Suitable Optical Filter for Self-phase Modulation Regenerators

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Abstract: In this paper a 2R all-optical regenerator will be presented, which based on the nonlinear self-phase modulation. The regenerator was simulated with the VPI TransmissionMaker and its optical filter module was examining, because the optical filter is the main element of these types of regenerators.

1 INTRODUCTION

Long haul optical networks need regenerators because of fibre attenuation and the dispersions. Signal reshaping can be performed in the electrical or optical domain, although the 3R (re-amplifying, reshaping, retiming) regenerator exists only in the electrical domain. Nonlinear effects in the optical networks are usually the source of signal distortion, but they are the bases of the all-optical regenerators' reshaping mechanism. A nonlinear device can be a nonlinear fibre or a semiconductor optical amplifier (SOA). In this paper a 2R optical regenerator will be introduced which will use the nonlinear self-phase modulation (SPM) effect for reshaping. The regenerator was simulated with the VPI Photonics TransmissionMaker 8.7 (VPI) software. Increased attention was given to the optical filter, because its price can be high if special needs arise or special parameters are required.

2 NONLINEAR PHASE MODULATION

There are two types of nonlinear phase modulation: self-phase modulation (SPM) and cross-phase modulation (XPM). In the first case the signal's own intensity causes an additional phase modulation on the signal, while in the second case the phase modulation is caused by another signal's intensity. Nonlinear phase-modulation is based on the optical Kerr-effect. The refractive index of the fibre core changes as light propagates through on it. The value of this change can be calculated (Ferreira, 2011) with equation (1), where n_2 is the nonlinear index of the fibre and I is the intensity of the propagating light. This refractive index change causes different propagation velocity which results different propagation times, so the signal's phase will different at every point of the fibre. It seems that not only the signal's intensity was modulated, but its phase too. In fact it was modulated only in its intensity. The phase change can be calculated (Ferreira, 2011) with equation (2), where i is the channel number index. The first term on the right of (2) represents the phase change due to SPM, while the second term is the change caused by XPM. The created regenerator in VPI was based on the SPM effect.

$$\Delta n = n_2 \cdot I \tag{1}$$

$$\Delta\varphi_i = \frac{2\pi \cdot n_2 L}{\lambda_i}\left[I_i(t) + 2\sum_{i \neq j} I_j(t) \right] \tag{2}$$

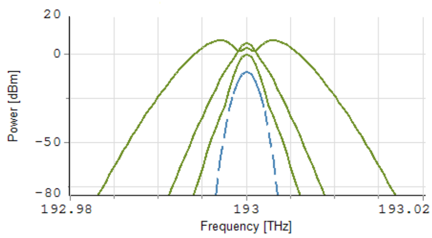

Figure 1: Spectral broadening caused by SPM. The blue dash curve is a 2mW pulse's spectrum without the effect of SPM, while the green solid curves show the spectral broadening effect on a 20, 100, 600mW (from inside to outside) power pulse.

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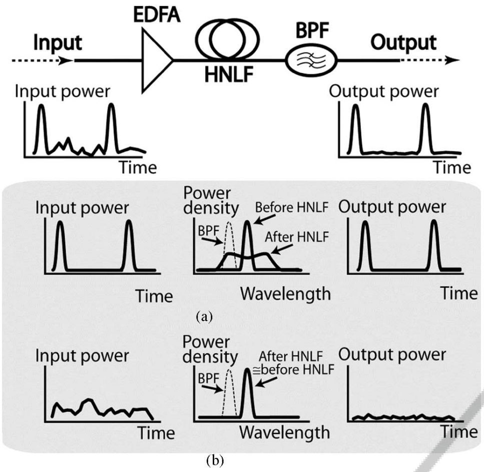

Figure 2: Block diagram of the simulated SPM regenerator. (a) Signal and (b) noise are in the time and frequency domain. (Rochette, Fu, Ta'eed, Moss and Eggleton, 2006).

SPM does not change the pulse shape in the time domain. It just causes spectrum broadening in the frequency domain. Higher intensity causes bigger spectral broadening as reported in Figure 1. It was simulated with the VPI and the SPM effect was produced by the regenerator's nonlinear fibre section. The blue dash curve shows the spectrum of a pulse with 2mW power after the fibre. In this case the fibre's nonlinearity was turned off. Then it was turned on, but the effect of SPM was negligible, so it is not observable. The green curves show how the signal's spectrum broadening at higher pulse power levels.

3 WORKING PRINCIPLE

SPM regenerators consist of three elements: an amplifier, a fibre and an optical band pass filter (Figure 2). Use of a highly nonlinear fibre is recommended, because of the higher nonlinear effect and it needs less power to reach its nonlinear behaviour. The optical amplifier can be a commonly used EDFA (Erbium Doped Fibre Amplifier) or a SOA. It has to amplify the signal at least to a minimum power level, which needs for the effect of SPM to start taking place. If we reach or exceed that power, the signal's spectrum will be broadening by the SPM. The regenerator's principle of operation (Mamyshev, 1998) can be seen on Figure 2. The pulse's intensities are much higher than the noise level and the pulses have coherent phase, while the noise does not. Their spectrums' shapes are very similar, but completely different in the time domain. The nonlinearity of the fibre will broaden the signal's spectrum, but the noise spectrum will not broaden, because its power is too low for any noticeable broadening, as we saw in Figure 1. One piece of the broadened spectrum has to fall into the optical band pass filter's bandwidth, otherwise only noise is at the output of the regenerator. The regenerator works properly, if the whole noise's spectrum is filtered out by the filter. Its centre frequency is shifted away a little bit due to the noise. This can be critical in the DWDM (Dense Wavelength Division Multiplexing) systems, where the wavelength accuracy is important.

4 SIMULATIONS

The transmitter produces 2mW high RZ (return to zero) pulses at 193.1THz with a bit rate of 0.5Gbps. Its bit sequence was set to an alternating stream. The signal degradation was simulated with a white noise block and an attenuator. The white noise was added to the signal with a coupler which introduced an additional attenuation of 3dB. The noise was considered Gaussian-distributed and its spectral power density was 10^{-16}W/Hz. The attenuator was placed after the coupler. It created an overall loss of 10dB. In the regenerator a black box amplifier was used, because only the amplifier's gain was important in our investigation, not the amplifying technique. Its gain was 30dB and it also added noise to the signal. A standard single mode fibre was used instead of a highly nonlinear fibre, because its price is much lower, but we had to use higher intensity for the nonlinear effect to appear and a longer fibre span.

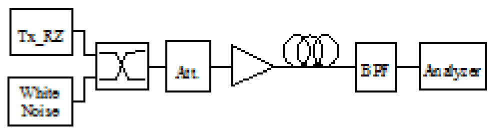

Figure 3: Block scheme of the simulated regenerator.

These two disadvantages can easily eliminate the price benefit of the standard fibre. In the simulation the fibre's length was 80km, which is four times longer, than an average dispersion compensating fibre's length which is used in networks. An optical filter was placed at the output of the regenerator and an analyzer connected to its output to monitor the signal (Figure 3). Three filter types were simulated, which had different kind of transfer function. The 1GHz wide spectrum is broadened to 5.5GHz using these settings. The width of the spectrum was measured between the -3dB points.

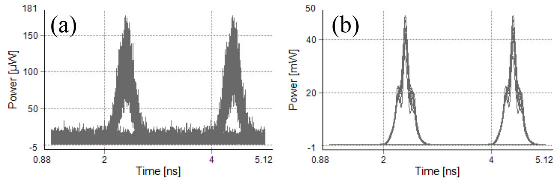

Figure 4: (a) Nearly closed eye diagram at the regenerator input. (b) Output eye diagram is distorted by nonlinearity and noise.

4.1 Ideal (Rectangular) Filter

In the simulation the filter's attenuation in the stop band was 80dB. Because of its ideal feature it was used for examine the filter roles and the required filter's bandwidth. The filter's bandwidth was set to 10GHz and its centre frequency was equal to the signal's frequency. The regenerator with these properties works as a simple amplifier. However the fibre produces a strong nonlinearity because of the input power level. It distorts the output signal. The filter filters out those noise components, which are out of the broadened signal's spectrum. This can improve the signal quality if the noise is out of the signal band (Figure 4).

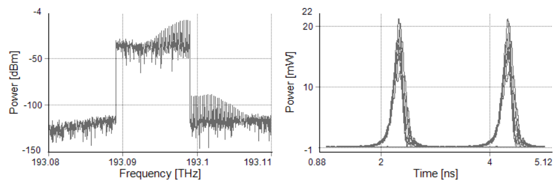

Figure 5: Spectrum and eye diagram at the filter's output.

In the second case the filter centre frequency was shifted by 6GHz to the 193.094THz, so that the signal's centre frequency was filtered out. The filter's other properties did not change. The result can be seen on Figure 5. Half of the filtered signal is part of the broadened signal and the other half of it is the noise. The pulses fluctuated stronger and their power decreased twofold compared to the previous case (Figure 4). This simulation shows that the filter's pass band must contain only a part of the broadened signal's spectrum.

Final simulations with the rectangular filter were carried out to find the optimal centre frequency and bandwidth. One of the -3dB point was at approximately 193.0972THz. This point and the 5.5GHz signal broadening rather limited our options. There is no sense to use lower frequencies than the -3dB point's frequency because they are near to the noise floor. The centre frequency of the filter was set up to 193.097 and 193.098THz. The filter's bandwidth was 2GHz, because if it had been bigger, we would have used the other half of the spectrum, which contains the noise (Figure 2). The higher centre frequency choice is better (Figure 6) because of the higher output power. The fluctuations at the high level are quite similar.

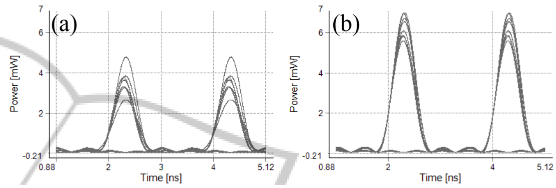

Figure 6: Eye diagrams at the output, when the filter's centre frequency was (a) 193.097THz and (b) 193.098THz. The bandwidths were same.

4.2 Trapezoid Filter

These filters are a better model to represent the real filters because their slope is limited. In the simulation the filter's centre frequency was set to 193.098THz and its bandwidth was 2GHz. The filter's slope was 40 and 20dB/GHz. The eye diagrams can be found in Figure 7. They are opened eye and the fluctuations are approximately 1mW high. When the filter's slope was changed to 20dB/GHz the eye had a slightly larger fluctuation.

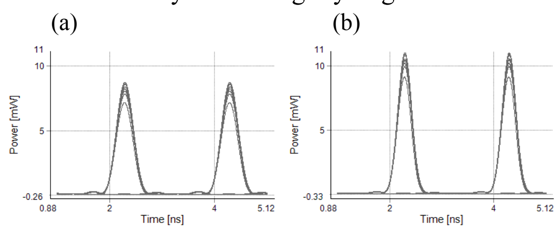

Figure 7: Eye diagrams after the filter when its slope was (a) 40 and (b) 20dB/GHz.

4.3 Butterworth Filter

This is a real filter type, which has maximal flat band pass. It has smaller slope between the pass band and the stop band, than the trapezoid filter. Its slope was about 5dB/GHz. The simulated filter was second order filter and its centre frequency was also set to 193.098THz with a bandwidth of 2GHz. The spectrum at the regenerator's output can be seen in Figure 8. The eye diagram is opened, but it is moderately asymmetric. It shows that the edges from high level to low level have a little bit smaller slope at the end than the low to high edges. This time the fluctuation was 2mW at the high level. It exceeds the previous case's result by 1mW. This considerable change results from the filter's smaller slope which causes worse noise spectrum filtering.

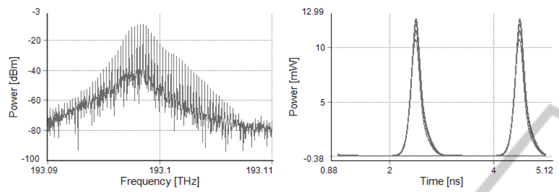

Figure 8: The output spectrum and the eye diagram when a second order Butterworth filter was used.

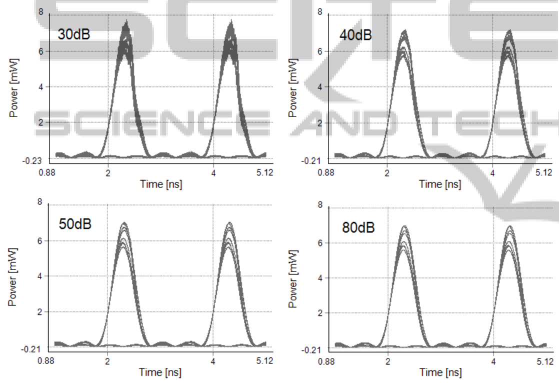

Figure 9: Eye diagrams at the output of the regenerator at different filter's stop band attenuation.

4.4 Attenuation at the Stop Band

The stop band attenuation is one of the critical aspects of the filters. If it is too low, the filter will not be sufficiently attenuating the disturbing components, so the output signal will be distorted. In this simulation the minimum stop band attenuation was examined. A rectangular filter was used with 2GHz bandwidth with a centre frequency of 193.098THz. The filter's stop band attenuation was changing from 30 to 80dB with 10dB increments. The eye diagrams are shown in Figure 9. At 30 and 40dB attenuation the filter can no adequately suppress the disturbing components, so the signal has a fast fluctuation at the high levels. Beside this fast fluctuation the output signal also shows slow changes. The pulses differ from each other by a small proportion. There are not any significant changes in the eye diagrams from the 50dB stop band attenuation. The pulses at the output differ from the others, but this difference has a maximum of 1mW. There are no fast changes on the high levels. In conclusion the output filter has to have at least 50dB attenuation at the stop band and it needs to reach this value as fast as it possible.

5 CONCLUSIONS

We demonstrated with simulations the nonlinear SPM effect and how it can be used in optical regenerators. The simulation showed that a standard fibre can be used instead of a highly nonlinear fibre. Using a standard fibre the spectrum broadening will be smaller or the signal's power has to be higher at the nonlinear device's input to get the same spectrum broadening. The regenerated signal's quality mainly depends on the filter. The signal frequency must be shifted away to get right regeneration. The signal regeneration depends on the filter's slope too. Higher filter's slope gives better signal reshaping as we showed. We also presented that the signal's shape do not improve if the stop band attenuation of the filter is higher than 50dB. All in all the applied filter's pass band has to be out of the range of the input noisy signal's spectrum, but inside of the broadened spectrum. That part of broadened spectrum should be selected practically where the signal's power is maximal. The filter has to attenuate 50dB out of the pass band and the slope between the pass band and stop band has to be as high as possible.

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