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On the jitter of mode-locked pulses introduced by an optical fibre ☆

R.F.X.A.M. Mols and G.J. Ernst

University of Twente, Department of Applied Physics, P.O. Box 217, 7500 AE Enschede, Netherlands

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Measurements on the jitter of mode-locked pulses of a Nd:YLF laser after travelling through an optical fibre are presented. For low powers self phase modulation occurs which leaves the jitter unaltered. For powers higher than the threshold of stimulated Raman scattering the jitter increases due to the exponential growth of the Stokes field.

1. Introduction

High power, ultra short pulses are applied amongst others in nonlinear optics, time resolved spectroscopy, pump-probe, optical sampling experiments and photo cathode based linacs to be used for FELs. For many of those applications small time and energy jitter are essential. So very stable mode-locked lasers have to be used like CPM lasers, soliton lasers and broad band solid state lasers. To obtain shorter pulses with higher peak powers pulse compressors are used, often consisting of an optical fiber, in which self phase modulation (SPM) causes an increase of the spectral width and a frequency chirp, followed by a negative dispersive path in order to compensate for the frequency chirp, leading to a shorter pulse. The SPM in the fiber increases with increasing power resulting in a faster increase of the peak power then the increase due to the higher input power. At a certain power level stimulated Raman scattering (SRS) starts up. It has already been shown by a few authors [1,2] that SRS gives a depletion of the incoming beam while pulse compression is still present. It has also been noticed [3,4] that due to the presence of SRS the output beam becomes noisier. When higher order stokes are generated they observe a stabilisation again of the output beam. In general, there is not much interest in this region since the losses of the input beam are upto 50% due to depletion and in most cases it is often required to have a high power after the fiber.

In this letter measurements are presented on energy and timing jitter of the optical pulses caused by an optical fiber for different power levels.

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2. Experimental set-up

In the experimental set-up as shown in fig. 1, a mode-locked Coherent Antares 76 Nd:YLF laser is used giving $\tau = 50$ ps Fourier limited pulses at a wavelength of 1053 nm. This laser is slightly modified to operate at pulse repetition frequency ν of 81.25 MHz. Two isolation stages were used to pre-

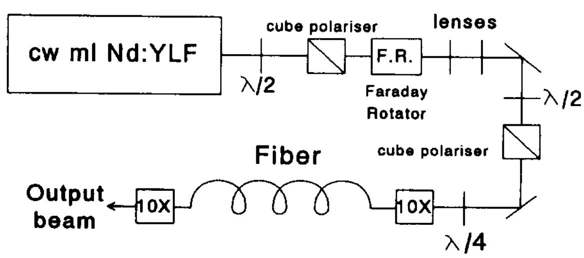

Fig. 1. Experimental set-up of the laser and the fiber.

vent back reflections of the fiber end faces into the laser. One of those isolators was also used as a variable attenuator to control the input power onto the fiber. The light pulses of the laser were coupled in a single mode fiber with $d=7.7$ μm core diameter using a 10× objective with an incoupling efficiency of typical 65–70%. The input power (P_{av}) will be referred to as the average power in the beam corrected for in coupling losses, i.e. the average pump power at the beginning of the fiber. At the end of the fiber the light was recollimated using a 10× objective.

3. Results

To interpret the behaviour of the jitter the threshold for SRS needs to be measured. This has been performed by measuring the generation of Stokes radiation using a grating. These results are presented in fig. 2 for 10 m and 25 m fiber lengths. For the 25 m a threshold of about 400 mW has been obtained while for the 10 m fiber this threshold was 900 mW. Also the gain of the stokes in the 25 m fiber was found to be larger than in the 10 m fiber. In the case of negligible depletion of the input beam the Stokes field grows exponentially $\sim\exp(gPL/A)$ where g is the Raman gain coefficient ($g=10^{-13}$ m/W), P is the peak power of the optical pulses ($P=\nu\tau P_{av}$), L is the length of the fiber and A is the effective area of the fiber ($A=\pi(d/2)^2$). The threshold power P_{th} for SRS

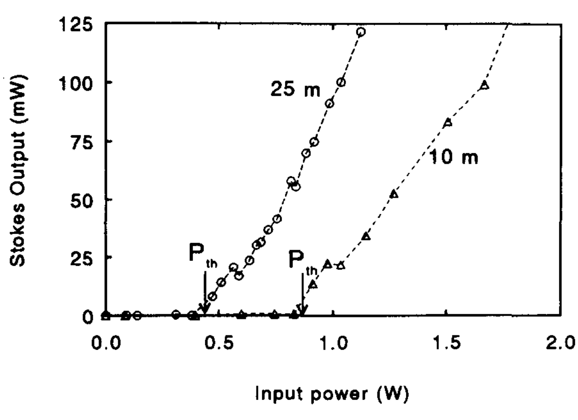

Fig. 2. The generation of Stokes as a function of input power. The threshold power for SRS is indicated for the different fiber lengths of 10 m and 25 m.

is proportional to A/gL. The jitter was measured using the method described in the classic paper of von der Linde [5]. The power spectrum of a train of mode-locked pulses was measured using a fast photo diode and a spectrum analyser. The power spectrum of an optical pulse without any jitter comprises discrete modes with a frequency spacing of $n\omega_c$ where ω_c is the longitudinal mode spacing of the cavity of the laser. This spectrum has an envelope given by the convolution of the gain bandwidth of the laser, the bandwidth of the photo diode and of the spectrum analyser. Due to jitter side bands are created around these discrete modes. The side bands generated by energy variations are independent of the mode number n. The jitter caused by phase variations causes the power in the side bands to increase with n^2. In this way energy and phase jitter can be distinguished by measuring the power spectrum for different n. The width of the side bands are caused by the time scale on which the jitter takes place. To obtain the phase ($\Delta t/T$) and energy jitter ($\Delta E/E$) we use the simplified relations from ref. [5]:

$$\left(\frac{\Delta E}{E}\right)^2=\left(\frac{P_c}{P_a}\right)_n\frac{\Delta f_E}{\Delta f_{RB}}, \tag{1}$$

$$\left(\frac{2\pi n\Delta t}{T}\right)^2=\left(\frac{P_b}{P_a}\right)_n\frac{\Delta f_t}{\Delta f_{RB}}, \tag{2}$$

where P_a corresponds to the maximum power of the discrete mode n and P_c, P_b respectively correspond to the maximum power of the side bands created by energy and phase jitter. The width of the side bands is given by Δf_E and Δf_t corresponding to the time scale in which the jitter takes place. Finally, Δf_{RB} is the resolution bandwidth of the spectrum analyser and T is the repetition time between the pulses. The jitter measurements were performed using a photo diode with a bandwidth of 10 GHz (Antel, model AR-S3) and a spectrum analyser, Hewlett packard, model HP 71209A with 26.5 GHz bandwidth, 10 Hz resolution bandwidth and a noise level of 130 dBm. For a number of laser input powers measurements have been made at several harmonics n. In this way statistical methods could be used to increase the accuracy. This was necessary because P_a is typical between -30 dBm and -45 dBm while P_b and P_c were between 85 dB and 55 dB lower which means that the maximum of the side bands are in many cases just above the noise level. We measured at the harmonics $n=1, 5, 15, 25, 35, 45$ with a span of 10 kHz. The measurements were averaged 6 times over this span. From these measurements the width of the side lobs for energy jitter was found to be 2 kHz. For the timing fluctuations a frequency width of 450 Hz was found. The energy and phase jitter were determined using eqs. (1) and (2) and are given in figure 3 for a 10 m and a 25 m fiber. In this figure the thresholds for SRS are indicated. It is clear from the figure that the jitter remains constant for input powers below threshold and there is a fast increase of jitter above threshold. The timing jitter of the pump laser is found to be 170 ± 10 fs and the amplitude jitter is 0.10 ± 0.01 % which is the same as the jitter measured below the threshold.

The effect of group velocity dispersion (GVD) is not observed in this case as shown in ref. [1]. The pulse length behind the fiber did not change much as a result of the absence of GVD. This pulse duration is measured using a background-free autocorrelation technique which is not very sensitive to changes in the pulse shape which are caused by SPM. The observed changes in the pulse length are due to changes in the pulse shape caused by SPM but since this measuring technique is not very sensitive we do not draw further conclusions from these observations.

Below threshold there is only the action of SPM. The most appropriate way to look at SPM is in the frequency domain. In this domain the mode-locked pulse of the laser consists of a discrete set of longitudinal eigen modes of the laser resonator. The amount of energy stored in the individual modes $n\omega_c$ depends on the envelope of the gain. The nonlinearity of the optical fiber couples these eigen modes through the third order susceptibility resulting in energy transfer to eigen modes at different frequencies. This nonlinear process can therefore also be described as diffusion of energy away from the central frequency. This diffusion evaluates in time and is therefore limited by the available fiber length. The evolution shows up as a broadening of the envelope. Since there is no interaction with other fields no energy is gained or lost which means that the amount of energy in a single pulse is constant. The energy jitter will not change by the action of SPM. Also the time of flight through the fiber is constant and not influenced by SPM which means that the time between all pulses remain the same yielding a constant timing jitter. For input powers above the threshold for SRS Stokes pulses are generated with a power P_{SRS}, shown in fig. 2. Variations in the output beam P_{out} are estimated using

$$P_{out} = P - P_{SRS} . \tag{3}$$

Therefore the energy jitter of the pulses after the fi-

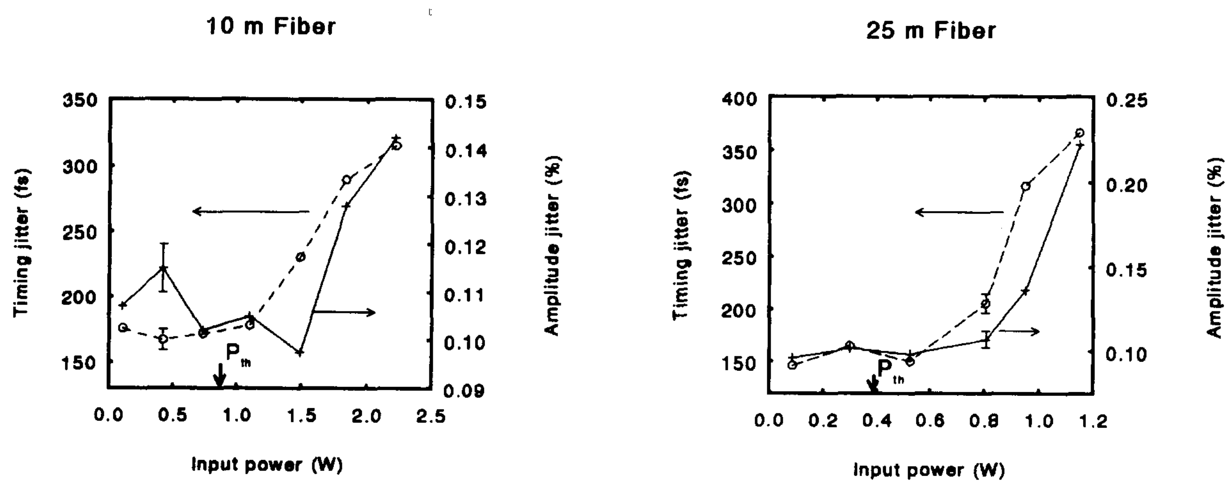

Fig. 3. The amplitude and phase jitter measured as a function of the input power. A fast increment of the jitter is measured above threshold for SRS.

ber will have a dependence on P:

$$\frac{\Delta P_{\text{out}}}{P_{\text{out}}} = \frac{\Delta P}{P_{\text{out}}} \sqrt{1 + \left(\frac{\partial P_{\text{SRS}}}{\partial P}\right)^2} \,. \tag{4}$$

The first term on the right hand side just shows the initial jitter of the pulses. The second term is caused by the gain of SRS. A small variation in the input beam will be amplified by the gain responsible for the generation of the Stokes. The influence of the jitter caused by the second term only shows up when this term becomes of the order of 1. This onset depends on the initial jitter and only depends on the gain at a certain input power P. For powers just above the threshold P_{SRS} grows exponentially resulting in an exponential growth of the jitter. Since the amount of SRS changes the pulse form of the optical pulse due to depletion the timing jitter is expected to behave in the same way as the energy jitter. In fig. 3 the fast increase of the jitter is seen. The measurements were limited by the decreasing power in the different modes of the power spectrum due to the spectral broadening caused by SPM.

4. Conclusions

In conclusion we showed the influence of an optical fiber on the jitter of mode-locked pulses. This is of particular interest because optical fibres are used in optical pulse compressors. It is shown that SPM does not increase the jitter. At higher power levels SRS starts up resulting in an increased jitter. The effect of both SRS and SPM on the jitter has qualitatively been described.

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