Research Article

SCLC Degradation in 980 nm Pump Laser by Using Electrical Noise

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The knowledge of the noise levels is important for pump laser diodes as it allows to study and to locate the noise sources and their origin. 980 nm fresh and aged pump lasers have been characterized by using electrical noise measurements. At 10 Hz, the spectra are dominated by $1/f^m$ ($1 \leq m \leq 2$) noise. Current noise spectral density (CNSD) is dominated by I_L^m ($1 < m \leq 2$). The trapping defect density near the n^+n^- and p^+p^- interfaces is related to pinching of the space-charge-limited current (SCLC) effect. An excess electrical noise due to longitudinal mode hopping is correlated with optical power fluctuations.

1. Introduction

In this work, we present the electrical noise at low frequency for fresh pump laser diodes emitting at 980 nm (reference laser), and we study the parametric evolution and the defects generated in aged 980 nm, stressed during 400 hrs at 50°C and high current injection (500 mA) (aged laser).

2. Device Description

The device used in this study is a conventional ridge waveguide AlGaAs/InGaAs pump laser with a GRIN-SCH (Graded Index Separate Confinement Heterostructure) and a Single Quantum Well (SQW) (p^+p^- , n^+n^-) emitting at 980 nm. The laser has a cavity length of 1200 μm and is coated, for the 50°C aging tests, with standard low- ($\cong 1\%$) and high-reflectivity ($\cong 90\%$) coatings on the facets. A different coating reflectivity and aging configuration has also been studied in a previous work [1–3].

3. Static Characteristic of the Pump Laser Diode

From the static analysis, current laser versus externally applied voltage $I_L(V_L)$, we then deduce in Figure 1 the

evolution of the differential resistance $R_d = dV_L/dI_L$. The $R_d(I_L)$ characteristic recorded after 400 h of aging under a stress at 50°C and high current density injection (500 mA) was compared with the same laser diode before aging.

Before threshold, differential resistance is proportional to I_L^{-1} ; above threshold current ($I_L > 18 \text{ mA}$), R_d decreases to $I_L^{-1/2}$. This phenomenon is usually observed when the carriers are injected from high doping material to low doping material. In our structure, the carriers are injected from n^+ or p^+ into n^- or p^- .

The physical phenomenon can be explained in Figure 2. The p^+p^- and n^+n^- interfaces form space charge regions. The carriers are prevented to go into quantum well by the two space charge effects; then, the carrier injection is associated to space-charge-limited current effect (SCLC) [4, 5].

Consider the relation of Mott-Gurney:

$$I_{L,\text{SCLC}} = \frac{9\varepsilon\varepsilon_0\mu}{8L^3} V^2, \quad (1)$$

where ε is the dielectric constant, ε_0 the free space permittivity, L the junction thickness, and μ the carriers mobility.

FIGURE 1: Dynamic resistance R_d versus laser current I_L .

FIGURE 2: Space-charge-limited current effect observed in the laser layers.

We then deduce the evolution of the differential resistance $R_d = dV_L/dI_L$:

$$R_d = \frac{1}{2} \cdot \frac{1}{\sqrt{9\epsilon\epsilon_0\mu/8L^3}} \cdot \frac{1}{\sqrt{I_{L,SCLC}}}. \quad (2)$$

The typical evolution of the electrical and optical parameters is shown in Table 1.

We show that the static characteristics do not allow making difference between the aged laser and the reference laser. This difference can be made with electrical noise measurements.

4. Low-Frequency Noise Measurements

4.1. Noise Equivalent Circuit. In order to obtain a better analysis of the behavior of the devices studied, it is necessary to give the noise equivalent circuit of multimode laser diode (4 modes for this Pump laser) at low frequency (Figure 3).

This circuit is obtained by deriving the rate equations including Langevin white noise sources and $1/f$ noise sources describing in [6], and we are considering all other noise sources to be produced by the interfaces and the trapping defect density [7].

Where R is a differential diode resistance, R_{sek} is an additional resistance due to coupling of spontaneous emission into lasing mode for k mode, v_{nek} is a voltage noise source due to the fluctuation of the photon population, and i_n is the

FIGURE 3: Noise equivalent circuit of a multimode laser diode at low frequency.

FIGURE 4: Current noise spectral density versus frequency.

current noise source due to the fluctuation of the electron population. The input signal is the modulation current i_{L1} or the modulation voltage v_1 for intrinsic circuit; $S_{V,R_s} = (\alpha I_L / f \tau_s) R_s^2$ is the thermal noise due to series resistance R_s ; $S_{V,SCLC}$ is the noise source due to space-charge-limited current effect.

4.2. Current Noise Spectral Density (CNSD). We make a noise analysis by Fast Fourier Transform FFT measurements and very low-noise amplifier. The Current Noise Spectral Density (CNSD) S_{IL} represents the current intensity fluctuations at $20 \pm 0, 1^\circ\text{C}$. The CNSD has been measured over a wide frequency range from 1 Hz to 1 MHz; we give in Figure 4 a typical noise spectrum: $1/f^m$ ($1 \leq m \leq 2$) decreases followed by flat noise level.

Figure 5 exhibits the low-frequency current noise measured at 10 Hz, as a function of the laser current. We notice that the spectra are dominated by $1/f$ (flicker) noise due to the carrier mobility fluctuations given by TGM Kleinpenning's model [8]; the CNSD varies as I_L^2 :

$$S_{ILI} = \frac{\alpha_H I_L^2}{f N}, \quad (3)$$

with α_H being Hooge parameter, N being free carrier number, and f being frequency.

TABLE 1: Evolution of the electrical and optical parameters.

Laser diode	R_s (for $I_L = 100$ mA) (Series resistance)	I_{th} (Threshold current)	P_{opt} at $I_L = 200$ mA (Optical power)	η (Efficiency)
Reference	1 ohm	17.5 mA	220 mW	90%
Aged	1 ohm	17.5 mA	215 mW	88%

FIGURE 5: Electrical noise spectral density S_{IL} at 10 Hz versus I_L .

In this case, we can calculate α_H (Hooge parameter) at very weak current, $f = 10$ Hz, $I = 1$ nA, and we found [9] that

$$\alpha_H = f \cdot \frac{S_{i,1/f}}{I^2} \frac{L^2}{q\mu R} = 8,5 \cdot 10^{-4}, \quad (4)$$

where

$$N = \frac{L^2}{q\mu R}, \quad (5)$$

$L = 1200$ (μm) is the sample length, $q = 1,6 \cdot 10^{-19}$ (C) is the elementary charge, $\mu = 11000$ ($\text{cm}^2\text{V}^{-1}\cdot\text{s}^{-1}$ at 300 K for AlGaAs/InGaAs) is the carrier mobility, and $R = 10^8 \Omega$ is the dynamic resistance. The α_H value is in agreement with those given by Hooge for AlGaAs/InGaAs at 300 K [10].

Region II. At 10 Hz, the CNSD varies as $I_L^{3/2}$, it can be explained by fluctuations of diffusion current, and, it is due to the traps placed near the n^+n^- and p^+p^- interfaces [4]. Then,

$$S_{IL(10\text{Hz})} = C(N, A) \cdot \frac{I_L^{3/2}}{f} = \frac{I_L V_j}{R_L} \sum_i \frac{D_i \tau_i}{(1 + \omega_i^2 \tau_i^2)}, \quad (6)$$

where $C(N, A)$ is the coefficient that depends on the section and on the number of free carriers, R_L is junction resistance of n^+n^- and p^+p^- interfaces, V_j is the applied voltage of junction, D_i is a statistic factor, depending on the material, and τ_i is the recombination time.

This noise is related to pinching of the space-charge-limited current SCLC effect superposed with the noise due to fluctuations of current in the MQW outside the space charge region [11].

Region III. At 10 Hz, we observe saturation of CNSD, the CNSD as predicted by Vandamme and Ruyven, when the laser current is lower than the threshold current I_{th} [12], because series resistance R_s , in this region, is not neglected in comparison with differential resistance R_d [13].

Regions IV and V. The CNSD increases at 10 Hz, due to the optical gain fluctuations in the active layer related to increase of number of photons around threshold [14, 15]. In this case modeling is given by

$$S_{id,1/f} = \frac{2 \cdot Z^2 \sum_{k=1}^4 \sum_{l=2}^4 (S_{Vnk,Vnl}/R_{Sek}^2)}{(Z + R_L + R_s)^2} + \frac{R_s^2 (q\alpha I_L / f \tau_s) + R_L I_L V_j \sum_i (D_i \tau_i / (1 + \omega_i^2 \tau_i^2))}{(Z + R_L + R_s)^2}, \quad (7)$$

where Z is the equivalent impedance of intrinsic circuit, $S_{Vnk,Vnl}$ is the noise source giving an excess noise due to longitudinal mode hopping which is related to output power fluctuations (exchange of power between two voltage noise sources due to the fluctuation of the photon population), τ_i is related to trap noise generators placed in the intrinsic layer and near n^+n^- and p^+p^- interfaces which absorb many photons in the aged active layer, and the end term of (7), in region V, becomes dominant.

Region V. At 10 Hz, the level of noise shows also that a proportionality of about $S_{i10\text{Hz}} \propto I^{3/2}$ originates to the traps in the vicinity of the n^-n^+ and p^-p^+ related to SCLC effect.

The CNSD in the aged laser is higher than that in the fresh laser; it is due to active layer degradation due to decrease of recombination time τ_i .

5. Summary

The study of the electrical noise that represents the fluctuations of current at low frequency is very significant of degradation of the active layer. The spectra are dominated by conventional $1/f$ (flicker) noise at weak current and the CNSD at 10 Hz is dominated by $I^{3/2}$. Pinching of the Space Charge shows limited current SCLC effect.

The defect is associated with carrier transport controlled by the n^+n^- and p^+p^- interfaces and the trapping defect density. An excess electrical noise due to longitudinal mode hopping is related with output optical fluctuations at low frequency. The CNSD in the aged laser is higher than that in the fresh laser, certainly due to the degradation of recombination time τ_i .

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