NOISE ANALYSIS FOR MODE-LOCKED LASERS

Nuran Dogru and M. Sadettin Ozyazici

Department of Electrical and Electronics Engineering, University of Gaziantep, 27310 Gaziantep, Turkey
E-mail:dogru@gantep.edu.tr

ABSTRACT

The noise of a hybrid soliton pulse source (HSPS) utilizing linearly chirped-Gaussian apodized fiber Bragg grating is described. The HSPS is modeled by a time-domain solution of the coupled-mode equations including spontaneous emission noise and relative intensity noise (RIN) is calculated using numerical solutions of these equations. It is found that transform limited pulses are not generated because of this noise although these pulses are obtained over a wide frequency range without noise. A noise peak locates at the resonance frequency in the RIN spectrum and RIN increases with increasing linewidth enhancement factor, gain saturation parameter and spontaneous coupling factor.

INTRODUCTION

Laser diodes are intrinsically noisy devices because of the quantum nature of the light. Even when the laser is biased at a constant current, with negligible fluctuations, the output of a semiconductor laser exhibits fluctuations in its phase and in its intensity. Spontaneous emission is the main source of noise and affects both the emitted optical intensity and the emission frequency. It perturbs amplitude and phase in a random manner. These amplitude and phase fluctuations can affect the performance of lightwave system and it is important to estimate their magnitude. There have been great deals of studies on these noise characteristics. In the past, for external cavity lasers relative intensity noise (RIN) has been explained successfully for different feedback levels [1-2] and effects of external cavity length on the RIN spectrum has been determined but, there have not been studies showing noise characteristics of hybrid soliton pulse source (HSPS) at the mode-locked condition.

In this paper, noise characteristic of the HSPS utilizing linearly chirped-Gaussian apodized fiber Bragg grating is described. The HSPS is modeled by a time-domain solution of the coupled-mode equations including spontaneous emission noise. The complete model is numerically solved and RIN is calculated from the results.

It is found that without noise near transform limited pulses are generated over a wide frequency range. But noise affects the operation of device so transform limited pulses is not obtained. It is also found that linewidth enhancement factor (α), gain saturation parameter (ε) and spontaneous coupling factor (β) are the most effective noise parameters and RIN increases with increasing these parameters.

THE MODEL

The HSPS consists of mainly of three sections as shown in Fig. 1. The system consists of a multi-quantum well (MQW) laser diode and an external cavity comprised of a lensed fiber and a fiber Bragg grating. One facet of diode is 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 field in this system travels between the HR coated laser end and effective cavity length of the grating. The output power is taken through the grating.

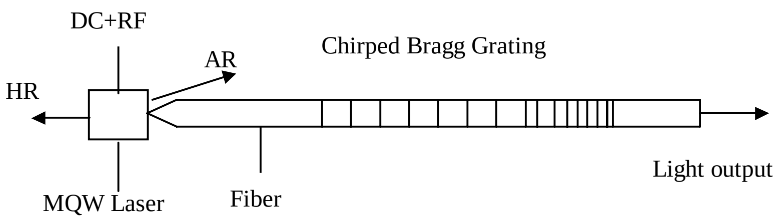

Fig.1. Schematic of HSPS.

The model is based on a time domain solution of the coupled-wave equations. The laser cavity is divided into sections with equal effective length of Δz. For a time step the $\Delta t = \Delta z / v_g$, the forward and backward fields are calculated from the transfer matrix. In each laser section the carrier density is calculated from the rate equation

$$\frac{dN(z,t)}{dt} = \frac{I(t)}{eV} - \frac{N(z,t)}{\tau_n} - \frac{a_o(N(z,t)-N_o)}{1+\varepsilon S(z,t)} v_g S(z,t) \tag{1}$$

where $I(t)$ is the injection current, V is the active layer volume, e is the electronic charge, τ_n is the carrier lifetime, $S(z,t)$ is the photon density and it is proportional to $|F|^2 + |R|^2$, N_o is the carrier density at transparency, a_o is the differential gain .
The spontaneous noise coupled into the forward and reverse field is given as s_f and s_r, respectively. The spontaneous emission fields coupled to the forward and reverse fields have equal amplitudes [3], e.g., $s(z,t)=s_f(z,t)=s_r(z,t)$. This emission is assumed to have a Gaussian distribution and to satisfy the correlation:

$$< s(z,t)s^*(z',t') >= \beta \frac{R_{sp}}{v_g} \delta(t-t')\delta(z-z') \text{ and } < s(z,t)s(z',t') >= 0 \tag{2}$$

Here, $R_{sp} = BN^2 / L_l$ is the electron-hole recombination rate per unit length contributing to the spontaneous emission. Here, B is the radiative (or bimolecular) recombination coefficient, L_l is the length of the lasing section, and N is the carrier density.
For each time step the new field values are calculated and boundary conditions applied. In order to model the complete HSPS, each section must be modeled separately. This process is repeated for a sufficient number of modulation periods to obtain stable mode-locked pulses.
RIN is defined as the relative fluctuation power and is given by

$$\frac{RIN(f)}{\Delta f} = \frac{2 < |\Delta S(w)|^2 >}{< S >^2} \; dB/Hz \tag{3}$$

where $<S>$ is the average optical power, $\Delta S(w)$ is spectral density of noise in a Δf bandwidth at a specified frequency. Note that the effective bandwidth is $2\Delta f$ since we must include both positive and negative frequencies.

RESULTS AND DISCUSSION

In our simulations, it is considered a HSPS with linearly chirped-Gaussian apodized fiber Bragg grating with maximum power reflectivity of 0.5 at 1.55 μm. A laser diode length of 250 μm and a grating length of 4 cm are used. The fundamental mode-locking frequency is chosen as 2.5 GHz and step size is 0.6875 ps. Applied DC and RF currents are 6 and 20 mA. MQW laser diode parameters are taken: Gain saturation parameter 2×10^{-17} cm^3, spontaneous coupling factor 5×10^{-5}, linewidth enhancement factor 2, differential gain 10×10^{-16} cm^2 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}.
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 [4]. In order to deduce whether the HSPS is properly mode-locked or not, the field spectrum, output pulse intensity and their time-bandwidth product (TBP) are examined. The TBP calculated as the product between the pulse and optical bandwidth and in this work it varies 0.3 to 0.5 in the locking range [5].
In this paper, without noise near transform limited pulses are obtained over a frequency range of 800 MHz (2.2-3 GHz) around a system operating frequency of 2.5 GHz, with pulsewidth of 45.381 ps, TBP of 0.394 and spectral width of 8.679 GHz. This results shows for us that HSPS with linearly chirped-Gaussian apodized grating is suitable to generate near transform-limited pulses over a wide frequency range. If noise is taken into account, pulsewidth is 40.554 ps, TBP is 0.349 and spectral width is 8.604 GHz. Mode-locking ranges is observed again 2.2-3 GHz.
From the obtained results, it is found that transform limited pulses are generated in spite of spontaneous emission noise. However, it is observed that output pulse is more affected from the noise at the resonance frequency and transform-limited pulses are not obtained at this frequency if noise is high. In this case, pulsewidth is 3.989 ps, TBP is 0.036 and spectral width is 8.987 GHz. As seen the results noise causes pulsewidth narrowing or suppression and these results are not proper for practical applications.

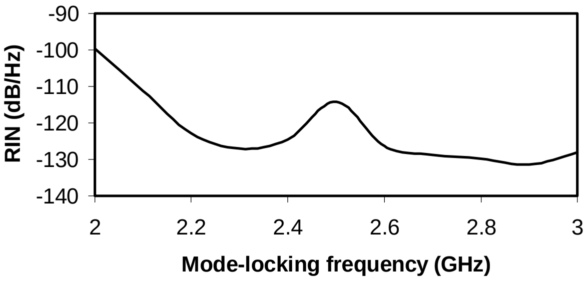

Fig.2. RIN spectrum of HSPS.

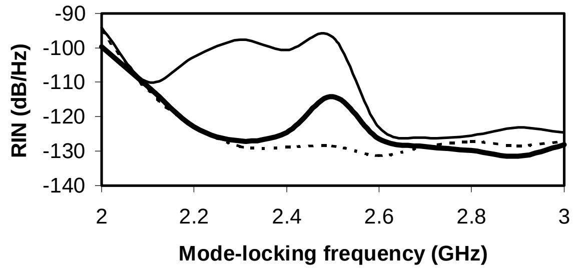

Fig. 3. RIN spectrum of HSPS for three values of α. (- - - - - α=0, ——— α=2, ——— α=5)

Calculation of RIN versus frequency is given in Fig. 2 if standard diode parameters are used. As seen in the figure a noise peak locates around 2.5 GHz in the RIN spectrum. This frequency is the high noise level of the device, providing a low signal/noise ratio. This explains that why system operation is more affected at this frequency.

Active mode locking is a resonance-like phenomenon in which the laser is modulated at a frequency corresponding to the inverse roundtrip propagation time of the laser cavity. That's the reason in the RIN spectrum a noise peak is expected at the resonance frequency that shows optical resonance due to cavity roundtrip time as seen in Fig. 2.

α determines spectral linewidth and frequency chirp. For a semiconductor laser the refractive index depends on the carrier density and α determines this dependence. Although zero dependence is impossible to obtain in practice, in our simulation α is varied 0 to 5. Table 1 shows the variation in pulsewidth, spectral width and TBP due to α without noise. The difference in pulsewidths when α is changed between 0 and 5 is very noticeable, being a reduction from 60.189 to 31.872. However, spectral width increases with α, possibly due to wavelength chirping. The effect of this parameter on RIN is given in Fig. 3. As shown in figure if its value increases, RIN increases. RIN is low for its zero value but in this case system is not mode-locked giving a TBP of 0.567.

Table 1. Effect of the varying α on HSPS.

α	Pulsewidth (ps)	Spectral width (GHz)	TBP
0	60.189	9.415	0.567
2	45.381	8.679	0.394
5	31.872	10.976	0.350

Effect of ε on RIN is given in Fig.4. As seen in the figure if ε increases, noise peak shifts towards to the lower frequency and its value increases. The reason for this the wavelength dependent gain gives a wavelength dependence of the number of photons. An increasing ε leads to a decreasing gain and increasing refractive index. An increasing refractive index means a decreasing frequency. It is also observed that if the value of ε is taken very large, RIN has a second peak in the lower frequencies of the mode-locking range besides the main noise peak.

Spontaneous recombination events happen to supply a photon into the lasing field a fraction of spontaneous coupling factor (β). This term is important for the dynamic behavior; without this term and with $S=0$ at $t=0$, S would remain 0. RIN increases with increasing β as shown in Fig. 5.

All of these results show that noise affects the operation of device giving a pulsewidth narrowing or suppression at the resonance frequency. Laser diode parameters has important effect on RIN, for that reason there should be a limitation for these parameters.

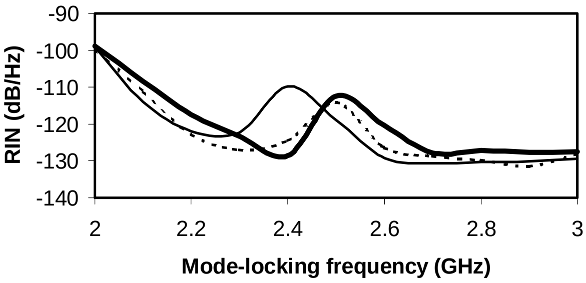

Fig. 4. RIN spectrum of HSPS for three values of ε. (_____ ε=0, _____ ε, _____ 2ε)

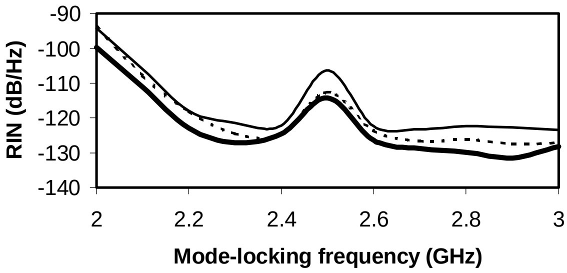

Fig. 5. RIN spectrum of HSPS for three values of β. (——— β, - - - - 2β, ——— 4β)

CONCLUSION

In 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, so transform limited pulses are not generated. It has been shown that at the resonance frequency RIN value is high and output pulse is more affected at this frequency. It was also showed that α, ε, and β are the most effective noise parameters and RIN increases with increasing these parameters. Even α affects the operation of device without noise. However, effect of ε and β on pulsewidth, spectral width and TBP are very little and these parameters are only effective at the resonance frequency with noise.

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