Sección Especial: Óptica No Lineal / Special Section: Non-linear Optics

Application of slow and fast light effects to microwave photonics

Aplicación de los efectos de luz rápida y luz lenta a la fotónica de microondas

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ABSTRACT:

We present 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 key desired functionalities as tunable microwave phase shifting and true time delay operations are considered. We focus on the description of the significant breakthroughs based on nonlinear optics technologies developed in this field by the Optical and Quantum Communications Group of the Telecommunications and Multimedia Applications Research Institute (ITEAM) at the Universidad Politécnica de Valencia. Particularly, recent approaches enshrined in two different Slow Light technologies are overall described: coherent population oscillations (CPO) in semiconductor optical amplifiers (SOAs) and stimulated Brillouin scattering in optical fibers.

Keywords: Microwave Photonics, Slow Light, Coherent Population Oscillations, Semiconductor Optical Amplifiers, True Time Delay, Stimulated Brillouin Scattering.

RESUMEN:

Presentamos una reseña global de la aplicación de técnicas basadas en luz lenta y luz rápida al campo de la fotónica de microondas. Para ello consideraremos los principios básicos que permiten la implementación de funcionalidades clave como son las operaciones de desfase sintonizable sobre una señal de microondas y líneas de retardo sintonizables. Nos centraremos en la descripción de los progresos más significativos, basados en tecnologías de óptica no lineal, desarrollados en este campo por el Grupo de Comunicaciones Ópticas y Cuánticas del Instituto de Telecomunicaciones y Aplicaciones Multimedia (TEAM) sito en la Universidad Politécnica de Valencia. En particular, realizaremos una descripción general de los principales trabajos de investigación enmarcados en dos tecnologías basadas en luz lenta: Oscilaciones coherentes de la población (CPO) en amplificadores ópticos de semiconductor (SOAs) y dispersión estimulada de Brillouin en fibras ópticas.

Palabras clave: Fotónica de Microondas, Luz Lenta, Oscilaciones Coherentes de la Población, Amplificadores ópticos de semiconductor, Líneas de retardo, Dispersión Estimulada de Brillouin.

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1. Introduction

The last years have witnessed an increasing interest in the study and development of novel materials, devices and technologies, with the aim of controlling the speed of light [1,2]. This field of activity, now known within the photonics community as slow and fast light (SFL), offers the potential of direct application to a wide variety of signal processing tasks which are currently needed both in digital and analog systems [2]. SFL can be achieved either by inducing modifications in the material properties or by modifying the structural properties of the SFL medium, thereby changing the propagation characteristics. Several optical phenomena and technologies have been reported in the literature to implement slow and fast light devices by exploiting several nonlinear effects, including electromagnetic induced transparency in cold atoms, solid state devices, stimulated Brillouin scattering (SBS), [5-7], and stimulated Raman scattering in optical fibers, photonic crystals, semiconductor waveguides [2,4], dispersion-compensating fibers (DCFs), fiber Bragg gratings (FBGs) and coupled cavities.

In general, the group velocity can be defined as:

$$v_g = \frac{c}{n} = \frac{c}{n' + \omega \frac{\partial n\prime}{\partial \omega}} \ , \qquad (1)$$

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 ($\partial n'/\partial\omega > 0$), i.e. $v_g < c_0/n'$, the term *slow light* propagation is employed whilst when the medium shows anomalous dispersion ($\partial n'/\partial\omega < 0$) $v_g < c_0/n'$, the case is referred to as *fast light* propagation.

A field of potential applicability of SFL techniques can be found in Microwave Photonics (MWP), where the basic functionalities of interest become the implementation of both tunable true time delays and broadband tunable microwave phase shifters, in contrast to digital applications in which the key desired functionality is the availability of delay lines for the design of optical buffers. The main MWP applications in which SFL based microwave phase shifting operation has been successfully demonstrated include MWP filters and tunable optoelectronic oscillators, while optical beamforming in wideband phased-array antenna (for radars and ultra wideband communication among others) is one of the promising fields where true time delay operation can be exploited.

In this context, one of the most relevant research lines related to nonlinear optics that is performed in the *Optical and Quantum Communications Group* (OQCG) of the *Telecommunications and Multimedia Applications Research Institute* (ITEAM) is the application of SFL techniques based on two different approaches: the so-called coherent population oscillations (CPO) in semiconductor optical amplifiers (SOAs) and stimulated Brillouin scattering in optical fibers. This work has been carried out in the framework of the European FP7 project GOSPEL (Governing the Speed of Light).

2. Slow light microwave photonic phase shifters based on coherent population oscillations in SOAs

One of the most successful nonlinear optics approach reported so far in the GCOC-ITEAM for the implementation of broadband tunable microwave phase shifters is based on the so-called Coherent Population Oscillations (CPO) in Semiconductor Optical Amplifiers (SOAs) [2-4]. Different contributions of our work related to the enhancement of the phase shifting operation and the analysis of different figures of merit in MWP applications can be encountered in [2], [4].

2.a. Coherent population oscillations (CPO) in semiconductor optical amplifiers

When an optical beam composed of an optical carrier and two RF sidebands interacts with carriers inside the semiconductor, through stimulated emission, a modulation of the semiconductor carrier density is produced introducing carrier population oscillations at the RF frequency Ω. These oscillations generate, in turn, a temporal grating, causing dispersive gain and index modifications on the two sidebands of the travelling optical field while inducing wave mixing between them. However, the effect of the refractive index dynamics, is of opposite signs in the upper and lower sidebands so eventually is cancelled upon beating at the detector, which does not allow significant microwave phase shift in the detected signal. Because of this, a slight variation must be introduced which generates an asymmetry in the effect of the refractive index gain dynamics. In the case of a SOA-based device, a notch filter is introduced after the SOA to suppress one of the sidebands. Both the phase excursion (up to 150º) and the bandwidth (range of 50 GHz) are considerably enhanced if the red-shifted sideband is blocked.

Semiconductor waveguides 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 or even CPO in other material systems. 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. In particular, it must be noted that tunable microwave phase shifting has been demonstrated in several applications such as microwave photonic filtering [2] and optoelectronic oscillators [2]. Coherent Population Oscillations (CPO) in Semiconductor Optical Amplifiers can actually support both MWP functionalities enabled by SFL: tunable true time delays (standalone SOA configurations) and broadband tunable microwave phase shifters, which as mentioned requires optically filtering the red-shifted RF sideband at the output of the SOA prior to photodetection [2,4]. Furthermore, by cascading several SOA + optical filtering stages a full tunable 360º phase shift can be achieved at very high frequencies [2].

2.b. Nonlinear distortion evaluation in SOA-based microwave phase shifters

As with any element in a microwave photonic link, the impact of the SOA-CPO device must be evaluated, especially in terms of noise and nonlinear distortion, which can degrade the systems performance. The activities performed in the OQCG have been precisely focused on the theoretical and experimental evaluation of the propagation, generation and amplification of signal, harmonic and intermodulation distortion terms inside a semiconductor optical amplifier (SOA) under coherent population oscillation (CPO) regime. For that purpose, we developed in first place a general optical field theoretical model that contains the equations accounting for any general order M of both harmonic and intermodulation distortions valid for a modulating signal composed of N any arbitrarily-spaced radiofrequency tones, which is in turn necessary to correctly describe the operation of CPO based microwave photonic phase shifters which must comprise an electrooptic modulator and a SOA followed by an optical filter, since the location of an optical filter after the SOA requires a description based on the propagation of optical fields. One of the most important novel features of this model lies in rendering the value of the optical field for any significant frequency component at the output of the SOA device. Regarding this issue, the main contribution with respect to the model presented in [3] relies on the consideration of arbitrarily frequency-spaced modulating tones, since [3] particularly accounts for equispaced channels. On the other hand, our description is based also on the consideration of the distortion introduced by an EOM, instead of presuming, as customary in the literature, an ideal [3] or a zero-chirp EOM.

For the experimental analysis of the nonlinear distortion introduced in the SOA based microwave phase shifter, our activities were mainly focused on evaluating the phase shifting performance as a function of the SOA input optical power, the electrical input power (dynamic range) and the modulation frequency (spectral response). The experimental setup that allowed us the evaluation of the nonlinear distortion up to 3rd order when the modulating signal is composed of two RF tones is depicted in Fig. 1. A CW laser is modulated by the RF tones by means of a dual-drive zero-chirp EOM, where we selected diverse modulating frequency cases representative of a broadband signal transmission scenario in order to cover different MWP applications. The microwave phase shifter is formed by a SOA and a filtering stage implemented by a fiber Bragg grating (FBG) operating in transmission, whose response is also illustrated in Fig. 1. The diagram of the frequency components at both the EOM output and the phase shifter output were also included, showing how the filter blocks the red shifted frequency sideband in order to enhance the achievable microwave phase shift.

One example of the performed evaluation of the photodetected RF power (P_d) versus the RF input power for the special case of f_1=9 GHz and f_2=12 GHz is shown in Fig. 2. These experimental (markers) and theoretical (lines) results are plotted for every signal [Ω_1, Ω_2], relevant IMD [$\Omega_1+\Omega_2$, $\Omega_2-\Omega_1$, $2\Omega_1-\Omega_2$, $2\Omega_2-\Omega_1$] and harmonic distortion (HD) [$2\Omega_1$, $2\Omega_2$] terms. It is also included (dashed curves and points) the equivalent power that would be collected if a photodetector were placed at the SOA input (P_{in}). It is important here to understand that the laser power was set to 0 dBm to guarantee the SOA is working under saturation regime. The filter modeling was performed meticulously applying the measured response values from Fig. 1. For the performance evaluation, we resorted to the Spurious Free Dynamic Range (SFDR) which is defined as the carrier-to-noise ratio when the noise floor in the signal bandwidth equals to the power of a given order IMD. Thanks to the dynamic range analysis, we can show the feasibility of obtaining a reasonably good margin of SFDR values limited by 3rd order nonlinearities in the range of 100 dB/Hz$^{2/3}$, high enough for the majority of applications where the phase shifter can be integrated. Our work has also confirmed that CPO based phase shifters are mainly limited by 2nd order nonlinear distortion which can, nevertheless, be overcome by pacing all the relevant input signals within an octave in the RF spectrum.

The evaluation of our device performance required us also to study the phase shifter operation in function of the optical power at the SOA input. Significant results of the measured and computed photodetected RF power and microwave phase shift for every fundamental, HD and IMD term up to order 3 are shown in Fig. 3 for the same representative scenario [f_1=9 GHz, f_2=12 GHz]. With this performance study we show mainly, at a first glance, the expected

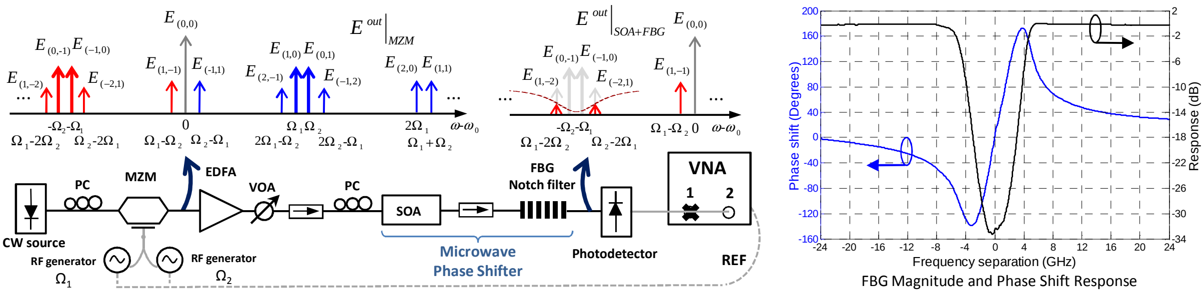

Fig. 1. Experimental setup. Diagrams of the field complex amplitude components. Measured FBG magnitude and phase shift responses.

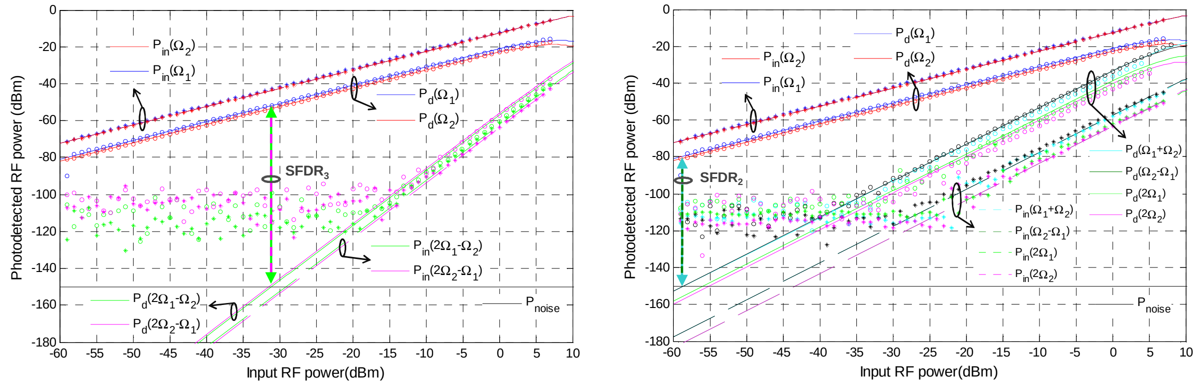

Fig. 2. Theoretical (lines) and experimental (markers) photodetected RF power (solid lines and circles) as function of the input RF power including 2nd and 3rd order SFDR. The dashed lines and the points correspond to the RF power at the SOA input.

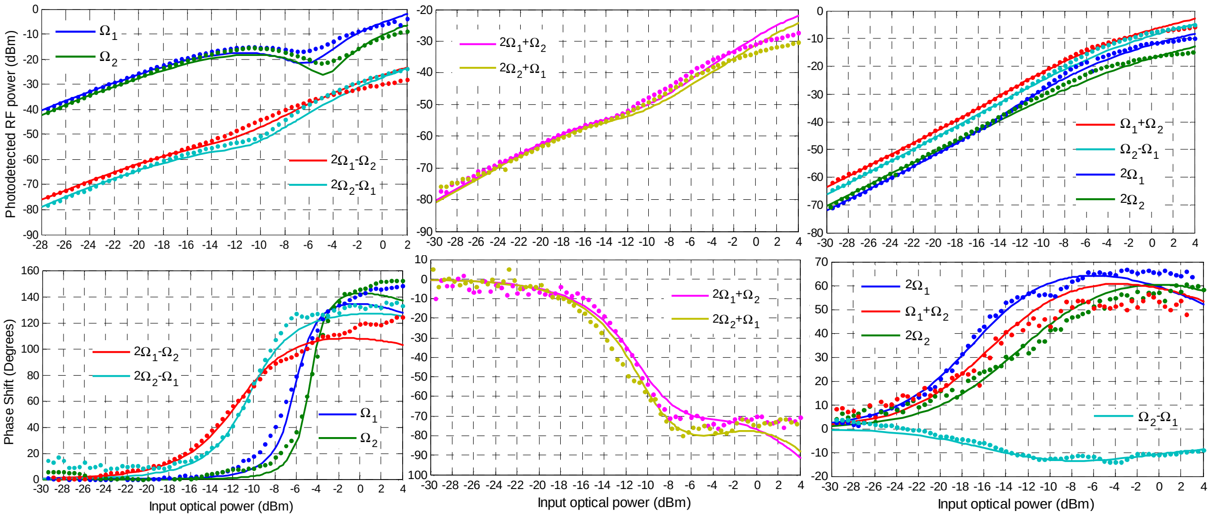

Fig.3. Theoretical (lines) and experimental (markers) photodetected RF power and microwave phase shift.

power dip/phase shift sharp transition of around 140º, 150º for the fundamental signals when filtering the red-shifted frequency sideband. Secondly, our work concluded that the intermodulation terms placed at $2\Omega_1$–Ω_2 and $2\Omega_2$–Ω_1 experience a phase excursion similar to that experienced by the fundamental signal although slightly reduced as a consequence of the implied filter attenuation reduction over these components.

On the contrary, the terms located at frequencies $2\Omega_1+\Omega_2$ and $2\Omega_2+\Omega_1$, although not suffering any optical attenuation after SOA propagation, experienced also the phase excursion characteristic of the microwave phase shifter operation, as it is corroborated by other activities performed in the OQCG regarding the spectral analysis.

3. Microwave photonic functionalities enabled by stimulated Brillouin scattering

3.a. General remarks

The second nonlinear optics technology that is being considered by GCOC-ITEAM researchers in the context of the GOSPEL project is based on exploiting slow and fast light effects enabled by Stimulated Brillouin Scattering in optical fibers. Within the context of Microwave Photonics applications it is again tunable phase shifters and true time delays for radiofrequency signals the functionalities that have focused our attention. In the following paragraphs, we briefly describe some of our main findings. The interested reader is directed to the literature for further details [5,6].

3.b. Phase shifters

The possibility of obtaining broadband and tunable phase shifting of radiofrequency carriers by means of exploiting SBS in fibers was first proposed and experimentally demonstrated by researchers at the public university of Navarra [7]. The rationale behind this technique is shown in the upper left part of Fig. 4.

Brillouin scattering stimulated by a pump carrier $\nu_B+\Delta\nu$ induces a narrowband (around 80-100 MHz) amplifying resonance in modulus and a 2π phase shift transition centered around ν_B. At the same time a Stokes wave at $\nu_B-\Delta\nu$ induces a narrowband absorbing resonance in modulus and a 2π phase shift transition centered around ν_B. A careful selection of the input powers of both pump and Stokes waves results in an overall unit gain in modulus and a 2π phase shift with double spectral slope around ν_B. To achieve a tunable radiofrequency phase shift, a single sideband modulated optical carrier at ν_B is sent to the fiber. Figure 4 clearly shows that the optical carrier is inside the narrowband spectral region where an optical phase shift from 0 to 2π can be achieved by changing the frequency detuning $\Delta\nu$. The RF sidebands on the other hand, experience no phase shifts as they are placed outside the SBS band. Therefore, upon beating at the photodetector the optical phase shift of the optical carrier is translated to the RF signal. This technique is inherently broadband and the work in [7] reported successful operation up to 20 GHz. In the context of the GOSPEL project, we have demonstrated the operation up to 50 GHz. The lower part of Fig. 4 depicts the setup employed in the experimental demonstration, while the upper right part of Fig. 4 shows the tunable and broadband phase shift obtained for different values of the frequency detuning $\Delta\nu$. The salient features of our reported results are the following: 2π full tunable PS with single external electrical control, less than 2 dB RF power variation, bandwidth (50 GHz) limited by RF generator and receiver deployed and fixed signal delay and pump.

3.c. True time delays

The narrowband spectral characteristic of the resonances induced by SBS in fibers initially precludes its possible operation as true time delays, since for this application both the optical carrier as well as the RF sidebands must experience the same delay. However, a recently proposed technique known as Separate Carrier Tuning (SCT) [8] can be employed to circumvent this, otherwise unsurpassable limitation. To explain the implementation of true time delays using SBS in optical fibers and the SCT technique we refer to Fig. 5.

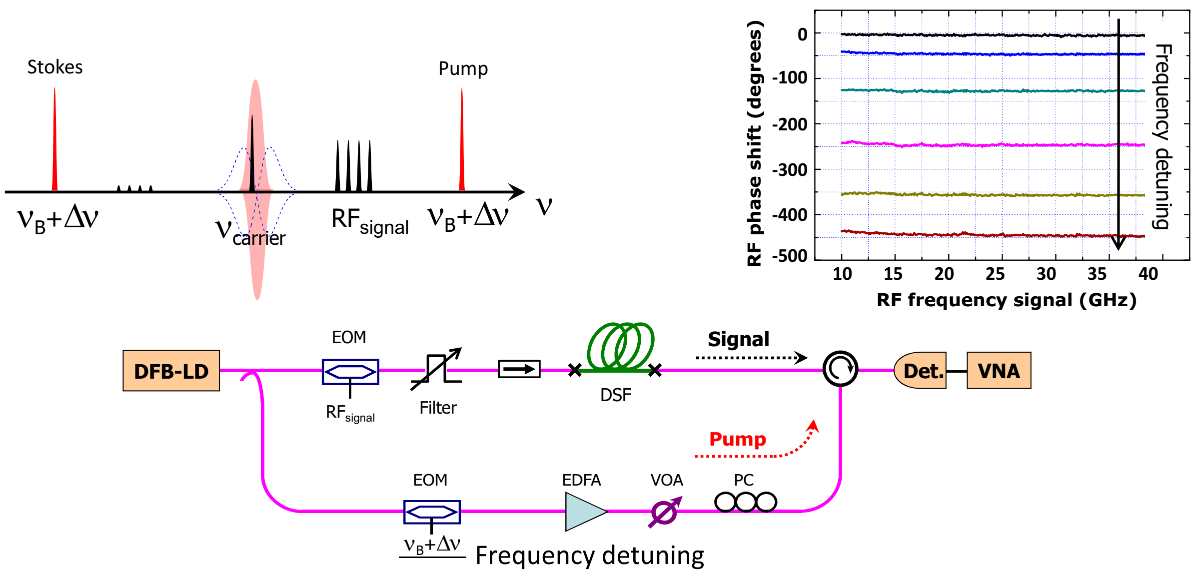

Fig. 4. Rationale (upper left), experimental configuration (lower) and results (upper right) for the implementation of tunable RF phase shifts using SBS in optical fibers.

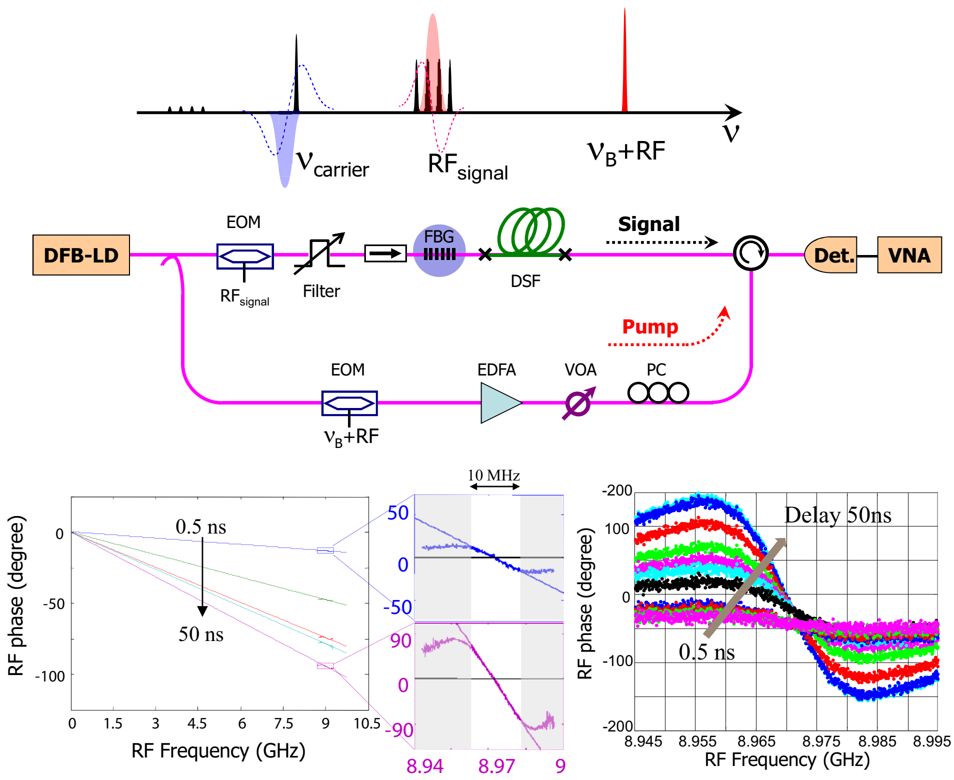

Fig. 5. Rationale (upper), experimental configuration (middle) and results (lower) for the implementation of tunable RF True Time Delay using SBS in optical fibers.

The upper part describes the principle of operation. In this case only a pump wave is required. The signal carrier is such that the RF sideband falls inside the SBS amplifying resonance. By changing the power of the pump wave the spectral slope of the phase shift (or in other words the group delay) experienced by the RF sideband can be changed or tuned. This can be appreciated in the lower right part of figure 5. In addition, the signal carrier must be passed through a separate optical filter implementing a phase shift that corresponds to the extrapolated value of that achieved in the RF spectral region assuming that the phase spectral slope is kept constant. The intermediate part of Fig. 5 shows the setup that was assembled in the laboratory to provide the world first-ever implementation of a true time delay line based on SBS [6,7]. Some of the most important results are shown in the lower left part of Fig. 5. In particular both theoretical and experimental curves are depicted and insets are also provided to explicitly show the excellent agreement between both of them in the region of 8.95 GHz, which was the initial target of the experiment. The following summarises the characteristics and values obtained in our experiments: Pump power tuning: 0.5 to 50 ns of delay tunability, 10 MHz TTD bandwidth, limited by the SBS bandwidth, independent on the operating RF frequency and carrier phase shift required for real TTD implemented by means of a Fiber Bragg Grating (FBG) filter.

4. Conclusions

We have provided an overall review of the main contributions to the field of nonlinear optics performed by the OQCG-ITEAM in the context of Slow and Fast Light Effects applied to Microwave Photonics. The promising results obtained in two of the main technologies enshrined in the European project GOSPEL have been described, that is, the Coherent Population Oscillations (CPO) in Semiconductor Optical Amplifiers (SOAs) and stimulated Brillouin scattering in optical fibers. This work confirms the feasibility of extending nonlinear optics based approaches for the implementation of two of the most relevant MWP key functionalities, tunable broadband microwave phase shifters and tunable true time delays, essential both for applications such as microwave photonic filters and optical beamforming in wideband phased-array antennas.

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