Bandwidth and dynamic range of a pulsed local oscillator coherent optical receiver. Application to the linear optical sampling.

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ABSTRACT

The optical transfer function of a pulsed local oscillator coherent receiver is derived. We point out that the transfer function is the amplitude of the spectral envelope of the locked optical modes of the pulsed local oscillator source. Using quantum theory of homodyne detection, and assuming an additive Gaussian circular optical noise, with a spectral density $h\nu/2$, at each optical input port of the optical mixer, a general discussion on the fundamental limit of the Signal-to-Noise Ratio of a pulsed coherent receiver is provided. It includes the influence of the time jitter of the sampling pulses. Results are numerically discussed in the context of time equivalent under sampling technique, but may be obviously extended to any real time sampling of optical signals.

Keywords:
Optical sampling, Homodyne detection, Pulse local oscillator optical detection, Error vector measurement, Signal-to-noise ratio, Optical transfer function, Mode locking, Phase jitter.

1. INTRODUCTION

Post photo detection electrical sampling is widely used in optical communication systems using one or several sample(s) during each of the symbol duration. For optical communication systems operation, sampling in real time is mandatory. Only a single sample is required during each of symbol duration, for simple modulation format, such as OOK or PSK, transmitting a single bit per symbol Advanced optical communication systems use more sophisticated modulation format, such as QPSK or QAM in association with coherent detection techniques[1]. Because optical phase is preserved, they are able to take benefits of dedicated post detection digital signal processing for the compensation of linear optical channel impairments. Several samples may be taken during the symbol duration, at the expense of a stronger photo receiver(s) and associated electronics bandwidth requirement. This situation turns, with fiber dispersion, to a strong limitation in the bit rate of single wavelength optical channels and therefore in the time domain multiplexing (TDM) in the electronics domains.

Thanks to real time and synchronized operation, heavy and expensive signal processing is mandatory for clock recovery and data phase recovery and a decision on all the transmitted symbols is to be performed, to recover of the transmitted data flow. In this case, the overall systems performances are usually simultaneously limited by the optical channel impairments and by the receiver bandwidth limitation, making the intrinsic characterization of channel difficult.

However, as far as only the characterization of the optical channel, or the monitoring of an optical system, is concerned, only the access to the intrinsic statistical properties of received signal is required and high bandwidth and heavy and expensive signal processing operation can be avoided.

Optical mixing has been early recognized as a performing tool for the investigations of the statistical spectral properties of incoherent optical signal[2,3,4], for phase noise characterization[5,6] or for the statistical analysis of phase modulation[7,8]. More recently, the same technique has been used for investigation of phase modulated signals[9,10,11] and for optical communications signal monitoring[12,13]. The non-linear optical sampling has been also proposed to analyze intensity based communications system performances by using a non-linear device before optical detection[14,15,16,17,18,19]. It will be not considered here despite most of the reported results remain valid.

The optical linear sampling uses, before the photo receiver(s), the coherent mixing of the signal to be detected, or simply analyzed, with a pulsed local oscillator (LO)[20,21,22,23,24]. Using a dual sampling arrangement may solve the phase noise impairments[25,26]. Synchronous real-time linear optical sampling may be used to overcome photo receiver(s) and electronics bandwidth limitation. It allows the multiplexing of optical time domain multiplexing (OTDM) optical signal at Tb/s rate[27,28] by using a parallel implementation at coherent receiver and its associated digital signal processing. Pulsed local oscillator has been also investigated for quantum cryptography application using a QPSK constellation[29].

Another application is the under sampling technique, providing a high bit rate, low cost, blind and asynchronous characterization of optical data flows, free of receiver bandwidth limitation for symbol rate of 100Gbd/s and more. Basics of this unsynchronized, in equivalent time, under sampling technique are given in the Section 2.

In any of these 2 applications of optical linear sampling, the Error Vector Magnitude (EVM) of the signal is directly related to the accuracy of its 2-quadrature measurements. Therefore it depends on the optical frequency detuning of the 2 mixed signals and on Signal-to-Noise Ratio (SNR) of the optical sampling process. The optical transfer function of the optical sampling process is derived in Section 3 as a function of the optical frequency detuning of the 2 mixed signals.

By using quantum theory of homodyne detection, and assuming an additive Gaussian circular noise with a spectral density $h\nu/2$ at each optical port of the optical mixer, the section 4 provides a general discussion on the SNR of pulsed local oscillator coherent detection. Results are discussed in the under sampling context, but may be obviously extended to real time signal system operation. The influence of the sampling pulse time jitter conversion into amplitude fluctuation by the time slope of the signal is discussed in section 5.

2. REAL-TIME AND EQUIVALENT-TIME OPTICAL SAMPLING FOR SIGNAL

The optical linear sampling uses, before the photo receiver(s), the coherent optical mixing of the signal to be detected, or simply analyzed, with a pulsed local oscillator (LO) in a balanced and symmetric a 4X4 hybrid mixer. The optical mixing with a powerful LO provides simultaneously a temporal gating and a mixing gain for the optical field. Depending on application requirement, the optical sampling can be either synchronous or asynchronous.

Fig.1 shows, on the left, the typical synchronized real time optical sampling operation in which a single sample with the duration τ_S is taken during each of the symbol duration τ_D. Fig.1 shows, on the right, the typical synchronized real time, optical over sampling situation where several sample are take during $\tau_D >> \tau_S$. Synchronous linear optical sampling has been essentially introduced for real-time configuration to overcome post-detection electronics. Optical over sampling allows a time bin parallelism receiver implementation to overcome bandwidth limitation. This technique may be used more for than one sample per symbol QAM receiver and for the de-multiplexing optical time multiplexed signal. It allows Tb/s rate OTDM coherent demultiplexing and implementation of dedicated digital signal processing for the compensation of linear channel impairments in a parallel coherent receiver.

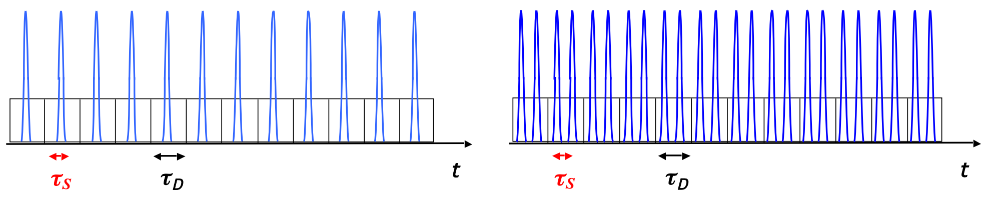

Figure 1: Synchronous and real time optical sampling (left) and over sampling (right).

In all of theses applications real time techniques requires a frequency synchronization of the data and sampling rates and the symbol phase recovery. These operation are performed by costly high-speed usually operating only at a specific bit rate and for a specific modulation format. A decision has to be taken for each of the transmitted symbol to recover all the transmitted data.

Another application optical sampling is the under sampling technique, depicted on Fig 2. The local oscillator is a train of brief optical pulse (typically in the 1ps range) with the sampling period T_S that is far larger than symbol duration τ_D. The pulse repetition rate is typically in the few hundreds of MHz range and allows a low frequency photo receivers and post detection signal processing.

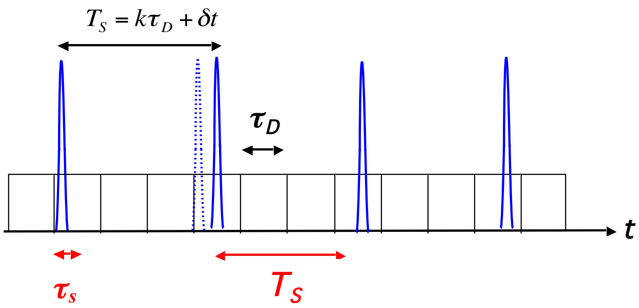

Figure 2: Asynchronous equivalent time under sampling.

As a low rate sampling signal is used for high symbol rate data flow, and only a few symbol of the durations are sampled. No frequency and phase relations between the symbol and the sampling rates are required and an unsynchronized random sampling is obtained. Furthermore a deterministic relationship between the sampling rate and symbol rate is to be avoided. Only an appropriate non-integer part δt of the sampling period T_S is required for the fast acquisition of a statistically representative set of samples

$$T_S = k\tau_D + \delta t \qquad k \in N^*, \quad 0 < |\delta t| < \tau_D \tag{1}$$

From only this statistically representative set of samples, an equivalent time sampling technique can be recovered. Such a technique allows a low cost performance characterization or a monitoring of optical communication systems. It does not require a hardware clock rate recovery and a reconstitution of the frame, but only a low frequency signals processing in equivalent time[20,22]. The dedicated software signal processing is required, to perform the blind optical frequency and phase recovery will be not discussed here. This asynchronous characterization method of optical data flows is free of receiver bandwidth limitation, transparent to the bit rate, transparent to the modulation format and requires only low speed and low cost electronics. Because it is free of receiver limited bandwidth impairments, it allows an intrinsic channel impairment characterization.

3. THE MIXED SIGNALS AND INFLUENCE OF OPTICAL FREQUENCY DETUNING

The signal under test is written as

$$e_D(t) = E_D(t)\exp j\left[\omega_C t + \varphi_C(t)\right] \tag{2}$$

where $E_D(t)$ is the complex envelope to be sampled, ω_C the carrier angular frequency and $\varphi_C(t)$ the technical fluctuations and quantum phase noise.

The sampling signal $e_S(t)$ can be classically obtained from self-pulsating mode locked semiconductor laser[30], from Fabry-Perot intra cavity modulation or from pulse shaping by non-linearity and dispersion[31]. The sampling signal is assumed to be a train of pulse with a periodic envelope $E_S(t)$, a recurrence period T_S, a central optical angular frequency ω_S and with technical fluctuations and quantum phase noise $\varphi_S(t)$.

$$e_S(t) = \left[\sum_{\text{pulses}} E_S(t-nT_S)\right] \exp j\left[\omega_0 t + \varphi_S(t)\right] \tag{3}$$

which can be obviously written as a sum of equally frequency spaced, and linearly phase related, optical modes

$$e_S(t) = \sum_{\text{modes}} \hat{A}(\omega_0 + m\Delta\omega_S) \exp j\left[(\omega_0 t + m\Delta\omega)t + \varphi_S(t)\right] \tag{4}$$

$\hat{A}(\omega)$ is the amplitude of the spectral envelope of the modes of the sampling source and $\Delta\omega_S = 2\pi/T_S$ is the angular frequency of the mode spacing. The pulse envelope $E_S(t)$ is obviously the Fourier transform of the baseband spectral amplitude of the mode envelope $\hat{A}_0(\omega) = \hat{A}(\omega + \omega_0)$ as shown on Fig.3.

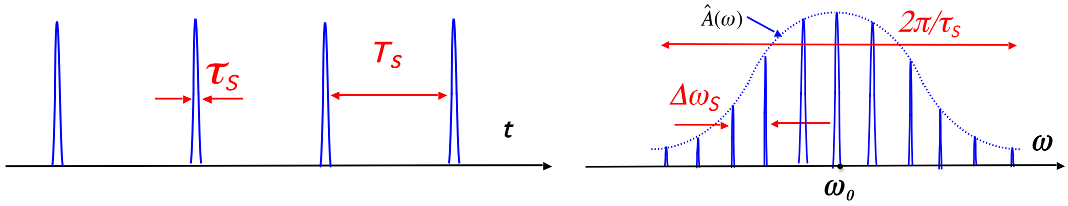

Figure 3: Time and frequency representation of the optical sampling signal.

By using a 4X4 hybrid mixer, these 2 signals are mixed and the *I* and *Q* output signals are the real and the imaginary part of the complex signal envelope

$$e_D^*(t)e_S(t) = \sum_{\text{pulses}} E_D^*(t)\exp\left(-j\left(\Delta\omega_C t + \Delta\varphi(t)\right)\right)E_S(t-nT_S) \tag{5}$$

$\Delta\omega_C = \omega_C - \omega_S$ and $\Delta\varphi(t) = \varphi_C(t) - \varphi_0(t)$ are the angular optical difference and phase difference, between the signal under test and the LO, respectively. As we are in a pulsed LO configuration, the integration time for the 2 mixed signal interaction is the LO pulse duration τ_S and not the integration time τ_E of the photo receivers. The later is to be selected in relation with pulse periodicity to avoid the overlap of consecutive samples. Assuming a small variation of the sampled signal and of the relative phase technical fluctuation and noise over the short sampling pulse duration τ_S, the sample energy is

$$W_n = \left\langle e_D^*(t)e_S(t)\right\rangle\tau_S = E_D^*(nT_S)\exp\left(-j\Delta\varphi(nT_S)\right)\int_{-\infty}^{+\infty}\exp\left(-j\left(\Delta\omega_C t\right)\right)E_S(t-nT_S)dt \tag{6}$$

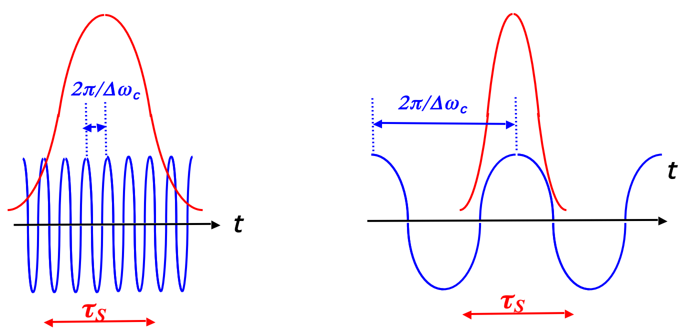

Figure 4: Typical beating situations as a function of the beating frequency period and of the sampling pulse duration.

As a function of the relative values of the beating frequency period and of sampling pulse duration, different situations may occur. As shown on Fig.4, for $\Delta\omega_C \tau_S >> \pi$, the output signal vanishes out, thanks to the fast variation of the beating term at the angular frequency $\Delta\omega_C$. On the other hand, for $\Delta\omega_C \tau_S << \pi$ the average signal is written as

$$W_n = T_S \hat{A}_0(\Delta\omega_C) E_D^*(nT_S) \exp\left(-j\left(\Delta\omega_C nT + \Delta\varphi(nT_S)\right)\right) \tag{7}$$

The optical transfer function appears to be the baseband amplitude envelope $\hat{A}_0(\Delta\omega_C)$ of the optical modes of the LO acting in the sampling pulse generation. An intradyne signal operation is mandatory and signal energy decay as a function of the detuning of the 2 optical fields accordingly with the transfer function $\hat{A}_0(\Delta\omega_C)/\hat{A}_0(0)$. Obviously only the optical modes acting in the locking process of the pulsed LO source, contribute to transfer function.

4. SIGNAL-TO-NOISE RATIO

The Error Vector Magnitude (EVM) of the signal under test estimation is directly related to the accuracy of its 2 quadrature (I and Q) measurements and therefore to the Signal-to-Noise Ratio (SNR) of the optical sampling process. We present here, for the first time to our knowledge, a general discussion on the SNR of pulsed coherent detection. Numerical results are presented in the under sampling context, but may be obviously extended to real time signal detection systems.

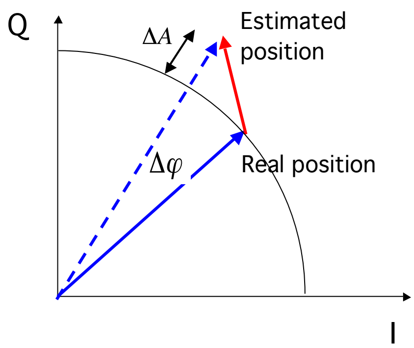

Figure 5: The Error Vector Magnitude (EVM).

The EVM of the signal estimation is directly related to the SNR of the measurements of the I and Q quadratures by the relation

$$\mathrm{EVM} = \sqrt{\frac{1}{2}\left(\mathrm{SNR}\right)^{-1}} \tag{8}$$

The balanced homodyne detection (BHD) scheme detects the field superposition at the two output ports of the 50/50 coupler and the electronic subtraction cancels the photon number sum at the input ports from the detected fields. Semi classical analysis of the BHD have been made by Abbas, Chan and Yee[32], demonstrating the property of canceling the local oscillator excess noise, but still interpreting the quantum limit as the result of the LO shot- noise. Yuen and Chan[33], Shumaker[34], Machida and Yamamoto[35], Collett, Loudon and Gardiner[36], introduced a quantum mechanical treatment, interpreting the BHD as canceling both the LO excess and quantum noises, demonstrating that the quantum limit is the signal quantum fluctuation and not the shot noise associated to the LO. Because we are concerned by fundamental limitation, we will consider this noise as the vacuum fluctuations entering though the signal input port. Eventual additional noise at the input, such as Amplified Spontaneous Emission (ASE), is not an intrinsic property the characterization set up, but features of the signal under test itself.

A perfectly balanced and symmetric a 4X4 hybrid mixer and an operation at the center of the optical bandwidth are assumed in the following. Using the quantum theory of homodyne detection and assuming an additive Gaussian circular with a spectral density $S_{NO} = h\nu/2$, at each optical input port[37,38,39,40], the best achievable SNR for the output ports is

$$\text{SNR} = \frac{2W_S W_D \frac{\tau_S}{\tau_D}}{h\nu\left(F_L W_S + F_S W_D \frac{\tau_E}{\tau_D}\right) + 2\frac{F_S F_L k T_{EQ}}{R^2 R_{EQ}}\tau_E} \tag{9}$$

where $W_S = P_S T_S$ is the pulse sampling energy, $W_D = P_D \tau_D$ is the average symbol energy, τ_D the symbol duration, R the photodiodes sensitivity and $2kT_{EQ}\tau_E / R^2 R_{EQ}$ the equivalent spectral density of the thermal noise at the mixer input. F_S and are F_L are the noise figure associated to the total loss of signal under test input and sampling signal input respectively. It can be equivalently expressed as the function of the sampling power P_S and data signal power P_D

$$\text{SNR} = \frac{2P_S P_D T_S \tau_S}{h\nu\left(F_L P_S T_S + F_S P_D \tau_E\right) + 2\frac{F_S F_L k T_{EQ}}{R^2 R_{EQ}}\tau_E} \tag{10}$$

For high value of the sampling power P_S and for the electronics bandwidth to integration time relation $\tau_E B_E = 1/2$, half of quantum limited SNR of homodyne detection is obtained for F_S with its minimum value of 2, as a price to pay for simultaneous measurement of the 2 quadratures of the field[38].

$$\text{SNR} = \frac{P_D}{2h\nu B_E} \tag{11}$$

Symbol	Quantity	Numerical Values
τ_S	Sampling pulse duration	$10^{-12} s$
T_S	Sampling period	$4.10^{-9} s$
F_S	Sampling frequency	250 MHz
$P_S = W_S/T_S$	Sampling laser power	1mW
W_S=$P_S T_S$	Sampling pulse energy	$4.10^{-12} J$
$N_S = W_S/h\nu$	Photon number per sampling pulse	$3.15\ 10^{+7}$
R_D	Symbol rate	10^{11}Bd
τ_D	Symbol duration	$10^{-11} s$
P_D	Signal power	
$W_D = P_D \tau_D$	Signal energy	
$N_D = W_D/h\nu$	Photon number per sampling pulse	$2.0\ 10^{3}$
τ_E	Photo receiver integration time	$10^{-9} s$
$h\nu/kT_{EQ}$	Quantum to thermal energy ratio	23
T_{EQ}	Equivalent noise temperature	400K
R_{EQ}	Loading impedance	50Ω
$R = \eta e/h\nu$	Photodiode sensitivity	1A/W
$4kT_{EQ}/R_{EQ}$	Spectral thermal noise density	$4.410^{-22} A^2/Hz$
ν	Optical frequency	193 THz
$h\nu$	Photon energy	$1.2710^{-19} J$
ρ_S	Power loss at the signal input	0 .5
ρ_L	Power loss at the local input	0 .5
$\rho_L = \sqrt{\rho_S \rho_L}$	Average power loss at the inputs	0 .5
F_S	Noise figure associated to the excess of loss for the signal input port	2
F_L	Noise figure associated to the excess of loss for the local input port	2
F	Common value for noise figures	2

Table 3. List of parameter and numerical values used in simulations

Let us consider now the under sampling application, assuming R =1, F_S = F_L = 2, a symbol duration τ_D=$10^{-11}s$, a sampling duration $\tau_S = 10^{-12} s$, a sampling period $T_S = 10^{-9} s$ and an electrical integration time $\tau_E = 10^{-9} s$. The Table 3 gives the numerical values of the parameter used in the following simulations.
Fig 6 shows the signal to noise ratio, as a function of the local oscillator power, for various values of the signal power. For a LO sampling power $P_S = W_S / T_S$ equal to 0dBm, a SNR ratio of 25 dB is obtained for a signal under test level of -5dBm.

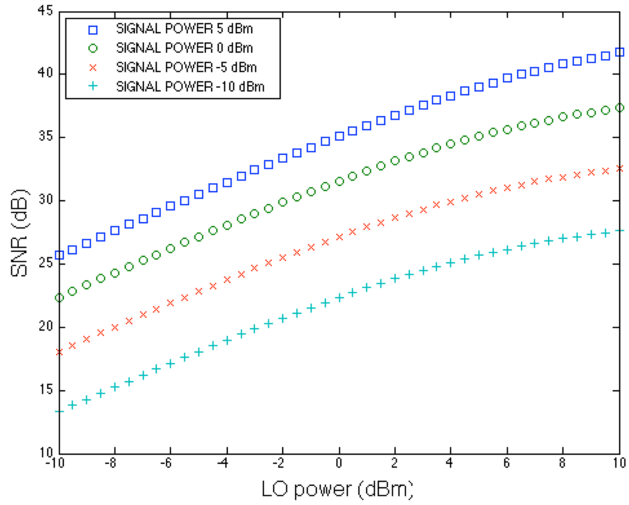

Figure 6: Signal to noise ratio, as a function of the local oscillator power, for various values of the signal power.

The so-called "limitation by the shot noise" of the local oscillator is, in the quantum coherent detection theory, the limitation by the fundamental quantum fluctuations incoming through the signal port. In this ideal situation the SNR no longer depends on the LO power but it requires being more than 10 dBm.

Fig. 7 shows the signal to noise ratio, as a function of the signal power, for various values of the local oscillator power. For a signal power P_D equal to -5dBm, a SNR ratio of 26dB is obtained for a local oscillator level of -0dBm.

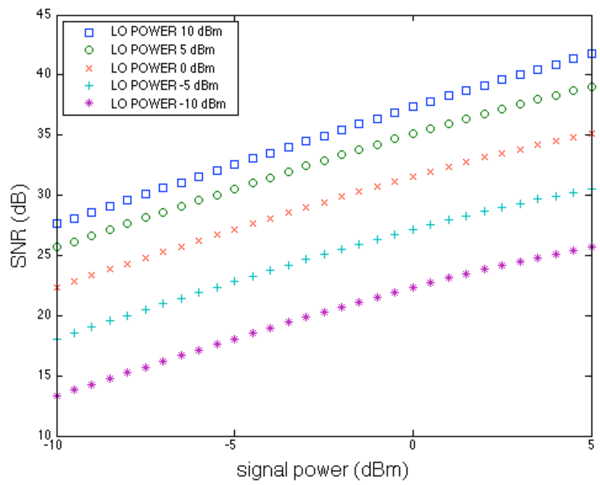

Figure 7: Signal to noise ratio, as a function of the signal power, for various values of the local oscillator power.

The so-called "limitation by the shot noise" of the signal under test is, in the quantum coherent detection theory, the limitation by the fundamental quantum fluctuations incoming through the local oscillator port. In this ideal situation the SNR no longer depends on the signal under test power but it requires being more than 10 dBm.

5. INFLUENCE OF SAMPLING PULSE TIME JITTER

Time jitter of the sampling signal is a consequence of phase noise in the sampling rate, turning into deviations Δt of the sampling pulse time position from its nominal position. Under Gaussian assumption it usual to characterize pulse jitter by its standard (i.e. r.m.s.) deviation, whose square value is related to the power spectral density of phase of noise of the pulsation by

$$\sigma^2 = \frac{1}{(2\pi f_0)^2}\int_{-\infty}^{+\infty} S_\varphi(f)df \tag{12}$$

The sampling pulse jitter does not induce only time imprecision but also turns into sampling errors. As displayed on Fig. 8 the time slope of the sampled signal converts the sampling pulse time jitter into an error on the measured energy of the sampled signal.

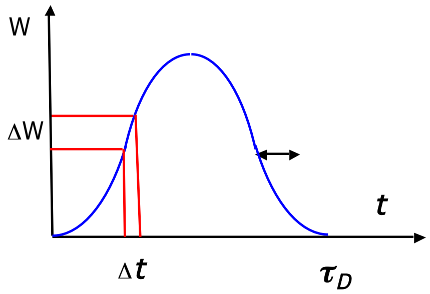

Figure 8: Sampling jitter into amplitude noise conversion.

The corresponding adding noise is obviously larger during the transient, but the corresponding average energy fluctuation ΔW can be estimated by assuming an average slope corresponding to one leading edge and one tailing edge during the symbol duration

$$\Delta W = 2\sigma\frac{W_{MAX}}{\tau_D} \tag{13}$$

Assuming for instance, a 0.2ps average jitter for the sampling pulses and a symbol time duration $\tau_D = 10^{-11}s$, (i.e. a symbol rate of 100Gbd), the SNR associated to the pulse jitter alone is

$$\text{SNR} = \left(\frac{W_{MAX}}{\Delta W}\right)^2 = 0.25\frac{\tau_D^2}{\sigma^2} = 6.2510^2 \text{ i.e. } 28dB \tag{14}$$

Under LO shot noise limitation, the SNR degradation is only negligible for $\sigma < 0.2ps$, for moderated values of the SNR. However time jitter may degrade SNR larger than 30dB. The research of short pules duration is not to be been done at the expense of an enlarged jitter.

6. CONCLUSION

A general discussion of the optical bandwidth and of the dynamics of a pulsed local oscillator coherent optical detection has been presented. We point out that the optical transfer function is the amplitude envelope of the optical modes acting in the locking of the modes of the pulsed laser local oscillator. Using quantum theory of homodyne detection, a general discussion on the SNR of pulsed coherent detection is provided for the first time to our knowledge. The best achievable

SNN has been presented as a function of the local oscillator and signal under test power levels. The influence over performance degradation of the sampling pulse time jitter has been discussed. Results are discussed in the under sampling context, but may obviously be extended to real time signal detection systems.

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