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A Thresholder for All-Optical Digitising Radio-over-Fibre Transceivers

Ricardo M. Ribeiro, Frédéric Lucarz and Bruno Fracasso

Abstract—**This paper describes an *optical Thresholder* (*o-Thresholder*) intended to be part of a transmitter module for future all-optical Digitising Radio-over-Fibre (*o-DRoF*) transceivers. The proposed device is based on an *Attenuation-Imbalanced Semiconductor Laser Amplifier Loop Mirror* (AI-SLALOM) in self-switching regime, using the nonlinearities of a semiconductor optical amplifier. Simulations of the proposed AI-SLALOM based *o-Thresholder* have shown promising results in comparison with the use of standard optical fibre and highly nonlinear fibre only. The newly proposed device is rather compact, optically integrable and requires much less input optical power than conventional devices (by several orders of magnitude). It provides enhanced optical RZ bits at 1550 nm wavelength window, 1.25 GHz repetition rate and 80 ps time-width.**

***Index Terms*—Analogue-digital conversion, Microwave Photonics, Optical Signal Processing, Semiconductor optical amplifiers.**

I. INTRODUCTION

ANALOGUE Radio-over-Fibre (ARoF) is a key-technology for the convergence of fibre-based wireline and wireless networks [1] and by means of which a large variety of mobile and wireless services including UMTS, LTE, Wi-Fi and WiMAX may be seamlessly delivered to customers. Merging RoF and FTTx (Fibre-To-The-x) technologies, namely FTTA (A = Antenna), is a promising approach to provide reliable mobile and wireless broadband access with a higher level of densification and enhanced network capacity. ARoF allows a relatively simple distribution of RF signals over an optical carrier along optical fibres connecting a Central Station (CS) to Base Stations (BSs) or Remote Antenna Units (RAUs). Therefore, all signal processing may be centrally carried out at the CS [1,2], leading to simple RAUs design that only needs to implement optoelectronic conversion and power amplification.

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However, ARoF systems are constrained by two basic requirements, which are inherent to analogue transmissions [1]: all used devices should be highly linear and the received signal should have higher SNR (Signal to Noise Ratio) when compared with digital systems. Since ARoF networks require high SNRs, their analogue nature limits the accepted fibre attenuation and the splitting ratio of optical signals, both critical in FTTH (H = Home) networks. Furthermore, the accelerated deployment of wireless networks operating at increased carrier frequencies up to ~ 100 GHz, leads to networks with naturally reduced coverage area per antenna.

In order to circumvent the limitations of ARoF networks, the use of digitised radio-over-fibre (DRoF) technologies [2,3] is an interesting alternative. In electronic DRoF links, the analogue RF input signal is first digitised by an analogue-to-digital converter (ADC). The generated electrical bits drive a light source thus generating optical bits then transported over optical fibre and finally reconstructed by a digital-to-analogue converter (DAC) at the output of a photo-detector. Each BS (or RAU) comprises one ADC and one DAC, while more complex digital signal processing is carried out in the CS [2]. Due to the digital nature of the optical link, the dynamic range is independent of the fibre length as long as the power of the received signal is lower than the link sensitivity. Electronic DRoF technologies still exhibit some advantages of ARoF [2,3] except for its relative higher complexity, but include further characteristics as follows: centralized digital signal processing such as digitisation itself, enhanced sharing capacity and better compatibility of digital equipments and communication channels, significant increase in transmission distance using optical fibre (larger dynamic range), larger coverage capacity or larger number of RAUs, possible cost reduction and energy saving.

The all-photonic signal conversion and processing are required due to the accelerated growth of demanded traffic reaching Exabyte per month. Therefore, high-speed processing and transmission are essential. Next-generation networks will face congestion in the backbone, metropolitan and access networks. Congestion in the backbone is due to the bottleneck of 3R processing (re-timing, re-shaping and re-amplifying) in the electronic domain. All these processes require optical/electrical (O/E) conversion that introduces complexities and delays. The switching and routing electronic process of the traffic in the backbone and metropolitan networks may also cause congestion. The use of all-optical switching and routing devices together with proper protocols

can significantly mitigate this problem. Therefore, by using all-photonic DRoF more operations and signal processing centralisation at the CS could be achieved. The main challenges in the electronic DRoF link implementation are: high-speed ADC and DAC, dispersions, nonlinearities (in the electrical and optical domains), additive noise, integration of system and devices, size and system cost.

An *o-DRoF* transmitter comprises an RF interface, an all-optical ADC and an enhancer/amplifier to significantly increase the optical-bit contrast. To the best of our knowledge, no complete experimental all-optical DRoF communication system has been reported in the literature. However, some recently published papers [3-6] from Brunel University (UK) report valuable theoretical simulations of an *o-DRoF* system but without any detailed description of the operational principles of both all-optical ADC and DAC.

In the present paper, the use of an AI-SLALOM configuration is proposed as a self-switched *o-Thresholder* circuit to be part of a future *o-DRoF* transceiver. Simulation results on VPI Transmission Maker ™ and comparisons of the proposed AI-SLALOM and Attenuation Imbalanced Nonlinear Optical Loop Mirrors (AI-NOLMs) using standard (SF) and highly nonlinear optical fibres (HNLFs) *o-Thresholder* configurations are presented for 1550 nm wavelength window, 1.25 GHz repetition rate with 80-ps RZ pulses. Because the proposed *o-Thresholder* uses a laser amplifier as the nonlinear optical element, their optical circuit may potentially perform additional signal processing, such as wavelength conversion and modulation format conversion [7,8]. The *o-DRoF* systems may well integrate the next generation of all-photonic telecommunication networks [3-6] and provide the connection between the access and metropolitan or even transport networks.

II. All-Optical Digitising Radio-over-Fibre (*o-DRoF*) Transmitter

This section proposes an *o-DRoF* transmitter able to receive and process ARoF signals that essentially comprises a photonic-ADC and a photonic-thresholder.

Electronic ADC and DAC boards seem to exhibit an intrinsic limitation in their stability, "bit resolution x input frequency" product and data conversion rates of up to a few tenths of GSa/s [3-6,9]. Besides, the vast majority of all-optical ADC and DAC systems have always been separately reported and for various types of applications, but excluding any communication link application.

Figure 1 depicts a typical and simplified transmitter module flowchart of an *o-DRoF* link [9,10].

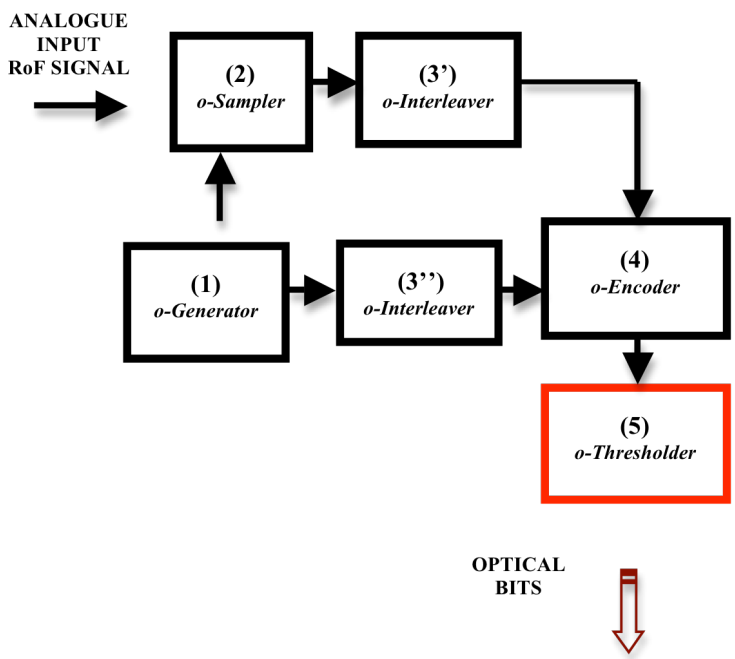


Fig. 1. The simplified flowchart of a complete *o-DRoF* transmitter. The *o-Thresholder* sub-module treated in this paper is numbered as (5).

The *o-DRoF* transmitter comprises at least five main optical sub-modules: (1) optical pulse generator (*o-Generator*), (2) optical sampler (*o-Sampler*), (3'and 3'') temporal interleavers (*o-Interleaver*), (4) encoder (*o-Encoder*) and (5) thresholder (*o-Thresholder*). The *o-Sampler* carries out the optical sampling of an input ARoF signal. It is driven by an optical pulse comb that is generated by the *o-Generator*. This pulse comb is also used as a reference clock signal by the *o-Encoder* that optically encodes the sampled signal, thereby accomplishing the photonic AD-conversion itself.

The *o-Thresholder* is provided mainly to enhance the contrast between the "0" and "1" optical bits at the output of the *o-Encoder*.

The *o-Generator* is preferably implemented by a mode-locked laser, a key component used to generate a series of

picosecond pulses at GHz rates with high temporal stability, i.e. with very low jitter in the femtosecond time-scale [9,10] so that these pulses can be used as the clock signal for the optical sampling and coding. The *o-Interleavers* essentially multiply the repetition rate of the clock signal generated by the *o-Generator*.

III. Modelling and Simulations of the *o-Thresholder*

Sagnac interferometric fibre rings have been used as a nonlinear device based on self-phase modulation (SPM) or cross-phase modulation (XPM) – NOLMs – that are very useful for many ultrafast signal-processing applications [11]. The use of a laser amplifier as a nonlinear medium instead of the optical fibre leads to an interesting class of devices usually named as SLALOM [12] or Terahertz Optical Asymmetric Demultiplexer (TOAD) [13].

Three different optical circuits of the *o-Thresholder* were designed and simulated using VPI Transmission Maker^{TM}. All circuits were probed at 1550 nm wavelength window with 1.25 GHz repetition rate, 80 ps time-width RZ pulse stream. The peak power of the input pulses (P_{input}) could be varied from 10 μW to 10 W in order to obtain the transfer functions – the P_{output} /P_{input} curves – for the three optical circuits.

The input pulses at 1553.6 nm wavelength were generated from a continuous-wave laser diode with null linewidth after traversing a Mach-Zehnder modulator (MZM). The MZM is biased at the quadrature point and is driven by 2.5 Gb/s RZ electrical pulses in an alternate pattern with 0.1 duty-cycle.

The optical circuits are attenuation-imbalanced Sagnac interferometers instead of using fibre-couplers with coupled-ratio ≠ 50:50 thus allowing a maximum interference visibility contrast. The insertion of an attenuator (passive component) in the Sagnac fibre ring provides the necessary differential phase-shift between the clockwise (CW) and counter-clockwise pulses (CCW). The polarisations of the CW and CCW pulses are assumed to be always aligned. Such a condition can be achieved in practice by using polarisation controllers in the optical circuits or by using polarisation-maintaining fibres.

Figure 2a depicts a *first design* of the *o-Thresholder* with an optical circuit using a NOLM with standard fibre. Table I shows the optical fibre parameters as used in the simulations. The A_{eff} is the effective area of the fibre. The physical model solves the nonlinear Schrödinger equation (NLSE) taking into account the SPM and XPM in the single-mode fibre [14].

The 10 dB attenuator breaks the reciprocity of the Sagnac ring thus CW and CCW pulses accumulate a Δϕ differential phase-shift. Therefore, the Δϕ parameter determines the relative amount of reflected (Pr) and transmitted (Pt) power.

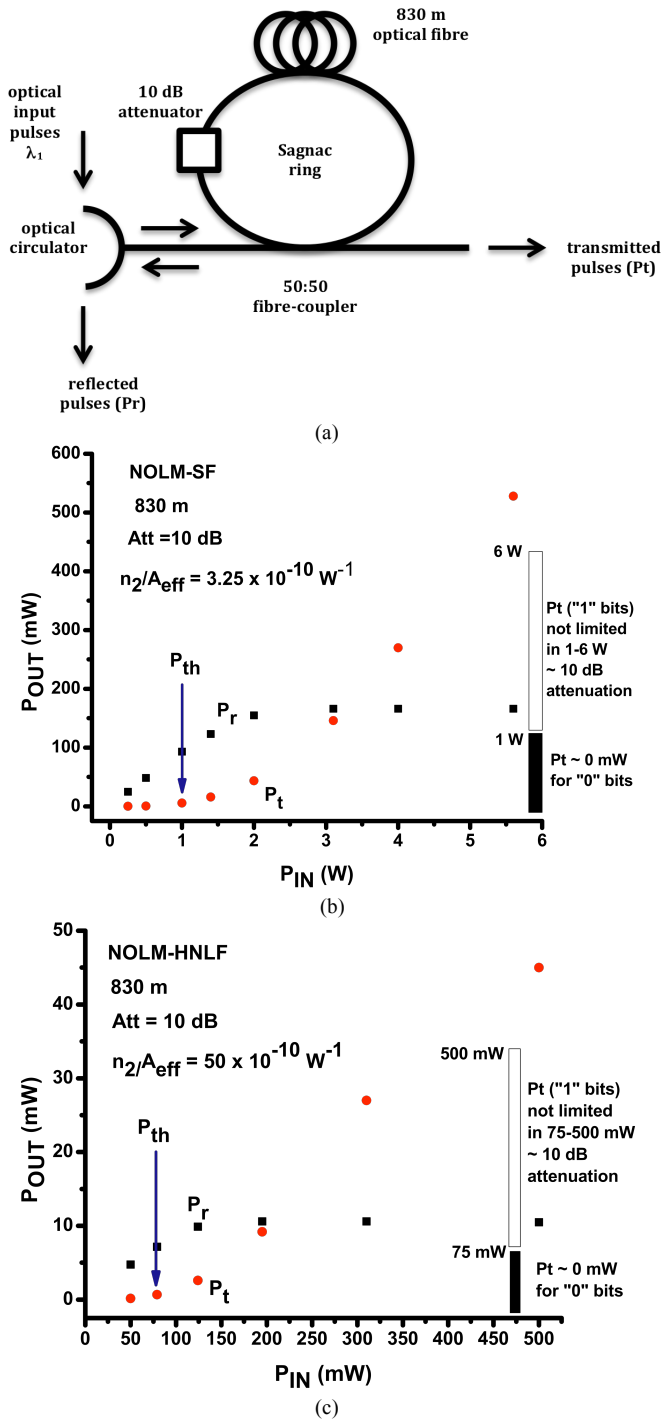


Fig. 2. (a) The optical circuit of the *o-Thresholder* based on NOLM-SF (according to the *first design*) or NOLM-HNLF (according to the *second design*), (b) the transfer function of the NOLM-SF and the (c) NOLM-HNLF configuration as a result from simulations.

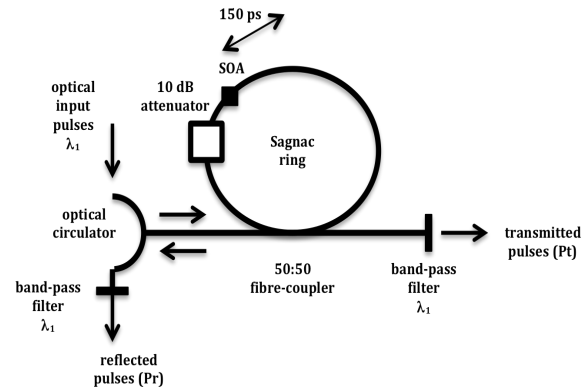
TABLE I
SIMULATION PARAMETERS OF SOA AND FIBRES

Parameter	AI-T-NOLM-SF	AI-T-NOLM -HNLF	AI-T-SLALOM
Dimensions	830 m length A_{eff} = 80 μm²	830 m length A_{eff} = 12 μm²	1 mm length 2.5 x 0.2 μm
Attenuation	0.25 dB/km	0.668 dB/km	3000 m⁻¹
Dispersion	16.0 ps/nm.km	0.0 ps/nm.km	---
Optical Nonlinearity	3.25x10⁻¹⁰ W⁻¹	50.00x10⁻¹⁰ W⁻¹	---
Recovery Time	10-100's fs	10-100's fs	60 ps
Confinement Factor	---	---	0.35
Facets Reflectivities	---	---	0.0
Linear Gain Coefficient	---	---	30x10⁻²¹ m²
Nonlinear Gain Coefficient	---	---	10⁻²³ m³
Nonlinear Gain Time Constant	---	---	0.5 ps
Linewidth Enhancement Factor	---	---	6.0

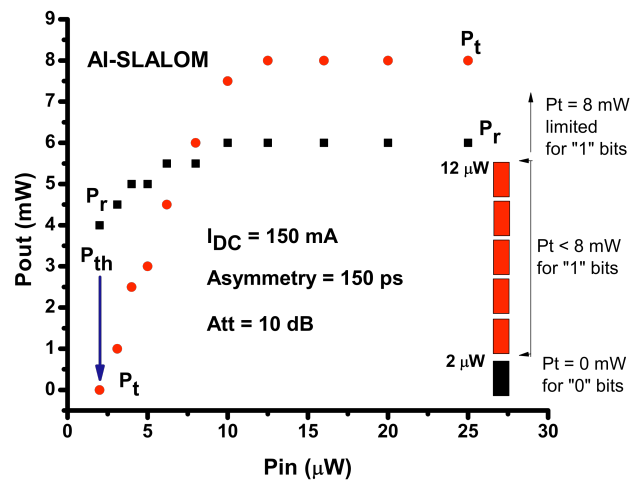
Figure 2b shows the result of the transfer function simulations according to the *first design* (see Figure 2a). All pulses up to ~1 W peak power are reflected, i.e. the "0" bits with almost zero power are transmitted. A least from 1 W to 6 W input, the power of the transmitted "1" bits are not really limited. As expected, despite the P_{IN} input power, the Pr + Pt power sum is 10 dB attenuated. For this *first design* the threshold power Pth of the AI-NOLM-SF may be set at 1 W.

According to a *second design*, the topology of the NOLM-HNLF optical circuit was exactly the same as shown in Figure 2a, with the exception that now the fibre is Dispersion-Shifted Fibre (DSF) [9]. Table I shows the optical fibre parameters as used in the simulations where the optical nonlinearity of the HNLF is 50/3.25 ~15 times higher than that of the SF. Figure 2c shows the result of the simulations obtained with the *second design*. All pulses up to 75 mW peak power are reflected, i.e. the "0" bits with almost zero power are transmitted. A least from 75 to 500 mW input peak power, the output power of the transmitted "1" bits are not really limited. As again expected, despite the P_{IN} input power, the Pr + Pt power sum is 10 dB attenuated. For this *second design* the threshold power of the AI-NOLM-HNLF may be set at Pth = 75 mW. In these first two designs, the switching mechanism is driven by the SPM effect occurring into the optical fibre [11,14].

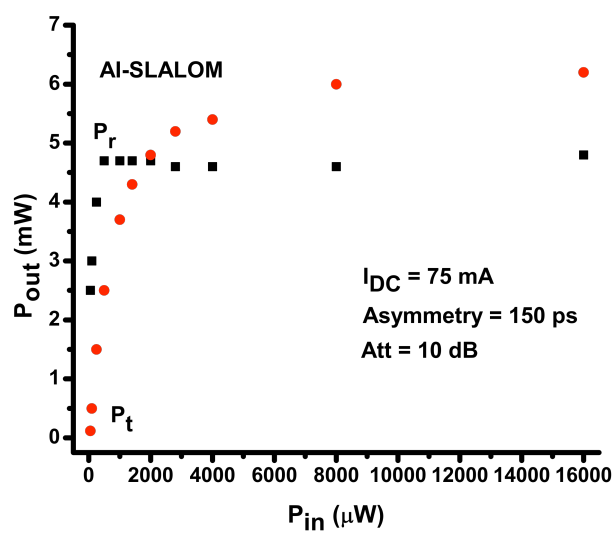
Figure 3a depicts a *third design* of the *o-Thresholder* based now on an AI-SLALOM optical circuit using a SOA as the nonlinear optical element instead of an optical fibre. The physical model takes into account a bulk SOA with low feedback neglecting the polarisation effects (isotropic model) and uses the Transmission Line Model (TLM) to compute the differential nonlinear phase-shift induced by a change in carrier density in the semiconductor. In this way, the switching is again driven by the SPM effect now occurring into the SOA. Table I shows the SOA parameters as used in the computer simulations.



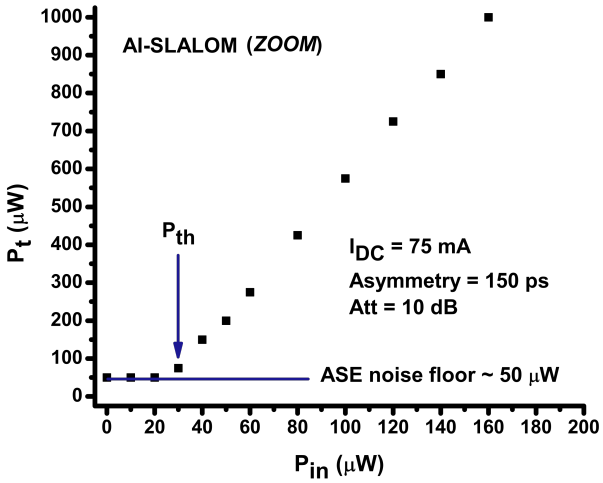
(a)



(b)



(c)



(d)

Fig. 3. (a) The optical circuit of the AI-SLALOM based *o-Thresholder* (according to the *third design*), the transfer function as a result from simulations (b) with I_{DC} = 150 mA and (c) I_{DC} = 75 mA bias current, and the *zoom* of the transfer function at low input power (from Fig. (c)).

The asymmetric placement of the SOA at 150 ps from the mid-point of the fibre ring ensures that the gain is completely recovered for either the CW or CCW pulses. This limits the speed of the device as explained in the "Conclusions". The optical circulator allows the separation between the input and reflected pulses. The band-pass filters reduce the Amplified Spontaneous Emission (ASE) generated by the SOA and detected by the analysers. The centre frequency and spectral width of the filters are set to be 1553.6 nm and 100 GHz (0.8 nm), respectively.

Figure 3b shows the simulation results obtained for the *third design* (see Figure 3a) with a bias current set to I_{DC} = 150 mA. All pulses with a peak power of up to 2 μW are reflected, i.e. the "0" bits with almost zero power are transmitted. In the 2-10 μW range is observed a fast transition from ~ 0 to 8 mW output power. For input optical pulses with a peak power greater than 10 μW, the output power of the transmitted "1" bits are now limited at 8 mW. Therefore, the transmitted (and also the reflected) pulses are now optically amplified/limited. For this *third design* with I_{DC} = 150 mA, the threshold power may be set at Pth = 2 μW.

Figure 3c shows the simulation results obtained for the *third design* (see Figure 3a) with a bias current set to I_{DC} = 75 mA. Figure 3d is the *zoom* of Figure 3c at low input powers. All pulses with peak power of up to Pth = 30 μW are essentially reflected because only noisy signals are calculated, even for Pin = 0 μW. This may be due to ASE noise combined with numerical artefacts. Therefore, the "0" bits with almost zero power are transmitted. In the 30 μW - 6 mW input power range is observed a non-abrupt transition presenting output gain. For input optical pulses with a peak power greater than 8 mW, the output power of the transmitted "1" bits are now limited at 6 mW (negative gain). Therefore, the transmitted (and also the reflected) pulses are optically amplified and/or limited. For this *third design* with I_{DC} = 75 mA, the threshold power may be set at Pth = 30 μW. As expected, the amplifier gain is reduced because the bias current is also reduced. However, the ASE power level is also significantly reduced. It is also shown that it is possible to easily tune the threshold power of the *o-Thresholder* from 2 μW to 30 μW.

Comparing the three designs of *o-Thresholders*, the use of HNLF instead of SF requires over 11 dB less input power. The use of SOA instead of HNLF requires less than 30 dB input power to obtain the switching. Furthermore, the SOA is only 1-mm long while the HNLF is 830 m in length. The results with SOA are in agreement with a similar work [15]. For fibre lengths greater than a few hundred meters, the stability of the NOLM is significantly degraded. Furthermore, the long fibre introduces excessive latency for some optical processing applications [16]. By comparing the active length and threshold power between the AI-SLALOM and the AI-HNLF configurations, i.e. by setting $(\Delta\phi)_{AI\text{-}SLALOM} = (\Delta\phi)_{AI\text{-}HNLF}$, it is easy to estimate an optical nonlinearity (n_2) of ~ 5 x 10^{10} times greater when a semiconductor laser amplifier is used as a nonlinear optical element instead of a DSF-fibre. D. Cotter *et al* have described the implementation of a SLALOM circuit on a single 1x2 mm InP semiconductor chip [16] that demonstrates the possibility of optical integration of the proposed *o-DRoF* transmitter.

Figure 4 shows an example of application of the AI-SLALOM based *o-Thresholder* with the SOA set at I_{DC} = 75 mA bias current, useful for an *o-DRoF* transmitter.

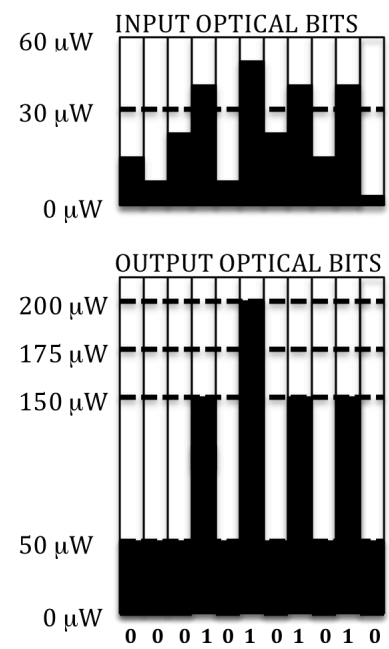


Fig. 4. An example of application of the 1-stage AI-SLALOM based *o-Thresholder* that is useful for an *o-DRoF* transmitter.

After the simulation of Figure 3c and 3d using an AI-SLALOM biased at I_{DC} = 75 mA, the threshold power of 30 μW at 50 % (or the corresponding threshold voltage level) may be a *conservative* choice for the decision circuit of a digital receiver. The example of Figure 4 shows a "00010101010" poor quality input bits sequence assumed to be generated by the *o-Encoder*. After traversing 1-stage *o-*

Thresholder, the output optical bits are fairly enhanced, i.e. the "0" bits present 50 μW maximum output power whereas the "1" bits are all amplified to reach (175 ± 25) μW peak power. Using 4-stage *o-Thresholders* with alternated 3-dB attenuators, it is now possible to achieve "0" bits presenting 50 μW maximum output power whereas the "1" bits are all amplified to reach (3.1 ± 0.1) mW peak power, i.e. a highly improved limitation. Of course, a better design of the *o-Thresholder* shall enable the use of 1 or 2 circuit stages only.

Alternatively, the transmission port of a first AI-SLALOM biased at I_{DC} = 75 mA may be followed by an ~17 dB optical attenuator in turn connected to the input port of a second AI-SLALOM biased at I_{DC} = 150 mA (or 75 mA < I_{DC} < 150 mA) presenting a threshold power of 2 μW or (2 μW P_{th} < 30 μW) (or the corresponding threshold voltage level). The previous optical circuit comprising 2-stage AI-SLALOMs allows that the transmission output could be almost perfect "0" bits (null optical power) and "1" bits with 1.0 – 2.5 mW optical power.

IV. Conclusions

To the best of our knowledge, neither experimental nor commercially available *o-DRoF* links or networks have been reported as they are still under R&D stage. This paper proposes a system comprising five optical sub-modules for use in an *o-DRoF* transmitter link. The present paper only described the back-end sub-module of the *o-DRoF* transmitter, i.e. the AI-SLALOM based *o-Thresholder* in a self-controlled (or self-switched) regime operating at 1550 nm wavelength window. The proposed AI-SLALOM configuration when compared with the AI-HNLF [9] may provide some advantages: compactness, prone to optical integration, requirement of ~10^3 less optical power and automatically amplified output optical bits. Mainly to demonstrate the *proof-of-principle*, in this paper the simulations were constrained to only 1.25 GHz & 80-ps RZ input pulses. However, SOAs operating at 80 Gb/s are already commercially available. Furthermore, SOAs in R&D stage able to operate up to 160 Gb/s [17] and beyond were already reported. The newly proposed *o-Thresholder* is intended to significantly enhance the contrast of digitised signals (optical bits) exiting an *o-Encoder* thus improving the Bit-Error Rate (BER) and also providing optical amplification eventually dispensing the use of Erbium-Doped Fibre Amplifier (EDFAs) in a fibre link transmission.

Further simulations (and laboratory experiments) of the *o-Thresholder* and the other sub-modules of the *o-DRoF* transmitter are currently planned or in progress and will be presented in a near future. Examples of scheduled device simulation improvements to be carried out include: operation at higher pulse rate (> 1.25 GHz) with shorter timewidth (< 80-ps), smaller asymmetry (< 150 ps) of the SOA placement in the Sagnac fibre ring in order to speed the operation [12], to tune the threshold power and to obtain a steeper transition region, *etc*.

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