Governing the speed of light and its application to the Microwave Photonics field

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Abstract

We provide a comprehensive review of the application of Slow and Fast light techniques to the field of Microwave Photonics. The implementation of phase shifters using semiconductor optical amplifiers are first considered. We then focus on the main results obtained by our group in the implementation of broadband, full 360º phase shifting in semiconductor waveguides. Finally, we have implemented a tunable Microwave Photonic Filter to show the potential of the Slow/Fast Light techniques based on SOAs in the Microwave Photonics Field.

Keywords. Slow/Fast Light Effects, Microwave Photonics, Semiconductor Optical Amplifiers

1. Introduction

The last years have witnessed an increasing interest and activity by several research groups spread around the world on the possibility of controlling the group velocity of light by means of different physical mechanisms and technologies. This field is now widely known by the name of Slow and Fast Light (SFL) within the photonics community. The pioneering experimental and theoretical studies of slow light were performed in the context of nonlinear optics in the 60s and the early 70s [1]. However, it was only recently that an experiment carried out by Hau and coworkers [2], demonstrating the slow-down of the light group velocity to a value comparable to that of cyclist speed, that research interest in this discipline boosted. The Hau experiment, performed using the effect of Electromagnetically Induced Transparency (EIT), required cryogenic temperatures and was induced over a very narrow bandwidth, two facts that limit the range of applications, at least within the telecommunication field. Nonetheless, since that demonstration, SFL research has been flourishing, with the quests for increasing the bandwidth and developing SFL technologies capable of operation at room temperature. A number of different media and technologies allow control of the group velocity at room temperature, such as crystals [3], semiconductor waveguides [4-5], as well as optical fibers [6-9]. Also dispersion–compensating fibers (DCFs) [10], Fiber Bragg Gratings (FBGs) [11-12] and coupled cavities have been recently proposed as a means to implement tunable delays [13-15].

The initial promising performance figures of several SFLs techniques fostered the research on optical buffering and tunable delay lines in areas which have direct applications in Telecommunications like [16]: optical synchronization, multiplexing, storage and logic gates. However, in spite of several important achievements, a critical analysis based on a detailed understanding of current SFL approaches leads to the conclusion that the state-of-the-art SFL schemes are not yet capable of supporting many of the envisioned practical applications. Notwithstanding, the potential of SFL is immense; and its impact awaits to be furnished in applications where its characteristics can unleash its entire potential. In this context, a relevant application can be found in the framework of Microwave Photonics (MWP) as anticipated in [17]. In particular, there are numerous applications where the potential of a tunable broadband phase shift of 2π between the carrier and the subcarrier that transport the data is required.

Semiconductor Optical Amplifiers (SOAs) constitute one of the most promising SFL technologies as they offer a bandwidth of several tens of GHz, which is much larger than slow light based on other physical mechanisms. It must be noted that, in addition to the optical pump, the bias voltage or the electrical injection current can also be used in this technology to control the speed of light providing another degree of freedom for manipulation of the optical signal. MWP applications are targeting higher operation frequencies and functionalities that are demanding small devices with low weight. Semiconductor based structures provide these features and also allow on-chip integration with other devices while lowering the manufacturing costs. Amongst the most significant advances, we include the implementation of fully tunable 360º phase shifters over bandwidths in excess of several GHz.

2. Basic Concepts of SFL Devices for Microwave Photonics

In general, the group velocity can be defined as:

$$v_g = \frac{c}{n_g} = \frac{c}{n' + \omega \frac{n'}{\omega}} \tag{1}$$

where n_g is the group index and n' is the real part of the refractive index n. When the medium shows so-called normal dispersion ($\delta n'/\delta\omega > 0$), i.e. $v_g < c_0/n'$, the term slow light propagation is employed whilst when the medium shows anomalous dispersion ($\delta n'/\delta\omega < 0$) $v_g > c_0/n'$, the case is referred to as fast light propagation. The Kramers-Kroenig (KK) relations which link the real and imaginary parts of the effective index in a given medium by means of the Hilbert transforms [18] are useful to understand the SFL effects produced in a device, which is traversed by an optical signal. Furthermore, for minimum phase shift media [19], also the related dispersion and the absorption/gain magnitudes are linked by similar transforms. For instance, a medium or device showing an amplitude dip or resonance, as shown in Fig. 1(a), will feature a phase shift and a group delay response with a shape similar to those shown in Fig. 1(b) and Fig. 1(c) respectively. Observing Fig. 1(c) and recalling (1), it becomes apparent that the frequencies for which significant SFL effects are observed is limited to a range around a resonance condition. In Fig. 1 we illustrate, for instance, how to implement a tunable phase shift in a photonic resonant medium with a field transfer function given by $H(\omega)$, such as a coupled resonator optical waveguides.

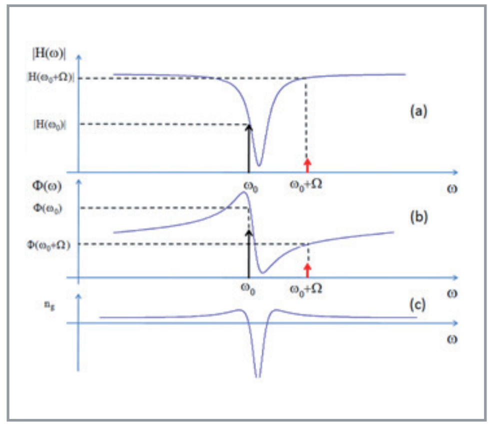

Figure 1. *a) Lorentzian shape of a resonance. b) Phase response of the resonance. c) Variation of the group index in the vicinity of the resonance. The positions of the carrier and subcarrier to achieve a tunable microwave phase shift are indicated.*

Here, a single sideband (SSB) optical signal is employed which, for instance can consist of an optical carrier of frequency ω_0 and the upper (lower) RF subcarrier at frequency $\omega_0+\Omega$ ($\omega_0-\Omega$),where Ω represents the frequency of the RF modulating signal. The electric field at the input of the resonant medium can be described by:

$$E_{in}(t) = E_0 e^{j\omega_0 t}\left(1 + m e^{j\Omega t}\right) \tag{2}$$

where E_0 is the carrier amplitude and m is the RF modulation index (usually $m<<1$). Placing the signal such that the optical carrier is inside the resonance and the RF subcarrier is outside (i.e. $|H(\omega 0+\Omega)| \approx 1$), we have at the output of the resonant medium:

$$\begin{aligned} E_{out}(t) &= E_0 e^{j\omega_0 t}\left(\left|H(\omega_0)\right| e^{j\Phi(\omega_0)} + m\left|H(\omega_0+\Omega)\right| e^{j(\Omega t+\Phi(\omega_0+\Omega))}\right) = \\ &= E_0 e^{j\omega_0 t}\left|H(\omega_0)\right| e^{j\Phi(\omega_0)}\left(1 + m\frac{\left|H(\omega_0+\Omega)\right|}{\left|H(\omega_0)\right|} e^{j(\Omega t + \Phi(\omega_0+\Omega) - \Phi(\omega_0))}\right) \approx \\ &\approx E_0 e^{j\omega_0 t}\left|H(\omega_0)\right| e^{j\Phi(\omega_0)}\left(1 + \frac{m}{\left|H(\omega_0)\right|} e^{j(\Omega t - \Delta\Phi(\omega_0))}\right) \end{aligned} \tag{3}$$

which, upon beating at the photodetector, yields a radiofrequeny photocurrent proportional to:

$$i_{RF}(t) \propto \left|E_0\right|^2 \left|H(\omega_0)\right| m \cos\left(\Omega t - \Delta\Phi(\omega_0)\right) \tag{4}$$

Thus, by changing or tuning the position of the optical carrier within the filter resonance, the phase shift imposed upon the detected RF subcarrier can be changed. Another approach to obtain tunable SFL effects, without requiring the change in the frequency of the optical signal, is focused on the modification by external means of the spectrum of the resonance. For example, in a medium showing absorption, a saturation effect can be obtained by exciting the medium with an optical signal at a given frequency. This is illustrated in Fig. 2(a) and 2(b) for the case where the Lorentzian resonance describes the inhomogeneous broadening of a medium, which is saturated by an optical signal. By comparing Fig. 1 and Fig. 2, it can be appreciated how the SFL effect for a given set of frequencies within the resonance has been altered. This scheme is qui-

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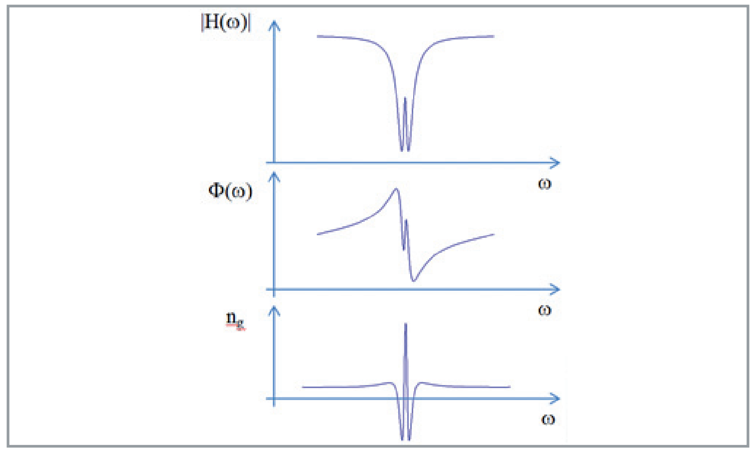


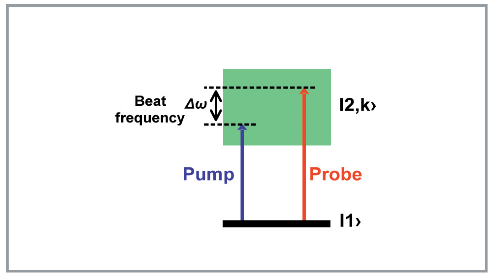
■ **Figure 2.** *Amplitude a) and phase response b) of a Lorentzian resonance that is saturated by an optical signal. c) The saturation effect induces a change from a fast light effect to a slow light effect.*

te flexible because it provides the control of the group velocity by means of an external control signal, in this case an optical pump.

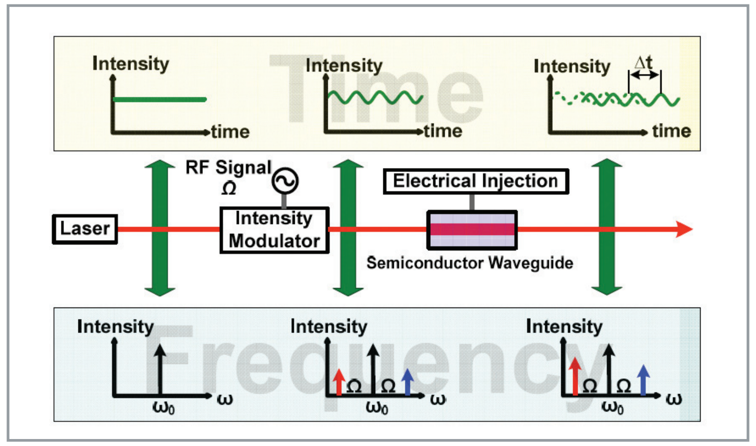
3. Controlling the Speed of Light in Semiconductor optical amplifiers

SFL effects created SOAs are based on Coherent Population Oscillations (CPO) [3]. CPO relies on the direct interference between two laser beams, pump and probe, as shown in Fig. 3. The carrier density of the conduction and the valence band oscillates at the beat frequency determined by the frequency detuning $\Delta\omega$. Hence, the carrier oscillation alters the gain of the SOAs.

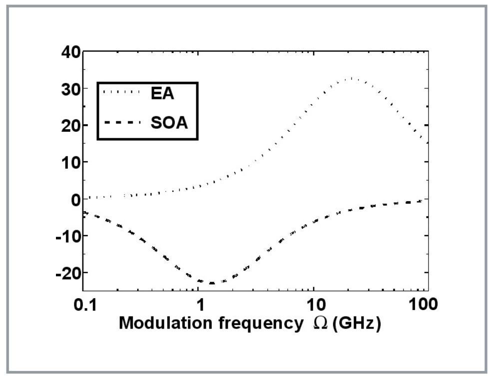
Fig. 3. Aimed at the potential applications in microwave photonics, the strong pump and weak probe are generated through the modulation technique with a high speed intensity modulator, as shown in Fig. 3. A continuous-wave laser is intensity modulated by a microwave signal at a frequency of Ω. In the time domain, the optical signal has a sinusoidal envelope. In the frequency domain, the modulated optical signal is comprised of a strong carrier, at frequency ω_0, and two weak sidebands, a red-shifted sideband at ω_0-Ω and a blue-shifted sideband at $\omega_0+\Omega$. The strong carrier will act as the pump, and the two weak sidebands as probes. Due to the modulation of the intensity, the gain and the refractive index are modulated in time and these temporal gratings will scatter the strong pump ω_0. The components scattered to the two sidebands will modify the susceptibilities seen by the probes. Further, the magnitude of the modification can be controlled by the electrical injection or the optical pump power. Therefore, after the propagation in the semiconductor waveguide, the signal envelope will experience a time delay or advance of Δt, see Fig. 4. The time delay or advance also corresponds to a microwave phase shift of $\Delta t\Omega$.



■ **Figure 3.** *Level diagram for CPO effects.*



■ **Figure 4.** *Basic experimental scheme to realize slow and fast light effects in semiconductor waveguides. The top and bottom rows are the time-domain and frequency-domain descriptions, respectively. ω_0: angular frequency of the laser; Ω: RF signal frequency.*



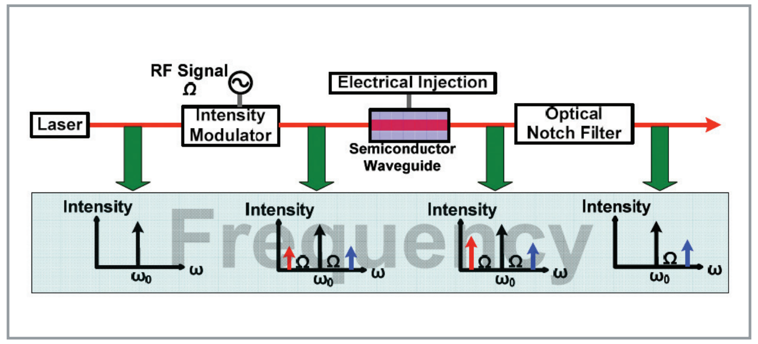
■ **Figure 5.** *Calculated RF phase shifts as a function of the modulation frequency. The phase shifts are induced by changing the injection current for an SOA or bias voltage for an EA.*

Therefore, the RF phase shift $\Delta\varphi RF$ can be controlled either optically by the input optical power, or electrically by the electrical injection. For an *SOA*, $g_0>0$, $\Delta\varphi$ is negative, which means fast light. On the other hand, slow light dominates in an absorbing waveguide. Fig. 5 shows and example of numerically calculated phase shift from (11) for an SOA and EA. These frequency variations have been experimentally confirmed [20].

Fig. 5 shows moderate phase shifts, to increase them a novel scheme of optical filtering prior to detection has been proposed [21]. Fig. 6 depicts the basic configuration. After propagation in the waveguide, the red-shifted sideband is blocked by an optical notch filter, which can be accomplished by a Fiber Bragg Grating (FBG). For an SOA, Fig. 7 presents the simulated and experimental results for the microwave phase shifts and power changes when the input optical power is increased from -10 dBm to 12 dBm. For the conventional case without optical filtering, ~20º phase advance at 19 GHz is achieved, as the black markers and line show in Fig. 7(a).

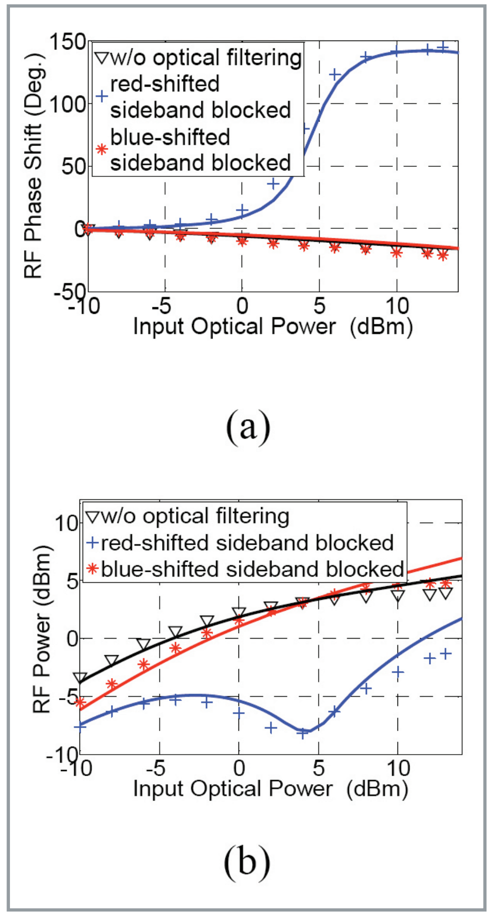
The corresponding microwave power shows an ~8 dB increase in Fig. 7(b). For the case of blocking the blue-shifted sideband by optical filtering before the detection, as shown by the red '*' markers, the microwave phase shift as well as the power change is very close to the conventional case. However, when the red-shifted sideband is blocked, ~150º phase delay can be continuously obtained, as the blue '+' markers shown in Fig. 7(a). The microwave power, shown in Fig. 7(b), shows a drop which is always correlated with the sharp increase of the phase of the microwave signal. Similar results are obtained by varying the injection current. We have also investigated the modulation frequency dependence when the red-shifted sideband is blocked. We have demonstrated that ~150º phase shifts can be achieved over a large microwave bandwidth, even up to 40 GHz [22].

To meet the 360° phase shift required for many applications in microwave photonics, we have investigated the possibilities of cascading several elements of the proposed phase shifter in order to scale the absolute phase shift. Thus, after performing optical filtering but before detection, a sideband regenerator that restores the red sideband is included, which enables cascading an additional phase shifter, since the signal now resembles the original double-side band input signal. Fig. 8 illustrates the basic cascaded scheme. After passing through the first phase shift stage, the red-shifted sideband will be removed, as shown by the inset at point *A*, and the signal envelope will experience a >100º phase delay by changing the input optical power or the injection current of SOA1. A further increase of the phase shift, e.g. by increasing the device length, is not possible due to saturation effects. Nevertheless, if the blocked red-shifted sideband is regenerated again, as shown in the inset at point *B*, by exploiting four-wave mixing (FWM) effects in SOA2, the optical signal will acquire an optical spectrum similar to the initial at the input of SOA1. Then, after propagating through the second phase shift stage, the signal will experience another large phase delay by changing the injection current of SOA3. Fig. 9 shows the measured RF phase shift and power change induced by the cascaded phase shifter shown in Fig. 8. Thus a tunable 360º microwave photonic phase shifter can be realized by cascading several SOAs [23]. Furthermore, SOA3 provides a possibility to simultaneously control the final microwave power.

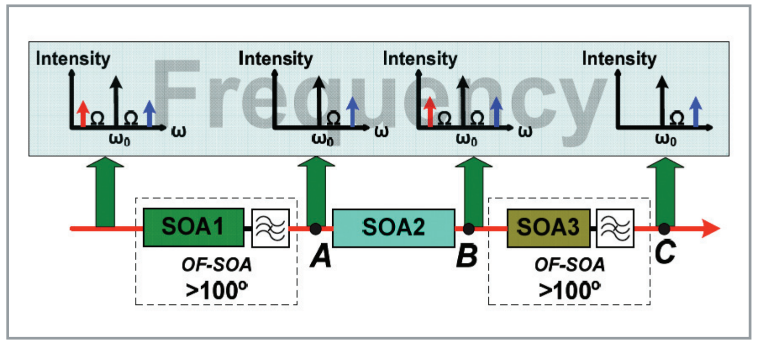


■ **Figure 6.** *The basic scheme to enhance light slow-down by employing optical filtering to remove the red-shifted sideband before the detection.*

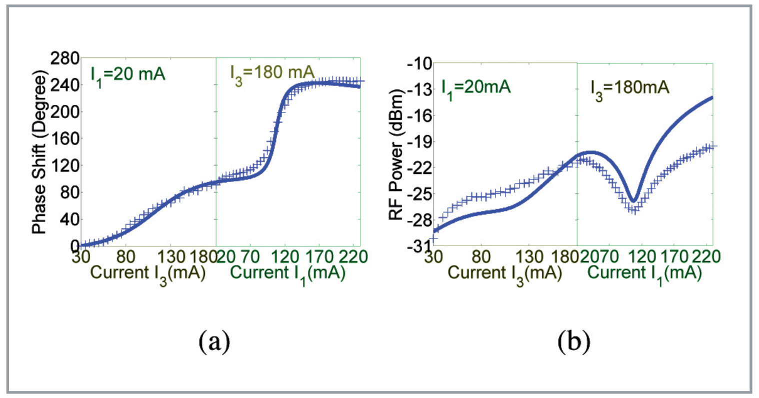
Semiconductor based structures also allow on-chip integration with other devices while lowering the manufacturing costs



■ **Figure 7.** *Microwave phase shifts (a) and power changes (b) at 19 GHz as a function of the optical power into an SOA. The markers are experimental data and the solid lines are theoretical simulations.*



■ **Figure 8.** *Configuration to increase the RF phase shift by cascading two phase shifter stages. OF: optical /spectral filtering.*



■ **Figure 9.** *Measured (markers) RF phase shift (a) and power (b) at 19 GHz as a function of the injection currents of SOA3 and SOA1. The solid lines are numerical simulations.*

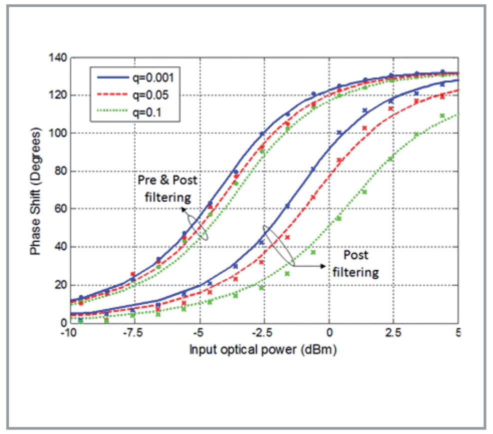
A tunable 360º microwave photonic phase shifter can be realized by cascading several SOAs

4. Distortion and noise analysis

The phase shifter performance can be compromised by the inherent nonlinear behavior of CPO as the harmonic distortion terms generated in the SOA device can bring a reduction in the expected microwave phase shift [24]. With the aim of proposing and comparing different optical filtering implementations for the proper reduction of harmonic distortion in microwave photonic applications, we have reported a numerical model accounting up to third-order harmonic distortion and tested it against the results provided by a experimental [24]. A CW laser at 1550 nm is modulated by a 20 GHz microwave tone by means of a dual-drive zero-chirp EOM. Harmonic levels were measured using a Lightwave Spectrum Analyzer (LSA), while the phase shift experienced by the fundamental tone was measured by a Vector Network Analyzer (VNA). We first address the theoretical and experimental harmonic distortion generated within the SOA device when optical filtering is included to suppress the red-shifted frequency sideband after SOA propagation. Two filtering configurations are compared when large signal operation is required for different modulation depths, $q=|E_1(0)|^2/|E_0(0)|^2$, where $E_1(0)$ represents the field amplitude of the component at $w_0+\Omega$ at the SOA input (z=0). One of the filtering schemes corresponds to the typical notch filter implemented by a Fiber Bragg Grating device operating in transmission.

The theoretical and the experimental microwave phase shift obtained for the fundamental tone, when achieving a 40 dB attenuation level by means of this notch filtering scheme, are shown in Fig. 10. The main issue to be pointed out is the remarkable dependence of the phase shift upon the value of q, which comes as a consequence of the power and phase fluctuations produced by the nonegligible interaction between the fundamental and the harmonics within the SOA.

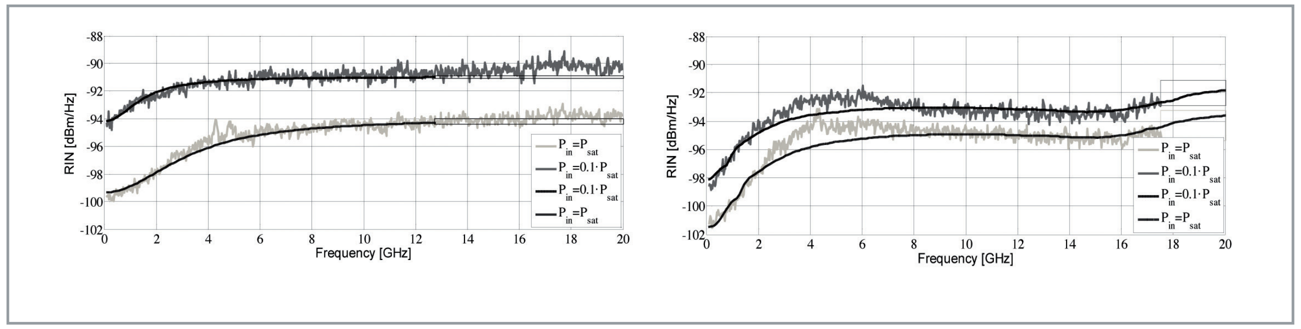
To overcome this nondesirable behavior, we propose a prefiltering scheme whereby a passband filter is included, prior to the SOA, in order to attenuate by more than 20 dB the high-order harmonics produced by the EOM. For the sake of comparison, the microwave phase shift corresponding to simultaneous pre and postfiltering implementations has also been plotted in Fig. 10. We can appreciate not only the reduced dependence on the value of the modulation index, but also that less optical power is required to achieve a particular phase-shift level.



■ **Figure 10.** *Theoretical (lines) and experimental (markers) RF phase shift for the fundamental tone in the presence and absence of the prefiltering scheme. Results are shown for different modulation depths, q.*

The SOA is an active device that generates amplified spontaneous emission (ASE) noise. Besides, it has been shown in the previous section that the red-shifted sideband at the SOA output must be filtered prior to the photodetection to obtain larger phase shifts of the microwave signal, yielding the main drawback of the attenuation of the signal. These two effects deteriorate the signal-to-noise ratio (SNR) of SOA-based optical phase shifters [25]. Fig. 11 shows the electrical power spectrum at the output of the photodetector after passing the microwave signal through a SOA. When injecting a strong optical signal into the SOA, saturation will affect the amplifier gain response. Thus, the RIN spectrum decrases in the low-frequency range when the input optical power is increased. Fig. 11(b) shows the results of filtering the SOA output by an FBG centered at a frequency that is red-shifted bv around 10 GHz from the optical carrier.

By considering the case in which no filter is used, the amplitude difference in the vicinity of 10 GHz is about 3 dB. In case of studying the aforementioned amplitude difference when the filtering process is implemented, one can notice that it becomes lower. Specifically the difference is reduced till 1.5 dB. This fact is consistent with the analytical model presented in [25]. Fig. 11(b) shows a discrepancy between calculated data and measurements at frequencies around 4.5 GHz. This effect is due to the properties of the laser source used for pumping the SOA. Specifically, the laser source is characterized by a relaxation oscillation frequency of approximately 4.5 GHz, giving as a result a RIN peak power at that frequency which becomes significant in the total RIN noise when filtering is performed.



■ **Figure 11.** *Electrical noise spectrum after photodetection as a function of the optical input power to the SOA. (a) Without Optical Filter. (b) With Optical Filter. Dashed and dotted traces correspond to those achieved by calculations, whereas continuous ones are obtained via measurements. For carrying the measurements out, time averaging of 20 traces has been set.*

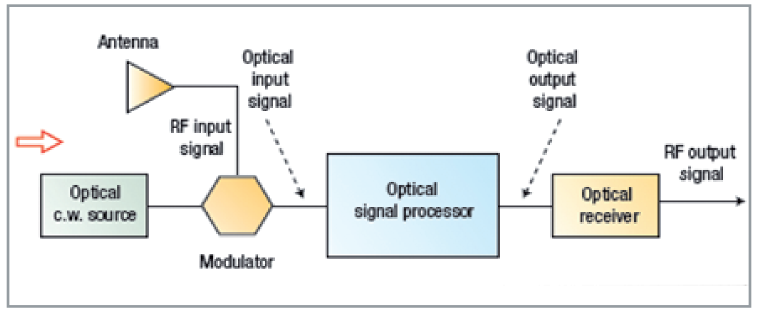
5. Microwave photonic filter based on soas

The basic configuration of a microwave photonic filter is shown in Fig. 12. The concept of the microwave photonic filter is to replace the traditional RF signal processing unit. An RF signal originating from an RF source modulates an optical carrier and it is directly processed in the optical domain. One of the advantages of using photonic components is that the microwave photonic filters can be made tunable and reconfigurable, a feature that is not possible with common microwave technologies. The electrical transfer function of a finite impulse response (FIR) microwave photonic filter is given by [17]:

$$H(\Omega)=\sum_{r=0}^{N} a_r e^{-j(r\Omega T+\phi_r)} \tag{5}$$

Here, T is the basic delay unit of the filter, and a_r, ϕ_r the amplitude and phase of the filter coefficients. It should be remarked that the phase coefficient should be constant in the range of frequencies where the filter is working. The use of a phase shifter based on SOAs can help in the design of an integrated version of a microwave photonic filter, and also gives some flexibility to control the amplitude coefficients (see Fig. 12). To demonstrate the validity of this assumption a microwave photonic filter was implemented [26].

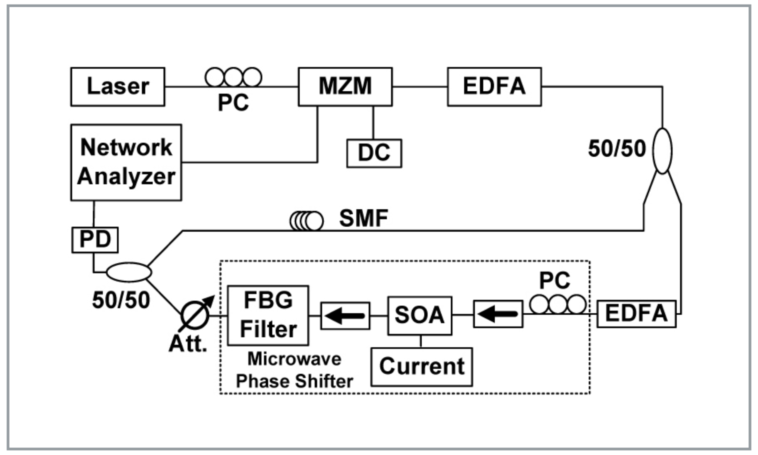
Fig. 12. Fig. 13 describes the experimental scheme. The filter itself has a Mach-Zehnder configuration composed of two arms, one of which incorporates the microwave phase shifter, shown in the dotted-line box, which is made up of an SOA followed by an FBG notch filter. The EDFA is used to adjust the SOA input optical power, in order to ensure that the SOA operates in the saturation regime. After the microwave phase shifter, a tunable attenuator provides amplitude balance between the two arms to compensate



■ **Figure 12.** *Schematic of the microwave photonic filter.*

the ~10 dB power change of the output signal after the SOA. The phase shift can be tuned by changing the injection current of the SOA or by changing the input optical power to the SOA. Fig. 14 shows the measured response of the microwave photonic filter. It has been tuned by changing the injection current to the SOA.

A phase shift of 360º can be achieved by cascading the structure SOA+filter or using the feature of the Mach-Zehnder Modulator to modulate the microwave signal in-phase or out-of-phase with the optical carrier. In this experimental setup, the bias point of the MZM has been chosen at V_1=4.5V and V_2=8.1V, to achieve the 360º phase shift. Note that the switching between the two different operating points of the MZM will



■ **Figure 13.** *Experimental set-up of a tunable two-tap microwave photonic filter. (Att.: tunable attenuator; PC: polarization controller.)*

We include the implementation of fully tunable 360º phase shifters over bandwidths in excess of several GHz

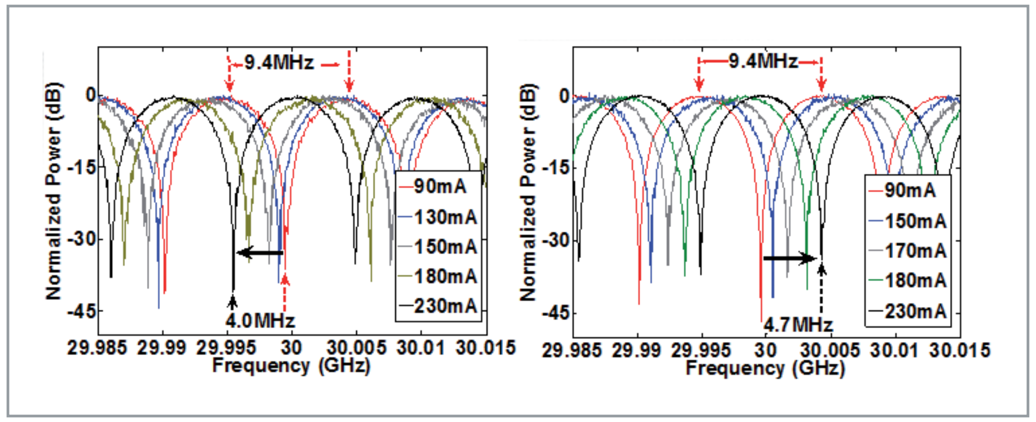


Figure 14. *Tunable RF response of the notch filter obtained by changing the injection current of the SOA, when the modulator is biased at (a) V_1=4.5 V and (b) V_2=8.1 V.*

not change the spectral shape of the filter. Fig. 14 shows that the Free Spectral Range (FSR) of the filter is 9.4 MHz, corresponding to the 22 m optical fiber length difference between the two arms. The notch rejection is larger than 30 dB over the entire tuning range.

6. Conclusions

We have provided a comprehensive review of the application of Slow and Fast light techniques to the field of Microwave Photonics. Basic principles leading to the implementation of phase shifting, which is instrumental in this field, have been explained. We have described the main results obtained by our group in the implementation of broadband, full 360º phase shifters based on coherent population oscillations in semiconductor waveguides. Finally, the main results obtained for the Microwave Photonic Filter application have been presented, pointing towards the potentials of the SFL techniques based on SOAs.

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