A new class of modulation instability in optical fibre with third-order dispersion under pulsed excitation

Lilian Emonin[1,*], *Andrei V.* Ermolaev[1], *Thibaut* Sylvestre[1], *Romain* Morel[1], *Goëry* Genty[2], *Christophe* Finot[3], *Govind P.* Agrawal[4], and *John M.* Dudley[1,5]

[1]Université Marie et Louis Pasteur, CNRS, Institut FEMTO-ST, 25000 Besançon, France
[2]Photonics Laboratory, Tampere University, FI-33104 Tampere, Finland
[3]Université Bourgogne Europe, CNRS, Laboratoire ICB, 21078 Dijon, France
[4]The Institute of Optics, University of Rochester, Rochester, NY 14627, USA
[5]Institut Universitaire de France, Paris, France

Abstract. Although it is generally believed that scalar modulation instability in fibres is governed by interaction between nonlinearity and only even orders of dispersion (β_2,β_4), we show here that, under pulsed excitation, modulation instability can still be observed with only third-order dispersion β_3. This behavior is attributed to an effective second-order β_2 dispersion induced by the interaction of β_3 and self-phase modulation.

The usual analysis of modulation instability (MI) with anomalous dispersion (AD) [1] predicts that MI gain is governed solely by the interaction of nonlinearity with only even-order dispersion (β_2, β_4), with the contribution of odd-order dispersion β_3 canceling out in the analysis. Here, we report the new result that MI sidebands can still be seen with pulsed pumping in a system governed with only β_3. We first consider the nonlinear Schrödinger equation (NLSE), with all terms having their usual meaning [1]:

$$\frac{\partial A}{\partial z} + i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial \tau^2} - \frac{\beta_3}{6}\frac{\partial^3 A}{\partial \tau^3} - i\gamma|A|^2 A = 0 \tag{1}$$

We consider 10 m of highly-nonlinear fibre with: $\beta_2 = 0\ \mathrm{s^2\,m^{-1}}$, $\beta_3 = 1\times10^{-40}\ \mathrm{s^3\,m^{-1}}$, $\gamma = 0.01\ \mathrm{W^{-1}\,m^{-1}}$. Figure 1 shows temporal and spectral fibre outputs from simulations of Eq. (1) with $\beta_2 = 0$ for: (a,b) a 100 W continuous wave (CW); (c,d) a 50 ps pulse with 100 W peak power. Input quantum noise is included. As expected, for CW excitation with only β_3, there is no instability, but for pulses, we see clear spectral sidebands and temporal modulation.

To further highlight the differences between the usual MI and the case of β_3-induced pulsed MI, Fig. 1(e,f) shows false-colour maps of the output spectra as β_2 is swept from anomalous to normal dispersion (ND) for a 10 ps input pulse. In Fig. 1(e), we set $\beta_3 = 1\times10^{-40}\ \mathrm{s^3\,m^{-1}}$ and observe sidebands evolution showing that instability still exists at the zero-dispersion wavelength (ZDW), and indeed persists into the normal-dispersion regime where conventional theory predicts it should be absent. This dynamics is very different from Fig. 1(f) where we set $\beta_3 = 0\ \mathrm{s^3\,m^{-1}}$ and see clear sidebands for anomalous dispersion which move to larger frequency shifts as β_2 approaches zero. There is no instability for $\beta_2 > 0$. This is the usual CW or quasi-CW MI as seen in experiment [4].

*e-mail: lilian.emonin@edu.univ-fcomte.fr

We also performed the experimental counterpart of these simulations, by measuring the output spectra of a 19 m HNLF fiber pumped by ∼2 ps pulses from an OPO tunable over 1535-1586 nm. In Fig. 1(g), one can observe that the MI sidebands persist even beyond the ZDW (dashed line), which was independently measured using a Mach-Zehnder interferometer [5]. Figure 1(h) shows simulation under conditions similar to the experiment with good agreement.

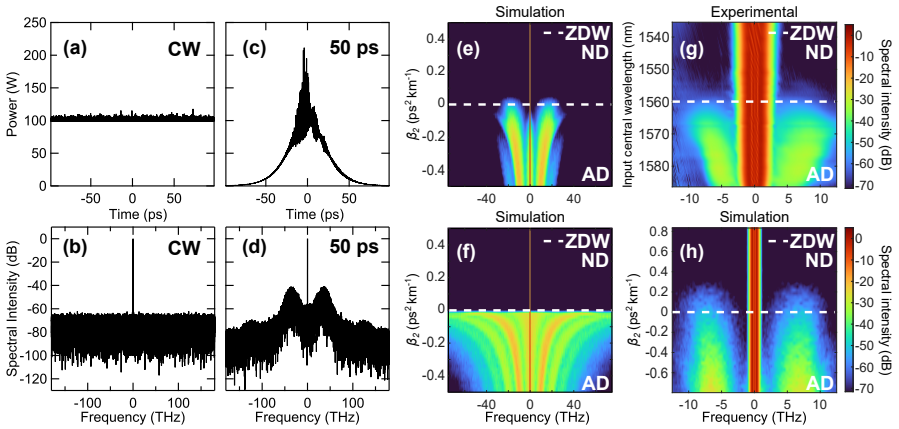


Figure 1. (a-d): temporal and spectral outputs from NLSE simulations for $\beta_2 = 0$ and $\beta_3 \neq 0$. (a,b) CW input shows no MI; (c,d) 10 ps pulses lead to clear sidebands. (e-h): output spectra as a function of β_2 sweeping across the ZDW (dashed line) for: (e) MI with pulsed input and $\beta_3 \neq 0$; (f) ideal MI with $\beta_3 = 0$; (g) experimental results; (h) simulation corresponding to the experimental results of (g).

Physically, these results can be explained by the fact that a pulse with a finite bandwidth will undergo self-phase modulation (SPM) during propagation, and the resulting spectral broadening will induce an effective β_2 through the nonzero β_3. Analysis for a Gaussian pulse of peak power P_0 and duration $\Delta\tau$ (FWHM) propagating over a length L of fibre shows that SPM induces spectral broadening $\delta\omega \sim \pm(8 \ln 2/e)^{1/2} \gamma P_0 L/\Delta\tau$ [1]. This broadening, combined with β_3, induces an effective $\beta_2^{\text{eff}} = \beta_3 \delta\omega < 0$. The frequency of maximum MI gain is then given by: $\Omega_{\max} = (2\gamma P_0/|\beta_2^{\text{eff}}|)^{1/2} \sim (e/2 \ln 2)^{1/4} (\Delta\tau/|\beta_3|L)^{1/2}$. For $\Delta\tau = 10$ ps and other parameters used above, this yields $\Omega_{\max}/2\pi \sim 19$ THz, in good agreement with the ∼17 THz obtained from simulations. Although this is clearly an approximate analysis, it nonetheless predicts sidebands shifts within ∼20% of those seen in the simulation. Further work is necessary to explore this novel dynamical regime in more detail.

Our results reveal the dramatic impact that higher-order effects can have on seemingly well-known nonlinear processes. In addition to these simulation and experimental results, potential observation of this novel MI regime in novel dispersion-engineered solid and hollow core fibres will also be discussed.

References

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