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ScienceDirect

Optics Communications 281 (2008) 824–830

OPTICS COMMUNICATIONS

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# Nonlinear optical correction of the pulse shape from a directly modulated DFB laser

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Received 1 July 2007; received in revised form 21 September 2007; accepted 8 October 2007

**Abstract**

In this work, the effect of modulation instability (MI) in optical fiber is used to reshape nanosecond pulses form a directly modulated diode laser. Our configuration includes a fiber where MI causes the side lobes in the signal spectrum and a filter at the fiber output rejecting the side lobes. Simulations show abrupt drop of the transmission of the setup if pulse power is above some critical value. We investigated the transmission for fibers with lengths in the range between 62-m and 4.5-km. The critical power was found to be inversely proportional to the fiber length. An average scaled critical power is 2.16 W km. We demonstrated the application of the method for rejection of the transient peak in a directly modulated diode laser.


*PACS:* 42.65.−k; 42.60.Rn; 42.81.−i

*Keywords:* Nonlinear optics; Fiber optics; Optical pulse regeneration

## 1. Introduction

Distributed feedback (DFB) semiconductor lasers have many applications because of their single-mode with high coherence continuous-wave output. These lasers are low cost, small-size, low driving voltage and current [1]. The directly modulated DFB lasers provide very simple method of pulse generation with tuned pulse duration. The performance of the directly modulated laser is limited by the relaxation oscillations in the laser output. Moreover, some amount of current oscillations causes output power oscillation. External modulators are commonly employed because they have much less chirping and relaxation oscillations are eliminated in the output pulse [2]. However, systems using directly modulation are simpler and fairly inexpensive than conventional systems with external modulation. The directly modulated DFB lasers can be preferable for many applications, such as a master oscillator in high power pulse system made in a master oscillator power amplifier (MOPA) configuration, nonlinear optics, lidars, and sensors (where the laser diode is used as a master oscillator with subsequent amplification) [3–6]. Furthermore, directly modulated DFB lasers with a constant current bias substantially lower than the threshold have a very low level of cw radiation. It allows very high pulse amplification using simple amplifier configurations [4]. However, in the last case relaxation and current oscillations represent a very important issue to be considered.

Recently, some experiments have been carried out to find mechanisms for suppressing the relaxation oscillations of DFB lasers. It was proposed to use external electrical resonant circuits, an optical feedback, light injection (employing GaAs injection lasers), and spontaneous emission [7–10]. Several exhaustive theoretical works analyzing the laser rate equations with the goal to reduce relaxation

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0030-4018/$ - see front matter 
doi:10.1016/j.optcom.2007.10.105

oscillations can be found in the literature [11–13]. Some methods using nonlinear all optical reshaping and limiting of signals have been reported recently [14–19]. Most of these methods use optical fibers to take advantage of many nonlinear phenomena that can be observed at moderate powers levels [15]. Four-wave mixing (FWM), self-phase modulation (SPM) and nonlinear couplers are considered for nonlinear optical reshaping [16–19]. All optical reshaping and limiting are considered essentially in the context of the 2R and 3R regeneration of ultrafast optical signals for communication and computing.

In the present work, we propose to use MI for nanosecond pulse reshaping. For the best of our knowledge, it was not discussed before. Modulation instability causes an exponential growth of small perturbations in the power, which consequently produces the side lobes in the spectrum at the fiber output. An essential fraction of the pulse energy is moved to the side lobes and can be rejected by the band pass spectral filter. That causes the limiting effect. We investigate the application of this mechanism for pulse reshaping of nanosecond pulses.

## 2. Experimental setup

Fig. 1 shows the experimental setup. The 1549 nm input pulse was obtained from the Mitsubishi 925B11F DFB diode laser. The laser was fed from the pulse generator SRS-DG535 that can provide pulses with temporal duration in the range from 1 ns up to several hours. The current pulses were placed on a 6.3 mA bias. The threshold current of the DFB laser was approximately 10.5 mA. The maximum power at the DFB laser output was 5 mW. The coupling efficiency to the fiber was 30%. Pulses from the DFB laser were amplified by a two-stage Erbium-doped fiber amplifier (EDFA) similar to that used in Ref. [4]. The highest gain of the amplifier is 50 dB allowing the 100 W peak power pulses at the EDFA output. A 99/1 coupler was used to monitor pulses entering the fiber under investigation. The EDFA included optical isolators both at the input and at the output. The output pulses were launched to the SMF-28 fiber with dispersion $D = 20$ ps/nm km and nonlinearity $\gamma = 1.52 \times 10^{-3}$ (m W)$^{-1}$. Pulses after the fiber were launched to a monochromator with the resolution of 0.5 nm, detected by a 1-GHz InGaAs photodetector and monitored by a 500-MHz oscilloscope.

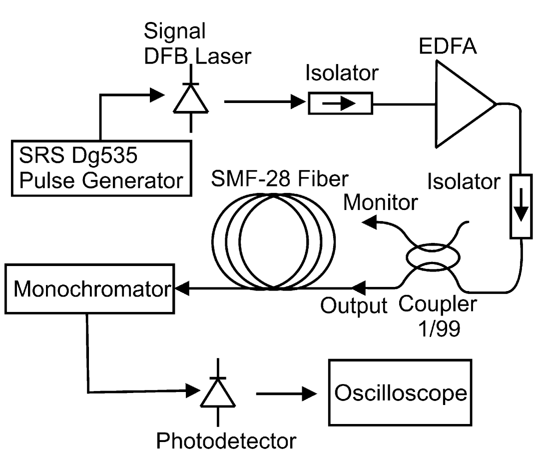


Fig. 1. Experimental setup.

Fig. 2a shows the typical pulse shape at the EDFA output. The 30 ns current pulse from the pulse generator was applied that is equal to the optical pulse duration measured as full-width at half-maximum (FWHM). The pulse shows the transient peak and the plateau. The transient peak duration measured as it is shown in Fig. 2a is 2.25 ns. The power of the transient peak is significantly higher than power of the plateau. The ratio between the transient peak power and the plateau power depends on the current from the pulse generator. In our experiments the ratio between the transient peak and the plateau powers was kept approximately as 2:1. The power launched to the investigated fiber was controlled by the EDFA gain. Fig. 2b shows the transient peak measured with a 20-GHz sampling oscilloscope and a 10-GHz detector. Fast relaxation oscillations can be seen.

## 3. Numerical results

We solved the Eq. (1) for nonlinear pulse propagation in the fiber using the split-step Fourier method [15]. The equation includes the group-velocity dispersion (GVD) term, Kerr nonlinearity, and Raman term.

$$\frac{\partial A}{\partial z} + \mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} = \mathrm{i}\gamma|A|^2 A - T_{\mathrm{R}} A\frac{\partial |A|^2}{\partial T}. \tag{1}$$

We used the dispersion with module $|\beta_2| = 25.5$ ps$^2$/km and nonlinearity $\gamma = 1.52 \times 10^{-3}$ (m W)$^{-1}$. The used parameters correspond to those for the SMF-28 fiber (GVD is 20 ps/nm km; effective area is 80 μm$^2$, $n_2 = 3.2\times 10^{-20}$ m$^2$/W). The variable $T$ represents the physical time in the retarded frame and $z$ is the physical distance. The response time for the Raman term is $T_{\mathrm{R}} = 3$ fs. To model the squared pulse similar to that emitted by the directly modulated diode laser we used for calculations super Gaussian pulses with the waveform given by

$$A(0,T) = \sqrt{P_0}\exp(-(T/T_0)^6), \tag{2}$$

where $P_0$ is the peak power of the input pulse and $T_0$ determines pulse duration. The pulse was placed on the noise with normal distribution. The split-step algorithm was used with following parameters: the length of the step was equal to 0.5-m, number of points $2^{14}$, and the time window was $-5T_0$ to $+5T_0$.

We calculated the spectrum of MI to determine the wavelength shift of the side lobes maxima and also to determine the wavelength shift at which the side lobe spectrum reaches the value of 0.1 of its maximum. The results are shown in Fig. 3.

The wavelength shift for the maximum is fitted by the square root dependence $\Delta\lambda = 0.46\sqrt{P_0}$. Analytically calcu-