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Hybrid optoelectronic device with multiple bistable outputs

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Abstract. Optoelectronic circuits which exhibit optical and electrical bistability with hysteresis behavior are proposed and experimentally demonstrated. The systems are based on semiconductor optical amplifiers (SOA), bipolar junction transistors (BJT), PIN photodiodes (PD) and laser diodes externally modulated with integrated electro-absorption modulators (LD-EAM). The device operates based on two independent phenomena leading to both electrical bistability and optical bistability. The electrical bistability is due to the series connection of two p-i-n structures (SOA, BJT, PD or LD) in reverse bias. The optical bistability is consequence of the quantum confined Stark effect (QCSE) in the multi-quantum well (MQW) structure in the intrinsic region of the device. This effect produces the optical modulation of the transmitted light through the SOA (or reflected from the PD). Finally, because the optical transmission of the SOA (in reverse bias) and the reflected light from the PD are so small, a LD-EAM modulated by the voltage across these devices are employed to obtain a higher output optical power. Experiments show that the maximum switching frequency is in MHz range and the rise/fall times lower than 1 us. The temporal response is mainly limited by the electrical capacitance of the devices and the parasitic inductances of the connecting wires. The effects of these components can be reduced in current integration technologies.

Acronyms

BJT:	Bipolar junction transistor
CW:	Continuous wave laser
EDFA:	Erbium-doped fiber amplifier
LD-EAM:	Laser diode externally modulated with an integrated electro-absorption modulator
MQW:	Multi-quantum well
p-i-n:	Semiconductor structure based on p-doped, intrinsic and n-doped materials
PD:	Photodiode
QCSE:	Quantum confined Stark effect
SEED:	Self-electro-optic effect device
SOA:	Semiconductor optical amplifier
S-SEED:	Symmetric-SEED
S-SOAD:	Symmetric-SOA device

1. Introduction

Optical quantizer and optical bistable devices have been under intense research and development due to its important applications such as optical computing, photonic signal processing, and telecommunication networks [1]. As a key component in optical sigma-delta modulators, optical quantizer plays a significant role for high frequency oversampling processing. The self-electro-optic effect device (SEED) has been applied as an optical bistable device for photonic switching system [2,3]. The intrinsic region of the SEED contains a MQW structure which produces the electro-modulation of the light propagating through the device when the reverse bias voltage is modified. Two SEED connected in series are named symmetric SEED (S-SEED) and produces bistable outputs when a reverse bias voltage is applied. Depending on the ratio of the optical powers incident on each SEED the switching points can be controlled. Thus, optical switching operation is obtained by varying the optical input power to the SEED. It changes the photocurrent and the voltage across the device, leading to the modulation of the optical transmitted light. Two alternative configurations employing two coupled SOAs (S-SOAD) or a PIN photodiode (PD) with and electro-absorption modulator (EAM) were recently proposed in [4,5].

This paper analyzes three variations of the S-SOAD: the first one is a structure based on the electrical coupling between a SOA and a bipolar juncture transistor (BJT), the second one between a PD and a BJT, and the third one between two PDs. An equivalent electrical circuit model provided the basis for the mathematical formulation to understand the optical/electrical quantization phenomena. The principle of operation of these systems is explained and the relationship between switching processing and several parameters are studied and investigated. In order to analyze and corroborate the system functionality, numerical simulations are performed in the third section. Section fourth summarizes the experimental results obtained for the SOA-BJT, PD-BJT and the PD-PD systems, which were built up in the laboratory. Besides, a modulated laser diode is added to the output to provide higher optical power. Finally, the conclusions are given in section five.

2. Principles of operation

The S-SOAD as an electrical and optical bistable device has been reported in reference [4]. This device operates under the same concept as the SOA-BJT, PD-BJT or PD-PD devices to produces electrical bistabilitity, because all these components (SOA, PD and BJT) are actually p-i-n semiconductor structures. The main difference is observed in the optical domain since to observe optical bistability, the intrinsic region of the SOA or the PD should include a MQW structure.

The following description is developed for the SOA-BJT device although can be extended to the PD-BJT or PD-PD devices. The circuit connection schematics are shown in the Figure 1(a). The anode of the SOA is connected to the collector terminal of a BJT, while a voltage (V_1) is applied to the cathode of the SOA. The base of the BJT is connected to ground, and the emitter is connected to a negative voltage (V_2) through a variable resistor. The equivalent electrical circuit model is given in the Figure 1(b) where a well-known Ebers-Moll model and an equivalent electrical circuit are employed to replace the BJT and the SOA respectively. The model includes current sources, capacitors, and series and parallel resistors. $S(V_{SOA})$ is the responsivity which is function of the voltage across the SOA, V_{SOA}, measured in Ampere/Watt.

By considering the load lines of the SOA and BJT devices it is possible to analyze the electrical switching. Figure 2 shows the load lines of the collector-base junction of the BJT (solid line) and the SOA (dashed lines), as a function of the voltage V_{CB} in the transistor. It can be seen in the figure that the shape of the I-V curves for the SOA has a positive slope in the flat region due to the QCSE. As the voltage across the SOA increases (V_{BJT} decreases), the absorption decreases and as a result the photocurrent also decreases.

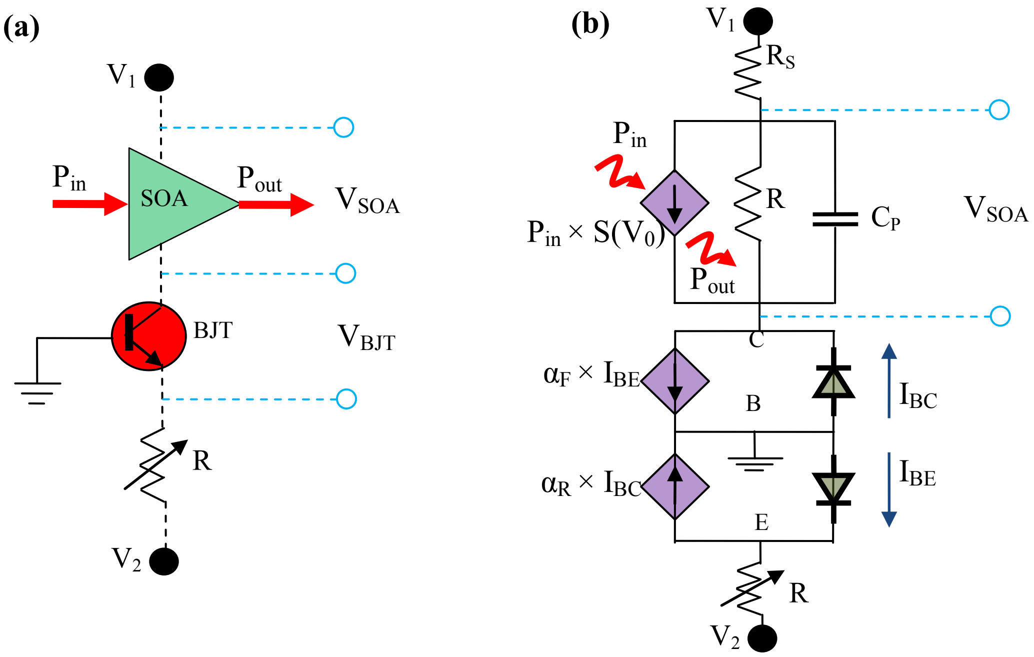

Figure 1. (a) Schematic of the SOA-BJT device. (b) Equivalent electrical circuit including a capacitance, series and parallel resistances and a current source, for the SOA, and the Ebers-Moll circuit model for the BJT.

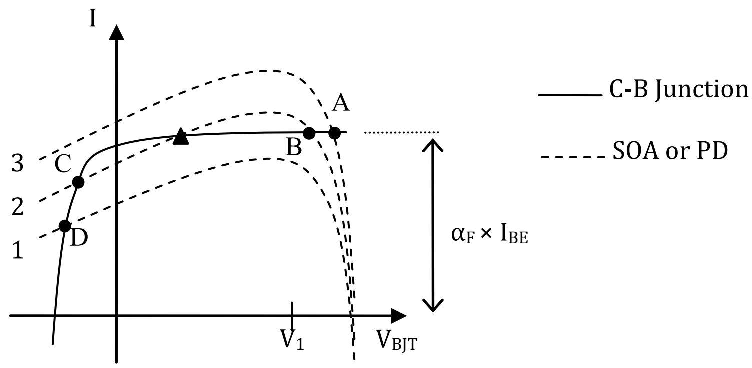

Figure 2. Load lines for the SAO-BJT device: ICB-VBJT curve in solid line and ISOA-VBJT in dashed lines. The photocurrent changes depending on the input optical power. The intersection points are the operation conditions except the triangle which is and unstable state.

The two components (SOA and BJT) are connected in series sharing the same current. Thus, the bistable system switches at points where the load lines intersect. The load line for the collector-base junction (solid line) is just that of a reverse biased diode, shifted up by the current $\alpha_F \times I_{BE}$. The load lines of the SOA (dashed lines) have been added for three different optical input powers, shifted up and down by the photocurrent. Line 1 represents a low optical input power, which is displaced to line 2 and line 3 as the optical power continuously increase. Starting with a low optical input power represented by line 1, the intersection point is at point D. Therefore, the voltage V_{BJT} is close to zero. As the input power increases continuously to line 2, there are three intersection points. While the center intersection (triangle) is unstable, the left and the right intersections are both stable. Therefore the point at which the device actually operates is determined by the direction in which the optical power is changing. Thus, when the optical power increases from a low power, the switching point remains at a voltage close to zero (point C). As the input power further increases, the intersection point C will move up and eventually will disappear from the left side, switching to a new stable value close to point A. The reserve condition is similar, as the power decreases back from line 3 to line 2, the voltage will change from the point A to the point B, remaining close to the voltage V_1. As the power decreases further to line 1, the intersection point will disappear at the point B and turn out to be at the point D, making the voltage switch to zero. The system switches at different optical inputs depending on whether the optical power increases or decreases, so a bistable system with hysteresis is exhibited.

As discussed above, if we consider the case where a high optical input is applied to the SOA, the voltage across the SOA is set close to zero and remains at this value forming the state "0". Similarly, when a low optical input is introduced, the voltage across the SOA is switched to V_1 forming the state "1". Therefore, if the optical input signal is sinusoid waveform, the V_{SOA} will switch from the state "1" to the state "0", back and forth.

Finally, because the QCSE in the MQW structure of optical component, the switched voltage across the SOA produces the electro-modulation of the transmitted light. Therefore, an optical bistable switch with hysteresis behavior is obtained. For the case that a PD is employed in place of the SOA, the output is given by the reflected light and it will suffer the mentioned electro-modulation.

3. Simulations

Based on the equivalent electrical circuit in Figure 2, a PSPICE simulation was designed to predict the performance of the SOA-BJT and the PD-BJT structures as shown in Figure 3. A novel method is used to model the electro-optics components (SOA and PD) given by a power-controlled current source represents the p-i-n diode structure where a power source represents the optical input the SOA. A diode connected in parallel is adopted in circuit to simulate the I-V curve. The used values for the capacitor, series and parallel resistances are defined through experimental measurements and specifications from the datasheet. The simulation results for the input and the output of the SOA-BJT device are shown in Figure 4. Because one SOA of the S-SOAD [4] is replace by a BJT, the total capacitance of the SOA-BJT device is smaller than that present in the S-SOA scheme. It contributes to a better frequency response. In Figure 4 (a), the optical input power (dashed line) is 300 KHz sinusoid waveform and its corresponding voltage output across the SOA (solid line) is bistable-quantized square shape. By plotting the input and the output in x-y format, the hysteretic curve is obtained In Figure 4 (b). It is easy to find out that the characteristic of the output possesses the inverted bistability. When the input is at high value, the output produces a low value, and vice versa. The SOA-BJT and the PD-BJT schemes have higher frequency response because the lower capacitance of the system. The parallel capacitances are the main limitation to reach higher speed switching. Therefore, in order to improve the performance of this architecture beyond GHz application, the photonic integration technology should be employed to minimize the system capacitances.

4. Experimental measurements

The experimental setup for the SOA-BJT, PD-BJT and PD-PD are shown in Figures 5(a)-(c) respectively. Also, for the SOA-BJT device it is shown the optical circuit employed to supply the input power to the SOA which is remained for the other structures. For the PD-PD device a second optical circuit to provide the input power to the bottom PD should be included.

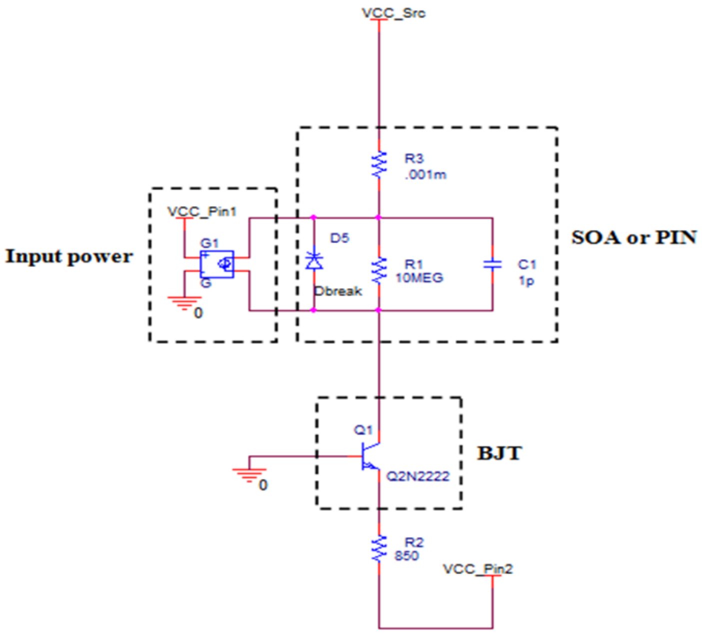

Figure 3. PSPICE-based simulation circuit for the SOA-BJT device.

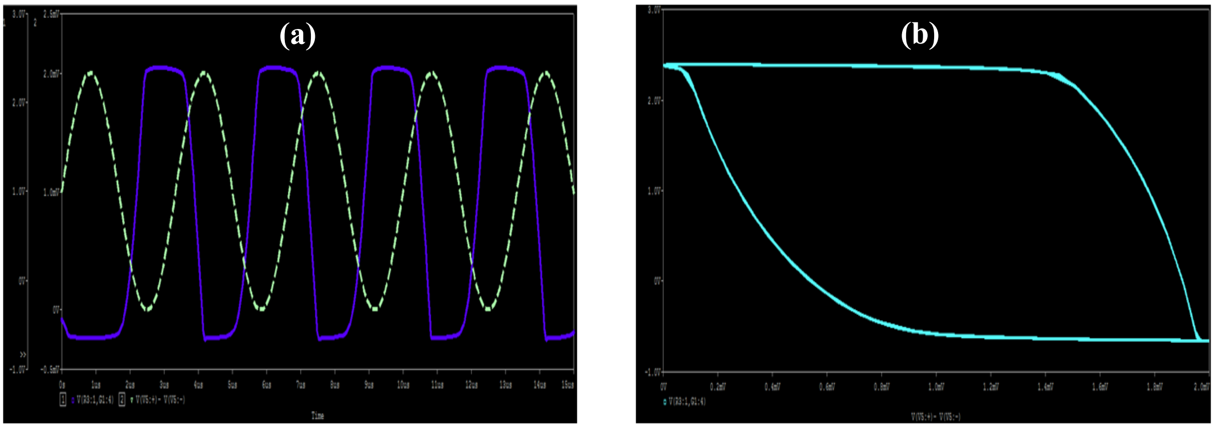

Figure 4. (a) Sinusoidal optical input power (dashed line) and output voltage across the SOA (solid line) at 300 KHz input frequency; (b) Hysteretic curve of the input power vs. the output voltage across the SOA at 300 KHz input frequency.

A Fujistu FLD5F10 integrated device which includes a laser diode (LD) and an EAM, which we name LD-EAM, is employed to produce the optical input signal at the wavelength 1553.3 nm. The RF signal generator modulates a sinusoidal waveform of hundreds of KHz and 2.5 V peak-to-peak. The Amonics EDFA (model AEDFA-C-15B-LCB-R) is positioned after the LD-EAM device in order to amplify the optical power supplied to the SOA. This is required to control the optical input power and adjust the switching characteristics of the system. A Covega SOA model 1117 is used to construct the SOA-BJT device together with a standard 2N2222A NPN transistor. In the PD-BJT setup (Fig. 5(b)), an Eudyna PIN photodiode model FID3Z1LX replaces the SOA while in the PD-PD setup two Eudyna photodiodes are employed. The bias voltage V_1 is adjusted to 0 V and the control voltage V_2 is chosen to -2.9 V for the SOA-BJT and PD-BJT architectures, while V_1 is adjusted to 1.23 V and V_2 to 0 V for the PD-PD device. A 5 KΩ potentiometer is employed to control the current through the base-emitter junction of the transistor, while it is set to zero in the PD-PD architecture because the current in the bottom photodiode is regulated by the corresponding optical input. This current needs to be adjusted to optimize the switching threshold of the bistable device to obtain the best hysteresis curve. . The driving currents for input laser and EDFA are 100 mA and 50 mA, respectively.

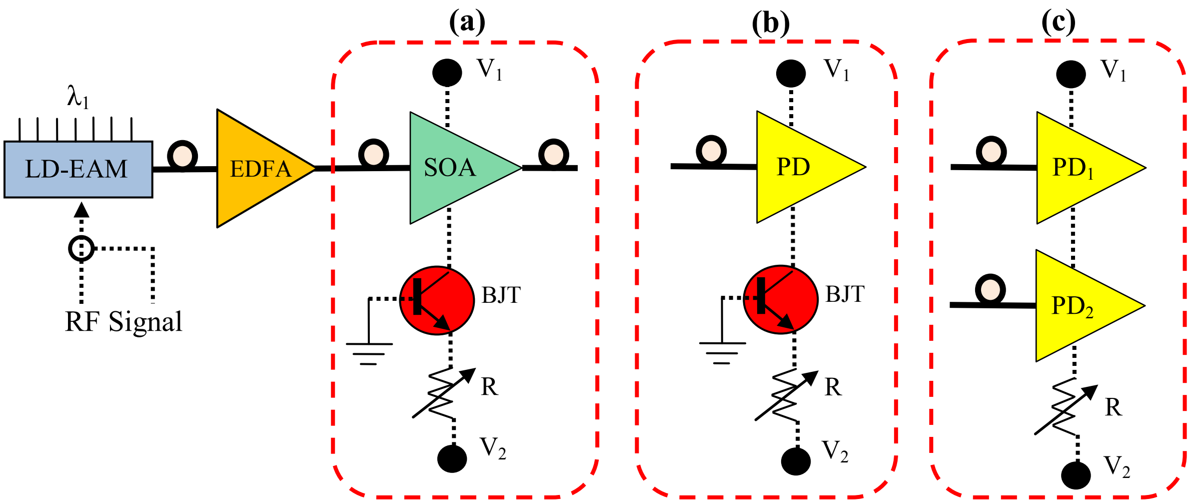

Figure 5. Three experimental setups to measure electrical and optical bistability: (a) SOA-BJT, (b) PD-BJT and (c) PD-PD devices. Solid lines are fiber-optic-based connections while the dotted lines represent wired electrical connections.

The operation of the SOA-BJT device is illustrated as follows (idem for the PD-BJT setup): the Fujitsu DFB laser generates a CW signal, which is modulated by a sinusoidal signal through the EAM. Then, the optical signal is amplified by the EDFA up to approximately 10 mW and is introduced to the SOA (or photodiode). If the generated photocurrent is bigger than that set by the transistor, then the SOA defines the current in the series circuit and the voltage V_{BJT} is high. Otherwise, the transistor fixes the current and the voltage V_{BJT} is low. By adjusting the 5 KΩ potentiometer a better and most stable hysteresis curve is obtained. Figure 6(a)-(d) show the measurements by considering input sinusoidal signals at different frequencies to the SOA-BJT and PD-BJT devices. The upper trace represents the input signal (modulation signal sent to the LD-EAM), the middle trace the quantized output, measured across the top device, and the x-y representation of these two signals is shown in the bottom trace. Figure 6(a) and (b) correspond to the SOA-BJT device for an input frequency of 100 KHz and 150 KHz, respectively, while Figure 6(c) and (d) correspond to the PD-BJT device for 200 KHz and 300 KHz.

Conceptually, the PD-PD device is similar to the SOA-BJT device except for the photocurrent in the bottom photodiode which is generated by a CW laser. When the input power to the top photodiode is bigger than the input power to the bottom photodiode, the current is fixed by the upper device and the voltage across it is low. Otherwise, if the input power to the top device decrease being lower than the input power to the bottom photodiode, the voltage across the top photodiode is high. Figure 7(a)-(d) show the measurements by considering input sinusoidal signals with two different frequencies to the PD-PD device. On the left side, the bottom trace represents the input signal (modulation signal sent to the LD-EAM) and the upper trace the quantized output measured across the top device. On the right side is shown the x-y representation of these two signals. Figure 7(a) and (b) correspond to 500 KHz while in Figure 7(c) and (d) the frequency is 1 MHz.

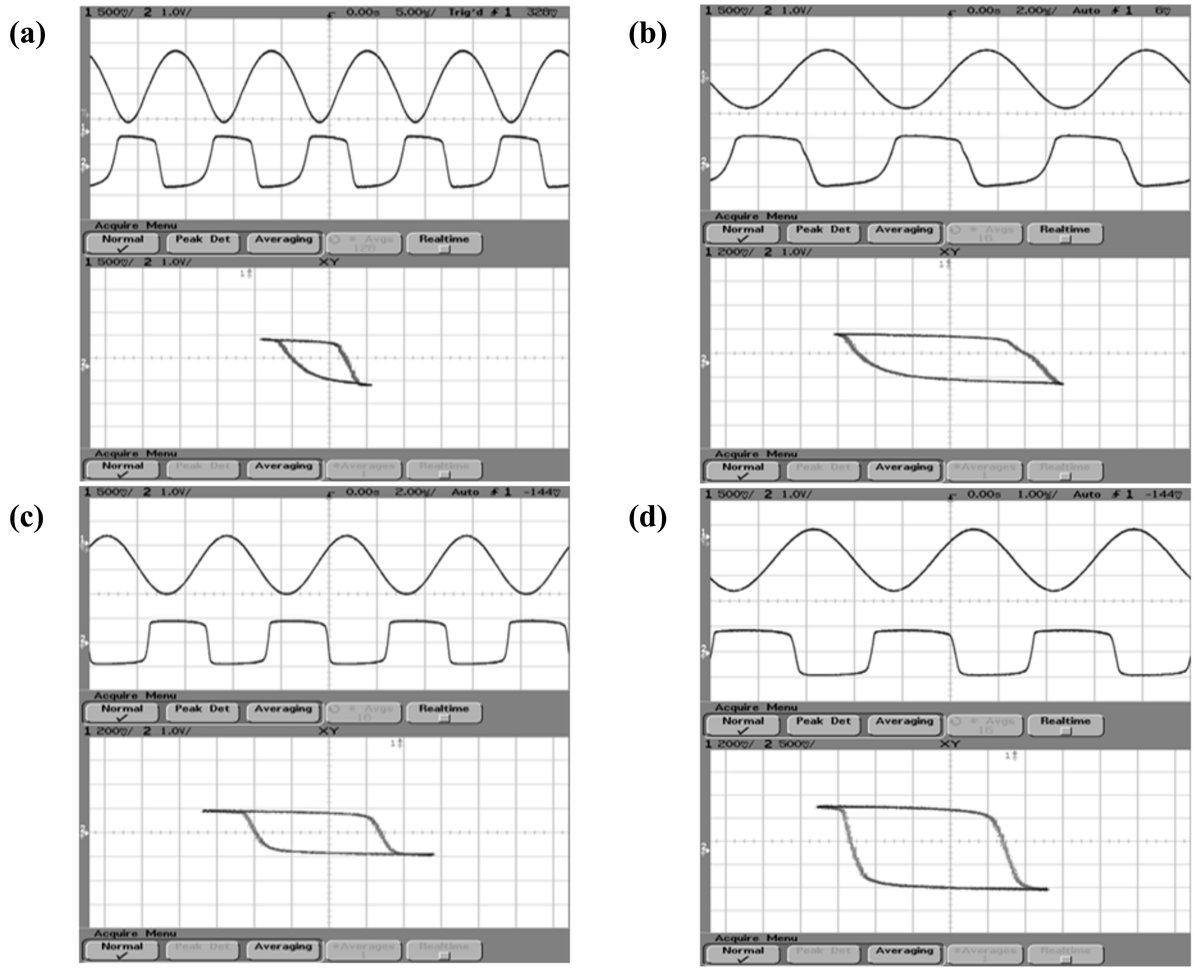

Figure 6. Input sinusoidal signal at different frequencies (upper trace), quantized output measured across the top device (middle trace) and x-y representation of these two signals (bottom trace) for the SOA-BJT and PD-BJT devices. (a) 100 KHz for the SOA-BJT device; (b) 150 KHz for the SOA-BJT device; (c) 200 KHz for the PD-BJT device; and (d) 300 KHz for the PIN-BJT.

The maximum switching frequencies of the implemented prototypes are limited by the junction capacitances of the involved components (SOA, BJT and PD). The SOA capacitance about 380 pF is the biggest, being the BJT and PD capacitances around 130 pF and 0.9 pF respectively. Thus, the frequency response of the SOA-BJT device is the poorest because they have the maximum capacitance, reaching switching frequencies of 150 KHz. The PD-BJT device has a lower capacitance and it works at 300 KHz frequencies with a better performance than the SOA-BJT device (compare Figures 6(b) and (d)). Finally, the PD-PD device has the lowest capacitance producing the maximum frequency response. Figures 7(c) and (d) shows that switching at MHz frequencies can be obtained in this configuration.

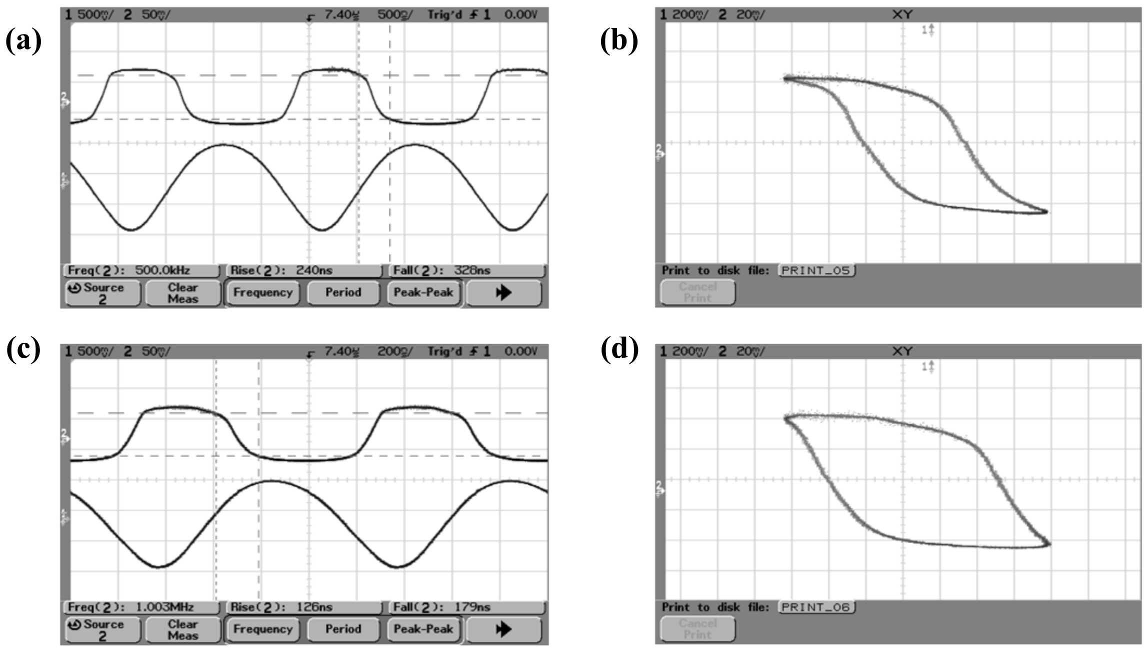

Figure 7. Input sinusoidal signal at different frequencies (bottom trace) and quantized output measured across the top device (upper trace), on the left side. X-Y representation of these two signals on the right side for the PD-PD device. (a) and (b) the frequency is 500 KHz; while (c) and (d) is 1 MHz.

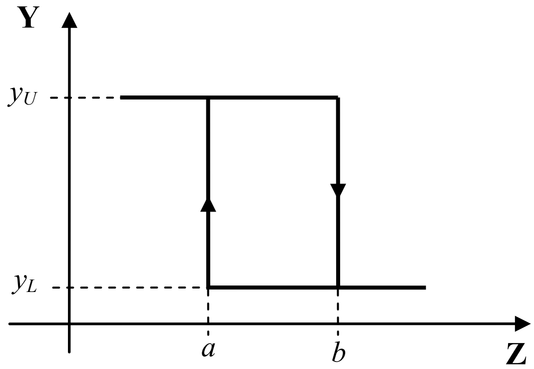

Figure 8. Ideal hysteresis curve for inverted bistable devices; the input is represented in Z-axis and the output in the Y-axis. The input voltage at point a is named switching-on voltage while at point b is the switching-off voltage. The output voltages are labeled as: yU and yL being the upper limit and the lower limit levels, respectively.

In order to compare the results and analyze the switching performance it is important to define the main characteristics of the hysteresis curve for the three devices. Figure 8 shows the ideal hysteresis curve illustrating the representative points such as the switching-on and-off voltages levels of the input signal (*a* and *b* respectively in the figure), and the upper- and lower-limit voltage for the quantized output signal (y_U and y_L respectively in the figure). Table 1 summarizes the measured voltages specified as the absolute value of the difference *a*-*b* and y_U-y_L. It can be seen from the table that as the frequency is increased, as the horizontal magnitude of the hysteresis window is increased. It reduces the switching performance of the device. On the other side, the output levels can be controlled through the employed source voltage which are adjusted for the better performance.

Table 1

Setup	Freq [KHz]	*b-a* [V]	y_U-y_L [V]
SOA-BJT	100	1.0	2.0
SOA-BJT	150	1.2	2.0
PIN-BJT	200	0.8	2.0
PIN-BJT	300	1.0	1.75
PD-PD	500	0.1	0.82
PD-PD	1000	0.14	0.85

Up to now, electrical bistable outputs measuring the voltage across the top side semiconductor were obtained for the three architectures. Optical bistability can be observed, as it was pointed out, because the QCSE in the MQW structure in the intrinsic region produces the elecro-absorption modulation of the transmitted light in the SOA device (or reflected from the PD). Because the SOA predominantly absorbs the transmitted light when it is reversed biased, the output power results extremely small and it is difficult to directly obtain good optical bistable output. On the other side, the reflected back optical signal from the photodetector is too small because the most commercially available photodetectors are built with an anti-reflection coating, in order that the light inside the device cannot get out. Figure 9 shows the optical bistability obtained in the SOA where it can be observed the small detected output in the vertical axis, which is approximately 2 mV peak-to-peak.

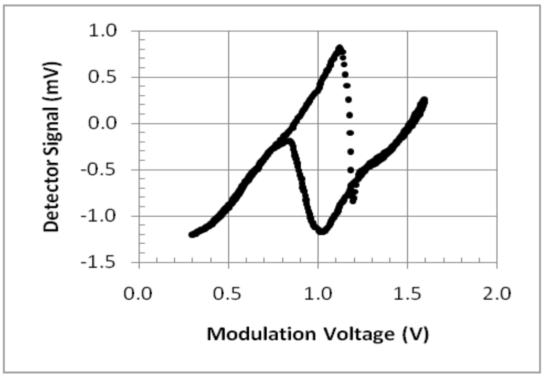

Figure 9. Optical bistability of the SOA-BJT device for 100 KHz sinusoidal input signal.

In order to overcome the drawback of the small optical output caused by the extremely low transmission of the SOA (or small reflected light from the PD), a Fujitsu DFB FLD5F10 laser diode with an integrated EAM is connected in parallel to the SOA (or PD) as is shown in Figure 10(a). Thus, the output quantized voltage is used as input to the EAM and so to obtain a more powerful optical bistable output. Figures 10(b) and (c) show the measurements for a 100 KHz and 150 KHz sinusoidal input signals respectively. The optical bistable switch is obtained and the hysteresis curve is formed in the optical domain. The detected output is around 40 mV peak-to-peak and the main advantage of this setup is that the optical output power can easily be controlled via the driving current of the LD-EAM without adding external optical amplifiers. By adjusting the voltages V_1 and V_2 to 0.5 V and -2.7 V, the output voltage across the SOA falls within the modulating voltage range of the EAM. It can be seen that the optical output and the hysteresis in Figures 10(b) and (c) present a better quality than the obtained in Figure 9.

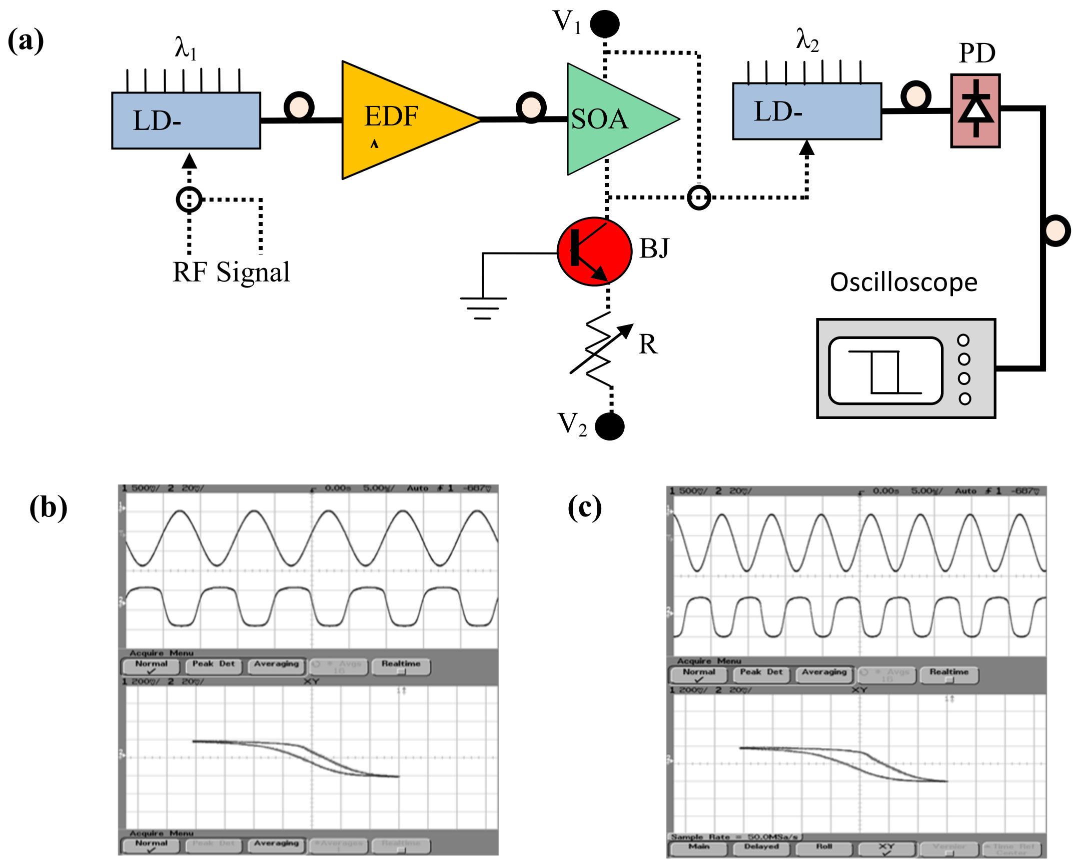

Figure 10. (a) Experimental setup for the SOA-BJT device including a LD-EAM to obtain the optical bistable output. Electrical input (upper trace); detected quantized output (middle trace) and x-y representation of the previous signals (bottom trace) for (b) 100 KHz and (c) 150KHz.

5. Conclusion

Three different electrical/optical bistable devices (SOA-BJT, PD-BJT and PD-PD) have been developed. The main advantages of these devices are: they are configured as non-interferometric structures and therefore the typical problem with the phase adjustment is not present. Measurement and numerical results show that it is possible to obtain electrical inverted/non-inverted bistable outputs (depending on if it is considered the upper or the bottom device). Also an optical inverted output is measured to the output of the SOA (in the SOA-BJT setup) or reflected from the PD (in the other two devices). Because the measured optical output from the SOA is so weak (a few mV), an auxiliary LD-EAM supplied by the voltage across the SOA is used in order to increase the output optical power.

In the demonstrated prototypes, the maximum switching frequency is around of MHz and the rise/fall times less than 1 µs. They are mainly limited by the electrical capacitance of the involved components and the parasitic inductance of the connecting cables. A detailed numerical model of the SOA-BJT device was developed, which reveals that the switching performance can reach frequencies of tens of GHz if the device is built in a hybrid electronic photonic integrated circuit with low capacitances (in the femtofaradads range).

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