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# Electrical Modulation of a Semiconductor Optical Amplifier Inserted into a Sagnac Loop by Injecting Microwave Carrier

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**Abstract**—This paper describes for the first time, the design and numerical simulations of an optical modulator from a semiconductor optical amplifier (SOA) inserted into a fibre-optic Sagnac loop electrically modulated by a microwave carrier at 20 GHz frequency and higher. Even though the adopted SOA model presents  $> 1.4$  ns gain recovery time, the device is optically modulated up to 30 GHz because a completely gain recovery is not needed. The interferometric device was shown to present better performance than the solely SOA. It is potentially useful to simultaneously carry out optical modulation, sampling and mixing or to be used simultaneously as a modulator (uplink) and amplifier (downlink) in analogue links.

**Keywords**—optical modulator; optical signal processing; Microwave-Photonics; semiconductor optical amplifier; radio-over-fibre

## I. INTRODUCTION

Radio-over-Fibre (RoF) technology enables the fusion of fibre-optic and wireless communications networks [1-3]. Classical RoF systems are relatively simple and very powerful. In the transmission end, signals at microwave carrier frequencies analogically modulate an optical source (ARoF) and the generated light signal is transmitted through an optical fibre. Reciprocally, in the receiver end, a photo-detector recovers the original analogue signal that modulates the optical carrier [1-3]. An arbitrary wireless signal in either standard is seamless despite the use of optical fibres. Because of the intrinsic nature of analogue transmission systems, ARoF links and networks feature limited dynamic range [1-3]. Furthermore, ARoF systems are more difficult to integrate with the conventional digital networks [2].

Although the high-frequency electrical modulation of SOAs is not new [4], it is not as usual when compared with the SOA used as an amplifier or optical signal processor fed only by a DC bias current.

The electronic digitisation of ARoF links and networks using fast AD and DA converters [5] have being gaining interest from Telecommunications carriers [6]. The digitised ARoF (DRoF system) may extend the coverage, increase the

system bandwidth together with a higher degree of capillarisation and enables a higher number of access points, improves the signal quality and energy saving when compared with the classical ARoF [2,5,6].

An advanced, interesting and underexplored issue is the all-optical digitising of ARoF links and networks (o-DRoF), i.e. all-optical ADC (transmitter) and DAC (receiver) both intended to process RoF signals, which the authors has been working [2,7-11]. Furthermore, in the best of our acknowledgement, there are none commercially available o-DRoF systems. Such all-optical approach does not require signal demodulation. Since multi-GHz sampling rates are offered by pulse train produced by stable mode-locked lasers, it may eliminate or reduce the number of mixer-stages (intermediary frequencies – IFs) that are needed to down-convert high frequency signals before digitisation and enables optical sampling with  $\leq 10$  fs timing jitter [12].

Previously [7-11], the authors described an o-DRoF system able to process analogue signals already in the optical domain. This paper proposes, designs and carry out numerical simulations using the *VPI Transmission Maker<sup>TM</sup>* platform of an interferometric front-end device able to directly receive microwave carriers. It is intended to be simultaneously an amplifier and broadband optical modulator regarding an ARoF network. Furthermore, the device may be simultaneously an optical modulator, optical sampling [8] & mixing [13,14] as to be the transmitter device of a future complete o-DRoF link. However, *only* the *proof-of-principle* operation of the ARoF generator (optical modulator) is here described. It is based on the optical switching provided by a Sagnac loop with an in-line inserted SOA [15] with a long recovery-time. Comparison of performance is carried out with a solely SOA-based device. Interestingly, the electrical modulation of SOAs may be classified as an intermediary kind between the “direct modulation” of LDs and LEDs and “external modulation” of electro-optic and electro-absorption modulators.

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## II. THE OPTICAL CIRCUITS & PRINCIPLE

Two optical circuits were designed and numerically simulated using the bulk model of SOA with  $L_{\text{SOA}} = 500 \mu\text{m}$  and alpha-factor  $\alpha = 6$  [16].

The *Circuit #1* is schematically shown in Fig.1. It uses a single SOA and as result the modulation is achieved by means of the gain modulation driven by the injected microwave carrier in a non-interferometric configuration. The *Circuit #2* is schematically shown in Fig.2. It uses a SOA inserted into a Sagnac loop and as a result the optical modulation is achieved by means of the gain and phase modulation simultaneously also driven by the injected microwave carrier now in an interferometric configuration. Comparisons between the performances of both circuits are outlined ahead. In both schemes, a microwave carrier generator replaces a microwave receiver antenna.

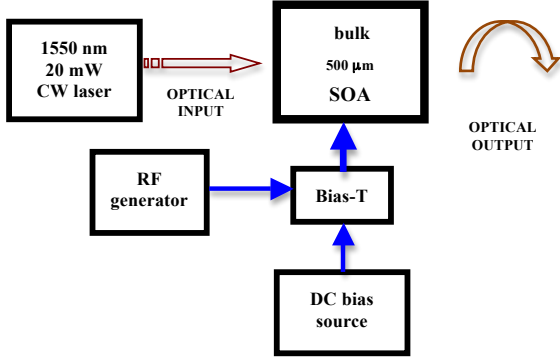


Fig. 1. Optical circuit diagram #1 of an optical modulator based only on an electrically driven SOA.

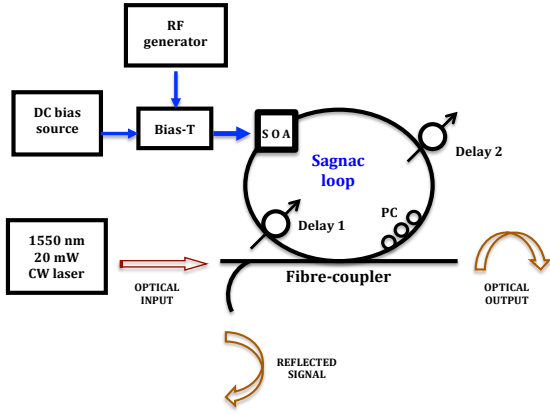


Fig. 2. Optical circuit diagram #2 of an interferometric optical modulator based on a Sagnac loop incorporating an electrically driven SOA.

The 1550 nm wavelength CW (unmodulated) light signal  $P_{\text{in}} = 20 \text{ mW}$  power to be modulated is launched into the single SOA or the Sagnac loop + SOA. In both circuits, the microwave carrier at  $f_{\text{RF}}$  frequency and  $I_{\text{RF}}$  current amplitude to be transmitted along the optical fibre is launched into the SOA superimposed with a bias current  $I_{\text{bias}}$  by means a bias-T. The composite signal is injected through the electrical port of the SOA. The SOA works as a one-travelling optical amplifier enhancing the energy of the switched light. In this way, the

launched optical signal is gain-modulated in the *Circuit #1* and gain + phase-modulated in the *Circuit #2* both by the  $I_{\text{bias}} + I_{\text{RF}}$  input. Because the SOA is asymmetrically inserted in the Sagnac loop (Fig. 2), a differential and periodic phase-shift  $\Phi_0 \text{sen}\omega t$  is modulated between the clockwise and anti-clockwise interfering signals when  $I_{\text{RF}}$  is launched, where  $\omega = 2\pi f_{\text{RF}}$ . Because of the long recovery-time of the SOA, the negative cycle of the input microwave current is likely to be not clipped. The constant  $\Phi_0$  depends on the nonlinearity strength of the SOA, the recovery-time, the bias current and the asymmetry (38 ps/62 ps) of the inserted SOA into the Sagnac loop. By setting the Sagnac loop to operate in the linear region of the transfer function, the  $P_{\text{OUT}}$  (transmitted power) for small phase-shift is given by (1) where the parameter B depends on losses and amplifier gain of  $P_{\text{IN}}$ .

$$P_{\text{OUT}} = \frac{1}{2} B P_{\text{IN}} \left[ 1 - \cos\left(\frac{\pi}{2} + \Phi_0 \text{sen}\omega t\right) \right]$$

$$P_{\text{OUT}} \approx \frac{1}{2} B P_{\text{IN}} (1 + \Phi_0 \text{sen}\omega t) \quad (1)$$

The numerical simulations were first carried out using a single SOA in a travelling-wave configuration (non-interferometric) subject only to gain modulation. The second set of simulations was carried out using a SOA in an interferometric Sagnac based device subject to gain and phase modulation simultaneously. The SOA and electrical/optical supply parameters were the same for both configurations and none band-pass filter is used despite the setting of  $I_{\text{bias}} > 0 \text{ mA}$ , but limited to 50 mA.

## III. RESULTS AND DISCUSSIONS

### A. Single SOA in travelling-wave configuration

Figure 3 shows three plots of the optical output from the *Circuit #1* at  $f_{\text{RF}} = 20 \text{ GHz}$  carrier frequency,  $I_{\text{RF}} = 80 \text{ mA}$  microwave current amplitude,  $I_{\text{bias}} = 0, 10$  and  $50 \text{ mA}$  bias current, respectively. All plots are assigned with the optical offset level  $P_{\text{DC}}$  and amplitude  $P_{\text{OUT}}$  of the output waveform.

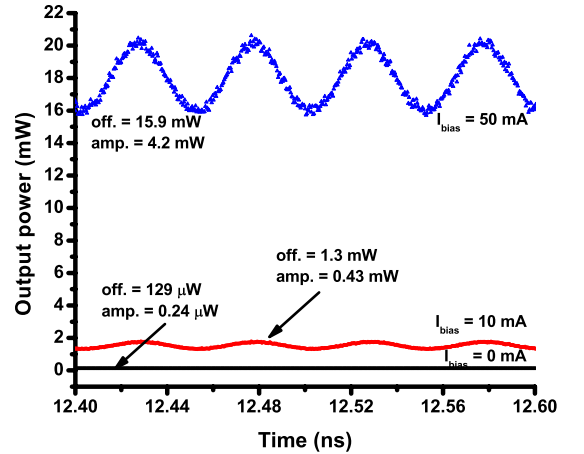


Fig. 3. Outputs from the single SOA optical modulator at 20 GHz for 80 mA microwave current, biased with  $I_{\text{bias}} = 0, 10$  and  $50 \text{ mA}$ .

When the SOA is unbiased, the output amplitude is very low ( $0.24 \mu\text{W}$ ) with a high optical offset ( $129 \mu\text{W}$ ). The origin

of the latter comes from the excitation of SOA with a high-frequency  $I_{RF}$  microwave carrier that interacts with long-lived charge carriers featuring recovery time  $> 1.4$  ns, since 1.4 ns was previously characterised for  $I_{bias} = 100$  mA (not shown here).

When  $I_{bias} = 10$  mA is applied, both offset  $P_{DC}$  and output amplitude  $P_{OUT}$  dramatically increases because much more charge carriers are available in the conduction band. Therefore, the ratio  $P_{OUT}/P_{DC}$  is increased from  $0.24/124 = 0.002$  to  $0.43/1.3 = 0.331$  (x 165.5 times). When  $I_{bias} = 50$  mA is applied, it leads to  $4.2/15.9 = 0.264$  comparable with the ratio achieved when  $I_{bias} = 10$  mA. For all injected  $I_{bias}$ , the SOA gain is not fully recovered because  $P_{DC} > 0$  mW.

### B. Sagnac interferometer with a SOA inserted into the loop

Figure 4 shows four plots of the optical outputs from the *Circuit #2* by injecting drive signal of  $I_{RF} = 80$  mA amplitude and  $f_{RF} = 20$  GHz microwave carrier frequency into the unbiased ( $I_{bias} = 0$  mA) SOA. Different output signals are achieved by varying the polarisation bias (phase angle) of the Sagnac loop.

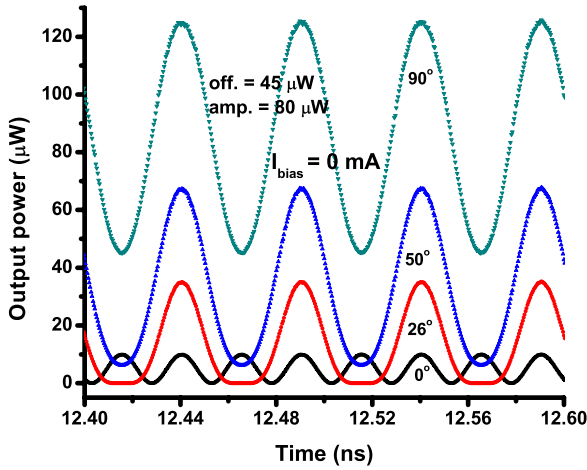


Fig. 4. Optical outputs from the Sagnac loop interferometer incorporating an unbiased ( $I_{bias} = 0$  mA) SOA driven with 20 GHz frequency and 80 mA microwave current amplitude. The polarisation bias of the loop are set at  $0^\circ$ ,  $26^\circ$ ,  $50^\circ$  and  $90^\circ$ .

As expected, for polarisation bias at  $26^\circ$  and  $50^\circ$  the output signals are distorted by clipping since the device operates in a non-linear region of the transfer curve. For  $90^\circ$  polarisation bias, a non-distorted signal very faithful with the input sinusoidal signal is calculated because the interferometer operates in the region of linear response with maximum derivative (quadrature). Nevertheless, for polarisation bias at  $0^\circ$ , the output waveform is little distorted because the interferometer operates in a maximum transmission around  $\Phi_0 = 0$  rad ( $I_{bias} = 0$  mA) since the light carrier is not suppressed and the 2<sup>nd</sup> harmonic contribution is not very high. An advantage by using  $0^\circ$  polarisation bias at  $I_{bias} = 0$  mA for small input signal (at least  $I_{RF} < 80$  mA), is to generate an output optical signal accompanied with an almost null optical DC [17], but with a reduced amplitude when compared with the  $90^\circ$  (maximum linearity).

Figure 5 shows three plots of the optical output from the *Circuit #2* by injecting unbiased and biased ( $I_{bias} = 0, 10$  and  $50$  mA) drive signal of  $I_{RF} = 80$  mA amplitude and  $f_{RF} = 20$  GHz microwave carrier frequency. Different output signals are achieved by using the same polarisation bias of  $90^\circ$ . When the  $I_{bias}$  is increased, the  $P_{DC}$  and the amplitude of optical output signal  $P_{OUT}$  are also increased.

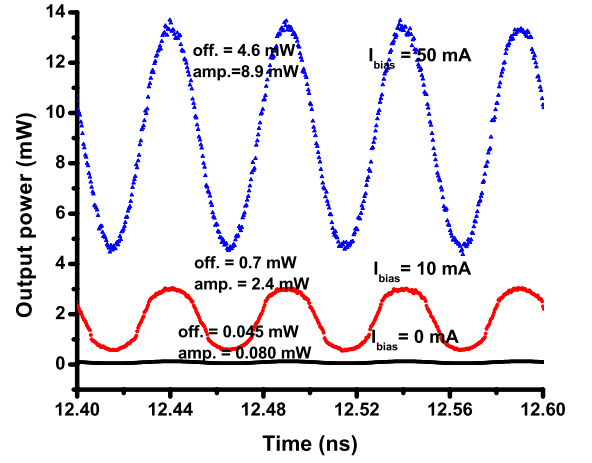


Fig. 5. Optical outputs from the Sagnac loop interferometer incorporating an unbiased ( $I_{bias} = 0$  mA) and biased at  $I_{bias} = 10$  and  $50$  mA SOA electrically driven with 20 GHz frequency and 80 mA microwave current amplitude. The polarisation bias is set at  $90^\circ$  for all bias current.

When  $I_{bias} = 10$  mA is applied, both  $P_{DC}$  and  $P_{OUT}$  dramatically increases because much more carriers are available. However, the ratio  $P_{OUT}/P_{DC}$  is increased from  $0.080/0.045 = 1.78$  to  $2.4/0.7 = 3.43$  (x 1.93 times). When  $I_{bias} = 50$  mA is applied, it leads to  $8.9/4.6 = 1.93$ , less than the ratio when  $I_{bias} = 10$  mA. For all applied  $I_{bias}$ , the SOA gain is not fully recovered. At least in the range 0-50 mA, the  $P_{OUT}$  increases with  $I_{bias}$ , but not the  $P_{OUT}/P_{DC}$  ratio.

### C. General discussions

From  $\sim 300$  MHz to 30 GHz even with unbiased SOA, none negative cycle clipping of the sinusoidal current input was already calculated for the optical output [17]. The clipping is expected since a SOA is a diode as LDs and LEDs are. A possible explanation is because the SOA presents a recovery-time greater than 1.4 ns when it is biased with  $I_{bias} < 50$  mA. Therefore, for  $f_{RF} > 300$  MHz the period of the input signal becomes lesser than the recovery-time, e.g.  $1/20$  GHz = 50 ps is at least  $\sim 28$  times less. The “memory effect” of SOAs seems to be useful for continuous analogue signals whereas the resulting pattern effect is likely to appear for digital streams [18]. When the SOA is biased, carriers are injected in the conduction band by the  $I_{bias}$  and the contribution of  $I_{RF}$  is less critical. However, the devices become noisier due the ASE generation. SOAs biased below the transparency current should be further investigated since it is still almost noiseless.

It was already reported [17] for low microwave current amplitude ( $I_{RF} = 1$  mA and  $f_{RF} = 5$  GHz) a flat response from 0.3 to 10 GHz and  $f_{CUT} = 26$  GHz cut-off frequency for the interferometric device whereas the single SOA was not able to respond in either input frequency.

Now, from the calculated plots shown in Figs. 3 and 5, the Table I show the comparison between the  $P_{OUT}$  and  $P_{DC}$  from the single SOA and Sagnac with an inserted SOA (polarisation bias =  $90^\circ$ ) modulators electrically driven by  $I_{RF} = 80$  mA and  $f_{RF} = 20$  GHz.

Table I shows that when both devices are unbiased a dramatic increase around x188 times is observed for the  $P_{OUT}$  whereas a modest decrease of  $P_{DC}$  is calculated when the SOA is inserted into a Sagnac loop. When the devices are biased, both  $P_{OUT}$  and  $P_{DC}$  increase as  $I_{bias}$  is augmented. However, the increase of  $P_{OUT}$  is less dramatic when  $I_{bias} > 0$  mA and is increased when the SOA is again inserted into the Sagnac loop. Moreover, it is achieved a greater decrease of  $P_{DC}$ .

TABLE I. COMPARISON OF OUTPUT POWERS FROM SINGLE SOA AND SAGNAC INTERFEROMETER + SOA MODULATORS

$I_{bias}$ (mA)	Power	SOA	Sagnac with SOA	Increase (dB)
0	$P_{OUT}$	0.24 $\mu$ W	45 $\mu$ W	+ 22.7
	$P_{DC}$	129 $\mu$ W	80 $\mu$ W	- 2.1
10	$P_{OUT}$	0.43 mW	2.4 mW	+ 7.5
	$P_{DC}$	1.3 mW	0.7 mW	- 2.7
50	$P_{OUT}$	4.2 mW	8.9 mW	+ 3.3
	$P_{DC}$	15.9 mW	4.6 mW	- 5.4

As a result of present simulations and those shown on [17] for small microwave current amplitude, a significant improvement of performance is achieved when the electrically driven SOA is merely inserted into a Sagnac loop despite the long recovery-time of the amplifier when compared with the period of the microwave carrier to be modulated.

As modulation frequency increases, traveling-wave effects can degrade the bandwidth of directly modulated laser diodes (LDs) [19]. Furthermore, pulses are generated with optical chirp that in general negatively interacts with the fibre chromatic dispersion thus limiting the bandwidth. In order to circumvent the limitations of directly modulated light sources, some devices have being used and are firmly established as external optical modulators as Mach-Zehnder electro-optic (MZ-EOM) and electro-absorption (EAM) modulators in analogue [20] and digital modulations.

In principle, the SOA itself exhibits a reduced intrinsic capacitance because of its low length typically of 0.5 mm whereas a typical MZ-EOM presents electrode length in the few mm to few tenths mm range [21]. However, the package parasitics of SOAs should not be neglected [22]. By using an unpackaged device [23] the parasitics of SOA may be reduced and  $f_{RF} > 10$  GHz electrical modulation was already achieved. It has been shown that at microwave frequencies, typically above 10 GHz, usually the electrode geometry of SOAs yields a large propagation loss, which means that the details of the way the modulation signals are fed to the device becomes important [4].

A more detailed comparative analysis still needs to be carried out amongst the MZ-EOMs, EAMs and SOAs-based modulators. However, SOAs can automatically amplify the signals, has a very high and fast nonlinearity (e.g. quantum-dot SOAs), when inserted in an interferometric device it can perform several functions simultaneously and due it reduced size the resulting circuit is prone to optical integration.

#### IV. CONCLUSIONS

In this work, were reported two electrically driven SOA-based devices able to receive a guided or free-propagating microwave carrier thus creating a sub-carrier onto the light wave.

The first device is the well-known single SOA operating in travelling-wave regime where the microwave carrier modulates the gain of the amplifier. In the second device, the same SOA is merely inserted into an interferometric Sagnac loop where the microwave carrier simultaneously modulates the gain of the amplifier and the differential phase between the counter-propagating signals. As a result, the modulation efficiency was significantly improved for very low microwave current amplitude ( $< 1$  mA) at 5 GHz when the device is used as a probe [17] and for electrically amplified input (80 mA) at 20 GHz.

Even though the adopted SOA model presents a long recovery-time  $> 1.4$  ns, both configuration and mainly the interferometric one, could be modulated at 20 GHz carrier frequency and higher.

The main aims of this paper were to show the improvements when an interferometric configuration is used instead of a single SOA and to take the advantage of the partial recovery gain for high-frequency modulation. In practice, it is not easy to directly modulate a SOA in carrier frequencies higher than 10 GHz [22,23], but improvements have being achieved.

Further numerical simulations regarding device sensitivity under variations of many physical parameters and also including the electrical model of SOA/package are on going. Experimental validations are also scheduled to be held in our laboratory.

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