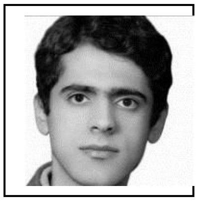
Modeling Mode-Locked Fiber Soliton Lasers based Optical Communication Networks



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Abstract

Consequences of utilizing Femtosecond Fibre Soliton Lasers in Optical Communication Networks are known as Modulation Instability, nonlinear optical output and period doubling route to chaotic waveform; however this provides to improve network security inasmuch as the highest network security belongs to optical chaos communication networks. This study is an attempt to model an optical network using femtosecond fibre soliton laser in order to investigate the nonlinear output characteristics; thus, firstly optical network based on fibre loop soliton laser is modelled to investigate the modulation instability in addition to theoretical approaches and then Nonlinear Schrödinger Equation is described to present a simple model for surveying the period doubling route to multiple pulsing in femtosecond mode-locked fibre lasers; the results confirm and complement the preceding studies in both cases; Finally high network security and other novel applications are explained as the features of optical network communication based on mode-locked soliton fibre lasers.

Keywords: Femtosecond Fiber Soliton Laser, Optical Communication Network, Nonlinear Shrödinger Equation, Period Doubling, Modulation Instability

1. Introduction

Solitons are a universal phenomenon that appears in the more diverse physical systems like shallow and deep water waves, charge density waves in Plasma, Sound waves in liquid helium, matter waves in Bose-Einstein condensates, excitations on DNA chains, "branes" at the end of open strings in superstring theory, domain walls in supergravity, QED electromagnetic nonlinearities and more of course in Optics. Solitons are present at different optics phenomena and thus called according to their phenomenological genesis such as photorefractive Solitons, photovoltaic solitons, coherent and incoherent solitons, bright and dark solitonns, etc[1]; in all cases, solitons can be intuitively understood as a result of the balance between the broadening tendency of diffraction (in spatial domain) or dispersion (in time domain) and nonlinear self focusing. Solitons can be also considered as stationary localized wave packets (wave packets that never broaden) that share many features with real

particles; their total energy and momentum is conserved even while interacting with one another; in the spatial domain, the light beam elevates through nonlinearity the local index of refraction, creating waveguide, which in turn guides the beam, forming a spatial soliton; stable soliton solution of this sort have been observed in numerous nonlinear systems[2,3].
Herein Modulation Instability (MI) is known as a process which closely relates to soliton formation; during MI, small amplitude and phase perturbations grow exponentially and a broad optical beam tends to disintegrate during propagation; the pulse trains that emerge from MI process are actually trains of almost ideal solitons[4].
Modulation Instability in the theoretical description of fiber loop soliton laser systems is as a reason of periodic, exponential amplification which leads to modulation of nonlinearity, the spatial harmonics of with the characteristic nonlinear period of the average soliton solution; this resonance reveals itself as sideband generation in the power spectrum of the laser output; thus, as a steering knob to investigate in this paper, it is notable that the experimental observations verify the dependence of MI process on the shape of the power spectrum; in addition to note that longer loops will exhibit the instability for longer pulses [5,6]; the experimental observations are reported as evidences of modulation instability in mode-locked fiber soliton lasers; in fact, dispersive waves of the laser can become unstable and consequently result in the generation of new spectral components in the soliton spectrum; however, the same experimental observations confirms that modulation instability affects only the dispersive waves of the laser and has no effect on the soliton pulses; in other word, the idea is based on the fact that in nonlinear media , the broadening of localized wave packets can be counteracted, resulting in a pulse or beam that does not change its shape during propagation; such a wave packet or pulse is the same soliton[4,7].
This paper deals with the optical communication networks based on femtosecond soliton fiber lasers and tries to model it in an accurate manner to investigate the modulation instability of laser output. Furthermore since it was experimentally shown that as a result of nonlinear propagation of intense soliton pulse in fiber soliton loop laser cavity, the output intensity pattern experiences period doubling bifurcation and period doubling route to chaotic waveform[8], thus this paper explains nonlinear Schrödinger equation as the dominant equation on laser cavity and investigates the period doubling as universal feature of nonlinear dynamic systems transiting from stable state to chaotic state. Finally the end of the paper dedicates to the applications of femtosecond fiber soliton lasers and their chaotic waveform in optical communication and the other aspects.

2. Nonlinear Schrödinger Equation dominant on Fiber Soliton Laser cavity

The nonlinear Schrödinger equation of fiber soliton laser cavity in one round trip is given as[9]:

$$E_{1,n+1} = \tfrac{1}{2}\frac{g_{net,0}}{1+(E_{1,n}+E_{2,n})/E_{sat}}(1-q'\cos(\pi E_{1,n}+\phi_0))E_{1,n}\ ,$$

$$E_{2,n+1} = \tfrac{1}{2}\frac{g_{net,0}}{1+(E_{2,n}+E_{1,n})/E_{sat}}(1-q'\cos(\pi E_{2,n}+\phi_0))E_{2,n} \qquad (1)$$

where $g_{net,0}$ is the net small-signal gain, E_{sat} is the gain saturation energy, q is the modulation depth of Saturable Absorber (SA); considering the linear bias, ϕ_0 =0, one can easily control the parameter E_{sat} experimentally through a pump power of laser.
Reconstructing the model described above, it will be obtained bifurcation diagram (figure 1) for such laser cavity which verifies the experimental observations [8,9].

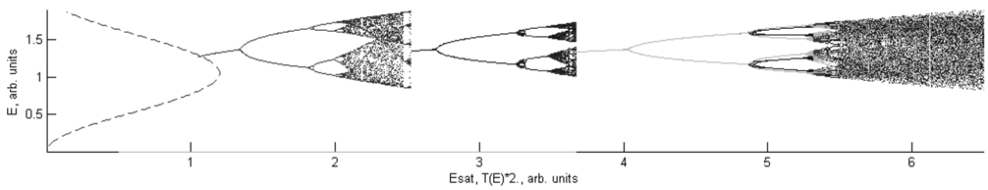

Fig.1. Bifurcation diagram of femtosecond fiber soliton laser cavity modeled on Nonlinear Schrödinger Equation

Figure 1 indicates period doubling which as mentioned earlier is considered the universal feature of nonlinear dynamic systems transiting from stable state to chaotic state [8]; however figure 1 states that the system returns period-one operation by the birth of second soliton during one round trip[9]; this indeed verifies the idea that in nonlinear media, pulse or beam does not change its shape during the propagation if the wave packet is considered as the solitons; so how can interpret MI in nonlinear medium? D.Y.Tangand P.D.Drummond have shown experimentally that before and after MI, no significant changes in soliton pulse's peak power and duration are observed [7]; in the case of period doubling route to chaos, observers believe that with fix pump power the states of period-one, period-two and chaos are very stable; there will be no great disturbances after even several hours; in all states the reporters assert that the average soliton duration is constant [8].

3. Results of modeling mode-locked fiber soliton laser based optical communication network

At the beginning, it is emphasized that the results are representative of MI process. Considering a mode-locked laser with the characteristics of peak power of 234.4596×10^{-3} watts, the wavelength of 1.550×10^{-6} m, repetition rate of 10^9 bit/s and RIN of -150 db/Hz, modulating an electric signal of 20×10^9 Hz on its light beam via a Mach-Zehnder Electro-Optical modulator of bias voltage of 1.0 V and half-wave voltage of 2.0 V, sending data into the fiber of 20×10^3 m length, 8×10^{-6} m diameter and included dispersion and constant nonlinearity, it is possible to model a mode-locked fiber soliton laser. Figure 2, 3 and 4 respectively indicates the signal waveforms of the initial electric signal, model-locked laser modulated output beam and fiber passed laser beam.

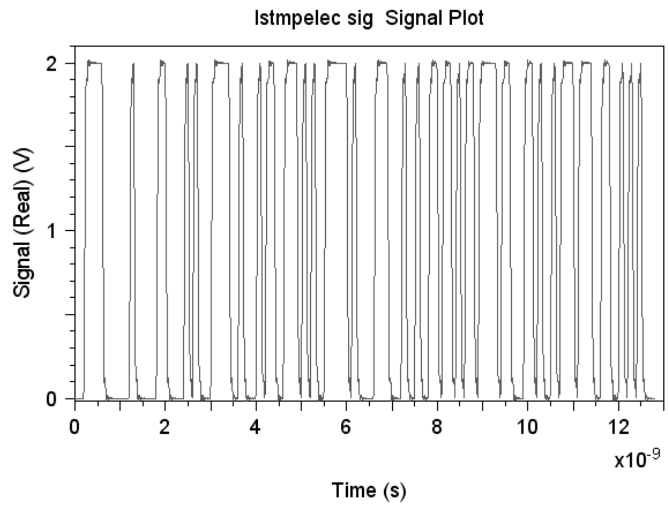

Fig.2. Signal waveform of initial electric signal vs. time

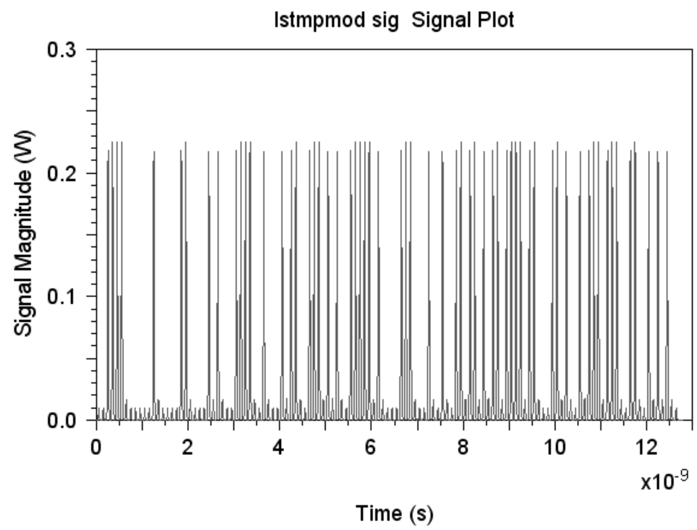

Fig.3. Signal waveform of modulated output beam of mode-locked laser vs. time

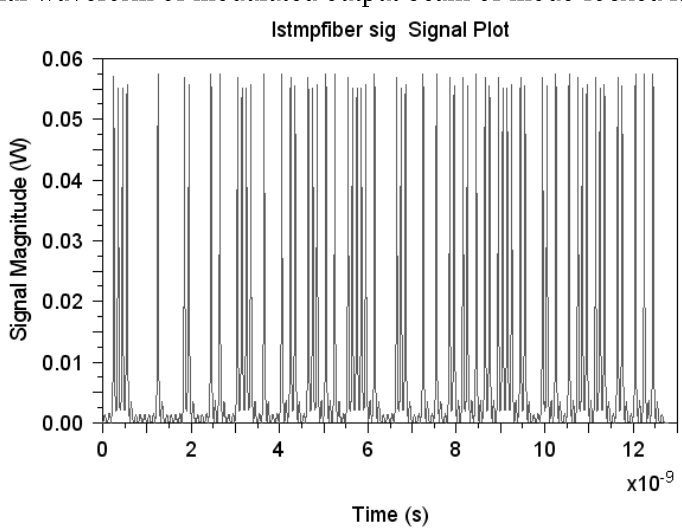

Fig.4. Signal waveform of fiber passed beam of mode-locked laser vs. time

If one has an exact look on these diagrams (as in figure 5 and 6, a zoom view of figure 3,4) he will recognize clearly the MI sidebands in the diagrams.

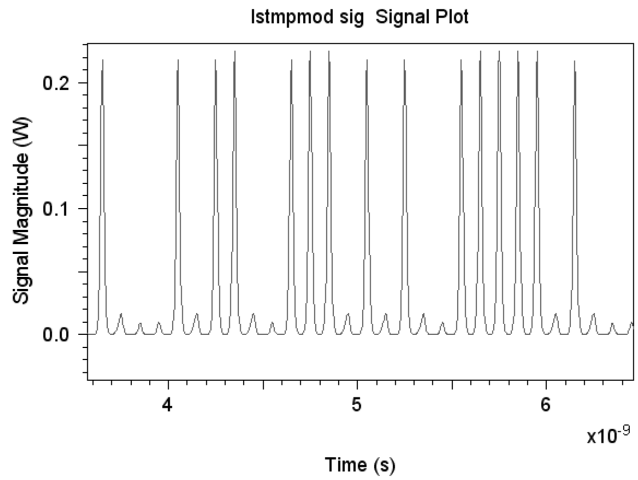

Fig.5. Signal waveform of modulated output beam of mode-locked laser vs. time in a close view

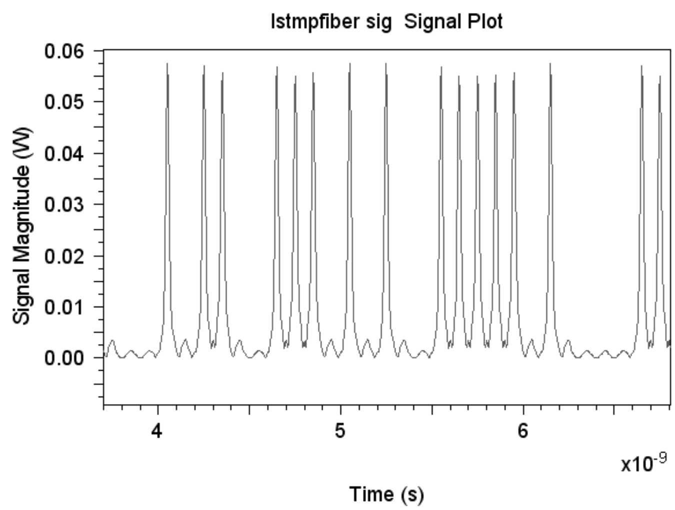

Fig.6. Signal waveform of fiber passed beam of mode-locked laser vs. time in a close view

According to figure.5 & 6 it is confirmed 1) the experimental observation of MI in mode-locked fiber soliton laser output and 2) long fiber will experimentally exhibit higher instability.
At the end of the section, it is worthy to highlight the application of period doubling route to chaos in mode-locked fiber lasers as data storage, electro-optic feedback device as secure optical communication data send/receive method and femtosecond cameras with the capability of looking around the corners[10,11,12].

4. Conclusions

In this paper firstly Nonlinear Schrödinger Equation is described to investigate period doubling route to chaotic waveform in femtosecond fiber soliton laser cavity; the results indicate that soliton pulse or beam shape does not change during the propagation despite of

the presence of bifurcation period doubling and in one round trip of the laser cavity, system returns to period one operation by the birth of second soliton.
As the second issue, the results of modeling the fiber soliton laser based optical communication networks are preventative of MI presence in fiber soliton lasers and verifies that longer loops exhibits the higher instability.

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References
[1] E. DelRe, M. Segev, D. Christodoulides, B. Crosignani, and G. Salamo (2004), *Photorefractive Solitons,* Springer Book
[2] Detlef Kip, Marin Soljacic, Mordechai Segev, Eugenia Eugenieva, Demetrios N.Christodoulides, 20 October, 2000, *"Modulation Instability and Pattern Formation in Spatially Incoherent Light Beams"*, Science, Vol 290.
[3] Marin Soljacic, Mordechai Segev, Tamer Coskun, Demetrios N. Christodoulides, and Ashvin ishwanath, 17 January, 2000, *" Modulation Instability of Incoherent Beams in Noninstantaneous Nonlinear Media"*, Physical Review Letters, Vol 84, No 3
[4] D. Anderson, L. Helczynski, M. Lisak, and V. Semenov, 15 Sep 2003, *"New features of modulational instability of partially coherent light; importance of the incoherence spectrum"*,arXive: physics
[5] N**.** Pandit, D. U. Noske, **S.** M. J. Kelly and J. R. Taylor, 27th February 1992, *" CHARACTERISTIC INSTABILITY OF FIBRE LOOP SOLITON LASERS*", Electronics Letters, Vol. 28, No. 5
[6] Marinko Jablan and Hrvoje Buljan, Ofer Manela, Guy Bartal and Mordechai Segev, 16 Apr 2007, *" Incoherent modulation instability in a nonlinear photonic lattice"*, Optics Express, Vol 15, No 8.
[7] D. Y. Tang and P. D. Drummond, W. *S.* Man, H. Y. Tam and M. S. Demokan, 1999, *" Observation of Modulation Instability in a Fibre Soliton Laser"*, IEEE
[8] L. M. Zhao, D. Y. Tang, F. Lin and B. Zhao, 20 Sep 2004, *"Observation of period-doubling bifurcations in a femtosecond fiber soliton laser with dispersion management cavity"*, Optics Express, Vol.12, No.19
[9] F. Ä O. Ilday, J. Buckley, F. W. Wise, 16 Dec 2002, *" Period-doubling Route to Multiple-pulsing in Femtosecond Fiber Lasers"*, Optics Express, Vol.10, No.25
[10] Ying Zhang, Jian Bin Li, Zhi-Ren Zheng, Yun Jiang and Jin Yue Gao, Feb 1998, *"Dynamic Storage Function by Chaos Control in a Hybrid Biastable System"*, Physical Review E, Vol. 57, No. 2
[11] LUCAS ILLING, DANIEL J. GAUTHIER and RAJARSHI ROY, 2007, *" CONTROLLING OPTICAL CHAOS, SPATIO-TEMPORAL DYNAMICS, AND PATTERNS"*, ADVANCES IN ATOMIC, MOLECULAR AND OPTICAL PHYSICS, VOL. 54
[12] MIT, http://cameraculture.media.mit.edu/femtotransientimaging