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A colloquium on the influence of versatile class of saturable nonlinear responses in the instability induced supercontinuum generation

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ABSTRACT

We investigate the modulational instability induced supercontinuum generation (MI-SCG) under versatile saturable nonlinear (SNL) responses. We identify and discuss the salient features of saturable nonlinear responses of various functional forms such as exponential, conventional and coupled type on modulational instability (MI) and the subsequent supercontinuum (SC) process. Firstly, we analyze the impact of SNL on the MI spectrum and found both analytically and numerically that MI gain and bandwidth is maximum for exponential nonlinearity in comparison to other types of SNL's. We also reported the unique behavior of the SNL system in the MI dynamics. Following the MI analysis, the proceeding section deals with the supercontinuum generation (SCG) process by virtue of MI. We examine exclusively the impact of each form of SNL on the SC spectrum and predicted numerically that exponential case attains the phase matching earlier and thus enable to achieve broad spectrum at a relatively shorter distance of propagation than the other cases of SNL's. Thus a direct evidence of SCG from MI is emphasized and the impact of SNL in MI-SCG is highlighted. To analyze the quality of the output continuum spectrum, we performed the coherence analysis for MI-SCG in the presence of SNL.

1. Introduction

One of the most advanced frontiers of nonlinear optics is the generation of intense ultrabroadband spectrum known to the scientific world as the supercontinuum generation (SCG) and has been recognized as "White-Light Laser" [1–8]. SCG is a complex nonlinear phenomenon featuring dramatic spectral broadening of intense light pulses of low energy less than few nano joules passing through a nonlinear media result in the extreme spectral broadening of few octaves [1,2,4]. Such requirement of low pulse energies for the continuum, its coherently pulsed nature, and its high spatial brightness in the fundamental mode of an optical fiber make the continuum, an ideal source for applications such as frequency metrology, femtosecond pulse phase stabilization, optical coherence tomography, ultrashort pulse compression, spectroscopy of materials and photonic structures, and fiber characterization [9–12].

The two vital mechanisms of generating broadband source are known to be soliton fission (SF) and modulational instability (MI) [1,2,4]. The propagation of intense pulses in the anomalous dispersion regime is typically driven by soliton dynamics. In the case of soliton fission, the spectral broadening is governed by the transformation of the pump pulse into a higher order soliton which break up into N fundamental solitons [13–15]. The resulting fundamental solitons emit dispersive wave in the normal group velocity dispersion (GVD) regime and achieve phase matching at a specific frequency in the presence of third order dispersion (TOD), thereby transfers energy between the soliton and dispersive radiation [16–18]. The generated soliton also shifts to lower frequencies via the soliton self-frequency shift (SSFS) [19,20]. The SSFS shifts the spectrum towards IR [21], and the dispersive wave shifts the spectrum towards the UV [22], thereby broadens the spectrum across the visible range [23–25]. It has been widely accepted that soliton fission is the dominant mechanism in the ultrashort pulse regime and relatively weaker in the longer pulses [26].

The latter technique of broadband generation is the MI, which is observed in the longer pulses typically in the picoseconds, nanosecond and the continuous wave regime [27–31]. MI is a ubiquitous good old phenomenon observed in diverse fields such as fluid dynamics, nonlinear optics and plasma physics. In the context of optical fibers, the MI analysis is deeply connected with the nonlinear Schrödinger equation (NLSE) which admits the formation of soliton or solitary wave through a delicate balance between anomalous group velocity dispersion (GVD) and self-phase modulation (SPM) [32,33]. In 1986, Akhmediev and Korneev have presented the exact solution of the NLSE to the problem of MI, through a class

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of periodic solutions [34]. Similarly Akhmediev et al. have extended the work to the case of N-modulation solution, describing the periodic sequences of pulses evolving through MI [35].

MI can be interpreted as the four wave mixing process (FWM) in which two degenerate pump waves under nonlinear interaction evolves as a pair of parametric sidebands that are frequency upshifted (anti-Stokes) and downshifted (Stokes) relative to the pump [1,3,36]. In the undepleted pump case, the parametric sideband grows exponentially with a gain given by $G = [(\gamma P_0)^2 - (\rho/2)^2]^{1/2}$, where $\rho = 2\gamma P_0 + 2\sum_{n=1}^{\infty}[\beta_{2n}/(2n)!]\Omega^{2n}$ is the phase mismatching condition, and Ω is the angular frequency shift from the pump and β_{2n} are the even order dispersion coefficients of the propagation mode. The maximum gain $G_{max} = \gamma\ P_0$ corresponds to $\rho = 0$. In the time domain, the initial noise component of the field leads to a decay of the bound states of the solitons to the stochastic instability of the N-soliton pulses leading to the so called soliton noise generation, a significant contender of coherence degradation. This soliton compression, fragmentation and spectral shifting is an important mechanism contributing to the long wavelength extension of SCG [37].

In Ref. [38,39], the authors exclusively studied the impact of third order dispersion (TOD) in the instability spectrum with an emphasize on the generation of dispersive waves [38,39]. Droques et al. described the symmetry breaking dynamics of MI spectrum as a result of TOD [38], and Soto-Crespo et al. illustrated the characteristics of Cherenkov radiation emitted as a consequence of TOD in the context of Fermi-Pasta-Ulam recurrence [39]. FWM, on the other hand plays the crucial role in the controlled MI process, which allows manipulation and enhancement of the SCG process [40,41].

Recently, Mahnke and Mitschke analyzed the similarities between the solitons and the Akhmediev breather and demonstrated the transformation of solitons from the Akhmediev breather solution [42].In the MI process the soliton dynamics relatively play a minor role in the initial stages of propagation unlike the SF. Although long pulse in the anomalous GVD regime could form higher order soliton [43], but the fission length is typically large for long pulses, thus soliton fission for long pulses generally not feasible, instead the noise trapping in the system results in the fast modulation of the pump envelope and break up into a train of femtosecond soliton like pulses. The reason for the occurrence of MI/FWM can be justified due to the fact that the characteristic length scale of the MI/FWM process is shorter than the fission length for the case of long pulses. Recently, Erkintalo et al. shown the possibility of higher order modulation instability through a suitable low frequency modulation on a CW field [44]. Also, Wabnitz and Akhmediev shown the frequency doubling by MI, through the efficient transfer of power from the pump to the second harmonic of the modulation [45].

It is worth noting that although both the MI and SF process appears to be similar in the end result, but the noise seeding pulse break up certainly differentiate MI from the SF. This noise seeding although assist the fission process at initial stages of propagation but gets amplified during the propagation down the fiber. Thus, the MI-SCG possess poor noise figure in comparison to its SF counterpart. However, the available high average power with long pulse pumping is an attractive feature, which pave the way for commercial SC sources. A comprehensive picture of MI or longer pulse based SCG can be seen from the Refs. [46–55]. Demircan et al. with their detailed theoretical analysis predicted the different parametric region where the MI dominates the SC process [53,54]. Also with their thorough insight analysis furnished a more comprehensive statement that higher order effects are not the prerequisite for the generation of SC and the pulse width is found to be immaterial except being deterministic of the nature of the generating mechanism of SCG. In most cases of SCG, spectral characteristics like bandwidth of the output spectrum, spectral flatness and brightness are exploited, but only a less attention is paved to the coherence of the output spectrum, since low noise figure and high degree of spectral purity are necessary for many applications [56,57]. Following the detailed introduction, we are moving onto the objective of the paper by providing a glimpse of the research activities on the diverse nonlinear effects in fibers and the motivation for us to go for this problem. SC stem on the optical nonlinearities of the medium associated with the pump pulse. Among the many nonlinear effects, stimulated Raman scattering and parametric FWM play vital role in the SC output [1,58,59]. The decisive agent of many of the nonlinear effects in fiber origins from the optical Kerr effect, i.e. the refractive index variation with intensity. This causes the self-phase modulation, which is identified as the fundamental prospect of the spectral broadening mechanism [60].

Recently much attention is paved to the saturable nonlinear response (SNL) of the medium, owing to the high power operation and the inherence in all types of materials. In reality, there is an upper limit for optically induced refractive index variation, beyond that the higher order susceptibility will inevitably come into the picture and eventually saturates the nonlinear response of the medium [61–63]. However, a system such as semiconductor doped fiber (SDF) [62–65] and liquid filled photonic crystal fiber (LCPCF) [58,66,67] attains saturation even at moderate power level, due to enhanced nonlinear index. We consider such a system in the saturation window for our SCG analysis, thus the inclusion of SNL is certainly very essential [64]. Moreover, increasing the pump power by several orders, not only saturates the nonlinear response of the medium but also elevates soliton order and thus ensures the affinity of the SCG towards MI process, thereby making MI as the governing mechanism for the SNL system.

Our argument bears a resemblance to our preliminary report [68], where we have introduced the concept of SNL in MI-SCG. In our previous work, we considered the conventional saturable nonlinear response (CSN), and studied the influence of SNL in SC process. The paper featured the elementary idea of MI and the subsequent SCG under the effect of CSN. However, our literature survey brings us the evidence of the existence of other types of SNL under different cases. The work of Lyra et al. [69], reports the existence of two other types of SNL's in addition to the CSN, which we named as (i) exponential saturable nonlinear response (ESN) and (ii) the third type of SNL is known to be coupled type saturable nonlinear response (TSN). In the recent report, Quong et al. [70] make use of the ESN type of SNL and analyzed the combined effects of higher order dispersion (HOD) on cross-phase modulation instability. Following our previous work of MI-SCG under CSN, and our understanding of MI scenario in various forms of SNL motivate us to go for MI-SCG analysis.

Thus in this research article, our aim is to provide a comprehensive picture of the influences of different functional form of SNL's on the SC spectrum in a self-explanatory manner. The current article deviates from the earlier one due to its optimized analysis and the insight picture of MI-SCG. The organization of the paper is as follows: Following the detailed introduction to MI-SCG in Section 1. Section 2 features the pulse propagation equation in the SNL system. The paper is of two fold, the former in the Section 3 the impact of SNL on MI is studied and the latter Section 4 is dedicated exclusively to the investigation of SCG in the presence of SNL. There will be subsection where different types of SNL cases are discussed. Section 5 features the results and discussion with a brief and interactive analysis between the individual cases towards broadband generation. Section 6 deals the quality analysis of the generated SC by calculating the coherence of the output spectrum. Finally, Section 7 concludes the paper with a summary of the results.