Slow Light Devices and Their Applications to Microwaves and Photonics

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Abstract – Recently developed, highly effective technologies enabling slow light propagation as a tunable feature in photonic devices, are reviewed. Several applications in ICT are also demonstrated. Controlling the group velocity of light offers a broadband solution to a necessary functionality in microwave and millimeter wave systems: a tunable time-delay/phase-shift line. Moreover, slow light can highly enhance the nonlinearity, thus opening the way to on chip, nonlinear photonics.

I. Introduction

Slow light (SL) refers to the possibility of controlling the group velocity of an optical signal, which can be achieved by modifying the dispersion of the medium or by designing the guiding structure [1]. The record (17m/s) in slowing down light group velocity was obtained through the electromagnetically induced transparency (EIT) [2]. Though the cryogenic temperatures and the very narrow bandwidth of EIT prevented the direct applications in the Information and Communication Technologies (ICT) domain, the results of ref. [2] fostered the search for SL devices at room temperature and with much broader bandwidth, like semiconductor waveguides [3, 4], optical fibers [5, 6] and coupled cavities [7, 8]. SL has been initially considered as a route to optical buffering; however, the intrinsic limitations of SL hinders its application in high bit rate telecom routers [9]. Nonetheless, the potential of SL in ICT applications is huge, as it will be shown here.

In the field of microwave-photonics (MWP), in which photonics is exploited to process microwave signals, breakthrough progress has been demonstrated [10, 11]. In MWP, SL enables a continuous tuning of the phase-shift or time delay of the microwave signals that modulate the optical carrier, with very low losses and distortion and over bandwidths that can be incomparably larger than those provided by electronic devices of comparable cost.

As for photonics, the striking property of structural SL to enhance optical nonlinearities is playing a major role in the progress toward on-chip, all-optical signal processing [12].

In this article, we will highlight the most recent and relevant research advancements in SL, in particular those obtained in the Future and Emerging Technology research project "GOSPEL" of the 7th European Framework Programme [13].

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The paper first presents some practical SL devices and then shows how they can be applied to achieve unique features both in MWP and photonics.

II. Slow Light: Physical Principles

First of all, it is useful to briefly introduce the fundamental principles of SL. For a wave-packet travelling in a medium or waveguide, SL entails the modification of the group velocity

$$v_g = \frac{dk}{d\omega} = \frac{c_0}{n + \omega \frac{dn}{d\omega}} = \frac{c_0}{n_g} \tag{1}$$

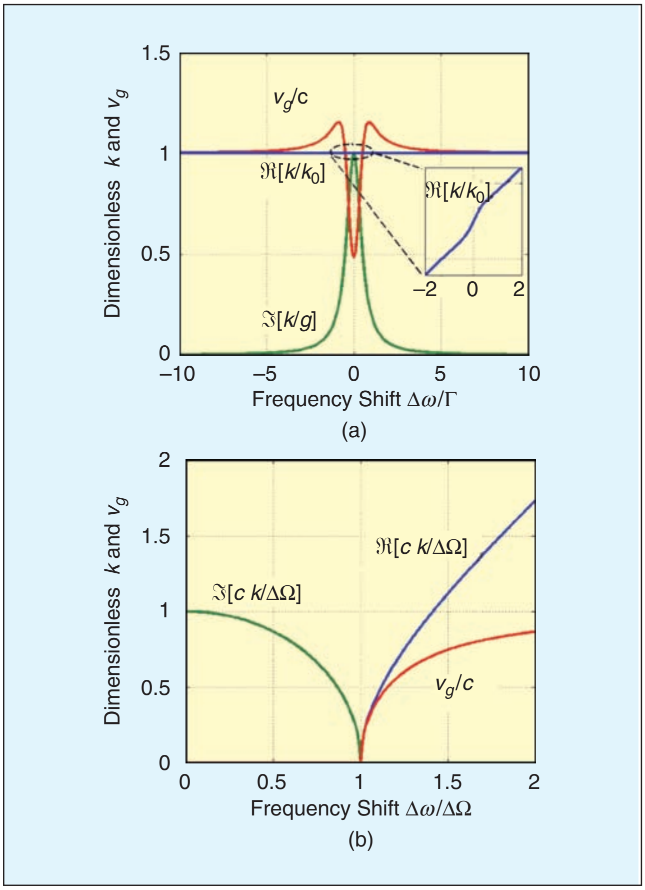

Figure 1. Typical frequency dependence of the real part (blue curve) and imaginary part (green curve) of the propagation constant k, and of the group velocity (red curve), in material SL, (a) (Γ resonance linewidth; $\Delta\omega$ frequency detuning from resonance ω_0; g gain coefficient, $k_0 = k(\omega_0)$, c light phase velocity in the medium) and in structural SL, (b) ($\Delta\Omega$ band-gap).

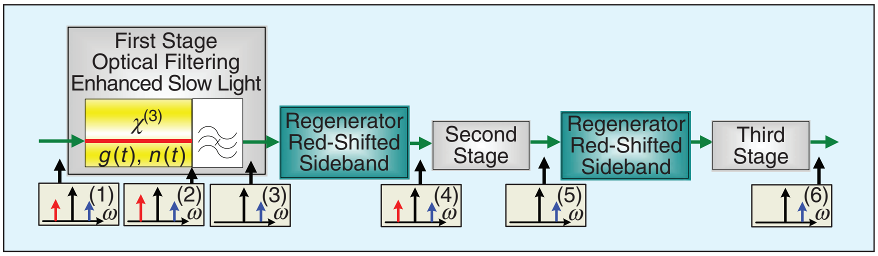

Figure 2. Simplified diagram showing the cascading of stages of phase shifters followed by regenerators to achieve a full 2π phase shift.

where $k(\omega)$ is the wavenumber, c_0 is the light speed in vacuum, $n(\omega)$ is the effective refractive index and n_g is the group index. When the dispersion is normal $(dn/d\omega > 0)$ then $v_g < c_0/n$ and SL propagation is achieved. Ultimately, SL entails the engineering of dispersion, in particular realizing conditions such that large group index, low distortion and low absorption are achieved at the same time. To modify n_g, two main approaches can be followed, depending on whether the changes are due to the material or to the structural dispersion.

In the first type, modifications of the material dispersion are achieved by means of an artificial manipulation of absorption or amplification in the medium, often through other optical effects (Fig. 1 (a) refers to stimulated Brillouin scattering – SBS). EIT, coherent population oscillation (CPO) in semiconductor optical amplifiers (SOAs), several nonlinear effects in optical fibers like Raman scattering, SBS, optical parametric amplification (OPA) are all examples of material SL effects. The main advantage of material SL is that the magnitude of the time delay is directly tunable through a control parameter (electrical current, optical pump power, etc.). The main limitation is that the delay-bandwidth product, a fundamental figure of merit of SL, is not much greater than unity, and so delays are of the order of the pulse-width. Moreover, material dispersion is large close to a resonance; hence, to achieve large delays, large absorption or gain [14], or a cascade of absorptive/amplifying elements [15,16] is needed. Then, noise or distortion, due to group velocity dispersion (GVD) or the reduced amplification bandwidth, can become too large at the device output.

In a second type of SL devices, the dispersion is modified by a proper design of the structural properties of the optical waveguides. This class of SL includes coupled cavities [7, 8] and photonic crystal (PhC) waveguides and cavities [17]. There are three key features that make these devices extremely attractive for applications. The first is that, differently from material SL, the propagation occurs virtually without loss (or gain). In fact, in the material transparency window, the SL regime is separated from the loss regime (i.e. the band-gap) (see Fig. 1, (b)). The second advantage is that such devices can be realized with integrated photonic circuit technology, thus having the potential for large footprints and parallelization. Finally, as mentioned in the introduction only in structural SL energy velocity coincides with group velocity and so the enhancement of the nonlinear effects can be expected [18].

III. Devices for Slow Light

In this section some recently developed SL devices, specially targeted to MWP and photonics applications, are presented.

In SOAs the control of the light group velocity is realized by using CPO effects [3, 4, 19]. In particular, the phase-shift induced on the modulating signal at the photodetector (see also Fig. 5) can be enhanced by suppressing one of the mixing optical waves by filtering the signal just before photodetection, and by cascading a few of such devices, like in Fig. 2. In ref.

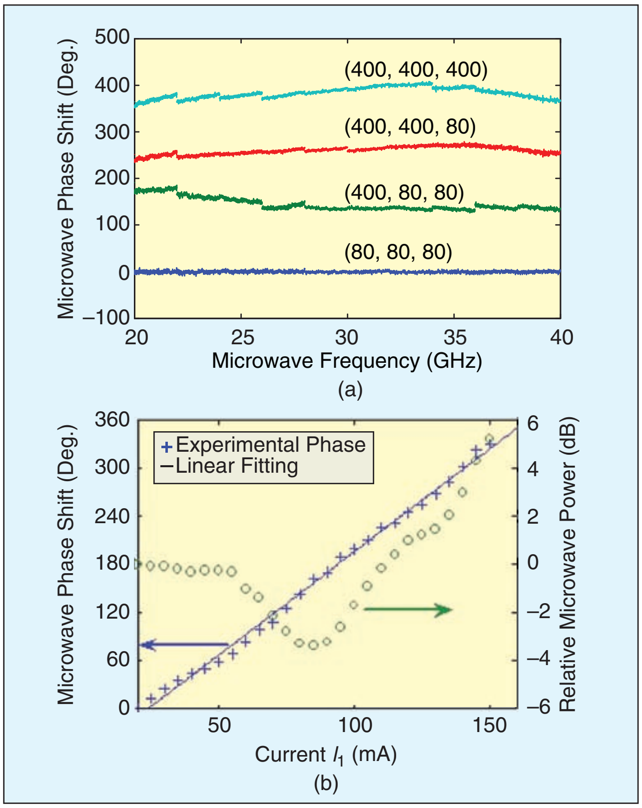

Figure 3. (a) Measured RF phase shift as a function of the modulation frequency (currents injected in each of threes SOAs, are given in mA for each curve). (b) measured RF phase shift and output power as a function of the SOA control electrical current of a microwave phase shifter based on SL in SOAs.

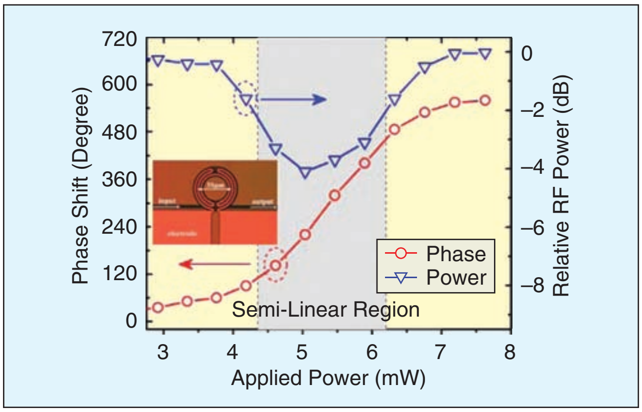

Figure 4. Measured RF phase shift and power as a function of the power applied to the micro heaters for a dual-MMR. Inset: top-view microscope picture of a fabricated tunable MRR with micro heater.

[19] it has been demonstrated that full phase tuning (0–2π), for microwave signals in the band 9–40 GHz can be achieved. The tuning curve is linear with SOA applied current and low amplitude distortion occurs (Fig. 3). An interesting alternative to increase the integration and reduce the power consumption of SL-based MWP phase shifters is represented by silicon-on-insulator (SOI) micro-ring resonators (MRR), previously used for photonic delay lines [8]. By tuning the resonance frequency, through temperature changes, full MWP phase tuning can be achieved (Fig. 4) over 40 GHz [20, 21].

The potential of photonic crystal waveguides (PhCWs) in SL is enormous [17] because these devices, through the dispersion engineering, can provide large group index (n_g up to 100) with very low distortion (GVD less than 1ps^2/mm). High quality membrane PhCWs for SL can be realized in silicon [17, 22] or III-V semiconductors [23].

The use of III-V compounds is particularly attractive for two reasons. The first is that losses can be minimized in such waveguides. In fact at telecom wavelengths (~1.5μm) the contribution of two-photon absorption is small [23].

Moreover the quality of membrane PhCW realized in III-V materials (Fig. 5 (a)) has reached state-of-art quality, with respect to surface roughness, another major contribution to losses in the SL regime [24]. Finally, the design of special mode adapters (Fig. 5 (b)) has finally reduce total insertion losses for mm-long waveguides to about 6 dB.

The second reason for using III-V compounds is clear: they are electro-optical and active materials, a property that might enable to achieve new functionalities in integrated, compact and robust devices. To this aim it will be fundamental to develop the ability of placing quantum dots (QDs) in specific positions within the PhC. An example of the result of site-controlled epitaxy of InAs QDs on pre-patterned GaAs substrates [25] is shown in Fig. 6.

We also note that the combination of structural and material SL can be beneficial. It has thus been predicted that by incorporating QDs in a PhC waveguide, the structural PhC dispersion can be used to enhance the weak, but readily tunable, SL effect due to EIT in QDs [26].

Optical fibers are very convenient devices for SL and SBS-based SL [4, 27] is a very flexible tool for manipulating MWP signals, as it will be shown in the following section. Moreover, the possibility of storing with high fidelity the optical wave (both amplitude and phase) in the acoustic wave (the so-called dynamic Brillouin grating – DBG) opens unprecedented chances for all-optical signal processing [28]. OPA is also very attractive for microwave and millimeter waves, because of the extremely large bandwidth for delay (more than 100 GHz). However, random birefringence, which causes a polarization mismatch between the pump and the signal waves, must be controlled and special fibers, very difficult to produce, are required [29, 30].

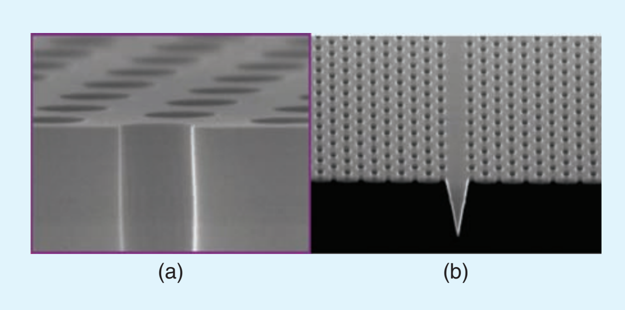

Figure 5. (a) high-quality InP PhC; hole distance is about 500nm, hole diameter 200 nm. (b) mode adapter to reduce coupling losses.

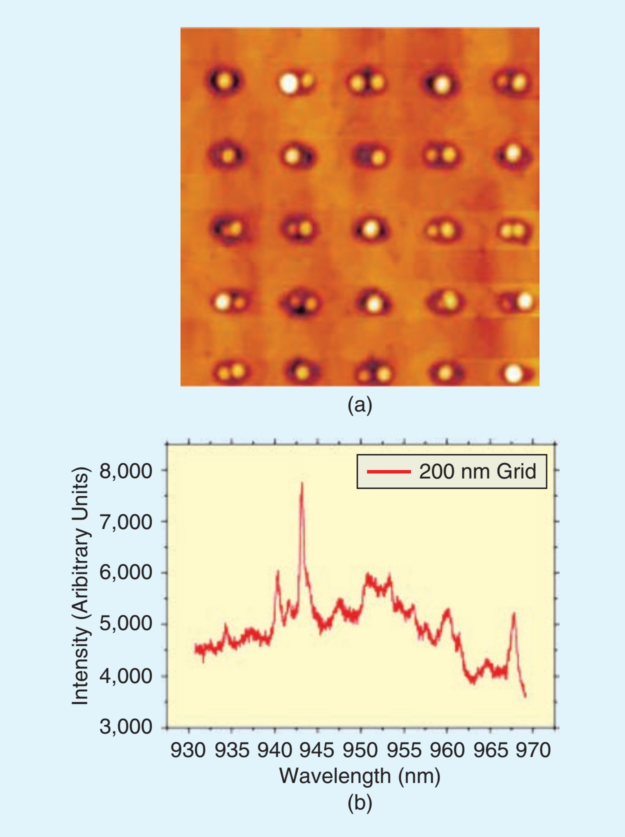

Figure 6. AFM image (a) and μ-PL spectroscopy (b) of 1.5 ML QDs on patterned substrate with 200 nm distance between the holes.

IV. Applications to Microwaves and Photonics

The advantages presented by an optical delay line in microwave signal processing are well known [31]. The microwave, or millimeter waves, modulating an optical carrier occupy a small fraction of the optical spectrum, so they are barely affected by losses and dispersion. So far, the inability to tune the delay has been the main limitation of optical delay lines. SL devices solve this problem and tunable phase-shift or time-delay for microwaves and millimeter waves can be achieved, as sketched in Fig. 7.

The fine tuning of the phase shift provided by SL can be exploited for the control of the emission of opto-electronic oscillators (OEO). The OEO loop is made of an optical section, typically a fiber that, by increasing the cavity Q factor, highly improves the purity of the microwave signal and by an electrical feedback (from the photodetector to the modulator – Fig. 8).

SOAs SL devices inserted in the optical section enabled the fine tuning of OEO [32], retaining high spectral purity and device compactness (Fig. 9).

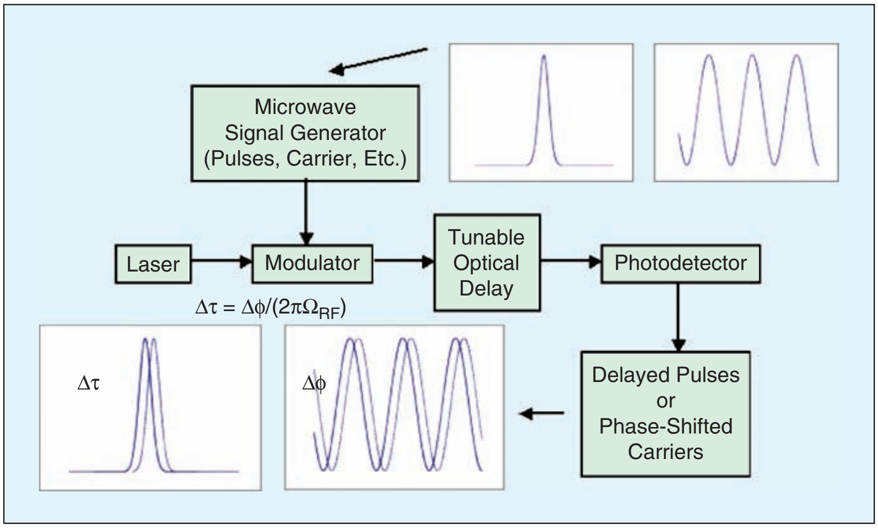

Figure 7. A tunable time delay imposed to the envelope of the optical carrier by a SL device is translated into a phase-shift or time delay for the electrical signal after photo-detection.

SL devices have fully shown their breakthrough potential, in the realization of MWP tunable filters. If a two-tap MWP filter is considered (Fig. 10, (a)), with T the tap time delay, the electrical transfer function (i.e. from the input to the modulator to the photo-detector output) is given by $|H(\Omega)|^2 = |1 + \exp(j\Omega T)|^2 = 2[1-\cos(\Omega T)]$ [33], i.e. the device is a notch filter at frequencies $\Omega = (2N+1)\pi/T$ (N integer). The SL devices, based on SOAs and SOI MRR enabled the full tuning of the notch, without distortion of the spectral response in the microwave band (Fig. 10, (b)).

The SOA-based filter (controlled in current) presents a fast reconfiguration time (from hundreds of ps to a few ns). MRR realization is thermally controlled, so reconfiguration time is typically slower but power consumption very reduced (see also Fig. 4). Low power and fast reconfiguration time devices are under realization by using electrically controlled silicon micro-disks [34].

SBS in fibers can be also exploited to realize MWP filters, in particular with variable free-spectral range, by exploiting the so called separate carrier tuning (SCT) technique [35] in which this narrow band effect can be effectively applied to the sidebands of the modulated optical wave; an example is given in Fig. 11.

SCT has proved to be very powerful also in generating another MWP function, i.e. a phase shift linear with frequency, to obtain true time delay (TTD) for radar beam steering. SOAs, MRR and SBS in fibers can be all exploited. In SBS

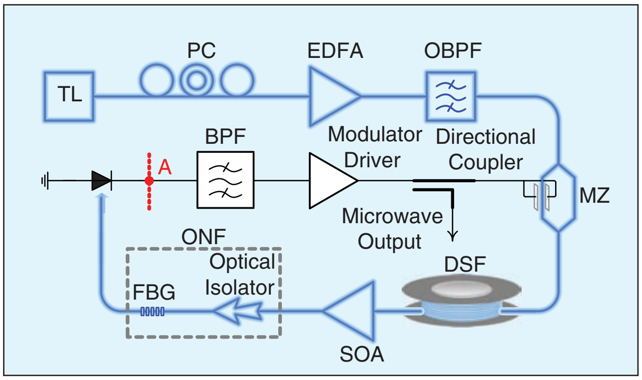

Figure 8. Experimental setup of an OEO, including a SL, SOA in the optical section.

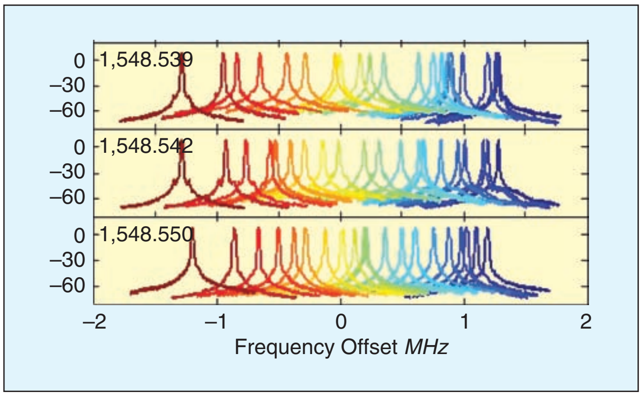

Figure 9. Tuning of a MWP, 10 GHz, OEO by means of SL in SOA.

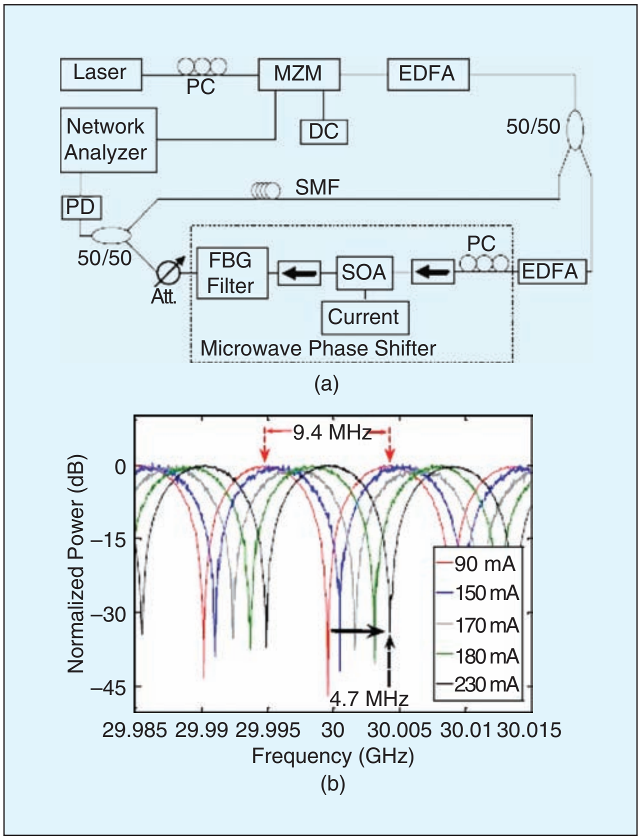

Figure 10. (a) experimental setup of a 2-tap MWP filter; SL SOA device was inserted in one of the branches of the filter. (b) tuning of the MWP notch filter by changing the SL SOA injected current.

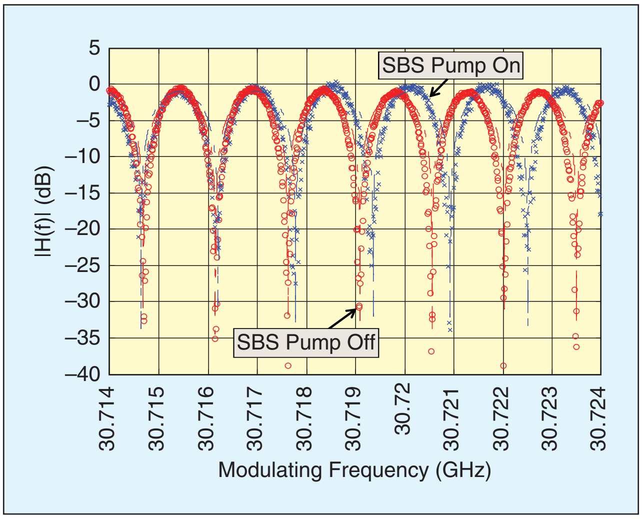

Figure 11. Measured (circles and crosses) and simulated (dashed lines) MWP filter frequency response at about 30 GHz, using SBS tunable delays.

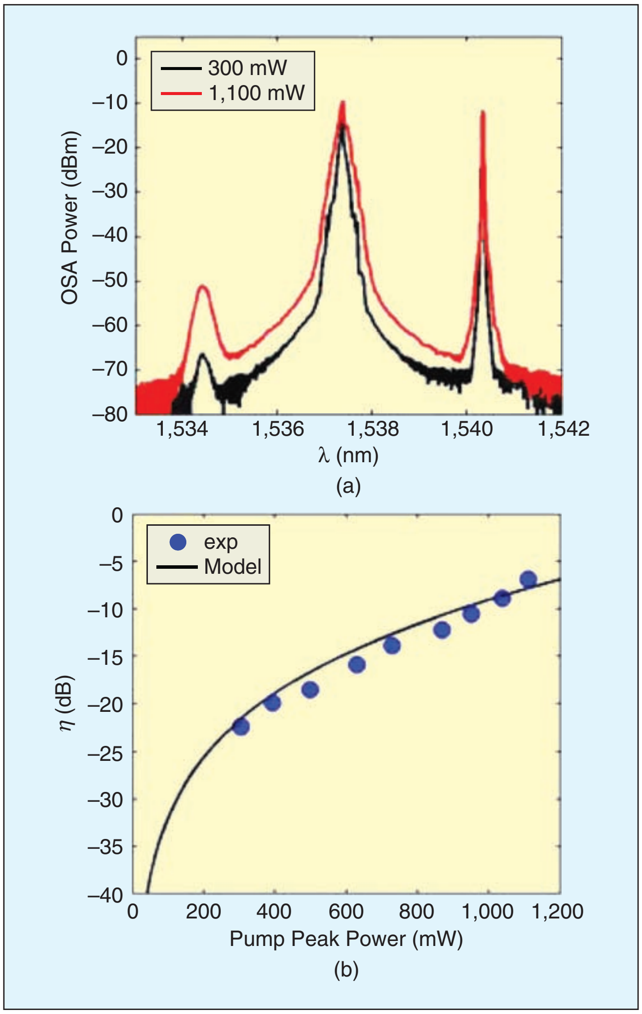

Figure 13. (a) FWM experimental spectrum in a GaInP PhCW of L = 1.3 mm length [pump, at 1537.5 nm, has 32 ps duration and peak power 0.3W (black curve) and 1.1W (red curve); signal, at 1540.5 nm, is a CW of 6.5mW]. (b) conversion efficiency from signal to idler $h = P_i(L)/P_s(0)$ as a function on input peak power.

10 ns delay, at any arbitrary central frequency, with an instantaneous bandwidth of 100 MHz have been reported [36]. When larger bandwidths are required SOAs proved much more suitable [37] as well as SOI MRR, that are under investigation. Finally, large time delays, limited only by the fiber length, can be achieved through the reflection from a DBG, because the DBG can be simply created anywhere within the fiber [38]. This technique has been also used to realize a self-synchronizing device for asynchronous all-optical packet switching [39].

TTD functionality in PhCWs is extremely promising, improving the compactness, the intrinsic parallelism, the robustness, with a continuous tuning of the delay, a fast reconfiguration time and a huge bandwidth.

A tunable TTD up to about 100ps has been realized over a very broad bandwidth [40], that actually extends over more than 40 GHz (in Fig. 12 measurement was limited by VNA bandwidth). Tuning is simply achieved by modifying the laser wavelength.

Besides the demonstrated impressive capabilities of SL to improve the functionality and performance of MWP devices, it is also worth to mention SL applications to photonic signal processing.

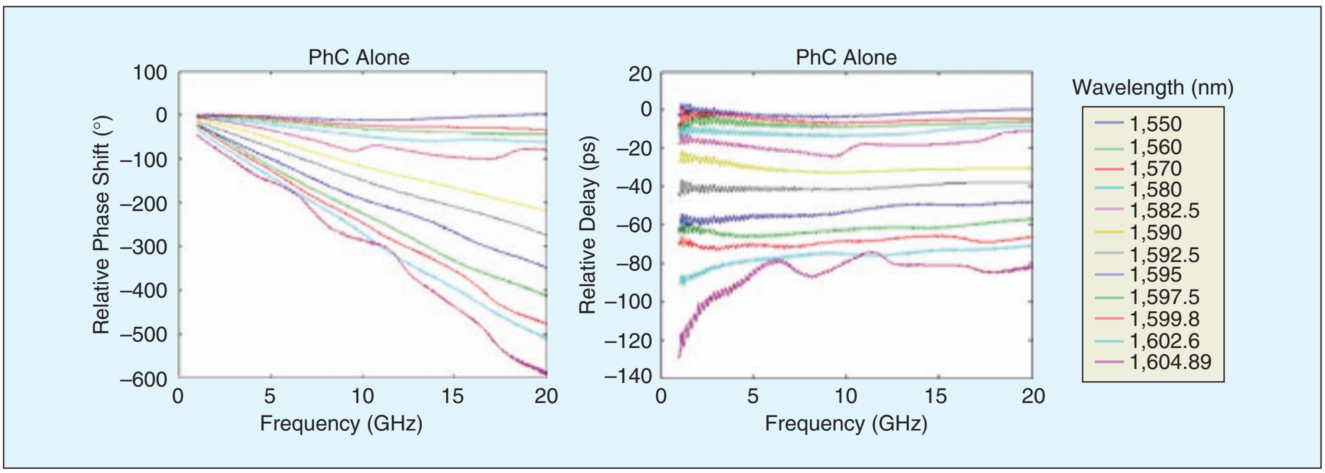

Figure 12. Tuning of TTD in a low loss PhCW.

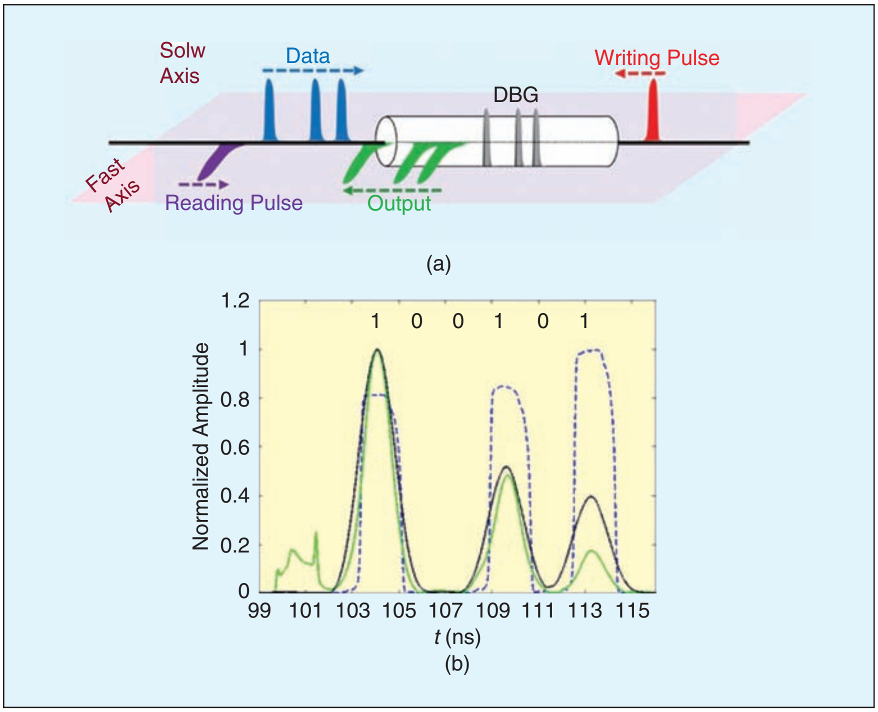

Figure 14. (a) setup to achieve TTR in polarization maintaining optical fibers. (b) time reversal of an optical waveform, achieved with 100W peak pulses of about 2 ns duration. Ideally time reversed experimental input waveform (blue dashed curve); experimentally reversed waveform (green curve); simulation with experimental parameters (black curve).

Among the devices mentioned in Sec. III, PhCWs are a paradigmatic example of structural SL, in which nonlinearity enhancement is made possible [12, 18]. The most impressive results on the nonlinearity enhancement have been first achieved in third-harmonic generation [41], soon after in four-wave mixing (FWM) [42, 43, 44, 45] and finally with the first-ever observation of temporal solitons in a short waveguide [46]. In particular in FWM, SL enhancement scales approximately with n_g^2 (the exact scaling has been actually determined in ref. [43]); so, when $n_g \cong 30$ an enhancement of almost three orders of magnitude is possible. In Fig. 13, a record FWM wavelength conversion efficiency of – 6.8 dB is demonstrated in a GaInP PhCW, of 1.3 mm length [45]. So, FWM can be actually exploited for high speed, on-chip, all-optical signal processing as shown by other groups [47,48].

It is also very interesting to finally mention the unconventional signal processing functionalities, such as true time reversal (TTR) [49], real time differentiation and integration [50], that were achieved through DBGs. The principle of TTR [49] is depicted in Fig. 14 (a).

The data input waveform, is first stored in the DBG created through SBS interaction with a writing pulse. Then, a reading pulse co-propagating with the data waveform is backscattered by the grating. So the portion of the data waveform stored last is the first to be read and TTR is achieved. As for all-optical calculus it can be achieved by using a properly selected read pulse [50]. The experiments of [49, 50] were realized in optical fibers, however very promising on-chip realization can be foreseen with chalcogenide waveguides [51].

V. Conclusions

Slow light techniques provide promising solutions for tunable and broadband time delay or phase shift lines, for microwave and millimeter wave systems. Moreover, the enhancement of nonlinearity and the capability of storing light provide promising routes towards achieving on-chip all-optical signal processing in photonic devices.

Here, the most recent results, in particular those obtained in the European project "GOSPEL", devoted to develop slow light technologies and to demonstrate their applications, have been presented. The microwave-photonic slow light devices show performance that are already superior to their electronic counterparts, and include several integrated solutions. The project also developed new solutions in the field of all-optical signal processing, with extended performance and functionalities.

Acknowledgment

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