Design of an Analogiser for Optically digitised Radio-over-Fibre Signals

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Abstract—**This paper discloses an Analogiser able to carry out digital to analogue conversion of the optically digitised Radio-over-Fibre signals. The Analogiser comprises many interconnected optical circuits based on the Sagnac interferometric rings with an inserted semiconductor optical amplifier. Numerical simulation results are shown for 2.5 GHz sampling rate and 4-bit resolution. The designed circuits are compact, thus enabling optical integration and require optical peak power control in the ~mW range.**

Keywords—Digital-Analogue Conversion, Microwave-Photonics, Optical Signal Processing, Semiconductor Optical Amplifier.

I. INTRODUCTION

The Radio-over-Fibre (RoF) technology in it classical analogue format (ARoF) have been regarded very useful for the wired and wireless network convergence [1]. ARoF technology is relatively simple. An RF carrier containing digital modulation *directly* modulates an optical source. However, the classical ARoF technology presents some limitations: limited dynamic range and high linearity requirements [1].

It was recently shown the digitisation of RoF networks using electronic analogue-to-digital (e-ADC) and digital-to-analogue (e-DAC) fast boards [2,3] that have been evolved along the time [4,5]. However, such converters exhibits some intrinsic limitations related to its electronic nature: receiver frequency x bit resolution product and sampling rate limitations [4-6].

On the other side, optical ADCs (o-ADC) and few optical DAC (o-DAC) [4] have been developed since the 70's. o-ADCs have been intended to be applied in satellite optical links, radar technology and electronic dispersion compensation [4,5]. It should be observed that o-ADCs and o-DACs deliver electrical bits or analogue signals, respectively. Some very interesting works were published by a team from Brunel University (UK) showing numerical simulations of RoF networks under general photonic digitisation, i.e. without details on the operation mechanism of the o-ADC and o-DAC [6]. The present authors have being publishing works dealing with digitisation of RoF signals, i.e. an o-ADC denoted as *o-DRoF-T* intended for fibre-optic communications purposes [7-10].

The *o-DRoF* may also be useful in other applications as HDTV transmission using an optical fibre. The paper [11] reports the requirement of 1.5 Gb/s rate for transmission of a single non-compressed HD-SDI channel. Some applications require the broadcast of multiple channels and then an RF carrier of frequency higher than 100 GHz turn to be needed. Figure 1 of [11] shows a possible *o-DRoF* application at least from the "relay point" to the "TV-station" that are connected to each other by means of an optical fibre.

The present paper describes the conception, design and numerical simulations using the *VPI Transmission Maker*^{TM} platform of a digital receiver able to all-photonically carried out the DAC (*Analogiser*) of RoF signals previously photonically digitised at 4-bit resolution. The *Analogiser* is based on Sagnac loops incorporating semiconductor optical amplifiers (SOAs) operating under few GHz sampled rate intended to be a *proof-of-principle*.

II. THE TRANSMITTER (*O-DROF-T*) AND THE DIGITISED STREAM

The *o-DRoF-T* conception, design, numerical simulations and some experiments were published elsewere [7-10]. It is composed by some suitably interconnected circuit modules based on Sagnac-loop incorporating a SOA. Regarding the *o-DRoF-T* as a "black-box", the input signal is an optical analogue time-domain waveform and the output is a digital Return-to-Zero (RZ) Gray code optical bits [9]. The Gray code is usually used because it reduces the error rate in ADCs and DACs [12].

For each sampled pulse generated from the input analogue waveform, N pulses are generated

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in each frame where N means the bit resolution. The "1" bits are equalized in amplitude and the residual power of "0" bits is reduced.

III. THE ANALOGISER CIRCUIT

The basic optical circuit scheme that forms the *Analogiser* is shown in Figure 1. It is the Sagnac loop interferometric structure using an inserted SOA as to be the nonlinear optical element. It works like a *Terahertz Optical Asymmetric Demultiplexer* (TOAD) [13].

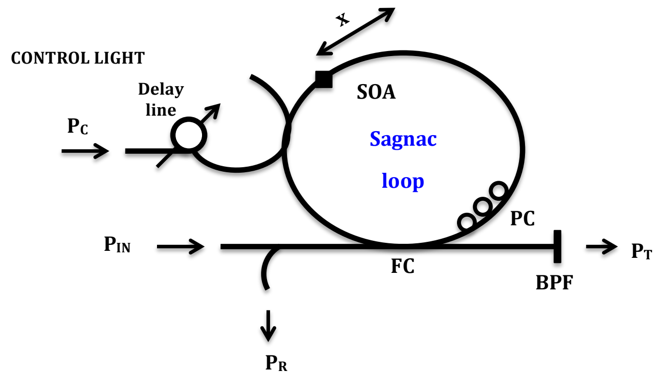

Fig. 1. Basic optical circuit (TOAD) that forms the *Analogiser*.

P_{IN} and P_C are the peak power of the (probe) input and control light pulses, respectively. P_C can control the switch between the reflected P_R and transmitted P_T pulses by means of cross-phase modulation (XPM) [8,9,13] provided by the SOA. The delay line allow the sinchronization between the control and probe pulses. The polarisation controller PC allow the setting of power levels P_R and P_T when P_C = 0 mW. The asymmetry "x" in SOA insertion is needed in order to open a "switching window" thus leading it to switch [13]. The distance of the SOA to the center of the Sagnac loop (Δx) is a critical parameter of the TOAD performance. There is no transmitted pulse if there are no input and/or control pulses. Therefore, a demultiplexer based on a Sagnac loop behaves like an AND gate logical processor in the optical domain. The band-pass filter (BPF) can block the ASE light generated by the SOA. The present simulations uses a SOA with ~1 ns recovery time. Depending on the recovery time, the steady state carrier density is almost or totally restored in the SOA before the arrival of the next control pulse.

Figure 2 shows the flowchart of the *Analogiser* built from circuits shown in Figure 1. As is shown by Figure 3, the input signal consists of temporally serialized RZ-formatted optical bits in the Gray code at Nf_S bits/s rate where f_S represents the sampling rate determined by the sampling module of the *o-DRoF-T* [8]. The input signal is structured in frames each containing N bits. Figure 3 illustrates a N = 4 bits pattern as the input to be processed by the *Analogiser*.

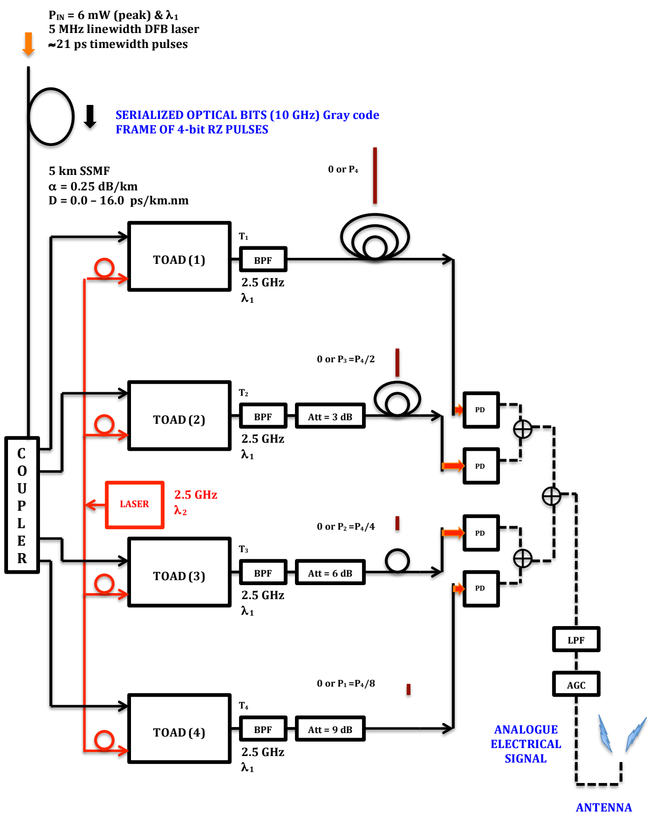

Fig. 2. Optical circuit diagram of the 4-bit resolution *Analogiser*.

Assuming an *Analogiser* of 4-bit resolution, one frame will present 4 pulses or absences (bits) with powers $P_i = 2P_{(i-1)}$ for the "i" pulse that is the digital word. Of course it is expected degradation due to fibre propagation.

In a first layer, the optical bits traverse a 1x4 splitter and 4 identical copies are generated. The second circuit layer is built from TOADs [13] to sequentially demultiplex the bits in the time domain, i.e. each of 4 signals traverses the TOADs thus parallelizing the bits. The first TOAD receive the RZ-bits, demultiplex the first channel of the N frame (N=4) through the transmitted port "T_1" and the remaining bits are reflected from "R_1" port and are discarded. Reference [14] shows the use of an NOLM for demultiplexing where the reflected pulses exit with the same amplitude. This is because there are no pattern effect [15]. The process can be extended up to the $TOAD_N$. In this way, the second layer generates a number N of bit trains at f_S bit/s rate, i.e. optical bits parallelization. Only one mode-locked laser is needed to control the TOADs, since the delay lines are correctly adjusted in order to put each control/probe pulse (or absence) in time coincidence. In the third layer, the delay lines should be adjusted in such way that the transmitted pulses are summed in the same time-slot for each of the pulses contained inside the original frame.

The fourth layer is designed to weighting the amplitude of each pulse. This process was carried out by adjusting the attenuation in optical output of the each branch as to be 0, 3, 6 and 9 dB. In the fifth layer, each parallelized bit train is photo-detected and in present stage of design the summings were carried out electronically thus avoiding optical interference artifacts.

The electronic output of the *Analogiser* Just after the summation should be an envelope of pulses similar that it was generated by the *o-Sampler* [8]. It traverses a low-pass filter to recover the original waveform in the electrical domain is amplified and radiated by means of an antenna.

IV. RESULTS AND DISCUSSIONS

Numerical simulations were carried out by first generating each one of the 16 possible 4-bit frames at 4 x 2.5 GHz = 10 GHz (or 20 Gbit/s) maximum. Figure 3 shows the time waveforms of three possible optical inputs: 1111, 0010 and 0001 digital sequences. The 4-bit frame is assigned.

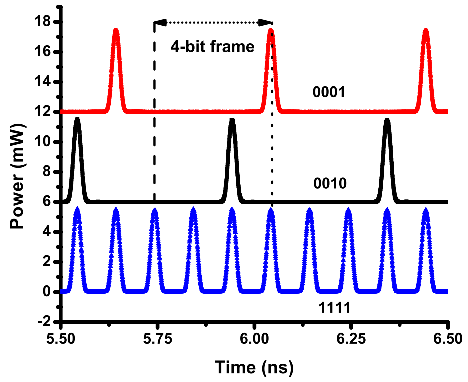

Fig. 3. Time waveforms of 1111, 0010 and 0001 optical input digital sequences.

Figure 4 shows waveforms of the 1111 optical input, the control pulses at 2.5 GHz and the demultiplexed pulses by $TOAD_1$ with 164 ps delay time assuming *none* chromatic dispersion (0 ps/km.nm). The 0.15 duty-cycle RZ at 5.0 Gb/s or 2.5 GHz control pulses are launched in the TOADs as is shown in Figure 1. The wavelength of the control pulses was 1545.99 nm with 23.5 mW peak power. The wavelength of the probe pulses was 1562.09 nm. Both wavelengths and peak power were used for without and with chromatic dispersion.

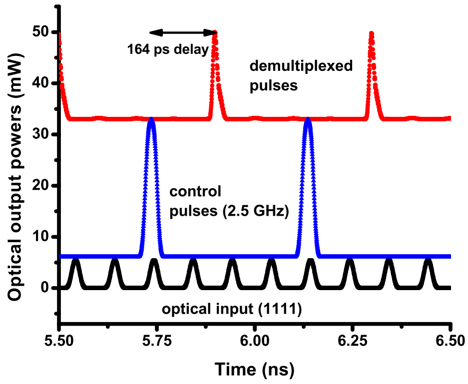

Fig. 4. Time waveforms of 1111 optical input, 2.5 GHz control and demultiplexed pulses by $TOAD_1$.

Figure 5 shows the time waveforms of three possible electrical outputs: 1111, 0010 and 0001 digital sequences, by assuming *none* chromatic dispersion in 5 km fibre link. The amplitude of each waveform is the weighted sum of the corresponding bit-frame.

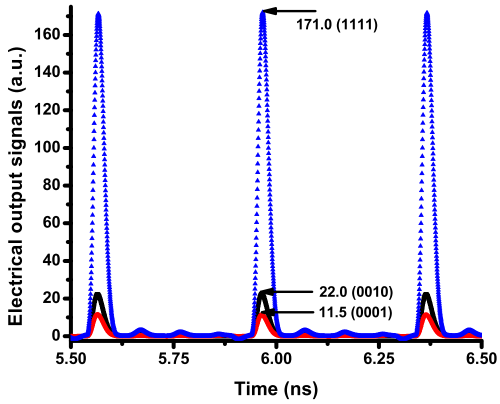

Fig. 5. Time waveforms of 1111, 0010 and 0001 weighted summing electrical output signals.

The reflected signal (not shown here) by each TOAD has shown the *pattern effect*, i.e. the reflected pulses are amplitude modulated. This is because the adopted SOA model presents a long recovery time (0.5 ns – 1.4 ns, depending on the bias current). One assumes ≈ 1 ns recovery time since relatively low bias current (< 100 mA) on the SOA was used.

Testing the sums of the "1000", "0001", "0010" and "0000" digital sequences without chromatic dispersion, the summing result is the same up to 30 dB attenuation for the "0" bits relative to 6 mW peak power of the "1" bits.

Now is taking into account the *full* chromatic dispersion of SSMF link (5 x 16.0 = 80.0 ps/km.nm) and the 0.25 dB/km attenuation. For *null* and *full* chromatic dispersion it were required delays of 253.0 ps and 775.8 ps between control and signal pulses for each TOAD, respectively.

Figure 6 shows the plot of the 1111 digital sequence waveform probe signal at 10 GHz exiting the *o-DRoF-T* and just after propagation along the fibre. The later is the signal input of the *Analogiser*. The pulses before and after fibre propagation present 21 ps and 24 ps timewidth, respectively.

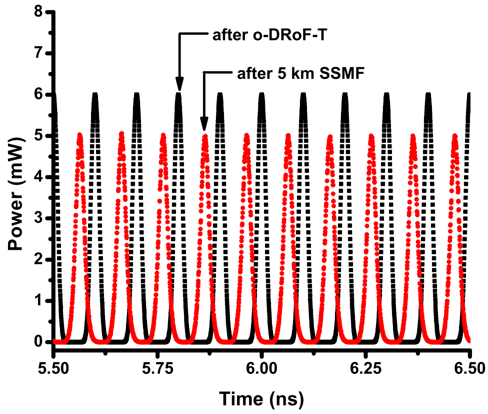

Fig. 6. Time waveforms of 1111 digital sequence in the output of the *o-DRoF* and after propagation along 5 km SSMF with 16 ps/km.nm dispersion and 0.25 dB/km attenuation.

The demultiplexed pulses from TOADs and the electrical signals outputs regarding *full* chromatic dispersion are quite similar of those calculated for *null* dispersion (see Figures 4 and 5).

Figure 7 essentially shows the same 4-bit resolution linear dependence of digital-to-analogue conversion for both SSMF link presenting *null* and *full* chromatic dispersion.

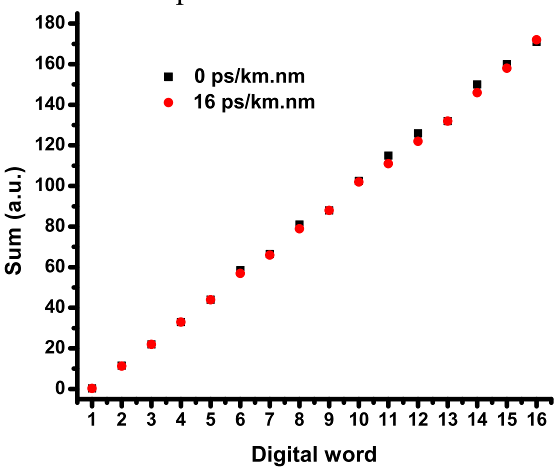

Fig. 7. The linear dependence of 4-bit resolution digital-to-analogue conversion at 2.5 GHz sampling rate regardind null and full SSMF link chomatic dispersion.

In the horizontal axis of Figure 7, the digital word "1" means "0000", "2" means "0001",…. and "16" means "1111" sequences.

V. Conclusions

It was numerically shown the *proof-of-principle* of a relatively simple design of an *Analogiser* intended to be an all-optical DAC for a Telecommunication link. Calculations have shown that the systems can withstand against chromatic dispersion, at least for 5 km SSMF link and assuming 5 MHz linewidth of the probe laser pulses. The *Analogiser* can work since the correct N-bit frame is generated by the *Digitiser* (*o-DRoF-T*). The proposed device is built from chained TOAD-based optical circuits prone to be optically integrated in a photonic chip with compact footprint requiring low optical control power pulses [16,17]. Because none optical fibre is used as the nonlinear element, the *Analogiser* present low latency, dispersion and walk-off between control and probe pulses, thus management between such pulses are not required [18].

The analogue signal envelope that outputs the *Analogiser* may be transmitted along an ARoF network and in their extremity the signal should be photo-detected, traverses a low-pass filter to recover the original waveform in the electrical domain, can be amplified and radiated as a wireless signal by means of an antenna. Alternativelly, the Gray-coded serialised optical bits may be detected and demodulated by a suitable digital receiver thus leading an optical-DAC with long distance fibre transmission.

Further designs and numerical simulations in order to optimise the optical circuits of the *Analogiser* and to include all-optical bit regeneration are ongoing while experiments are scheduled to be carried out.

Acknowledgements

Ricardo M. Ribeiro thanks the team at Département d'Optique of Telecom Bretagne and the CapilR^{TM} platform for hosting his Post-Doctoral study during which the present work was carried out. The authors also thank INCT-Fotonicom/CNPq.

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