

# Modeling and characterization of VCSEL-based Avionics Full Duplex Ethernet (AFDX) gigabit links

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## ABSTRACT

Low cost and intrinsic performances of 850 nm Vertical Cavity Surface Emitting Lasers (VCSELs) compared to Light Emitting Diodes make them very attractive for high speed and short distances data communication links through optical fibers. Weight saving and Electromagnetic Interference withstanding requirements have led to the need of a reliable solution to improve existing avionics high speed buses (e.g. AFDX) up to 1Gbps over 100m.

To predict and optimize the performance of the link, the physical behavior of the VCSEL must be well understood. First, a theoretical study is performed through the rate equations adapted to VCSEL in large signal modulation. Averaged turn-on delays and oscillation effects are analytically computed and analyzed for different values of the on- and off state currents. This will affect the eye pattern, timing jitter and Bit Error Rate (BER) of the signal that must remain within IEEE 802.3 standard limits. In particular, the off-state current is minimized below the threshold to allow the highest possible Extinction Ratio. At this level, the spontaneous emission is dominating and leads to significant turn-on delay, turn-on jitter and bit pattern effects. Also, the transverse multimode behavior of VCSELs, caused by Spatial Hole Burning leads to some dispersion in the fiber and degradation of BER. VCSEL to Multimode Fiber coupling model is provided for prediction and optimization of modal dispersion. Lastly, turn-on delay measurements are performed on a real mock-up and results are compared with calculations.

**Keywords:** AFDX, gigabit, VCSEL, turn-on delay, jitter, bit-pattern effect, spontaneous emission, modal dispersion.

## 1. INTRODUCTION

To date, avionic datacom buses remain dominated by electrical switches and interconnects. Requirements in terms of electromagnetic compatibility, size reduction and weight saving have motivated intense research on optical solutions. Also, some high-speed links such as video transmissions have urged the need to increase data rates. Hence, for short range, and modern high speed transmission links, using Vertical Cavity surface Emitting Lasers (VCSELs) as light sources in short distance links has been studied and realized for many applications, and has shown interesting results [1]. The advantages of VCSELs over edge emitting lasers are well known: circular output beam, low threshold current and size reduction [2]. But above all, due to their surface normal orientation, VCSELs can be on-wafer fabricated, which make them very cost effective. However, there are still several problems related to the operation of these devices, the most important being the transverse multimode behavior of high power 850nm VCSELs. This fact points out the need to optimize the modal dispersion of the multimode fiber. Besides, due to important losses in harsh environment conditions, there is a need to maximize the Extinction Ratio (ER). Also, bit error rate (BER) performances are influenced by turn-on delay and jitter and have been extensively analyzed previously [3, 5]. Bit pattern effects and spontaneous emission are the main causes of the degradation of jitter induced by the modulated VCSEL. The turn-on event is also accompanied by a further delay when below threshold biasing is applied. Below threshold biasing has been investigated in order to maximize this ER and achieve good performances in terms of turn-on delay, jitter and BER.

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In this paper, we investigate VCSEL characteristics under high-speed modulation to evaluate the turn-on delay, turn-on jitter and BER performances. Also, the modal dispersion of the fiber is modeled for optimization. We consider an annular VCSEL profile, mainly due to the Spatial Hole Burning (SHB), and change the coupling conditions. This dispersion is enhanced by the presence of transverse multimode profile at VCSEL output.

In section 2, the AFDX link is presented and the characteristics of the studied link that must be achieved in regard to the IEEE requirements listed. In section 3, a model for optimization of the fiber dispersion is provided in function of the coupling conditions. Hence, both VCSEL to Fiber distance and the bias currents are studied. We evaluate the modal dispersion in function of injected current but also of the VCSEL output apertures. The model takes into account the mode mixing along the fiber transmission link. In section 4, theoretical model of the large signal modulation of 850 nm VCSEL is presented, in the basis of singlemode rate equations in order to evaluate the performances in terms of delay and jitter. In section 5, measurements results of the turn-on delay, jitter and BER are shown and conclusions are drawn in section 6.

## 2. AFDX LINK – CHARACTERISTICS

The Avionic Data Communication Network (ADCN) is the new aircraft system in charge of interconnecting avionic equipment. It's a Local Area Network (LAN) based on Avionics Full Duplex (AFDX) technology. The AFDX has been developed by Airbus to replace ARINC 429 due to the increasing of data-communications. This technology uses the Ethernet concept and Internet protocols namely the IEEE 802.3 [6], and has been standardized by ARINC 664, part 7 [7]. Also, the media of communications uses the twisted pair technology for all cables. Frames are switched and the topology is a network star built around switches. For avionics constraints, a special cable (**Star Quad** cable) has been developed, and transmissions are at 10 or 100Mbps. The link is full duplex, which means that the systems in the AFDX network can transmit and receive at the same time on the same link. This is possible because a link is made up of two pairs of wires, one pair for transmitting and the other for receiving.

For future aircraft programs, due to the increasing data communications to gigabit Ethernet and weight saving, aircraft manufacturers begin to prefer optical fiber physical layer rather than copper wires. Developing an optical solution at gigabit Ethernet is hence more and more investigated. The 1Gbps AFDX optical physical layer shall comply with IEEE 802.3 Standard Gigabit Ethernet 1000BASE-SX Physical Medium Dependant (PMD) requirements [6] and also with ARINC 804 requirements [8].

The aim of this work is to study timing performances on a short distance link based on 850 nm VCSEL for application to an optical AFDX gigabit link. The worst case-scenario corresponds to the link between the equipments located in the main avionic bay at the cockpit and those at the rear part of the aircraft (cf. Fig. 1). The total link loss is evaluated by considering this case link, including production breaks (representative of a real aircraft-type application).

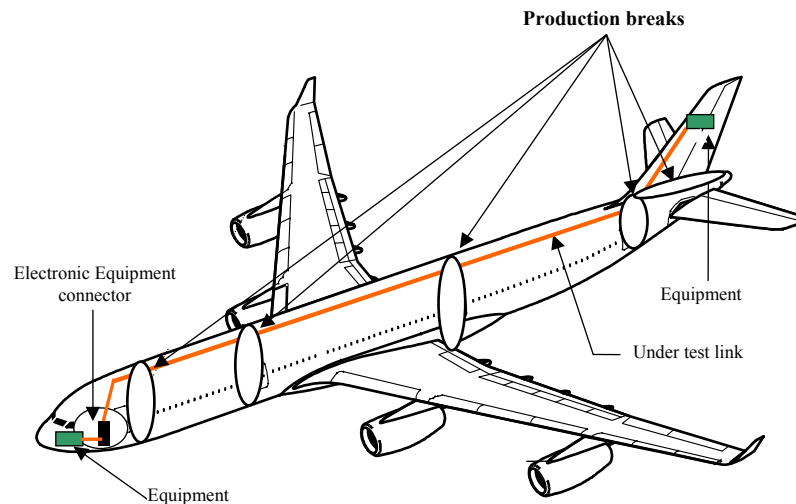


Fig. 1 Production breaks on A380 aircraft

### 3. VCSEL – FIBER COUPLING AND MODAL DISPERSION

Due to their very high bandwidth compared to other transmission media, Multimode optical fibers (MMF) are the most widely used transmission medium for Local Area Networks (LANs). However, dispersion, attenuation and non linearities reduce optical fiber communication performances. Data rates within LANs being rapidly increasing, MMF systems have to support higher and higher data rates. The IEEE 802.3z standard [6] describes the current state of the art for Gigabit Ethernet at 1 Gbps data rate. Even at gigabit Ethernet operation, the capabilities of MMF are degraded while the bandwidth performances are generally specified for overfill launch conditions [9] with the LED as the light source. For laser transceivers, required at gigabit rates, the overfill launch conditions can't be applied. In particular, 1000BASE-SX VCSELs transceivers emit light over an area in the same order than the fiber core size. Furthermore, for high power VCSELs, the transverse multimode behavior leads to annular beam. In the following, our aim is, on one hand to define an appropriate way for the modal dispersion evaluation according to coupling conditions for an annular profile source, and on the other hand to find means to optimize dispersion with a proper combination between VCSEL-to-fiber distance and polarization current of the injecting current VCSELs.

For that purpose, this section deals, in the first part, with evaluation of the fiber dispersion and intensity distribution on the fiber propagating modes, and in the second part, with the coupling evaluation under varying coupling conditions. Obtained results are then discussed.

#### 3.1 Fiber dispersion and field distribution

We consider a step-index multimode optical fiber and do not review the propagation conditions thoroughly described in [10-11]. Within modal theory, the MMF modes can be divided into degenerated mode groups with nearly the same phase velocity. We consider the propagation described in the lossless scalar case [12] meaning that the polarization effects are neglected during the propagation [12, 13]. Real wave-numbers being only considered for the given fiber lengths (less than a hundred meter), the attenuation is not taken into account in searching procedure for the propagation constants. In our case, the relative refractive index difference between core and cladding  $\Delta n$  is around 2% with a standard core diameter of 62.5 $\mu\text{m}$  and a fiber cladding of 125 $\mu\text{m}$ . This fiber is seen supporting 460 non-orthogonal propagating modes.

Pulses launched into the fiber split on these several hundreds of fiber modes and travel at different group velocities, coupling between propagating modes being considered. The group velocities are determined from the fiber dispersion laws according to the index profile, the losses being seen independently of the injected beam or the propagation effects along the fiber. Besides, we also assume that air-fiber interface is not included in the study.

The Poynting vector distributions  $\Pi_{nm}$  associated to the propagating fiber modes with propagation constants  $\beta_{nm}$  constitutes a set of basis functions properly defined to expand VCSEL intensity distribution  $\Phi_0$  on the fiber modes. The amplitudes  $\alpha$  of the projection of the VCSEL intensity distribution on this basis functions is given by  $\alpha_{nm} = \langle \Pi_{nm} \Phi_0 \rangle$ ,

where the brackets stands for the hermitian inner product.

Due to the no-orthogonal property of the  $\{\Pi_{nm}\}$  set of basis functions, the amplitudes of the VCSEL intensity distribution  $\Phi_0$  on the fiber modes is given by:

$$\alpha' = \mathbf{M}\alpha \quad (1)$$

where M is the mode coupling matrix with entries given by  $M_{ij} = \langle \Pi_{i(n,m)} \Pi_{j(n'm')} \rangle$ .

In the following sub-section, the simulation results of the coupling between VCSEL and fiber modes are illustrated.

#### 3.2 Coupling evaluation

Several coupling efficiency models already exist but more often rely on severe approximations [13] in the case of VCSEL-fiber coupling evaluation. Hence, approaches such as classical geometrical optics, Gaussian beam approximation, Laguerre Gaussian and Hermite Gaussian approximations are not completely suitable for transverse multimode VCSELs.

The power distribution at the air-fiber input interface is assumed to be given by the emitted VCSEL power distribution driven by a continuous current I. The coupling efficiency evaluation is based on the modal decomposition of the VCSEL

power distribution previously discussed. In the following, the model is applied to a high power 850nm VCSEL with threshold current  $I_{th}=5\text{mA}$ . In Fig. 2(a) and 2(b), the amplitudes of the VCSEL intensity on the fiber propagating modes given in expression (1) are given, for a 10mA bias current, the waist having respectively 20 $\mu\text{m}$  and 31.25  $\mu\text{m}$  extension.

Lower waist extension, corresponding to the closer distance between the VCSEL output and the fiber input, is seen providing a propagation mainly concerning the first part of the propagating modes spectrum while the wider waist, corresponding in this case to a VCSEL spot matching the fiber core diameter, is seen mainly resorting to the higher part of the propagating modes spectrum whose Poynting distribution maxima are concentrated at the border of the fiber core.

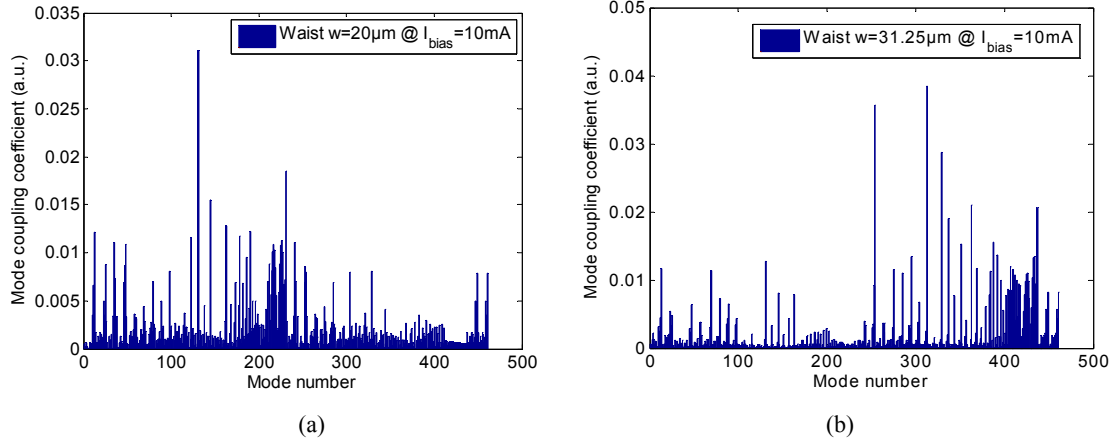


Fig. 2. Influence of waist on VCSEL – MMF coupling at  $I_b = 10\text{mA}$  and for (a) waist  $w = 20\mu\text{m}$ , (b) waist  $w = 31.25\mu\text{m}$

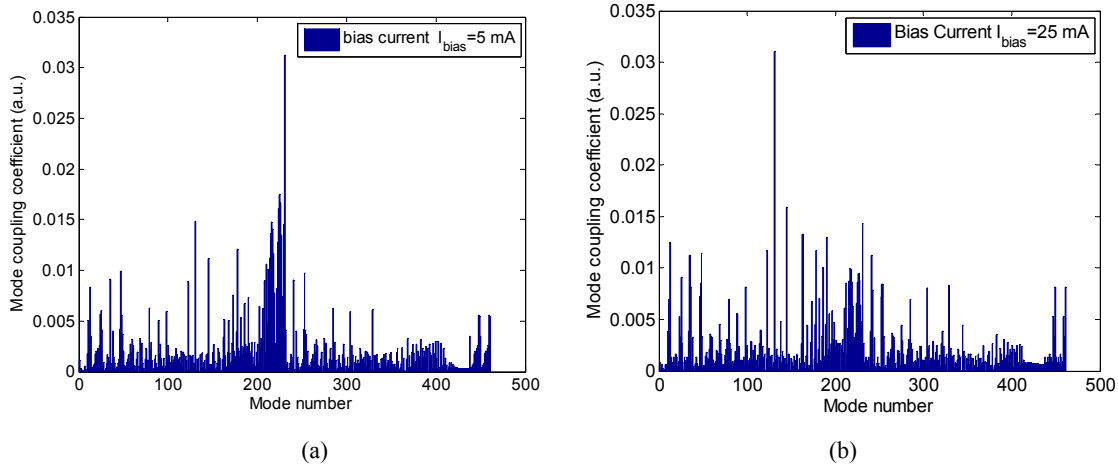


Fig. 3. Influence of injected current on VCSEL – MMF coupling for waist  $w = 20\mu\text{m}$  and (a) at  $I_b = 5\text{mA}$ , (b)  $I_b = 25\text{mA}$

In Fig. 3(a) and 3(b) the influence of the VCSEL bias current on the mode distribution of the VCSEL intensity profile is inspected. The bias current controlling the VCSEL emitted intensity distribution it also seen determining the more concerned part of the propagating mode spectrum involved in the fiber-VCSEL coupling.

#### 4. LARGE SIGNAL MODULATION: THEORETICAL STUDY

In order to enhance the extinction ratio, it is of great importance to bias the VCSEL below the threshold for large signal modulation. However, this operation leads to further turn-on delay and jitter, and then degradation of BER. In order to define the best performance operation, we have modeled the modulation response in terms of delay, jitter and BER versus the OFF and ON currents  $I_{off}$  and  $I_{on}$  respectively. When the laser is directly modulated by a current pulse train with  $I_{off} < I_{th}$  to  $I_{on}$ , there is a delay before optical emission. This delay comes with damped ringing at the relaxation resonance frequency  $f_R$  yielding upper limit for the achievable modulation frequency. For discussing the modulation

characteristics, we don't consider the transverse mode competition of VCSEL. The coupled rate equations of electrons and photons are the basis of this study:

$$\frac{dN}{dt} = \frac{\eta_i I}{q N_w} + \frac{N}{\tau_e} - G \cdot P \quad (2)$$

$$\frac{dP}{dt} = \Gamma \beta B N^2 + N_w G \cdot P - \frac{P}{\tau_p} \quad (3)$$

where  $P$  is the photon number in the lasing mode,  $N$  is the electron number in each quantum-well,  $N_w$  is the quantum-well number,  $\Gamma$  is the confinement factor,  $\beta$  is the spontaneous emission factor,  $\tau_e$  is the electron lifetime, also given by  $\tau_e^{-1} = (A + B \cdot N)$ ,  $A$  is the non-radiative recombination coefficient,  $B$  is the bimolecular recombination coefficient.  $G$  is the modal gain,  $\tau_p$ , the photon lifetime,  $\eta_i$ , the quantum efficiency,  $I$ , the driving current,  $q$ , the electron charge.

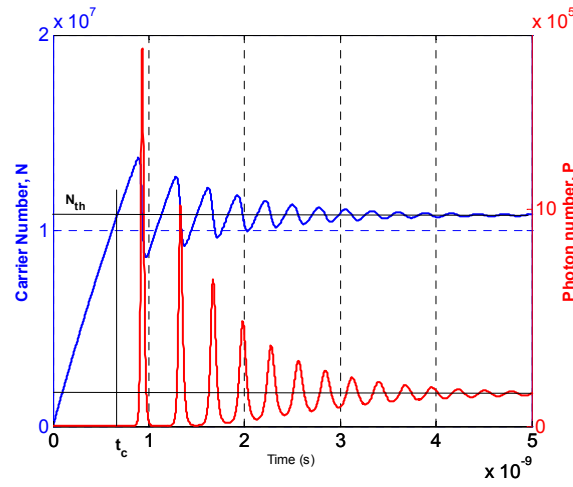


Fig. 4. Turn-on event from  $I_{\text{off}}=0$  (without prebias) to  $I_{\text{on}}>I_{\text{th}}$  (far above threshold)

For a large signal modulation, laser response to a current step is not instantaneous as sketched in Fig. 4, where the laser is directly modulated from  $I_{\text{off}}<I_{\text{th}}$  to  $I_{\text{on}}>I_{\text{th}}$ . The crossing time  $t_c$  is defined as the time at which the carrier number reaches  $N_{\text{th}}$ , the threshold carrier population in the active region. This crossing time is strongly dependent of  $I_{\text{on}}$  and mostly  $I_{\text{off}}$ , as will be shown below.

In order to quantify the effects occurring during the turn-on event, the dynamics of the photon number  $P(t)$  is separated into a stochastic regime ( $t < t_c$ ) and a deterministic regime ( $t > t_c$ ). There is a delay time  $t_d$  between the applied bias and the pulse rise time to the ON level, equal to the sum of the carrier density rise time to the lasing threshold  $\tau_D$  and the optical switch-on time to the optical ON level  $t_{\text{on}}$ :  $t_d = \tau_D + t_{\text{on}}$ . Resolution of the two-coupled equations (2)-(3) under large signal direct modulation leads to these turn-on delay times  $\tau_D$  and  $t_{\text{on}}$  in the stochastic and deterministic regimes respectively.

The turn-on delay  $\tau_D$  is defined as the time delay between the application of an ideal step current and the lasing threshold [14] and can be determined from the carrier equation (Eq. 2). According to Joyce and Dixon, we can express the turn-on delay  $\tau_D$  as follows (when the OFF state is slightly below the threshold) [15]:

$$\tau_D = \tau_e' \cdot \frac{I_{\text{on}} - I_{\text{off}}}{I_{\text{on}} - I_{\text{th}}} \quad (4)$$

where  $\tau_e' = (A + 2B \cdot N)^{-1}$  is defined as the differential lifetime, assumed to be constant in the entire range of integration and equal to its threshold value:  $\tau_e' = (A + 2B \cdot N_{\text{th}})^{-1}$ .

Modulating the laser under pseudorandom bit sequences leads to fluctuations of this delay  $\tau_D$  due to bit-pattern effect, represented by the crossing time  $t_c$ . The statistics of the turn-on delay time  $\tau_D$ , due the predominance of spontaneous emission below threshold, allow the derivation of the turn-on jitter. Previous studies [3-5] have led to the expression of the probability density function (PDF) of the turn-on delay  $t_c$  where  $B$  is the data rate:

$$p(t_c) = \ln 2 \cdot B \cdot \frac{\tau_c}{\tau_D} \left(1 - \frac{t_c}{\tau_D}\right)^{\ln 2 \cdot B \cdot \tau_c - 1} \quad (5)$$

Considering the two orthogonal polarizations that both contribute to the emitted VCSEL light, the PDF of the rise time  $t_{on} = t_d - t_c$  can be derived from the photon rate equation (Eq. 3) [4,5]:

$$p(t_{on}) = 4 \cdot \omega_R^2 \cdot \frac{P_{on}^2}{\langle P_{off}^2 \rangle} \cdot t_{on} \cdot \exp[-(\omega_R \cdot t_{on})^2] \cdot \exp\left[-2 \cdot \frac{P_{on}}{\langle P_{off} \rangle} \cdot \exp\left(\frac{-(\omega_R \cdot t_{on})^2}{2}\right)\right] \quad (6)$$

where  $\tau_c$  is defined above (Eq. 4),  $\langle P_{off} \rangle$  represents the mean value of the photon number at the turn-on delay  $t_c$  and  $f_R$  the resonance frequency at the ON state. The jitter is defined as the standard deviation of the PDF. Since those two processes are not correlated, the PDF accounting for both bit pattern effect and spontaneous emission is obtained by the convolution of expressions (5) and (6), leading to:

$$p(t_d) = \int_0^{\tau_D} p(t_c) \cdot p(t_{on}) \cdot dt_c \quad (7)$$

In order to study the VCSEL behavior during the turn-on event, different conditions of modulation are applied to investigate the impact of the spontaneous emission and the bit pattern, but also data rates. We apply the model to a 850nm VCSEL with current threshold  $I_{th}=2mA$ . Fig. 5(a) shows the turn-on delay  $\tau_D$  as a function of the ON and OFF states. In Fig. 5(b) is depicted the jitter induced by bit-pattern effect in function of  $I_{off}$ , showing a minimum slightly below threshold. The transit across threshold causes further jitter; this contribution corresponds to the summation of the jitters for each current level during the transition from  $I_{off}$  smaller than  $I_{th}$ . Jitter is increased because of the pattern generator used for VCSEL modulation from current levels separating the OFF level to the threshold. The standard deviation of the PDF expressed in (Eq. 6) gives the turn-on jitter due to spontaneous emission as can be seen in Fig. 6(a). Further studies of VCSEL's behavior versus data rates and OFF levels have been realized in Fig. 6(b-c). Evaluation of the jitter performances allows prediction of the bit error rate (BER) degradation.

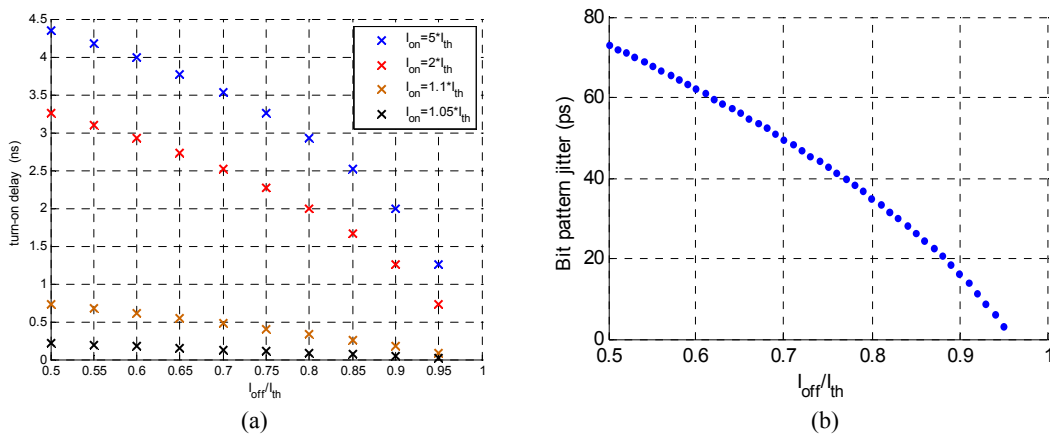
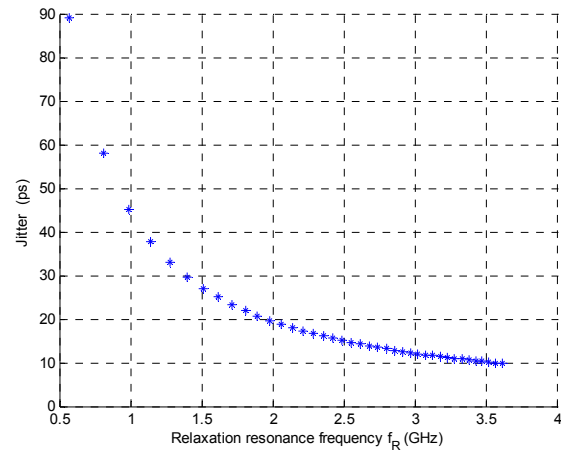
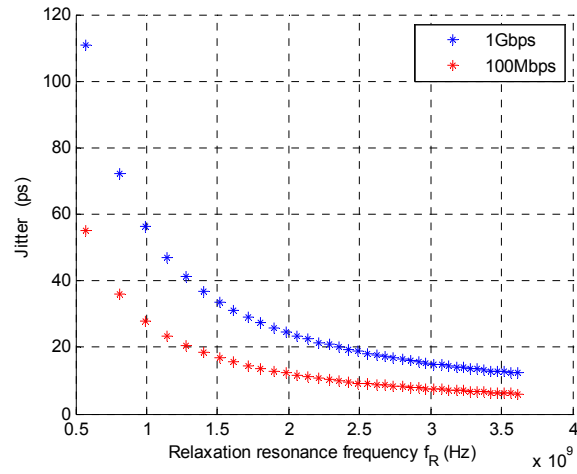


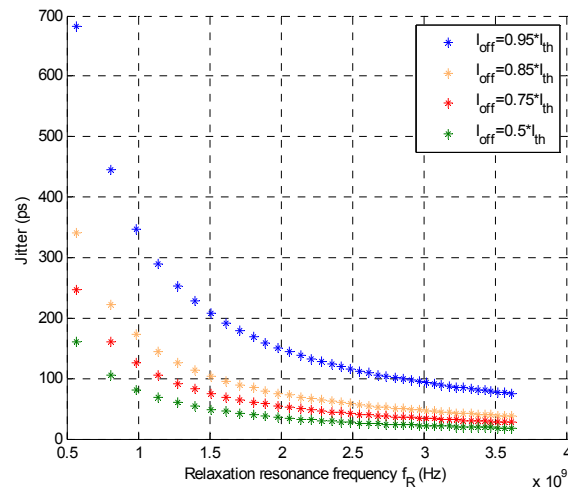
Fig. 5. (a) Turn-on delay  $\tau_D$  for different  $I_{on}$ , (b) Jitter due to bit pattern effects for  $I_{on}=5 \cdot I_{th}$



(a)



(b)



(c)

Fig. 6. (a) Jitter due to spontaneous emission, (b) Jitter function of data rate, (c) Total Jitter for different  $I_{off}$

## 5. TURN-ON DELAY MEASUREMENTS

Here we study experimentally the turn-on delay of a 850nm VCSEL with threshold current  $I_{th}=0.87\text{mA}$ . The laser diode is driven by a pattern generator with “11111000000” word at 1Gbps NRZ data rate. For a first measurement of the VCSEL optical pulse, no bias is applied. A second measurement is performed with a bias tee applied to combine the CW and the DC bias current [16]. In order to eliminate the delay time of the electrical setup and evaluate the turn-on delay, bias-free and biased optical pulses are compared. The optical sampling scope allows comparing bias-free modulation with biased modulation, as illustrated in figure 7.

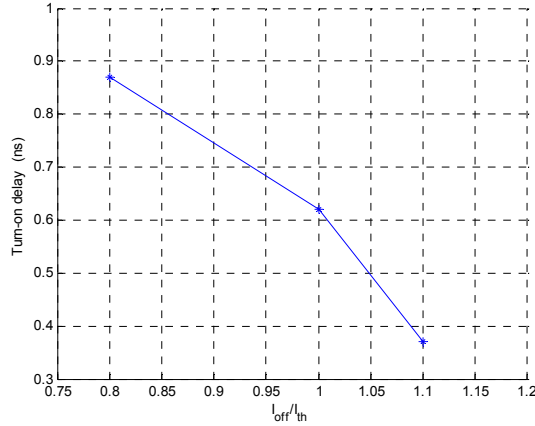


Fig. 7. Turn-on delay  $\tau_D$  of biased modulation in comparison with bias-free operation depicted from optical pulses for  $I_{off}/I_{th}=\{0,0.8,1,1.1\}$

## 6. CONCLUSION

For AFDX application, we have performed two models in order to predict 850nm VCSEL and multimode fiber performances. The first model studies the timing statistics of modulated VCSEL at 1Gbps. The second model studies the modal dispersion of optical fiber. The standards defining both Ethernet and avionics are reviewed in order to be compared to modeling results. Jitter and BER measurements will be realized on a real mock-up and results will be compared with calculations. In addition, the impact of the production breaks shall be thoroughly studied to take into account the return losses.

## REFERENCES

- <sup>1</sup> Iga K. "Surface-emitting laser-its birth and generation of new optoelectronics field", IEEE Journal on Selected Topics in Quantum Electronics, **Vol. 6, No. 6**, pp. 1201-1215, Nov./Dec. 2000.
- <sup>2</sup> R. Michalzik and K.J. Ebeling, *Operating Principles of VCSELs*, Chap. 3 in Vertical-Cavity Surface-Emitting Laser Devices, H. Li and K. Iga (Eds.), pp. 53–98. Berlin: Springer-Verlag, 2003.
- <sup>3</sup> D.M.; Lau, K.Y. Cutrer, "Ultralow power optical interconnect with zero-biased, ultralow threshold laser-how low a threshold is low enough?" IEEE Photonics Technology Letters, vol. 7, pp. 4-6, Jan 1995.
- <sup>4</sup> L. Zei, K. Petermann, R. Jager, and K. J. Ebeling, "Operation range of VCSEL-interconnect links with “below-threshold”-biasing" J. Lightwave Technol, vol. 18, no. 4, pp. 477-481, April 2000.
- <sup>5</sup> R.S.Tucker, "High-speed modulation of semiconductor lasers", IEEE J. Lightwave Technol., 3, 1180-1192, 1985.
- <sup>6</sup> IEEE 802.3 Standard, section Three, clause 38, 1998.
- <sup>7</sup> Aeronautical Radio, Incorporated, ARINC 664, part 7.
- <sup>8</sup> Aeronautical Radio, Incorporated, ARINC 804.
- <sup>9</sup> J. B. Schlager, M. J. Hackert, P. Pepeljuginoski, and G. Gwinn, "Measurement for enhanced bandwidth performance over 62.5  $\mu\text{m}$  multimode fiber in short wavelength local area networks" J. Lightwave Technol. 21(5), 1276-1285, 2003.
- <sup>10</sup> N. Grote and H. V. Venghaus, eds., *Fiber Optic Communication Devices*, Springer-Verlag, New York, 2001.



- <sup>11</sup> P. Pepeljugoski, S. Golowich, J. Ritger, P. Kolesar, and A. Risteski, "Modeling and simulation of next-generation multimode fiber links" *J. Lightwave Technology*, vol. 21, pp. 1242–1255, May 2003.
- <sup>12</sup> E. Silvestre, M. V. Andrés, and P. Andrés, "Biorthonormal-basis method for the vector description of optical-fiber modes," *IEEE J. Lightwave Technol.* 23, 923-928, 1998.
- <sup>13</sup> H. Apithy, Y. Bouslimani et H. Hamam "Méthodes de simulation de la propagation optique Simulation methods in optical propagation", *Can. J. Elect. Comput. Eng.*, Vol. 30, No. 1, Winter 2005.
- <sup>14</sup> K. Petermann, *Laser Diode Modulation and Noise*, Kluwar Academic Publishers, 1988.
- <sup>15</sup> R. W.Dixon and W. B.Joyce, "Generalized expressions for the turn-on delay in semiconductor lasers", *J. Appl. Phys.*, vol. 50, no. 7, pp. 4591-4595, 1979.
- <sup>16</sup> P. Schnitzer, U. Fielder, G. Reiner, B. Weigl, W. Zick, and K.J. Ebeling, "Bias-free 1-Gb/s data transmission using top Vertical Cavity surface Emitting laser diodes", *IEEE Photon. Technol. Lett.*, vol. 9, pp. 693–695, May 1997.