



Observation of modulation instability in a fiber soliton ring laser

D.Y. Tang^{a,*}, P.D. Drummond^a, W.S. Man^b, H.Y. Tam^b

^a Centre for Laser Science, Department of Physics, The University of Queensland, Brisbane, Qld 4072, Australia

^b Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

Received 22 February 1999; received in revised form 24 May 1999; accepted 26 May 1999

Abstract

We report on an experimental observation of modulation instability in a passively mode-locked fiber soliton ring laser. We show that although in fiber soliton lasers soliton pulses are inherently stable against modulation instability, dispersive waves caused by the periodic perturbation of solitons propagating in the cavity are not. Due to modulation instability the dispersive waves can become unstable and consequently result in the generation of new spectral components in the soliton spectrum. © 1999 Elsevier Science B.V. All rights reserved.

PACS: 42.55Wd; 42.65Sf; 42.65Tg

Keywords: Fiber laser; Modulation instability; Soliton; Mode-locking

Erbium doped fiber soliton lasers as a compact, stable source of ultrashort pulses have attracted considerable attention recently [1–11]. In an erbium doped fiber soliton laser, soliton pulses propagating in the cavity experience periodical perturbations caused by the cavity gain and output loss. It is a well-known fact that when the condition $Z_a \ll Z_0$ is not met, where Z_a and Z_0 are the amplifier and soliton period, respectively, a sideband instability characterized by the appearance of discrete spectral components in the soliton spectrum occurs [4,10,11]. Sideband instability arises as a result of the resonance between the periodic gain and loss perturbations experienced by a soliton and the characteristic frequency of the soliton [12–14]. It is the primary

mechanism limiting the minimum pulse duration obtainable in a fiber soliton laser.

In this paper we report on an experimental observation of another instability in a fiber soliton ring laser. We show experimentally that under certain conditions, new spectral components other than those caused by the sideband instability can appear in the soliton spectrum of the laser. Analyzing characteristics of these new spectra suggests that they are the result of modulation instability in the laser. In particular, we point out that due to modulation instability, dispersive waves in a fiber soliton laser can become unstable, and consequently generate new spectral components in the soliton spectrum.

The fiber soliton laser used in our experiment is schematically shown in Fig. 1. It is a unidirectional fiber soliton ring laser. Unidirectional operation is forced by the inclusion of a polarization dependent isolator in the cavity. The laser cavity is about 10 m

* Corresponding author. E-mail: tang@physics.uq.edu.au

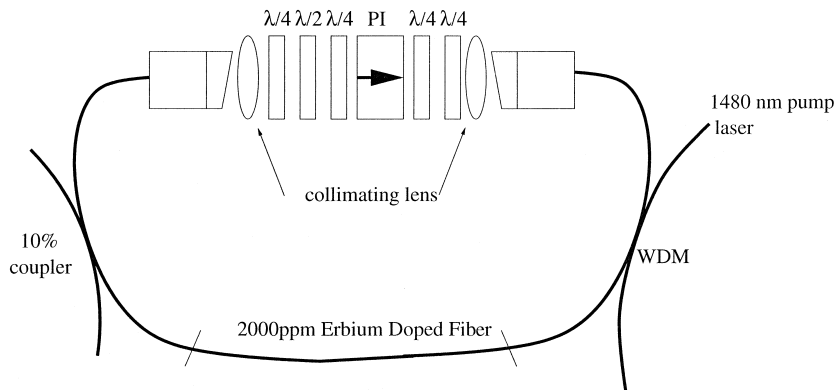


Fig. 1. Schematic diagram of the fiber soliton ring laser. $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate; PI, polarization dependent isolator.

long, and constructed of a 4 m long erbium doped fiber (Er^{3+} concentration ~ 2000 ppm) and two pieces of 3 m long dispersion shifted single mode fiber. The nonlinear polarization rotation technique is used to achieve mode-locking in the laser [15]. To this end two polarization controllers, one consisting of two quarter-wave plates, and the other one of two quarter-wave plates and one half-wave plate, are used to set the appropriate state of polarization of the light before and after the isolator. The polarization controllers and the polarization dependent isolator are mounted on a fiber bench, which makes the accurate adjustment of the state of polarization easier. The laser is pumped by a pigtailed InGaAsP laser diode of wavelength 1480 nm. The pump laser beam is coupled to the cavity through a customized wavelength-division-multiplexing (WDM), and the pump power is continuously adjustable with a maximum fiber output power of 120 mW. The output of the laser is taken via a 10% fiber coupler, with spectra recorded on an optical spectrum analyzer (HP 70004A), and the pulse durations measured with a commercial optical autocorrelator (Inrad 5-14-LDA). Self-started mode locking is obtained in the laser simply by increasing the pump power and adjusting the relative orientation of the wave plates. When the polarization states of the polarization controllers are appropriately selected, soliton operation of the laser is readily obtained after mode locking. Otherwise a minor adjustment of the polarization controllers is required to achieve soliton operation.

Fig. 2 shows a typical soliton spectrum observed in the laser when the central wavelength of the

soliton is about 1558 nm. The sidebands caused by the sideband instability of the laser are clearly visible in the spectrum. In our experiment when the laser is in a soliton operation state, the sideband instability is observed. However, we find that before a new soliton pulse is created or an existing one is destroyed, changing the pump power will change significantly the power of sidebands, while the power of soliton pulses varies only slightly. Fig. 3 shows as an example a typical peak spectral intensity variation of the soliton and one of the sidebands with the pump power. The strength of sidebands reflects directly the strength of dispersive waves in the laser. This experimental result demonstrates that by carefully changing the pump power, one can control the strength of dispersive waves in the laser cavity.

The new instability of the laser is observed when the strength of dispersive waves has become strong

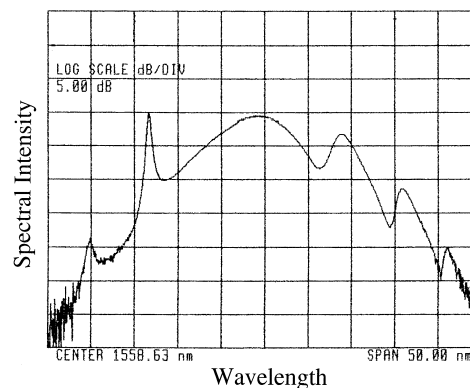


Fig. 2. A typical soliton spectrum of the laser observed.

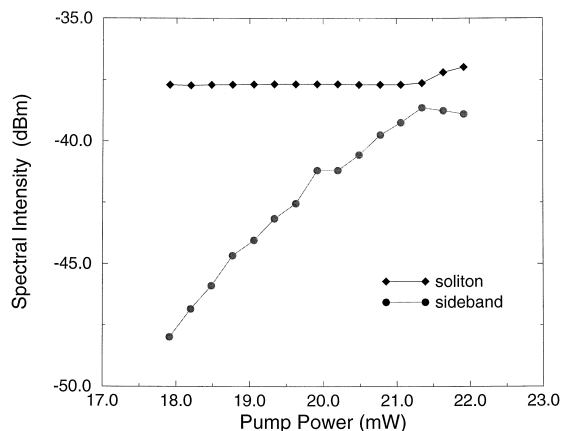


Fig. 3. Peak spectral intensity variations of the soliton and a sideband with the pump power.

enough. In Fig. 3 this corresponds to the maximum point of the spectral intensity variation curve of the dispersive wave. Fig. 4 shows a typical spectral evolution of the soliton as the new instability occurs. Fig. 4a shows the soliton spectrum immediately before the instability, where only those discrete spectral components caused by the sideband instability are visible in the soliton spectrum. Fig. 4b shows that as the pump power is increased, a new distinct spectral component suddenly appears in the soliton spectrum. The new discrete spectral component appears near the strong high frequency sideband in the soliton spectrum. Accompanying the appearance of the new spectrum, the strength of the original sideband decreases (also see Fig. 3), indicating that energy has been transferred from the sideband to the new spectrum. We also note that as the pump power is increased, a new broadband spectral component also appears close to the top of the soliton spectrum. We believe that the mechanism of this new spectral component could be the zero-order sideband instability of the laser [13]. Details about this spectral component will be discussed elsewhere. Fig. 4c shows the soliton spectrum with further increased pump power. The strength of the new spectral component increases with the pump power. Comparing the position of the new spectral component shown in Fig. 4b and c, it is clearly to see that it shifts with the pump power. In Fig. 4c two further spectral components have also become visible. One appears at the higher frequency side of the new spectral component

and can just be identified, while the other one at the lower frequency side of the new spectrum and can be clearly seen in the soliton spectrum.

The appearance of the new spectra depends on the strength of dispersive waves in the laser, rather than on the strength of the total laser beam. Experimentally, as the pump power is continuously increased, a new soliton pulse eventually forms in the laser.

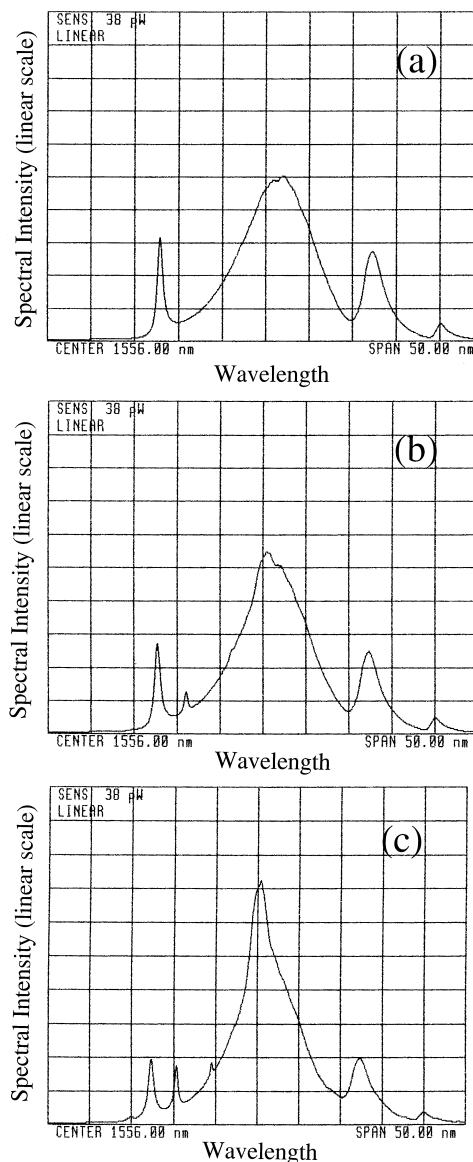


Fig. 4. A typical soliton spectral evolution measured as the new instability occurs. From (a) to (c) the pump power is increased.

Consequently the strength of the dispersive waves in the laser becomes weaker, and all the new spectral components described above disappear. Further increasing the pump power, as the strength of the dispersive waves build-up and become strong enough again, the new spectra come back, and the whole process repeats itself.

To find out the effect of the instability on the soliton pulses, we have measured autocorrelations of the soliton pulses corresponding to the soliton spectra shown in Fig. 4. Comparing them with those obtained from the laser without the instability, the autocorrelations have a very strong pedestal. The stronger the new spectra are, the higher is the pedestal. However, the existence of the pedestal does not affect the average duration and power of soliton pulses, indicating that the soliton pulse is still stable.

The new instability exhibits three significant characteristics. First, it is a threshold effect. The instability occurs only when the strength of dispersive waves is strong enough. Second, the new spectra caused by the instability possess the feature of power tuning. Third, the instability has no effect on the soliton pulses, it is only related to dispersive waves of the laser. These characteristics are in good agreement with those of the modulation instability in erbium doped fibers [16]. In fact, further numerical simulations of the laser dynamics have confirmed the appearance of these new spectra due to the modulation instability [17]. Based on our experimental results and supported by results of numerical simulations, we conclude that the generation of these new spectral components in the soliton spectrum is a result of the modulation instability in the laser. In particular, we point out that due to modulation instability, dispersive waves of the laser have become unstable. To our knowledge this is the first experimental observation of modulation instability in a fiber soliton laser.

In summary we have experimentally observed a new kind of spectral generation in a passively mode-locked fiber soliton ring laser. This new kind of spectral generation occurs when the dispersive waves of the laser have become strong enough, and is characterized by that they appear near to the

unstable sideband in the soliton spectrum and their frequency shifts in relation to the unstable sideband are the sideband strength dependent. Based on characteristics of the new spectra, we attribute their generation as results of the modulation instability in the laser. Our experimental results show that although a soliton pulse is stable against modulation instability, the dispersive waves are not. They can become unstable, and consequently result in the generation of new spectra, leading eventually to the generation of new solitons in the fiber laser.

Acknowledgements

W.S.M. and H.Y.T. acknowledge support from the university research grant of The Hong Kong Polytechnic University.

References

- [1] K. Tamura, E.P. Ippen, H.A. Haus, L.E. Nelson, *Opt. Lett.* 18 (1993) 1080.
- [2] A.B. Grudinin, D.J. Richardson, D.N. Payne, *Electron. Lett.* 29 (1993) 1860.
- [3] M.E. Fermann, M.J. Andrejco, M.L. Stock, Y. Silberberg, A.M. Weiner, *Appl. Phys. Lett.* 62 (1993) 910.
- [4] D.J. Richardson, R.I. Laming, D.N. Payne, V.J. Matsas, M.W. Phillips, *Electron. Lett.* 27 (1991) 1451.
- [5] D.J. Richardson, R.I. Laming, D.N. Payne, M.W. Phillips, V.J. Matsas, *Electron. Lett.* 27 (1991) 730.
- [6] A.B. Grudinin, S. Gray, *Electron. Lett.* 29 (1993) 1860.
- [7] D.J. Jones, H.A. Haus, E.P. Ippen, *Opt. Lett.* 21 (1996) 1818.
- [8] M.L. Dennis, I.N. Duling III, *Appl. Phys. Lett.* 62 (1993) 2911.
- [9] M. Hofer, M.H. Ober, F. Haberl, M.E. Fermann, *IEEE. J. Quantum Electron.* 28 (1992) 720.
- [10] M. Nakazawa, E. Yoshida, Y. Kimura, *Appl. Phys. Lett.* 59 (1991) 2073.
- [11] D.U. Noske, N. Pandit, J.R. Taylor, *Electron. Lett.* 28 (1992) 2185.
- [12] S.M.J. Kelly, *Electron. Lett.* 28 (1992) 806.
- [13] D.U. Noske, N. Pandit, J.R. Taylor, *Opt. Lett.* 21 (1992) 1515.
- [14] J.N. Elgin, S.M.J. Kelly, *Opt. Lett.* 18 (1993) 787.
- [15] M. Hofer, M.E. Fermann, F. Haberl, M.H. Ober, A.J. Schmidt, *Opt. Lett.* 16 (1991) 502.
- [16] G.P. Agrawal, *IEEE. Photonics Technol. Lett.* 4 (1992) 562.
- [17] D.Y. Tang, W.S. Man, H.Y. Tam, *Phys. Rev. A.*, unpublished.