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A comparison study of a quality of transmission for an analog fiber-optic interconnect line with direct or external modulation

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Abstract

In this paper, with the goal to discover an optimal approach of designing a prospective analog fiber-optic interconnect line, the comparative computer simulation of the quality of transmission parameter is carried out using well-known commercial software VPI Photonics Design Suite. For this purpose, a series of model experiments was realized to measure the laser's relative intensity noise and the output signal-to-noise ratio for cases where direct or external modulation by a radio frequency signal in the band 0.1-20 GHz is used in the transceiving optoelectronic module. In the result, it is clearly demonstrated that, both from a technical and economic point of view the best option for designing a transmitting optoelectronic unit of optical interconnect line is external modulation using off-the-shelf electroabsorption modulated laser.

Keywords: Fiber-optic interconnect transmission line; quality of transmission; semiconductor laser emitter; direct and external intensity modulation; signal-to-noise ratio

1. Introduction

At present, connection links of simple configuration, which carry analog or digital radio-frequency (RF) signals, high-speed digital baseband signals or analog-digital composite signals, are becoming more and more widely used in photonic and electronic industries (Li, at al., 2010; Iannuzzo, 2020). Their main areas of application include local communications, multi-static radars and remote metering systems. Standard means for the implementation are interconnect transmission lines (ITL), which can usually be wireless or wired (Li, at al., 2010). The known advantages of the first option are the simplicity and economy of creation and operation. However, its main disadvantage, especially for a millimeter-wave electronic area, is the limited length of the ITL, as well as the instability and unreliability of communication due to fading and mutual interference. The connection according to the second option, where a coaxial cable is a typical modern information carrier (LaMeres, at al., 2010; Wang, at al. 2021) is much more stable and of high quality of transmission (QoT), but less economical, taking into account not only the high cost of the metallic cable assembly itself, but also the cost of laying the cable. Another fundamental problem of coaxial ITLs is the significantly increasing insertion losses with increasing operating frequency band of the signals under transmission, where the dependence corresponds to the square root of the frequency being used.

The multiyear study of ways to solve the problem has shown the promise of using optical ITL based on fiber-optic cables (FOC) for these purposes ((Kubar, 1999; Chang, 2003). The main reason is that the FOC based on quartz fiber has four orders of magnitude lower losses and two orders of magnitude better phase-to-temperature characteristics as compared with the coaxial counterpart (Hofmann, 2012;

Effenberger, F., 2019). In addition to the benefits of a FOC, which provides a significantly longer length compared to a coaxial ITL, the important advantage of the fiber-optic ITL is in ultra-wide bandwidth of electro-optical and optical-to-electrical converters (EOC and OEC), which makes it possible to transmit ultra-wideband RF signals with high quality (Chang, 2003). Thus, the QoT parameter considered in this paper will be determined by distortions during signal transmission over a FOC and during frequency conversions in EOC and OEC.

The effect of the first source determined by the attenuation and dispersion of optical signals in a FOC, is well studied (Govar 1983) and does not require additional research. The OEC operation is typically implemented by direct detection using a pin-photodiode and a low noise electronic amplifier, which is also fairly well understood (Govar, 1983; Chang, 2003; Belkin, 2018). However, in the scientific literature on fiber-optic ITLs, the issue of choosing the optimal EOC circuitry from a technical and economic point of view is not clearly covered. To fill the gap, the purpose of this paper is a comparative study of the optimal principle and scheme for designing EOC in fiber-optic ITLs. The study is carried out by means of computer simulation in the world spread software environment VPI Photonics Design Suite.

2. State of the art

Figure 1 shows a typical block diagram of a fiber-optic ITL including a FOC ended by two identical transceiving optoelectronic modules (TCOM), each of which contains a transmitting and receiving optoelectronic units (correspondingly, TOU and ROU). In the TOU, an electro-optical conversion and in the ROU, a return optical-to-electrical one are realized. Therefore, the main schematic element of a TOU Is an EOC and of a ROU is an OEC.

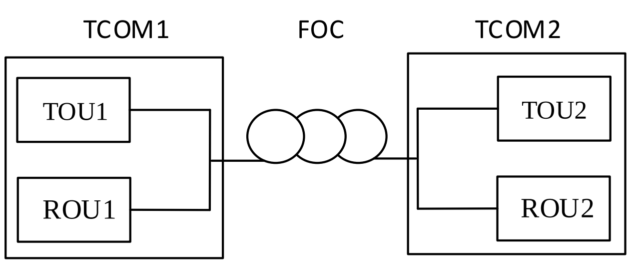

Figure 1. Block diagram of the fiber-optic Interconnect transmission line under study

To date, in fiber-optic communication, there are two main approaches to design an EOC: based on direct modulation of the intensity of a semiconductor laser emitter (SLE) controlling its injection current and based on external modulation of a continuous laser output power using a special electro-optical modulator (EOM). The advantage of the first version is the simplicity and economy of the circuitry, since a single expensive optoelectronic component is implemented to perform the both functions. However, its use is associated with QoT degradation due to limited modulation bandwidth, excessive noise, and parasitic chirp, which are practically absent in the case of external modulation. Following this, at present, TCOMs using an external Mach-Zehnder modulator as an EOC and a pin-photodiode as an OEC are gradually replacing traditional coaxial counterparts in various branches of RF electronics, where cost does not play a decisive role (Hofmann, 2012).

However, such a design principle is inefficient for the problem considered in this paper due to high requirements for cost-efficiency of fiber-optic ITLs, and additional solutions are required to develop an optimal approach. The first obvious step on this path is to replace the expensive and bulky Mach-Zehnder modulator with a cheaper and more compact electroabsorption modulated laser (EML) (Fukano, 2007; Kazmierski, 2009; Belkin, 2018) containing an integrated structure based on SLE and electro-absorption modulator (EAM), which has been deeply studied features and are currently produced by a number of well-known companies with a modulation band up to 40 GHz.

To select the optimal principle for designing a TOU of a fiber-optic ITL, the following sections describe the measurement setups and present the results of model experiments for its two versions using a directly modulated laser (DML) or EML. For this goal, the key parameters of the QoT including the relative intensity noise (RIN) of the SLE and the signal-to-noise ratio (SNR) at the output of the ITL under study are calculated.

3. Model Experiment

In this work, the subject of the study is the fiber-optic ITL including TOU and ROU (see Figure 1); the devices of study are DML, EML for external modulation, and standard FOC using single-mode fiber (SMF). For the both modulation formats, the same most common SLE such as distributed feedback (DFB) laser, is chosen. For external modulation, in accordance with the technical advantages described above and lower cost compared to the Mach-Zehnder modulator, EAM was chosen. A tool for the computer simulation is well-known commercial software VPI Photonics Design Suite. The study estimates QoT parameter in the form of SNR taking into account three key distortion sources of the transmitted signal: a laser RIN, a chirp of lasers and modulators, and chromatic dispersion of the SMF. Table 1 lists the common reference data for simulating the ITL under study using the DML or EML. Note that due to the lack of a library model for the EML in this tool, it is created by connecting in series the SLE and the EAM library models, which does not reduce the correctness of the analysis. The numerical values for the calculations are taken from the data sheet of the industrially produced EML: Optilab, DFB-1550-EAM-12, as well as from relevant publications

(Belkin, 2012; Belkin, 2018; Chang, 2003; Fukano, 2007; Kazmierski, 2009; Kim, 2018; Salvatore, 2002).

Table 1. Reference data for the simulation

Object	Parameter	Value
Fiber-Optic ITL	Optical carrier frequency	193,1 THz
	Modulation format	intensity
	Detection format	direct
	RF carrier range	0.1-20 GHz
	Input RF signal power	-10-5 dBm
SLE	Model	DFB-1550-EAM-12
	Operating current	60 mA
	Linewidth: external modulation	500 kHz
	Linewidth: direct modulation	10 MHz
	Typical RIN	-150 dBc/Hz
	Threshold current	10 mA
	Conversion slope	0,14 W/A
	Emission linewidth spreading factor (α)	4,6
	Adiabatic chirp factor (k)	3,2 GHz/mW
EAM	Model	DFB-1550-EAM-12
	Operating voltage	-1 V
	Extinction ratio	14 dB
	Conversion slope	0,14 W/V
	Emission linewidth spreading factor (α)	1.0
	Adiabatic chirp factor (k)	0.0
pin-PD	Model	EM169
	Responsivity	0,9 A/W
	Dark current	100 nA
	Bandwidth	20 GHz
	Input optical power	≤3 mW
RF amplifier	Model	RLNA01M10GA
	RF operating bandwidth	0,01-10 GHz
	Gain	27 dB
	Noise factor	3.5 dB
FOC	Fiber model	SMF-28+
	Connector type	FC/APC
	Length	100 m
	Edge reflection	-70 dB

3.1. Unmodulated mode

In this mode, the RIN of the SLE is studied, which is the key TOU parameter (see Figure 1) that has the main effect on the SNR. The schematic of the measuring setup for carrying out the model experiment, including the analog SLE library model and the so-called galactic model of the RIN meter, containing an ideal ROU (see Figure 1) and a RF noise analyzer, is shown in Figure 2.

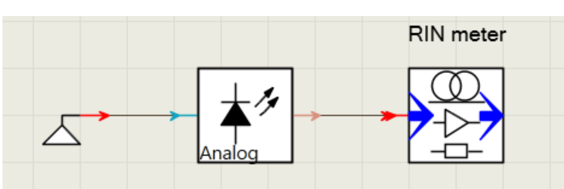

Figure 2. The setup for RIN measuring

3.2. Direct modulation

Schematic of the measuring setup for carrying out a model experiment is shown in Figure 3. The scheme includes a DFB laser's library model, an optical attenuator library model that simulates the attenuation in the FOC, and a ROU model containing library models of pin-PD and RF amplifier. In addition, library models of the RF generator (RFG), RF bandpass filters for signal and noise isolation in the 1-Hz bandwidth at a detuning of 20 MHz, as well as optical and RF spectrum analyzers (OSA and RFSA) are also shown in Figure 3.

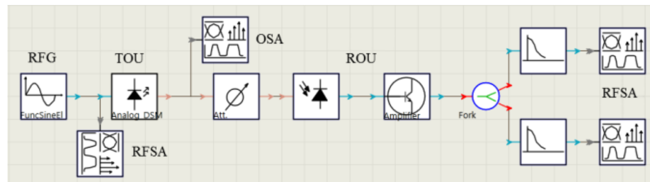

Figure 3. The setup for the DML's SNR measuring

3.3. External modulation

The schematic of the measuring setup for carrying out a model experiment referred to external modulation in TOU, which differs from the scheme of Figure 3 only the TOU configuration containing the DFB SLE and EAM (EA) library models, is shown in Figure 4.

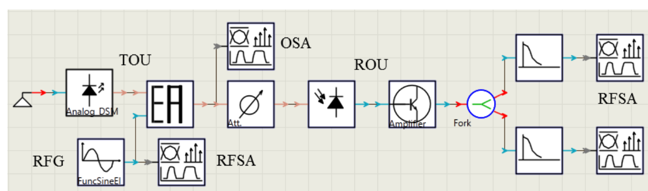

Figure 4. The setup for the EML's SNR measuring

4. Simulation Results

4.1. Unmodulated modes

The results of the model experiment using the reference data of Table 1 of the SLE model, are presented in Figure 5.

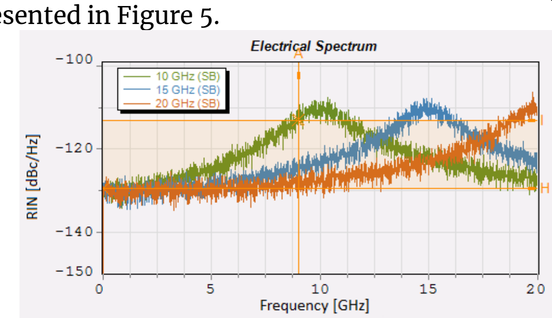

Figure 5. RIN vs offset frequencies from optical carrier 193.1 THz

The following outcomes can be drawn from the results obtained.

1) The RIN values at the lower and middle frequencies of the operating range of the SLE sample turned out to be at the level of -130 dBc/Hz (horizontal marker H),

which corresponds to the known data (Chang, 2003).

2) At the upper frequencies of the operating RF range, a significant increase in RIN is observed, the cause of which is the so-called electron-photon resonance that limits the frequency modulation characteristic of the SLE under test. Namely, at 9 GHz (vertical marker A), this increase is 18 dB (see the difference of horizontal markers I and H) at 10 GHz of SLE modulation bandwidth, 4 dB at 15 GHz, and less than 1 dB at 20 GHz. Therefore, in the unmodulated mode, in order to ensure that RIN does not increase over the entire operating RF range, it is necessary to use a SLE with a modulation bandwidth approximately two times wider, which will lead to an increase in the total cost of the fiber-optic ITL (see Section 2). Note that in the TOM with external modulation, the considered effect is completely absent.

4.2. Direct and external modulation

The results of a model experiment on measuring the SNR using the reference data of Table 1 are given in Table 2 for the direct modulation mode and in Table 3 for the external modulation mode.

Table 2. Output SNR for the direct modulation mode

Power of RF oscillator (dBm)	Power of output signal (dBm)	Power of output noise (dBm/Hz)	SNR (dB/Hz)
-10	-12	-100	88
0	-1,7	-100	98,3
3	1,2	-97	98,2
5	3,1	-87	91,1

Table 3. Output SNR for the external modulation mode

Power of RF oscillator (dBm)	Power of output signal (dBm)	Power of output noise (dBm/Hz)	SNR (dB/Hz)
-10	-14	-113	99
0	-4	-114,4	110,4
3	-1,3	-113,8	112,5
5	1,2	-112,4	113,6

The following outcomes can be drawn comparing the results in Tables 2 and 3.

1) When introduced into the ROU of Figure 1 of the same OEC and RF amplifier in both modes provides an approximately equal signal gain (the difference between the output signal power and the oscillator power), which is -2 dB for direct modulation and -4 dB for external modulation. The result obtained indicates approximately equal conversion efficiency of the both EOCs in setups of Figures 3 and 4.

2) However, in the case of direct modulation, significantly higher output noise powers are observed, increasing by 13 dB as the input signal power increases. On the contrary, with external modulation, their ascending Is only 0.6 dB. This effect led to a growth in the difference of SNRs for external and direct modulation in the EOC from 11 to 22.5 dB.

5. Conclusions

In the paper, with the goal to discover an optimal approach of designing a prospective analog fiber-optic interconnect line, the comparative computer simulation of the quality of transmission parameter is carried out using our multiyear roots to design in well-known commercial software VPI Photonics Design Suite (Belkin and Iakovlev 2015; Belkin, Iakovlev and Sigov, 2016; Belkin, Bakhvalova and Sigov 2019). For this purpose, a series of model experiments was realized to measure the laser's relative intensity noise and the output signal-to-noise ratio for cases where direct or external modulation by a radio frequency signal is used in the transceiving optoelectronic module. In the result of model experiment, it clearly follows from the comparison of data in Tables 2 and 3 that, both from a technical and economical point of view the best option for designing a transmitting optoelectronic unit of a fiber-optic interconnect transmission line under study is an option with external modulation using electroabsorption modulated laser. The main limitation of calculations in the VPI Photonics Design Suite software used is the ideality of models of optoelectronic elements operating in the microwave band, which significantly reduces the accuracy of modeling. In principle, we have shown that it can be improved by simulation in much more advanced microwave electronic software, such as Cadence AWRDE (Belkin, Bakhvalova, Golovin, Tyschuk, and Sigov, 2019). Following this, the direction of our future research on the topic of the paper is to use this software environment.

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