Observation of moduationally unstable multi-wave mixing
Julien Fatome, Christophe Finot, Andrea Armaroli, Stefano Trillo

To cite this version:
Julien Fatome, Christophe Finot, Andrea Armaroli, Stefano Trillo. Observation of modulationally unstable multi-wave mixing. Optics Letters, Optical Society of America, 2013, 38 (2), pp.181-183. <10.1364/OL.38.000181>. <hal-00765933>

HAL Id: hal-00765933
https://hal.archives-ouvertes.fr/hal-00765933
Submitted on 17 Dec 2012

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Observation of modulationally unstable multi-wave mixing

J. Fatome,¹ C. Finot,¹ A. Armaroli,² and S. Trillo³

(1) Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR 6303 CNRS-Université de Bourgogne, 9 Av. A. Savary, 21078 Dijon, France
(2) Max Planck Institute for the Science of Light, Gänther-Scharowsky-Str. 1/Bau 24, 91058 Erlangen, Germany
(3) Department of Engineering, University of Ferrara, via Saragat 1, 44122 Ferrara, Italy

*Corresponding author: jfatome@u-bourgogne.fr

Compiled December 13, 2012

We demonstrate experimentally that multiple four-wave mixing pumped by a dual-frequency input in a single-mode fiber is modulationally unstable. This collective type of instability leads, in the anomalous dispersion regime, to sideband growth around all-orders of four-wave mixing. This is in contrast with the normal dispersion regime where our measurements show that four-wave mixing exhibits no instability. Our conclusions are based on the first systematic mapping of the phenomenon as a function of the dual-pump input frequency separation.

OCIS codes: 190.4380, 190.4370.

Fig. 1. Experimental setup. ECL: external cavity laser; PM: phase modulator; OSA: optical spectrum analyzer.

MI to manifest, in the anomalous GVD regime, as the exponential growth of an extra-modulation at frequency $\Omega_m$ of the primary modulation and its mFWM harmonics, owing to the generation of photon pairs at frequency $\omega_0 \pm n\Omega_p \pm \Omega_m$ [10]. This prediction relies on the extension of the approach to stability to account for FWM via a Floquet type of analysis [10], thus considerably improving previous approaches based on incoherently coupled nonlinear Schrödinger (NLS) equations [22, 23], which were argued to neglect FWM [24]. The underlying mechanism of this MI process is the fact that the two pump frequencies $\omega_\pm$ are unstable, provided the GVD is anomalous, and transfer their modulation (arising from the growth of frequency $\Omega_m$ from noise) over all the mFWM products. However, at variance with conventional scalar MI, in this case the net amplification of the extra-modulation occurs over several periods of conversion and backconversion of mFWM. Moreover, mFWM sidebands do not acquire their modulation directly because otherwise they would be modulated at a different frequency owing to their much lower power. Because of these features we denoted this phenomenon as collective MI. The purpose of this letter is to report the first experimental observation of this process in a standard telecom fiber by means of a systematic mapping of the phenomenon as a function of the initial two pumps frequency detuning.

The experimental setup developed in order to characterize the collective nature of the MI building on top of mFWM process in fibers is illustrated in Fig. 1. It consists of two external cavity lasers (ECL) centered around...
Fig. 2. (a-c) Experimental output spectra showing MI developing over mFWM for balanced (a) and imbalanced (c) pumps at $\Delta f_p = 100$ GHz and $P = 800$ mW. (b-d) color maps of output spectrum as a function of detuning $\Delta f_p$ ranging from $-10$ to $250$ GHz, measured in the balanced (b) and imbalanced (d) case. Open dots correspond to the most unstable frequency $f_{MI}$ from theory.

The results of our experiments, obtained for a constant total average power $P = 800$ mW, are summarized in Fig. 2. Figure 2(a) show a typical output spectrum obtained for a balanced input (400 mW on each pump) detuned by $\Delta f_p = \Omega_p/\pi = 100$ GHz (in order to compare with the normalized units used in Ref. [10], this corresponds to a pump detuning $2\Omega = 2.8$). As shown in Fig. 2(a), MI sidebands corresponding to a extra-modulation at frequency $f_m = 34$ GHz grows spontaneously from noise over the mFWM. In Fig. 2(a), the MI sidebands owing to such extra-modulation are clearly seen around $n = 1, 3, 5$ FWM sidebands. The Floquet stability analysis [10] of the FWM predicts that the maximally unstable modulation frequency turns out to coincide with the peak gain frequency of the standard scalar MI associated with a single pump. Starting from the fiber parameters, namely a GVD $k'' \approx -22$ ps$^2$/km and a nonlinear length $Z_{nl} = (\gamma P/2)^{-1} \approx 1.9$ Km associated with the pump power $P/2 = 400$ mW, we estimate such frequency to be $f_{MI} = \sqrt{2/(|k''|Z_{nl})}/(2\pi) = 34.86$ GHz, in good agreement with the value observed from the spectra. It is important, however, to emphasize that the phenomenon possess an intrinsic collective nature, with the same modulation frequency $f_m$ growing on top of the pumps and higher FWM orders as well. Assuming, vice versa, that MI could develop around e.g. the first-order FWM sideband ($n = 3$) independently from the modulation acquired by the pumps, one should have been observed such sidebands to develop a modulation one order of magnitude slower according to their power level, which is $-20$ dB below the pump power, see Fig. 2(a).

In order to investigate the dependence of collective MI on the pump detuning, we have also recorded spectra [such as the one in Fig. 2(a)] for different pump detunings. In particular our set-up allows to tune the wavelength detuning between the lasers in steps of $\Delta \lambda = 0.01$ nm over a whole range which is equivalent to frequency detunings ranging from 250 down to $-10$ GHz (so to include as a reference $\Delta f_p = 0$, where FWM is expected to vanish), while keeping fixed the injected power at 800 mW. The result is illustrated in the (color) level map in Fig. 2(b). First, mFWM are clearly observed to correspond to the diagonal brighter narrow lines, which grows in number as the detuning $\Omega_p$ is decreased (mFWM becomes more and more efficient as its figure of merit $\gamma P/(|k''|\Omega_p^2)$ grows larger [13]), until a strong spectral broadening due to mFWM explosion is observed just near the dark point which corresponds to $\Delta f_p = 0$, where mFWM is found indeed to vanish. From the map we clearly see that the collective MI frequency $f_m$ remains locked to the value $f_{MI}$ (see empty circles in the figure), basically not exhibiting any dependance on the pump detuning, as expected from the linear stability analysis. Sidebands due to collective MI remain clearly visible in Fig. 2(b) in the range $70 - 250$ GHz. They disappear when they coalescence with the mFWM sidebands, which occurs around a pump detuning $\Omega_p \approx 70$ GHz. At lower detunings, not only the MI becomes resonant with the mFWM but also the latter looses its features of recurrence [13]. Under such conditions the Floquet
approach looses its validity and the assessment of the linear stability problem in the presence of (highly efficient) mFWM still remains a challenging open problem that will require new approaches. We have also studied the robustness of the phenomenon against the imbalance of the pumps. Figure 2(c-d) display a typical output spectrum and the relative map against the pump detuning obtained when the pumps are imbalanced by about 10% (input power fractions $\eta = P_+ / P = 0.56$ and $1 - \eta = 0.44$, respectively). As shown the collective MI is still visible, though the sidebands due to the extra-modulation at frequency $f_m$ are more clearly pronounced around the stronger pump. In our experiment we have found that the MI spectrum is very sensitive to the pump imbalance and tends to disappear for stronger asymmetries.

The collective MI process can be described by means of a single NLS equation, whose nonlinear term contains all the beating products that give rise to mFWM orders. In order to assess whether a satisfactory quantitative agreement exists, we have performed simulations of the NLS equation

$$i \frac{\partial E}{\partial Z} - \frac{k''}{2} \frac{\partial^2 E}{\partial T^2} + \gamma |E|^2 E = -\frac{\alpha}{2} E,$$

using the parameters of the fiber and the input $E_0(T) = \sqrt{P} [\sqrt{\eta} \exp(i \pi \Delta f_p T) + \sqrt{1 - \eta} \exp(-i \pi \Delta f_p T)]$ in the presence of white noise. A typical spectrum obtained with the same parameters as in Fig. 2(a) is reported in Fig. 3(a) for the balanced case $\eta = 0.5$ (similar results are obtained in the unbalanced case). The comparison between Fig. 2(a) and Fig. 3(a) allows us to conclude that a satisfactory quantitative agreement exists. As shown in Fig. 3(b) MI develops on top of a periodic evolution, from which the system adiabatically decays as soon as the MI leads to a substantial amplification of the extra-modulation, a feature which, however, we are not able to measure.

Finally we have also investigated experimentally the same phenomenon in the normal GVD regime. To access this regime we have replaced the SMF with a 6 Km long non-zero dispersion-shifted fiber (NZDSF) with dispersion $D = -2.5$ ps/nm km (slope $S = 0.07$ ps/nm$^2$ km), nonlinear Kerr coefficient $\gamma = 1.7$ W$^{-1}$ km$^{-1}$, and linear loss coefficient is $\alpha = 0.2$ dB/km. We report a typical spectrum obtained for $\Delta f_p = 100$ GHz and $P = 500$ mW and the relative map against the pump detuning in Fig. 4(a) and 4(b), respectively. By comparing Fig. 4(a,b) with 2(a,b), it is clear that, in the normal GVD regime, the dynamics is fully dominated by mFWM even at large detunings and we observe no sidebands arising from collective MI, as anticipated on the basis of the linear stability analysis [10].

In summary, our experiments show that mFWM mixing exhibits, in the anomalous GVD regime, the onset of collective MI process whose signature is the appearance of an extra-modulation at fixed frequency around all orders of the primary mixing process.

S.T. thanks Université de Bourgogne and in particular G. Millot for discussions and kind hospitality, as well as Italian Ministry of Research for funding (PRIN project no. 2009P3KT72Z). J. F. thanks the Agence Nationale de la Recherche for its financial support through the ANR Emergence grant SO FAST, ANR-11-EMMA-0005.

References

References


