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Noise in Mode-locked Hybrid Soliton Pulse Source

Nuran Dogru and M. Sadettin Ozyazici
Department of Electrical and Electronics, University of Gaziantep, Turkey

Abstract: The noise of the Hybrid Soliton Pulse Source (HSPS) utilizing a linearly chirped and Gaussian apodized fiber Bragg grating is described when it operates single mode and when it is mode-locked. The HSPS is modeled by coupled-mode equations and relative intensity noise (RIN) is calculated using numerical solutions of these equations. It is found that noise affects the operation of device and transform limited pulses are not obtained.

Keywords: Mode-Locked Laser, Fiber Bragg Grating, Relative Intensity Noise, Multi-Quantum Well Laser

Introduction

Laser diodes are intrinsically noisy devices because of the quantum nature of the light. Spontaneous emission is the main source of noise and it alters the phase and amplitude of the laser. The noise characteristics of semiconductor laser diodes are among the fundamental properties of the lasers and have important implications in the practical applications of laser. There have been a great deal of studies on these characteristics (Kallimani and Mahony, 1998; Schunk and Petermann, 1986; Morton *et al.*, 1994). Many qualitative features of the noise characteristics have been successfully explained by theoritically or experimentally for different feedback levels, but there have not been studies showing noise characteristics of hybrid soliton pulse source (HSPS) at the mode-locked condition.

In this paper, we investigate the effect of spontaneous noise on mode-locked HSPS utilizing a linearly chirped and Gaussian apodized fiber Bragg grating. The HSPS is modeled time-domain solution of the coupled-mode equations including spontaneous emission noise and these equations are solved numerically and then further processed in order to calculate the relative intensity noise (RIN).

The realization of long distance soliton based transmission systems requires a reliable, stable source of transform limited pulses of the correct pulsewidth at the wavelength peak of an erbium-doped fiber amplifier chain. A practical system may operate at 2.488 GHz with a pulse width of around 50 ps. But, in this work it is found that at the resonance frequency RIN value is high as expected and it affects the operation of device and the transform limited pulses are not obtained.

Materials and Methods

A schematic of the HSPS is shown in Fig.1. A 1.55 μm strained Multi-Quantum Well (MQW) laser diode is used, with one facet high reflectivity coated (HR) for improved cavity Q, and the other antireflection (AR) coated to allow coupling to the external cavity and suppress Fabry-Perot modes. The external cavity is composed of an AR coated lensed fiber and fiber Bragg grating. Active mode-locking is accomplished by applying a current waveform to the gain section, including a DC bias close to the the threshold value plus an RF compenent that can be varied in amplitude and frequency.

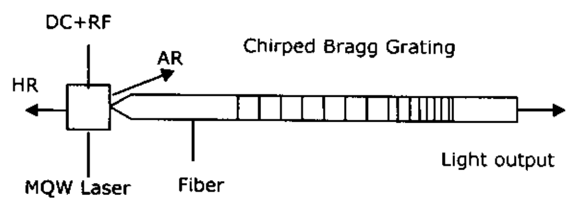


Fig. 1: Schamatic of HSPS

The model is based on a time domain solution of the coupled-wave equations (Kogelnik and Shank, 1972; Zhang and Carroll, 1992). The variations of forward field F(t,z) (+z direction) and backward field R(t,z) (-z direction) can be found over a uniform cavity section using the transfer matrix method (Bjork and Nilsson, 1987). The laser cavity is divided into sections with equal effective length of Δz. For a time step $\Delta t = \Delta z/v_g$, the forward and backward fields are calculated from transfer matrix. In each laser section the carrier density is calculated from the rate equation:

$$\frac{dN(z,t)}{dt} = \frac{I}{eV} - \frac{N(z,t)}{\tau_n} - GS \tag{1}$$

where I is the injection current, e is the electronic charge, V is the active layer volume, τ_n is the carier lifetime, and GS is the number of stimulated photons calculated in the coupled mode solution.

For each time step the new field values are calculated and boundary conditions applied. In order to calculate the progressive fields, either F_o *(z=0)* and R or R_o *(z=0)* and F are assumed to be known. Also, these equations must be modified in such a way that they include gain, loss and spontaneous emission noise in the laser. In order to model the complete HSPS, each section must be modeled separetely. Let us assume F_o and R are known, and write R_o and F in terms of these known fields:

$$\begin{bmatrix} F \\ R_o \end{bmatrix} = \frac{1}{\gamma\cosh(\gamma z) - (g_{net} - j\delta)\sinh(\gamma z)} \begin{bmatrix} \gamma & -j\kappa\sinh(\gamma z) \\ -j\kappa\sinh(\gamma z) & \gamma \end{bmatrix} \begin{bmatrix} F_o \\ R \end{bmatrix} + \begin{bmatrix} s_f \\ s_r \end{bmatrix} \tag{2}$$

Here g_{net} is the net field gain in the laser diode when the loss is subtracted from the gain, κ is the coupling factor, δ is the deviation from real part of propagation constant and ($\gamma^2=\kappa^2-\delta^2$). s_f and s_r are the spontaneous noise coupled to the forward and reverse waves, respectively. They are assumed to have equal amplitudes (Zhang *et al.*, 1994), e.g.,

$$s(z,t) = s_f(z,t) = s_r(z,t) \qquad (3)$$

Spontaneous emission is assumed to have a Gaussian distribution and to satisfy the correlation:

$$< s(z,t)s^*(z',t') >= \beta_{sp} \frac{R_{sp}}{v_g} \delta(t-t')\delta(z-z')$$

and

$$< s(z,t)s(z',t') >= 0 \qquad (4)$$

Here, $R_{sp} = BN^2 / L_l$ is the electron-hole recombination rate per unit lenght contributed to the spontaneous emission. Here, B is the radiative (or bimolecular) recombination coefficient, L_l is the length of the lasing section, N is the carrier density, β_{sp} is the spontaneous coupling factor, and v_g is the group velocity of light in the cavity.

This process is repeated for a sufficient number of modulation periods to obtain stable mode-locked pulses.

The intensity noises are characterized by the relative intensity noise (RIN) and they lead to a limited signal-to-noise ratio. The RIN of a laser diode as the ratio of the mean square intensity fluctuations to the mean intensity squared of the laser output as shown the equation (6).

Since the emitted optical power P of a laser exhibit noise which causes it to fluctuate around its steady-state value, it can be written as

$$P(t) =< P > +\delta P(t) \qquad (5)$$

where $<P>$ is the mean power. The RIN relates the noise of the optical power $\delta P(t)$ to $<P>$ and it is defined as

$$RIN = \frac{< \delta P^2(t) >}{< P >^2} = \frac{< P(t)^2 >}{< P >^2} - 1 \qquad (6)$$

The noise processes are considered to be stationary and ergodic, so that the symbol <> denotes either the ensemble or the time averages.

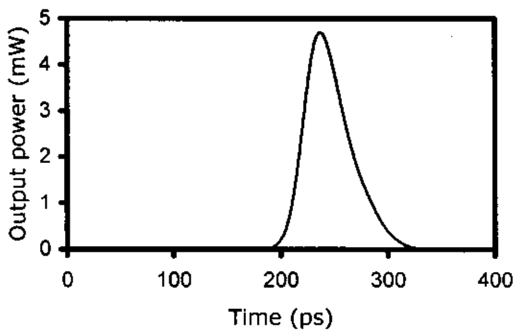
The values of RIN is calculated using expression (6) and then fast Fourier transform (FFT) is applied.

MQW laser diode parameters are taken: Gain saturation parameter 2×10^{-17} cm^3, differential gain 10×10^{-16} cm^2, spontaneous coupling factor 5×10^{-5}, field coupling from laser to fiber 0.8, HR coating field reflectivity 0.9, AR coating field reflectivity 0.01, optical confinement factor 0.1, carrier lifetime 0.8 ns and internal loss 25 cm^{-1}.

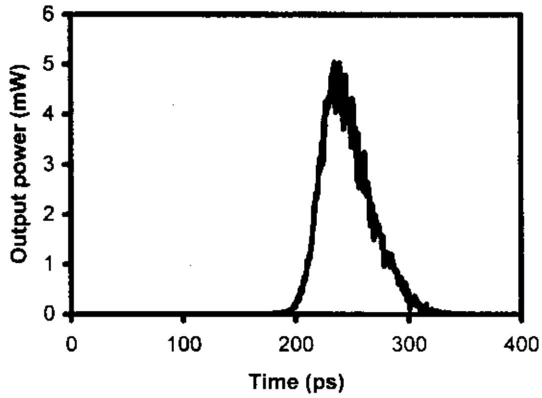
Results and Discussion

In the simulation, a laser diode length of 250 μm and a grating length of 4 cm are used. The fundamental mode-locking frequnecy is chosen as 2.5 GHz and step size is 0.6875 ps. Applied DC bias and RF currents are 6 and 20 mA.

It is known that if the modulation frequency of a conventional mode-locked system is changed from the designed frequency, mode-locking cannot be established. HSPS can make mode-locking of the pulses for a wide frequency range available (Morton *et al.*, 1993). In order to deduce whether the HSPS is properly mode-locked or not, the field spectrum, output pulse intensity and their time-bandwidth products are examined. The transform-limit range is included in this work as time-bandwidth product that is in the range of 0.3 to 0.5.



(a)



(b)

Fig. 2: Output intensity of HSPS;
(a) constant noise, (b) random noise

Output power through the Bragg reflector, which is used as the output is shown Fig. 2(a) and (b). If the spontaneous emission rate is constant, this result shows a pulsewidth of 45.38 ps and an optical spectrum of 8.68 GHz, giving a time bandwith product of 0.394 as shown the Fig. 2(a). Proper mode-locking range is observed between 2.2-3 GHz.

However, the spontaneous emission is a random process, and we only know what the average rate is. This randomness gives rise to noise as seen the Fig. 2(b). In this case, pulsewidth is 40.55 ps, optical spectrum is 8.67 GHz, time bandwidth product is 0.349 and mode-locking range is again 2.2-3 GHz. As seen the result there is a pulsewidth narrowing and it is observed that increasing noise causes pulsewidth suppression and so not transform limited pulses are obtained. If spontaneous coupling factor is taken $20e^{-5}$ (for increasing noise), pulsewidth is 3.989 ps, optical spectrum is 8.987 GHz and time-bandwidth product is 0.036. These results are not proper for practical applications.

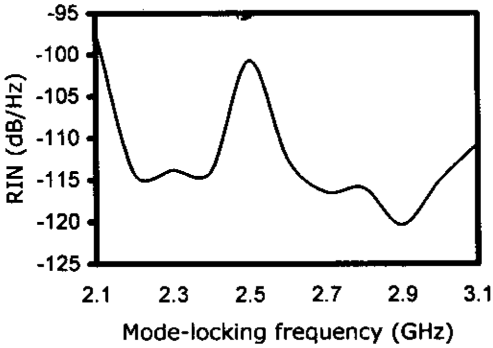


Fig 3: RIN Spectrum of the HSPS

Calculation of the RIN versus frequency is shown Fig. 3, for same laser parametres and currents. A peak around 2.5 GHz shows optical resonance due to cavity roundtrip time. This frequency is the high noise level of the device, providing a low signal/noise ratio. This explain that why pulse narrowing or suppression occurs at this frequency. Between the locking range except the resonance frequency pulsewidth is not affected from the noise and as seen the figure, in this range the RIN value is low but at the boundaries of the range, the RIN rapidly increases.

Conclusion

The main conclusion, near transform limited pulses are obtained over a frequency range of 800 MHz around a system operating frequency of 2.5 GHz and spontaneous noise does not affect these results if its value is low. But high noise affects the operation of device and transform limited pulses are not obtained. It has been shown that at the resonance frequency the RIN value is high and pulse narrowing or suppression occurs at this frequency.

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