in optical waveguides, in particular in photonic crystal fibers, has now become available and essential to the wider optics community with applications ranging from telecommunications to biophotonics, but also including metrology, spectroscopy and so on [1,2]. Supercontinuum generation is characterized by a dramatic spectral broadening of the optical field, which is mainly due to nonlinear effects that may operate in various different regimes [2]. It depends on whether the fiber is pumped in the normal or anomalous dispersion regimes, or with short (subpicosecond) or long (picosecond, nanosecond, and quasi-continuous wave) pump pulses. We refer the reader to the review [3] for a detailed discussion of these aspects.

As a rather general rule, the process of spectral broadening inherent to SC generation is interpreted through the analysis of the following main processes: the four-wave mixing, solitons and dispersive waves dynamics, and the Raman scattering [3–5]. Due to such a multitude of nonlinear effects involved in the process, a satisfactory theoretical description of SC generation is still lacking. However, there is a growing interest in developing new theoretical tools aimed at describing SC generation in more details. Besides the theories describing the interaction between individual soliton pulses and dispersive waves [5], we may quote the effective three-wave mixing theory and the underlying first-Born approximation successfully applied to describe femtosecond SC generation in different configurations [6,7]. We also mention the recent works aimed at providing a complete characterization of the coherence properties of SC light by using second-order coherence theory of nonstationary light [8,9].

The general physical picture of SC generation in PCFs can be summarized as follows. When the PCF is pumped with long pulses in the anomalous dispersion regime, modulation instability (MI) is known to lead to the generation of a train of soliton-like pulses, which in turn lead to the emission of Cherenkov radiations in the form of spectrally shifted dispersive waves. These optical solitons are known to exhibit a self-frequency shift towards longer wavelengths as a result of the Raman effect. One encounters the same picture if the PCF is characterized by two zero dispersion wavelengths (ZDWs). In this case the Raman frequency shift of the solitons is eventually arrested in the vicinity of the second ZDW. The SC spectrum then results to be essentially bounded by the corresponding dispersive waves [5,10–12]. The important aspect to underline here is that in all these regimes *the existence of these*

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conventional optical solitons plays a fundamental role into the process of SC generation.

This physical picture of SC generation changes profoundly when one considers the regime in which long and intense pump pulses are injected into the PCF. Indeed, in this highly nonlinear regime, the spectral broadening process is essentially dominated by the combined effects of the Kerr nonlinearity and higher-order dispersion, i.e., by four-wave mixing processes [13]. In this regime the optical field exhibits rapid and random temporal fluctuations, which prevent the formation of robust and persistent coherent soliton structures. It turns out that in this regime the optical field exhibits an incoherent turbulent dynamics, in which coherent soliton structures do not play any significant role. In the following we shall term this regime the 'incoherent regime of SC generation' [14].

In these last years a thermodynamic interpretation of this incoherent regime of SC generation has been formulated [14–18] on the basis of the wave turbulence theory (WT) [19–21]. This concise review is aimed at providing an overview on this nonequilibrium thermodynamic formulation of SC generation. More specifically, our aim here is to provide a unified presentation of two different phenomena which have been identified and discussed into different frameworks so far, namely (i) the process of optical wave thermalization through SC generation and (ii) the generation of spectral incoherent solitons through SC generation.

These two phenomena can be introduced through the analysis of the numerical simulation reported in Fig. 1a. It reports a typical evolution of the spectrum of the optical field in the incoherent regime of SC generation. It is obtained by integrating numerically the generalized nonlinear Schrödinger (NLS) equation (see Eq. (1)), with the dispersion curve reported in Fig. 1b. The initial condition is a high-power (200 W) continuous wave whose carrier frequency $\nu_0 = 283$ THz ($\lambda_0 = 1060$ nm) lies in the anomalous dispersion regime and thus leads to the development of the modulational instability process.

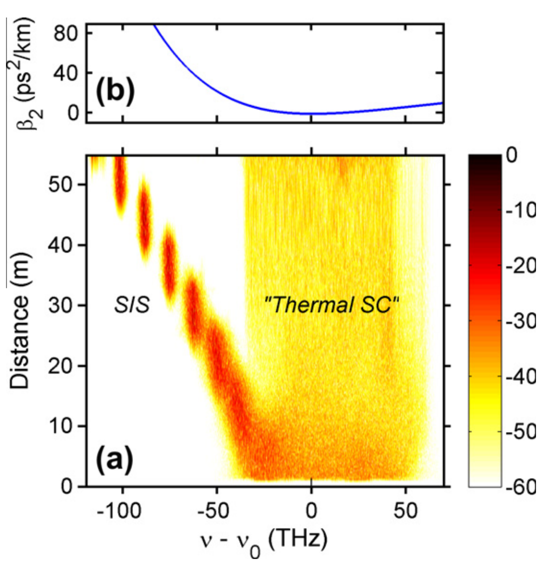

Fig. 1. (a) Numerical simulations of the generalized NLS Eq. (1) using a logarithmic intensity scale (dB) to illustrate the spectral evolution as a function of propagation distance in a 50 m long PCF, for an input CW power equal to 200 W ($\gamma = 0.05$ W^{-1} m^{-1}). The corresponding dispersion curve of the PCF used in the simulations is illustrated in (b). It can be obtained using the standard PCF structure whose parameters (pitch Λ and relative air hole diameter d/Λ) are close to $\Lambda = 1.45$ μm and $d/\Lambda = 0.43$. The optical spectrum shown in (a) is characterized by two main features: (i) A broad central part governed by the four-wave mixing process that exhibits a thermalization process. (ii) A narrower low-frequency branch governed by the Raman effect that self-organizes into a continuous SIS and subsequently a discrete SIS.

We remark in Fig. 1a that the spectrum of the field essentially splits into two components during the propagation:

(i) On the one hand, one notices a broad central part whose evolution is essentially governed by the dispersion effects and the Kerr nonlinearity. These effects are inherently conservative effects and lead to a process of *optical wave thermalization* through SC generation, a feature that has been discussed in Refs. [14–16] using the WT theory. Originally, the formulation of the WT theory was essentially aimed at describing fully developed turbulence in a dissipative system driven far from equilibrium by an external source. This occurs in a large variety of physical systems [19], such as, e.g., in wind generated surface sea waves or in some particular laser systems in the context of optical waves [22,23]. However, the kinetic equations of WT theory also describe the nonequilibrium evolution of random nonlinear waves in a conservative and reversible (Hamiltonian) system. In analogy with kinetic gas theory, an isolated system of incoherent nonlinear waves exhibits, as a rule, a thermalization process, which is characterized by an irreversible evolution of the system towards a thermodynamic equilibrium state, i.e. the Rayleigh–Jeans spectrum. Such irreversible behavior is expressed by the *H*-theorem of entropy growth [19,21], in analogy with the Boltzmann's *H*-theorem relevant for gas kinetics [24]. The kinetic wave equations thus describe the essential properties of this irreversible process of wave thermalization. In the particular context of optical waves, wave thermalization has been recently studied in various configurations and different type of nonlinear media [21,25–34]. It is in this framework that the process of SC generation has been interpreted as a natural thermalization of the optical field [15,16]. Accordingly, the saturation of SC spectral broadening can be ascribed to the natural tendency of the optical field to reach an equilibrium state, i.e., the state that realizes the maximum of nonequilibrium entropy. This analysis also reveals the existence of an unexpected phase-matching process which has a thermodynamic origin.

(ii) On the other hand, one notices in Fig. 1a that a low-frequency spectral branch moves away from the central part of the spectrum. This low-frequency branch is essentially governed by the dissipative Raman effect, whose noninstantaneous nonlinear nature is responsible for the generation of *spectral incoherent solitons* (SIS). The terminology 'SIS' stems from the fact that the incoherent soliton does not exhibit a confinement in the spatial or in the temporal domain, but exclusively in the frequency domain [35]. More precisely, because the optical field exhibits fluctuations that are statistically stationary in time, the soliton behavior solely manifests in the spectral domain (also see [36]). These incoherent soliton-like structures can be described in detail by the WT theory. The kinetic approach remarkably reveals that they owe their existence to the noninstantaneous nature of the nonlinear Raman effect and, more specifically, to the causality property underlying the Raman response function. The analysis reveals that SIS can be characterized by either a *continuous* or a *discrete* frequency shift. We note in particular that the evolution of the low-frequency branch in Fig. 1a rapidly evolves toward a discrete SIS. The discrete SIS is essentially characterized by three incoherent spectral bands, whose frequencies refer to the central frequency ω_0 and the corresponding Stokes and anti-Stokes components with frequencies $\omega_j = \omega_0 \pm \omega_R$, ω_R being the Raman resonant frequency ($\omega_R/(2\pi) \simeq 13.2$ THz).