An Investigation of Noise Influences in Optical Transmitters and Receivers in Cable TV Networks

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Abstract – **Optical transmitters and receivers are key elements of optical equipment in optical communication networks Taking into account all specific requirements of CATV networks it is necessary for the optical transmitters and receivers to meet the required specifications for downstream and upstream channel transmission. Basically, the major negative impact in them is caused by the occurrence of noises. This paper analyzes the cause of their origin and evaluates their consequent influence.**

Keywords **– Distributed-Feedback Laser, Relative Intensity Noise, Shot Noise, Thermal Noise, Carrier-to-Noise Ratio.**

I. Introduction

The subject of noise introduced by optical transmitters and receivers has an important implication for cable TV transmission.

The fundamental noise components in optical transmitters are:

- the relative intensity noise (*RIN*);
- the laser phase noise.

Noise components which are fundamental for receivers are:

- the shot noise;
- the thermal noise;
- laser *RIN* noise.

The performance of these transmitters and receivers is expressed by way of carrier-to-noise ratio (*CNR*).

II. Noise sources in optical transmitters

A. RIN of laser transmitter

The output power of laser fluctuates around its steady-state value due to quantum fluctuations in the electron density as well as spontaneous emission events that are converted to intensity noise. The laser relative intensity noise (*RIN*) can be defined as [1]

$$RIN = \frac{\left\langle \left| \delta S(\omega) \right|^2 \right\rangle}{S^2}, \qquad (1)$$

where δS is the output power fluctuation from the average power value S. Then the laser *RIN* can be written as

$$RIN(\omega) = \frac{2R_{sp}\left[\Gamma_N^2 + \omega^2 + G_N^2 S^2 \left(1 + \frac{\gamma_N .N}{R_{sp}.S}\right)\right]}{S\left[\left(\omega_R^2 - \omega^2\right)^2 + 2\Gamma_R^2\left(\omega_R^2 + \omega^2\right) + \Gamma_R^4\right]}, \qquad (2)$$

where $R_{sp} = \gamma_{sp} n_{sp} N / \tau_n$ is the spontaneous emission rate (γ_{sp} – the fraction of the spontaneous emission coupled into the cavity mode; n_{sp} – spontaneous emission factor; N – the carrier density; τ_n – the electron lifetimes; ω_R – the laser resonance frequency or relaxation oscillation frequency; $\Gamma_R \equiv (\Gamma_N + \Gamma_S)/2$ – the relaxation oscillation decay rate; $\Gamma_S = R_{sp}/S - G_S S$ – the photon decay rate; S – the photon density; $\Gamma_N = \gamma_N + N(\partial \gamma_N / \partial N) + G_N S$ – the small-signal decay rate; $G_N = \Gamma v_g (\partial g / \partial N)$; $G_S = \Gamma v_g (\partial g / \partial S)$; Γ – the carrier confinement factor in the active layer; v_g – the group velocity; g – the optical gain. At low frequency ($\omega < \omega_R$), the laser *RIN* is almost frequency independent, but it is significantly enhanced in the vicinity of $\omega = \omega_R$. At a given frequency, the *RIN* decreases with the bias current as $(I - I_{th})^{-3}$, where I_{th} is threshold current. As the bias current is increased, the *RIN* decreases more slowly as $1/(I - I_{th})$. The laser *RIN* imposes an upper limit on the maximum achievable *CNR* at the fiber node receiver. Consequently, the *RIN* of DFB laser transmitters, which are used for analog video transmission, are typically equal to *-155db/Hz* or better. It should be pointed out that the laser *RIN* can significantly degraded by multiple optical reflections [2].

B. Laser transmitter phase noise

It is well known that spontaneous emission events in the laser cavity change both the phase and amplitude of the optical field. Coupling of the spontaneous emission into the lasing modes as well as fluctuation in the electron density induce changes in both the real and imaginary parts of the refractive index, and produce phase noise. The spectral linewidth of a laser due to spontaneous emission can be written as [3]

$$\Delta v = \frac{v_g h v n_{sp} (\alpha_i + \alpha_m) \alpha_m \left(1 + \alpha^2\right)}{8\pi S}, \qquad (3)$$

where α_i and α_m are internal and mirror losses, respectively; α – the linewidth enhancement factor; n_{sp} – the spontaneous emission factor; h – the Plank constant; v – the photon energy. According to Eq. (3), the laser linewidth is inversely

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proportional to the output power and it is enhanced by the factor $(1+\alpha^2)$. The larger DFB laser linewidth is undesirable, particularly for relatively long-distance transmission (>*30km*).

C. Performance of DFB laser transmitters

Generally, the laser transmitter is designed to transport multiple AM/QAM video signals with the maximum possible *CNR* for a given optical received power at the fiber node. To achieve the maximum *CNR* for a given optical link budget, the output optical power as well as the optical modulation index *m* per channel must be as large as possible to overcome the laser *RIN*, fiber losses, and receiver noise. On the other hand, the maximum optical modulation index is limited to avoid unacceptably large nonlinear distortions and a clipping effect [4, 5]. The static clipping behavior increases the laser's nonlinear distortions and imposes an upper limit on the channel capacity. Consider a system with N channels, each with modulation index m and a total photocurrent at the receiver $I(t)$. For large N, the photocurrent $I(t)$ can be modeled as a Gaussian random process with mean I_p and standard deviation $\sigma_p = mI_p(N/2)^{i/2}$. The normalized modulation index can be defined as:

$$\mu = \frac{\sigma_p}{I_p} = m\sqrt{\frac{N}{2}} \ . \tag{4}$$

It can be shown that the carrier-to-nonlinear distortions (*C/NLD*) caused by clipping for small μ can be approximately given by [6]

$$C/NLD = \frac{1}{\Gamma}\sqrt{\frac{\pi}{2}}\mu^{-3}\left(1+6\mu^2\right)e^{1/2\mu^2} , \tag{5}$$

where Γ (≈*1/2*) is the fraction of the distortion power within the cable TV band. The resultant *CNR* is the sum of the *CNR* and the *C/NLD*.

Digital channels such as QPSK or 16-QAM are transmitted in the return-path portion of the cable TV networks [7]. The return-path laser transmitters are not required to provide the same *CNR* or linearity as the downstream laser transmitters since they are not intended to transport AM video channels. The optical signals can be transmitted at either *1310nm* or *1550nm*. Notice that at room temperature, an error-free QPSK transmission can be achieved over a wide range of optical modulation indices, from about *1%* to *11%*. The operating range of optical modulation indices is reduced by 5dB at a higher temperature (≈ 80^0C) indicating an upper limit on an upstream channel capacity. The upstream impairments include a laser RIN, thermal noise, and optical reflections, as well as cumulative ingress noise from all the homes connected to a given fiber node.

III. NOISE SOURCES IN OPTICAL RECEIVERS

A. Shot noise

Shot noise in photodetector is a quantum noise, which is due to the random generation of electron-hole pairs when the photodetector is illuminated by photons. To derive the noise variance of the photocurrent generated in response to an optical signal with constant amplitude, it is make the following assumptions:

- the probability of generating a single electron-hole pair in a very small time interval Δt is proportional to Δt;
- the probability of generating more than a single electron-hole pair in Δt is negligible;
- the electron-hole pair generation events are statistically independent.

Based on these assumptions, the probability of generating exactly n electron-hole pairs per unit time can be given by

$$p(n) = \frac{N_0^2 e^{-N_0}}{n!} , \tag{6}$$

where N_0 is the average number of received photons in the time interval Δt, which is equal to $P_{in}\Delta t / h\nu$ (P_{in} – the incident optical power). Let also assume that every photon generates an electron-hole pair at the receiver (*100%* quantum efficiency). Then, the average photocurrent is simply qN_0, where q is the electronic charge. The noise variance of the photocurrent at the receiver per unit frequency bandwidth is given by [8]:

$$\sigma_{shot}^2 = \left\langle \delta i_R^2 \right\rangle - \left\langle \delta i_R \right\rangle^2 = q^2\left[\left\langle n^2 \right\rangle - \left\langle n \right\rangle^2\right] = q^2 N_0 = qI_R . \tag{7}$$

Eq. (7) is also the spectral density of the shot noise, which is frequency independent. The single-sided spectral density becomes $2qI_R$. Under reverse-biased operation, the dark current (I_D), which is the residual photocurrent with no light due, also adds to the photodetector shot noise. Thus, the total photocurrent shot noise variance per unit frequency bandwidth will be:

$$\sigma_{shot}^2 = 2q\left(I_R + I_D\right). \tag{8}$$

B. Thermal noise

The electrons move randomly in any conductor due to a finite temperature, which manifests itself as random fluctuations in the current even when no electrical voltage is applied. The random photocurrent fluctuations cause random voltage noise over a load-resistor terminal. The thermal noise is also called *Johnson* noise or *Nyquist* noise.

The double-sided spectral density expression is given by

$$S_p(\nu) = \frac{2k_B T}{R_L} , \tag{9}$$

where R_L is the load resistor, k_B – the Boltzmann constant; T – the absolute temperature. The open-circuit single-sided spectral density of the photocurrent is given by:

$$S_p(\nu) = \frac{4k_B T}{R_L} = \left\langle \delta_{th}^2 \right\rangle . \tag{10}$$

If an RF amplifier with a noise figure F is connected directly to the photodetector, then the photocurrent variance per unit frequency interval due to thermal noise is given by:

$$\sigma_{th}^2 = \left\langle \delta i_{th}^2 \right\rangle = \frac{4k_B TF}{R_L} . \tag{11}$$

At room temperature with a *50Ω* load and a preamplifier with a noise figure of *3*, $\sigma_{th} = 31{,}5\,pA/\sqrt{Hz}$. In particular, at low reverse-bias voltages, the dark current increases by almost three orders of magnitude for a *60⁰C* temperature increase.

The thermal noise is can be expressed in terms of another useful parameter called noise-equivalent power (*NEP*), which is defined as the minimum optical power per unit of bandwidth that is required to produce *SNR = 1*. Therefore, the *NEP* can be written as:

$$NEP = \frac{hv\left[\left\langle \delta i_{th}^{2}\right\rangle\right]^{1/2}}{q\eta} = \frac{hv}{q\eta}\left[\frac{4k_{B}TF}{R_{L}}\right]^{1/2}. \qquad (12)$$

The *NEP* is useful to estimate the required optical power for a given *SNR* if the noise bandwidth *B* is known. Using the *NEP* definition, the noise-equivalent photocurrent N_R can also be defined as *NERP*, which has typical values in the range $1 \div 10\,pA/\sqrt{Hz}$.

C. Laser receiver RIN noise

The laser relative intensity noise (*RIN*) is due to the laser spontaneous emission and fluctuations in the electron density. The laser *RIN* is defined by

$$RIN = \frac{\left\langle \delta i_{RIN}^{2}\right\rangle}{I_{R}^{2}}, \qquad (13)$$

where $\left\langle \delta i_{RIN}^{2}\right\rangle$ is the photocurrent spectral density due to the laser *RIN*. Thus, the photocurrent variance due to the laser *RIN* can be given by:

$$\sigma_{RIN}^{2} = \left\langle \delta i_{RIN}^{2}\right\rangle = I_{R}^{2}RIN . \qquad (14)$$

It should be pointed out that the laser *RIN* has a frequency dependence similar to the small-signal modulation response of a DFB laser. In an optical communication system, the laser *RIN* is replaced by the system *RIN*, which includes the contribution of the various system elements such as the fiber *RIN*, laser *RIN*, and EDFA *RIN*.

D. Performance of optical receivers

Let assume a communication system with modulation index *m* per channel with a DC photocurrent of I_R and an effective noise bandwidth *B* at the receiver. Then, using the *CNR* definition, the *CNR* can be written as

$$CNR = \frac{\left\langle i_{R}^{2}\right\rangle}{\left(\sigma_{shot}^{2} + \sigma_{th}^{2} + \sigma_{RIN}^{2}\right)B}, \qquad (15)$$

where $\left\langle i_{R}^{2}\right\rangle = \left(mI_{R}\right)^{2}/2$ is the mean-square signal photo-current. Substituting Eqs. (7), (11), and (14) for the shot noise, thermal noise, and *RIN* noise, respectively, in Eq. (15) for the *CNR* at the photodetector, will finally obtain:

$$CNR = \frac{\left(mI_{R}\right)^{2}}{2B\left[I_{R}^{2}RIN + 2q\left(I_{R}+I_{D}\right) + \dfrac{4k_{B}TF}{R_{L}}\right]}. \qquad (16)$$

To gain further insight into Eq. (16), there should be analyzed the *CNR* in the following three cases: Fig. 1 illustrates the *CNR* behavior versus the received photocurrent according to Eq. (16) as well as the thermal noise, shot noise, and laser *RIN* contributions to the *CNR*. Let assumed that the photocurrent was operating at room temperature with a preamplifier with a noise figure of *3*, a *10kΩ* load resistor, laser *RIN = -155dBc/Hz*, a *4%* modulation index for the transmitted RF channel, a *4MHz* noise bandwidth, and the photodetector dark current was neglected. In most practical cases in witch the incident optical power is very small (*<-10dBm*), the thermal noise dominates over both the shot noise and the laser *RIN* in photodetector as shown in Fig. 1. Therefore, the *CNR* becomes:

$$CNR = \left(\frac{R_{L}(mR)^{2}}{8k_{B}TBF}\right)P_{in}^{2}. \qquad (17)$$

Eq. (17) shows that the *CNR* increases as the square of the input optical power in the thermal noise limit. Furthermore, increasing the load resistor and reducing the noise figure of the amplifier can improve the *CNR*.

Another interesting limit is the shot noise limit, which is where the shot noise dominates over both the thermal noise and the laser *RIN*. In this limit, the *CNR* becomes:

$$CNR = \left(\frac{\eta m^{2}}{4hvB}\right)P_{in}. \qquad (18)$$

Notice that the *CNR* increases linearly with the optical input power.

The third limit is the laser *RIN* limit, which is where the laser *RIN* dominates over both the thermal and the shot noise. In this limit, the *CNR* does not depend on the photocurrent in the receiver and can be improved by reducing the laser *RIN*. This limit plays an important role at high optical-input power levels (*>0dBm*), where the *CNR* at the receiver is upper limited by the laser *RIN*. Consequently, to maximize the *CNR* at the fiber-node receiver, directly modulated DFB laser transmitters with *RIN* of *-155dBc/Hz* or less are typically required.

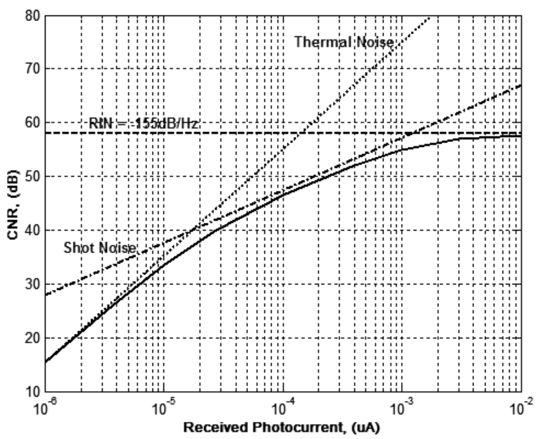

Fig. 1. Calculated *CNR* and its components due to shot noise, thermal noise, and laser *RIN* noise versus the received photocurrent

IV. CONCLUSION

The noise components in optical transmitters and receivers bring about to limitation of maximum achievable *CNR*. While for transmitters' performance it is very important to not allow the ingress of nonlinear distortions by transmission, it is necessary for the receivers to have optimal CNR at their input. The both maximum optical modulation index and the output optical power are limited to avoid unacceptably large nonlinear distortions and a clipping effect. Require performance of laser transmitters for the downstream and upstream channel is different due to the dissimilar nature oflarger temperature range than the downstream DFB laser transmitters. Optical receivers are impacted by a larger number of noise components. Methods of raising laser are typically installed inside the downstream optical receiver at the fiber node, they are required to operate over a much data transmitted along them. Since the return-path transmitters receivers performance vary depending on the prevailing noise component.

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