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Abstract—**A fiber optic digital link for on-board data handling is modeled, designed and optimized in this paper. Design requirements and constraints relevant to the link, which is in the frame of novel on-board processing architectures, are discussed. Two possible link configurations are investigated, showing their advantages and disadvantages. An accurate mathematical model of each link component and the entire system is reported and results of link simulation based on those models are presented. Finally, some details on the optimized design are provided.**

Keywords - on-board data handling; optical link; space photonics; optoelectronics.

I.   INTRODUCTION

In the last few years, the research effort on photonic systems for space applications is constantly growing [1-3], especially in three key application domains, i.e. analog and digital communication links [4], RF signal processing [5], and sensing [6-10]. In particular, as they allow both elimination of cable-to-cable electromagnetic-interference effects and reduction of size, weight, and power consumption, fiber-optic links for on-board data handling are the topic of an increasing R&D activity involving several research group all over the world, the main space agencies, and companies.

Since 1992, when the first spacecraft using a fiber-optic data bus [11] was launched in the framework of the NASA mission SAMPEX (Solar Anomalous and Magnetospheric Particle Explorer), high speed optical data links have been utilized on board of some other satellites, e.g. the ESA SMOS (Soil Moisture and Ocean Salinity) satellite, in which a fiber-optic network allows the clock signal distribution and the data transfer [12].

A fiber-optic digital link for space applications, called SpaceFibre, operating up to 3.125 Gb/s has been recently reported [13]. The system, which is based on two identical transceivers both including a directly modulated semiconductor laser @ 0.85 μm and a PIN GaAs photodiode, exhibits a bit error rate (BER) less than 10^{-12}.

In this paper we report on modeling, design and optimization of a high speed fiber optic data link to be included in a new complex processing architecture for SAR (Synthetic-Aperture Radar) applications that is under development at Thales Alenia Space-Italy in the framework of an ASI (Italian Space Agency) co-funded project. Data transfer from analog-to-digital converters and processing nodes has been envisaged as the link task. The link operating temperature is in the range -10 ÷ +50 °C.

The link configuration is discussed and all the design choices are justified. Two options for the transmitter module implementation are compared, i.e. the direct modulation of the laser source and the use of a continuous-wave (CW) laser together with an external electro-optic modulator.

Results of the link simulation in several operating conditions through an accurate mathematical model are shown. Finally, achievements of the optimization activity are summarized.

II.   LINK CONFIGURATION

Requirements of the digital processing architecture impose that the designed optical link has to transfer a number N_{sq} of digital sequences ranging from 2 to 16. Each sequence has a bit rate (BR) varying from a few Gb/s to few tens of Gb/s. The link BER should be less than 10^{-12}.

Since N_{sq} is not so large, the link configuration that appears the most appropriate is that one including N_{sq} separate fiber

transmission channels (see Fig. 1). N_{sq} transmitters and receivers should be used for the configuration implementation.
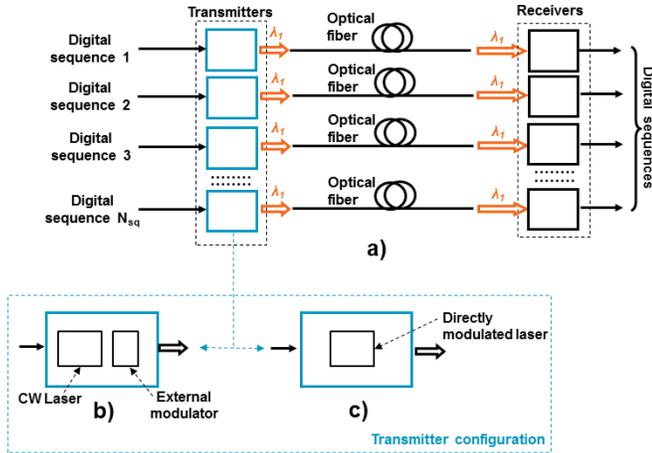

Figure 1. a) Link configuration including N_{sq} transmission channel; b) and c) are two options of the transmitter configuration.

An alternative link configuration (see Fig. 2) based on wavelength division multiplexing (WDM) was also considered and investigated. A deep study on this configuration was carried out and clear evidence that WDM scheme is justified only when the number of transmitted digital sequence exceeds some tens was derived.
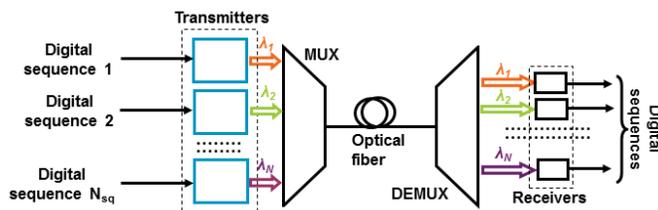

Figure. 2. Alternative link configuration based on WDM.

Compact and low-power semiconductor lasers have been selected for the transmitter module that can be implemented by either direct or external modulation. On the basis of our state-of-the-art review, we concluded that direct modulation can be considered the best choice for BR ≤ 2.5 Gb/s. In fact, for BR > 2.5 Gb/s direct modulation is not fully consolidated and, therefore external modulation of the CW laser would be the most appropriate choice.

For the laser technology selection, VCSEL (Vertical Cavity Surface Emitting Laser), DFB (Distributed Feedback) and FP (Fabry-Perot) lasers have been compared, pointing out advantages and disadvantages. Results are summarized in Table 1.

All considered classes of laser diodes have been already utilized in analog/digital links for space applications and experimental data available in literature allow to conclude that their resistance to radiation is comparable [14-17]. DFB lasers are currently the best performing ones and are available on the market in compact packages (TOSA or butterfly) including a TEC (thermoelectric cooler) for the thermal stabilization.

Therefore that class of laser has been first selected and compared to VCSELs.

TABLE I. COMPARISON BETWEEN FP, DFB, AND VCSEL.

	FP	DFB	VCSEL
Advantages	- Medium/low cost	- Single-mode spectrum - High efficiency - Consolidated technology - Low RIN (in the range -140 dB/Hz ÷ -160 dB/Hz)	- Multimodal spectrum - Low cost - Low power consumption
Disadvantages	- Low efficiency - Multimodal spectrum - High RIN* (-125 dB/Hz)	- Medium/high cost	- Not consolidated technology @ 1.3 µm and 1.55 µm - Low output power - High RIN (-120 dB/Hz)

*RIN = Relative Intensity Noise.

For BR > 2.5 Gb/s CW DFB lasers seem to be the best option because, when thermally stabilized, they can exhibit a very wide operating temperature range (-40 ÷ + 85 °C). For external modulation the best choice would be the use of lithium niobate electro-optic interferometric modulators.

PIN photodiodes have been selected for the optical/electrical transduction because they generate a lower noise level than APDs (avalanche photodiodes).

During the ESA SMOS mission the radiation resistance of single-mode optical fibers has been proved to be acceptable and this is why it has been selected for our data link.

III. LINK MODELLING, SIMULATION, AND DESIGN

Link design/optimization requires the development of an appropriate simulation tool based on realistic mathematical models of the optoelectronic components. By simulating the optical link in several operating conditions, it should be possible to identify the requirements that each component should exhibit to achieve the desired system performance.

The DFB CW laser model takes into account the phase noise generated by the device and the side modes excited within the laser cavity.

Modeling of the DFB directly modulated laser is based on the following rate equations:

$$\frac{dS(t)}{dt} = \Gamma\, g_0 \big[N(t) - N_t\big]\frac{1}{1+\varepsilon S(t)}S(t) - \frac{S(t)}{\tau_p} + \frac{\Gamma\,\beta\,N(t)}{\tau_n}$$

$$\frac{dN(t)}{dt} = \frac{I(t)}{q\,V_{att}} - \frac{N(t)}{\tau_n} - g_0\big[N(t) - N_t\big]\frac{1}{1+\varepsilon S(t)}S(t) \quad (1)$$

$$\frac{d\varphi(t)}{dt} = \frac{1}{2}\alpha_L\left[\Gamma\,g_0\big[N(t) - N_t\big] - \frac{1}{\tau_p}\right]$$

where $S(t)$, $N(t)$ e $\varphi(t)$ are the density of photons emitted by the laser, the carrier density, and the instantaneous phase of the laser beam, Γ is the confinement factor of the laser resonant mode, g_0 is the device differential gain, N_t is the carrier density at transparency, ε is the nonlinear gain factor, τ_p is the photons lifetime, τ_n is the carriers lifetime, q is the electron charge, V_{att} is the active region volume, β is the spontaneous emission factor, and α_L is the linewidth enhancement factor.

The laser output power is given by:

$$P(t) = \frac{\eta_0\,S(t)\,V_{att}\,h\,\nu}{2\,\Gamma\,\tau_p} \quad (2)$$

where η_0 is the laser quantum efficiency, h is the Planck's constant, and ν the laser operating frequency.
Parameters of the laser model can be derived on the basis of the specific device performance, by using the technique reported in [18].

Time dependence of the output optical power is shown in Fig. 3 for a DFB laser @ 1.55 μm with a linewidth = 10 MHz, a side mode suppression ratio of 30 dB and a RIN = -140 dB/Hz. The laser diode is modulated by a 2.5 Gb/s digital signal and its output power is 5 dBm (= 3.16 mW).
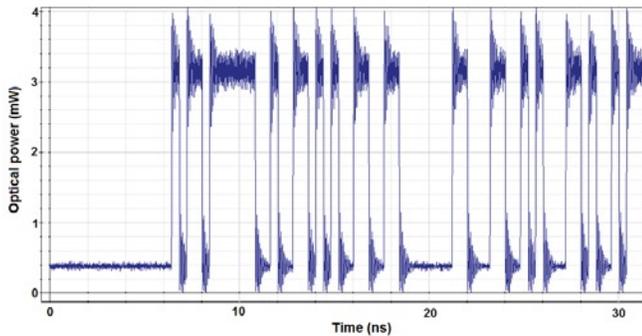

Figure 3. Time dependence of the DFB laser output. Laser power = 5 dBm.

The VCSEL model is rate equations-based, too. Since static/dynamic behavior of this component is strongly influenced by thermal drift, the model includes also thermal effects through an appropriate rate equation taking into account the device thermal resistance.

Mach-Zehnder electro-optic modulator has been modeled by the following equation:

$$E_{out}(t) = E_{in}(t)\,\cos\big[\Phi(t)\big]\,\exp\big[-i\,\alpha_M\,\Phi(t)\big] \quad (3)$$

where E_{in} and E_{out} are the electric field amplitudes at modulator input and output, respectively, Φ is the phase shift between the beams coming out from the modulators, and α_M is the chirp factor.

Current generated by the PIN photodiode has been modeled as:

$$i_{pd}(t) = RP_{pd} + i_{th} + i_{sh} \quad (4)$$

where R is the device responsivity, P_{pd} is the optical power at photodiode input, i_{th} is the contribution due to thermal noise, and i_{sh} is the contribution due to shot noise.

Thermal noise variance can be written as:

$$\sigma_{th}^2 = F_n \Delta f\,\frac{4k_B T}{R_L} \quad (5)$$

where F_n is the noise factor of the electronic amplifier included in the receiver, Δf is the photo-receiver bandwidth, k_B is the Boltzmann constant, T is the temperature, and R_L is the load resistance.

Shot noise variance is equal to:

$$\sigma_{sh}^2 = 2q\Delta f\big(RP_{pd} + i_d\big) \quad (6)$$

where i_d is the photodiode dark current.

Optical propagation characteristics within the fiber have been derived by using the following nonlinear Schrödinger equation:

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = -\frac{\alpha}{2}A + i\gamma A|A|^2 \quad (7)$$

where

$$\gamma = \frac{2\pi\,\bar{n}_2}{\lambda\,A_{eff}} \quad (8)$$

A is the optical beam amplitude, β_2 is the group velocity dispersion, $\bar{n}_2$ takes into account the Kerr effect, α is the propagation loss, A_{eff} is the propagating mode effective area, and λ is the wavelength.

Assuming a fiber length of 1 m, the link has been simulated for BR = 2.5 Gb/s. In this case direct modulation of the laser diode is the best option. Two laser sources, i.e. the VCSEL and the DFB laser, have been compared in terms of the link BER (see Fig. 4). On the basis of our performance investigation of laser diodes available on the market, we assume that maximum optical power of VCSEL and DFB laser is 3 dBm and 7 dBm, respectively. Other performance parameters of the two laser sources have been fixed considering typical values of devices available on the European market.
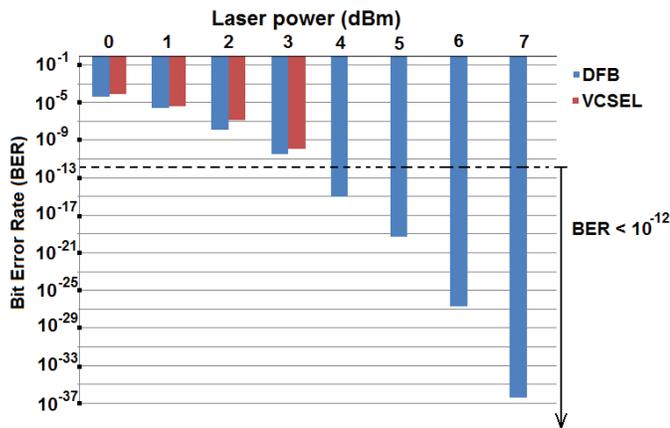
Figure 4. Bit error rate when a VCSEL or a DFB laser is utilized for the digital transmission.

Figure 6. Eye diagram for BR = 2.5 Gb/s and DFB laser power = 3.3 dBm, in case of RZ encoding.

For power values $\leq$ 3 dBm, the link performance achievable through the two laser is similar but the requirement BER < 10^{-12} is not fulfilled. BER values less than 10^{-12} can be obtained only by utilizing the DFB laser. The minimum DFB laser power for the specification achievement is 3.3 dBm. Assuming this power value, the eye diagram has been calculated by our simulation tool (see Fig. 5), for both NRZ (non-return-to-zero) and RZ (return-to-zero), encoding. The use of RZ encoding degrades the link performance. In fact, the BER is 10^{-12} for the NRZ encoding and 7×10^{-12} for the RZ one.
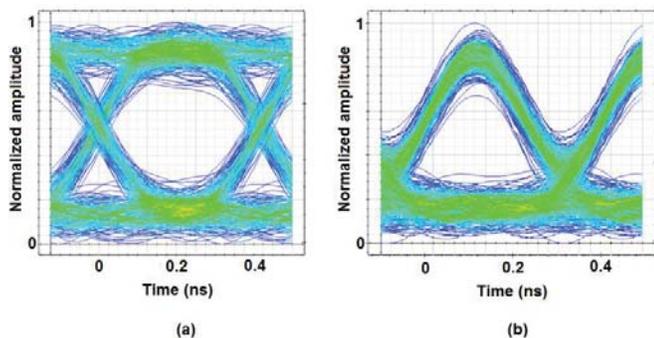

Figure 5. Eye diagram for BR = 2.5 Gb/s and DFB laser power = 3.3 dBm, in case of either NRZ encoding (a) or RZ encoding (b).

The link performance when BR = 10 Gb/s has been evaluated by assuming that, in this case, the transmitter is implemented through external modulation. The relevant eye diagram is shown in Fig. 6 for laser power = 10 dBm (typical value for CW DFB laser). In this case the design specification (BER < 10^{-12}) is fulfilled and the eye pattern is well open.

On the basis of our simulations in a wide range of operating conditions, the link has been designed/optimized when BR = 2.5 Gb/s and 10 Gb/s. Results are summarized in Table 2. Performance of the optoelectronic components to be used are clearly highlighted.
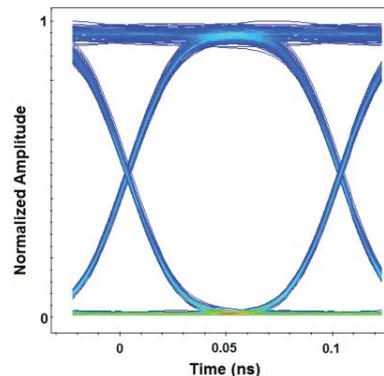
TABLE II.   COMPARISON BETWEEN FP, DFB, AND VCSEL.

	BR = 2.5 Gb/s	BR = 10 Gb/s
Fiber length	1 m	1 m
Data encoding	NRZ	NRZ
Optoelectronic components for E/O transduction	Directly modulated DFB laser with maximum output power = 5 dBm and RIN = -140 dB/Hz	CW DFB laser with maximum output power = 20 dBm and RIN = -140 dB/Hz + Lithium niobate electro-optic Mach-Zehnder modulator with bandwidth > 10 GHz and extinction ratio > 20 dB
Optoelectronic components for O/E transduction	PIN photodiode with a responsivity of 0.9 and a bandwidth > 2 GHz	PIN photodiode with responsivity > 0.6 and bandwidth > 10 GHz
Laser power	3.3 dBm	10 dBm
Average power of the fiber propagation beam	1.89 dBm	6.86 dBm
Power consumption	1 W	5 W
BER	1×10^{-12}	$\ll 10^{-12}$

IV.   CONCLUSIONS

A digital optical link for on-board data handling has been modeled, and designed. Design optimization has been also carried out. For bit rate values less than 2.5 Gb/s, the DFB diode laser direct modulation has been considered the best option for the transmitter implementation while external modulation of a CW DFB laser through a lithium niobate electro-optic modulator has been preferred for higher bit rate values. The receiver key component is a low-noise PIN photodiode.

All link components have been numerically modeled and the system has been simulated in a wide range of operating condition, comparing also different configuration options.

The optimized link has a power consumption of a few watts and a BER $\leq 10^{-12}$.

Experimental characterization of the components and their space qualification is crucial for further development of the reported technology. A very realistic link demonstrator could be fabricated after this development.

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