Noise squeezing due to Kerr effect nonlinearities in optical fibres with negative dispersion

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Indexing terms: Nonlinear optics, Optical fibres, Optical squeezing

A reduction of amplified spontaneous emission (ASE) related relative intensity noise (RIN) is observed to be caused by modulation instability on negatively dispersive fibres for the first time. Good agreement is obtained between experimental results and a new analytical model.

Kerr effect nonlinearities in optical fibres have been the subject of extensive studies [1 – 3]. Four wave-mixing (FWM) between the signal and the amplified spontaneous emission (ASE) noise was found to be an important source for system performance degradation, especially in systems using in-line optical amplifiers. With positive fibre dispersion, this effect is known as modulation instability (MI). Although most published works have dealt with a change of optical spectrum caused by MI, in intensity modulated systems with direct detection (IM-DD), performance degradation due to MI is caused by a nonlinear increase of the relative intensity noise (RIN) within the signal baseband [4, 5]. We demonstrate that the amplitude of RIN can be reduced by this FWM, in systems with negative fibre dispersion.

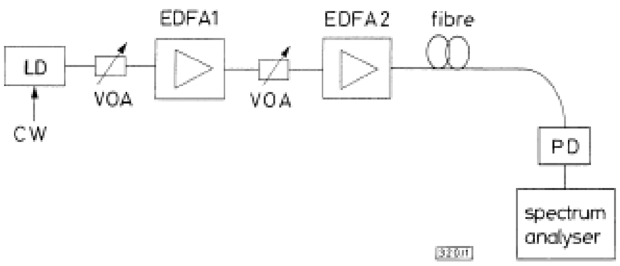

Fig. 1 *Experimental setup*

The experimental setup is shown in Fig. 1. A 1557nm continuous wave strained quantum-well laser diode is provided with a low frequency (10 kHz) dither to suppress stimulated Brillouin scattering in the transmission fibre. Two erbium doped fibre amplifiers (EDFAs) are used to amplify the CW light and to generate a certain level of ASE. A wideband photodiode and microwave spectrum analyser are used as a receiver which measures RIN spectra.

It has been observed that the laser phase noise can be converted to intensity noise through the fibre dispersion and has a strong impact in the receiver RIN spectrum [6]. In this Letter however, we concentrate our attention on the effect of modulation instability. To do so, we increased the broadband ASE noise from EDFAs intentionally to make sure that receiver RIN is dominated by signal-spontaneous emission beat noise. This was done by inserting a variable optical attenuator (VOA) before each EDFA as shown in Fig. 1.

Figs. 2 and 3 show the measured RIN spectra for fibres with positive dispersion and negative dispersion, respectively. The optical fibre used to obtain Fig. 2 is a 79.6 km normal fibre with dispersion of 16.98ps/nm/km at the signal wavelength and the loss coefficient is 0.21dB/km. The nonlinear parameter in this fibre has been evaluated to be 1.19 $W^{-1}km^{-1}$. Fig. 2 was obtained by subtraction (in logarithm scale) of the RIN spectrum with 11 dBm input optical signal power from that with 2 dBm signal power. This is done to reduce the effect of the source laser's residual RIN. Similarly Fig. 3 was obtained by subtraction of the RIN spectrum with 12 dBm input optical signal power from that with 2 dBm signal power. To obtain Fig. 3, a 13.7km dispersion compensation fibre was used with the dispersion of –88.7ps/nm/km at the signal wavelength and the loss coefficient is 0.5dB/km [7]. Since the effective core area in this dispersion compensation fibre is smaller than that in the normal fibre, the value of its nonlinear parameter is higher and was evaluated to be 3.35$W^{-1}km^{-1}$ [7].

It is obvious from Fig. 2 that with positive fibre dispersion, the amplitude of the RIN spectrum increases at the sideband which

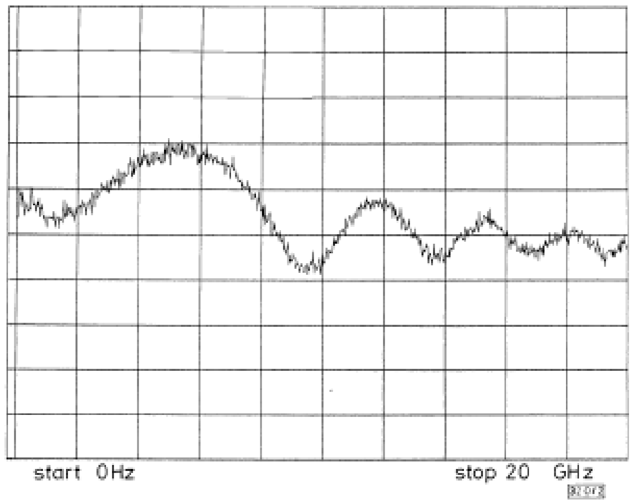

Fig. 2 *Measured RIN spectra in systems with positive dispersion +1352ps/nm and negative dispersion –1214ps/nm*

Attenuation: 44dB LW elec.
1dB/div
Average power: –4.3dBm opt.
Reference level: 4.66dBm

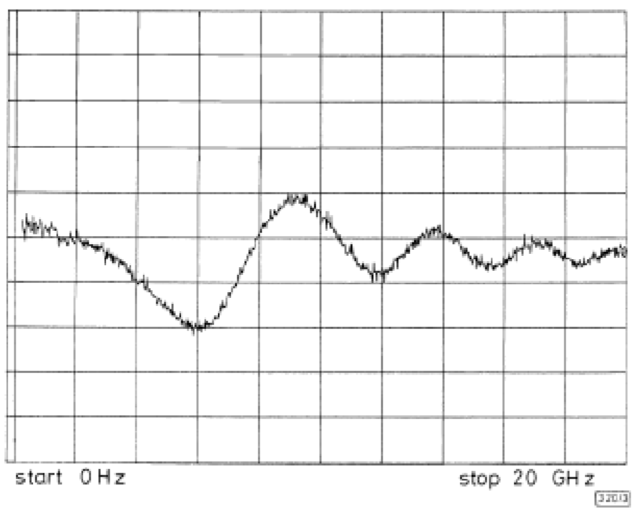

Fig. 3 *Measured RIN spectra in systems with positive dispersion +1352ps/nm and horizontal 2GHz/div, vertical 1dB/div*

Attenuation: 50dB LW elec.
1dB/div
Average power: 0.5dBm opt.
Reference level: 9.54dBm

peaks at ~6GHz in our case. The integration of this RIN spectrum over the receiver bandwidth gives rise to transmission system performance degradation [4]. Therefore, systems with positive dispersion may expect power penalty due to MI in the high power regime. Conversely, the RIN spectrum obtained with negative dispersion fibre and shown in Fig. 3 decreases in the low frequency part of the signal basband (for example, an 8GHz baseband filter is normally used in a 10Gbit/s system). This noise squeezing in the signal baseband would produce a system performance improvement due to modulation instability.

Theoretical calculations were carried out by solving the nonlinear Schrodinger equation [1]. A transfer matrix formulation was used to take into account the fibre loss. Details of the model will be reported separately [8]. Figs. 4 and 5 show the calculated spectra of the normalised RIN. These are the RIN at the fibre output normalised by the RIN at the fibre input. RIN spectra in Fig. 4 are calculated for systems with positive fibre dispersion. To be consistent with the implementation of the experiment, RIN spectra with 2 and 12dBm optical signal powers are calculated as shown in Fig. 4 as the dashed line and dash-dotted line, respectively, while the solid line is their difference. Similarly, in Fig. 5, the dashed line and dash-dotted line are spectra with signal power of 2 and 12dBm, respectively, while the

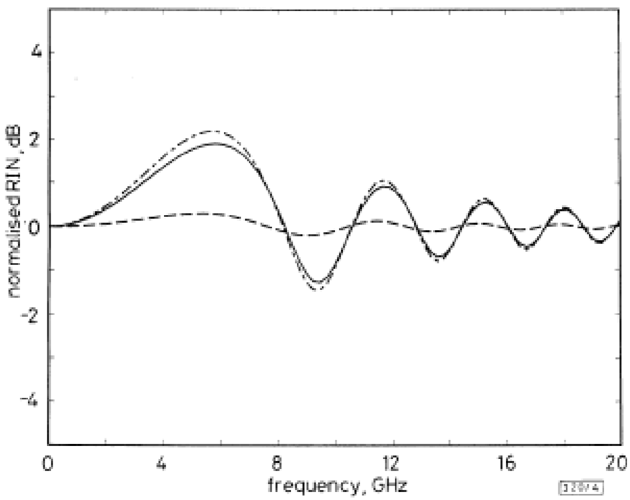

Fig. 4 *Calculated RIN spectra for systems with positive dispersion +1352ps/nm*

– – – – input signal optical power 2dBm
–·–·–·– input signal power 11dBm
——— subtraction between 2 and 11dBm

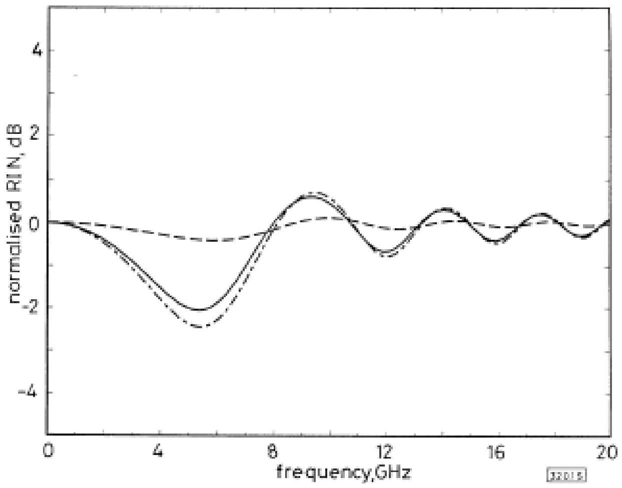

Fig. 5 *Calculated RIN spectra for systems with negative dispersion –1214 ps/nm*

– – – – input signal optical power 2dBm
–·–·–·– input signal power 11dBm
——— subtraction between 2 and 11dBm

solid line is their difference. Fibre parameters used in the calculation were the same as those in the experiment. Comparing solid lines in Figs. 4 and 5 with the spectra in Figs. 2 and 3, very good agreement is obtained between experimental and theoretical results. We believe that the physical reason for this RIN reduction is due to partial coherence between the signal and the ASE caused by FWM in fibres with negative dispersion.

In amplified optical transmission systems, performance degradation caused by FWM between signal and ASE can be described by the increase of the standard deviation σ of the photocurrent. In the case where signal-spontaneous beat noise dominates, system *Q* penalty due to MI is

$$\frac{\sigma}{\sigma_0} = \sqrt{\frac{1}{B}\int_0^B S_{RIN}(f)df}$$

where σ_0 is the standard deviation without the effect of MI, S_{RIN} is the normalised RIN spectrum as discussed above and *B* is the bandwidth of the baseband filter. With data given in Fig. 5, for example, ~0.54dB improvement in the *Q* value can obtained by the effect of MI with 12dBm signal optical power and an 8GHz receiver baseband filter.

Nonlinear noise squeezing in a negative dispersion fibre system is an important effect which may find some practical applications. In optical transmission systems with high optical powers, FWM may play an important role and must be considered together with nonlinear phase modulations, when designing appropriate dispersion compensation.

In conclusion, we have demonstrated both experimentally and theoretically that the RIN in an optical receiver, caused by ASE noise, can be reduced due to FWM in optical fibres with negative dispersion. This would lead to a performance improvement in the IM-DD system. Good agreement between experimental and theoretical results have been obtained.

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