Nonlinear Integrated Microwave Photonics

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(Invited Paper)

***Abstract*—Harnessing nonlinear optical effects in a photonic chip scale has been proven useful for a number of key applications in optical communications. Microwave photonics (MWP) can also benefit from the adoption of such a technology, creating a new concept of nonlinear integrated MWP. Here, we look at the potential of using nonlinear optical effects in a chip scale to enable RF signal processing with enhanced performance. We review a number of recent results in this field, with particular focus on the creation of frequency agile and high suppression microwave bandstop filters using on-chip stimulated Brillouin scattering. We also discuss the future prospect of nonlinear integrated MWP to enable a general purpose, programmable analog signal processor, as well as compact, high performance active microwave filters with enhanced energy efficiency.**

***Index Terms*—Analog signal processing, microwave photonics, photonic integrated circuits, RF filters, stimulated Brillouin scattering.**

I. Introduction

RECENTLY, there is a significant interest in exploiting photonic integrated circuits (PICs) for the processing of microwave signals [1]. The term integrated microwave photonics (IMWP) is used to describe research activities in this area. IMWP clearly promises a number of advantages compared to conventional fiber-based approach. The potential of integrating a number of different signal processing functionalities in a single chip will lead to significant reduction in size, weight, power consumption, and cost. Moreover, the ability to integrate various functions like modulation, passive signal processing, and detection in a single chip will lead to reduction in insertion losses, which is the key for MWP signal processor to compete with RF signal processor in terms of performance.

Thus far, IMWP has largely been limited to linear optical processing. It is interesting, however, to examine the potential of nonlinear optics in integrated platform for microwave signal processing. Optical nonlinearities [e.g., $\chi(2)$ and $\chi(3)$] [2], such as sum and difference-frequency generation (SFG/DFG), cross-phase modulation (XPM), degenerate/non-degenerate four-wave mixing (FWM), and stimulated Brillouin scattering (SBS), are suitable candidates for MWP signal processing. In the context of optical signal processing, these nonlinear optics effects have efficiently been harnessed, both in fibers and in integrated devices, for a number of functionalities such as all-optical delay [3], all-optical switching and multiplexing [4], and wavelength multicasting [5].

In this paper, we look at the potential of harnessing nonlinear optical effects in a chip scale to enable RF signal processing with enhanced performance. We review a number of recent nonlinear IMWP demonstrations for filtering and ultrawideband (UWB) signal generation, which exploited on-chip SBS, FWM, and XPM, in various platforms such as chalcogenide glasses (ChGs) and silicon. We particularly focus on the creation of frequency agile and high suppression microwave bandstop filters using a novel sideband processing technique [6]–[8] implemented with on-chip SBS. Finally, we discuss the future prospect of this exciting new field to enable a general purpose, programmable analog signal processor, as well as compact, high performance active microwave filters with enhanced energy efficiency.

II. Frequency Agile Filter with On-Chip SBS

SBS is a nonlinear scattering process where a pump wave, when encounter acoustic vibrations in the medium, gets backscattered, resulting in Stokes and anti-Stokes waves. A probe, centered at the Stokes frequency, experiences gain when counter-propagated to the pump whereas a probe that is up-shifted with respect to the pump (anti-Stokes), experiences absorption. SBS has long been exploited in optical fibers for MWP signal processing [9], [10], but the recent demonstration of on-chip SBS [11] has finally enabled the control of this process in a compact photonic chip scale. The photonic chip was a 6.5-cm long ChG As_2S_3 optical waveguide with a cross-section of 4 μm $\times$ 850 nm and a large SBS gain coefficient ($g_0 \sim 0.74 \times 10^{-9}$ m/W). Using this photonic chip, key SBS RF signal processing such as tunable delay line [12] tunable bandpass [13] and notch [14], [15] filtering have been demonstrated.

Recently, a remarkable progress has been made regarding MWP tunable notch filters based on SBS. A long standing problem in RF electronic filters is to achieve wide frequency tuning simultaneously with high resolution filtering. For example, state-of-the-art absorptive band-stop RF filters are capable of a high peak attenuation (>50 dB) and high resolution (<10 MHz 3-dB isolation bandwidth measured from the passband) but have limited notch frequency tuning range, in the order of 1.4 GHz [16]. MWP notch filters, on the other hand,

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are capable of multi-gigahertz tuning, but are often limited in peak attenuation (<40 dB) and resolution (gigahertz bandwidth instead of tens of megahertz). This limitation stems from the traditional way of implementing notch filters using single sideband (SSB) modulation and an optical filter (OF). In this scheme, the resolution and peak suppression of the MWP filter are limited by those of the OF. Unfortunately, for some OFs, there is a trade-off between resolution and peak suppression. Hence, the resolution and peak suppression of these MWP filters cannot be optimized simultaneously

In [6], we proposed a solution to this limitation. We introduced a new class of MWP notch filter operating by a novel concept of optical sidebands coherent control using an electro-optic (EO) modulator and an optical resonant filter. This scheme allowed the creation of an anomalously high rejection MWP notch filter from virtually any kind of optical resonance, irrespective of its type (gain or absorption), or its magnitude [7]. This enabled, for the first time, simultaneous optimization of the MWP filter resolution, peak attenuation, and frequency tuning range.

A. *Principle of Operation*

In this scheme, ultra-high rejection notch is obtained by perfect cancellation of mixing products between an optical carrier and two first-order modulation sidebands, ideally in a narrow range of frequency. This can be achieved by generating optical sidebands with unequal amplitudes and a tunable phase difference using an electro-optic modulator (EOM). An OF is then used to process one of these sidebands, equalizing the sidebands amplitudes for a particular frequency within the OF response. At this particular frequency, the beat signals generated from the mixing of the optical carrier and the two sidebands are designed to have equal amplitudes and opposite phase, and will perfectly cancel to form a notch with an anomalously high stopband rejection. The mechanism to achieve this frequency notch is similar to the well-known frequency fading effect in dispersive RF photonic systems.

If we represent the complex electrical fields of the optical carrier (E_C), upper sideband (E_U), and lower sideband (E_L) as $E_k(\omega) = |E_k| \exp(j\phi_k(\omega))$, where $k = C, L, U$, and the complex frequency response of the OF as

$$H_F(\omega) = |H_F(\omega)| \exp(j\phi_F(\omega)) \quad (1)$$

then, the conditions for achieving the notch are

$$2\phi_C(\omega_C) - \phi_L(\omega_C - \omega_N) - \phi_U(\omega_C + \omega_N) - \phi_F(\omega_C + \omega_N) = \pm\pi \quad (2)$$

$$|E_L| = |H_F(\omega_C + \omega_N)| \, |E_U| . \quad (3)$$

Here, ω_C and ω_N are the carrier and the notch frequencies, respectively, as illustrated in Fig. 1(a). The first condition in Eq. (2) guarantees opposite phase of the mixing products, while the second condition [Eq. (3)] guarantees equal mixing products amplitudes at the notch position.

In this part we focus on implementing SBS as the OF. The magnitude and phase responses of the SBS filter are shown in Eq. (4) and Eq. (5), respectively. Here, $G = g_0 I_p L_{\text{eff}}$ is the SBS *gain parameter*, g_0 is the SBS gain coefficient, L_{eff} is the effective length, and I_p is the pump intensity. The parameters Γ_B and ω_B are Brillouin line width and frequency shift, respectively. The positive and negative signs in these responses are respectively attributed to whether the gain spectrum or the loss spectrum is used

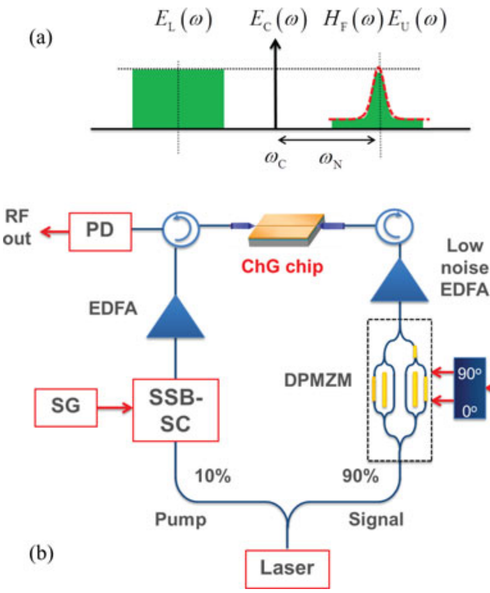

Fig. 1. (a) Illustration of the sideband amplitudes to achieve a necessary cancellation condition in a novel high extinction notch filter. (b) Experimental setup of ultrahigh rejection notch filter using SBS on chip. SG = RF signal generator, PD = photodetector, SSB-SC = single sideband suppressed carrier modulator, DPMZM = dual parallel Mach-Zehnder modulator.

$$|H_{F,\text{SBS}}(\omega)| = \exp\left[\pm\frac{G}{2}\frac{(\Gamma_B/2)^2}{(\omega-\omega_B)^2+(\Gamma_B/2)^2}\right] \quad (4)$$

$$\phi_{F,\text{SBS}}(\omega) = \pm\frac{G\omega\Gamma_B}{2}\frac{\omega^2-\omega_B^2}{(\omega^2-\omega_B^2)^2+(\omega\Gamma_B)^2}. \quad (5)$$

B. *On-Chip SBS Implementation*

In [6], this filter concept was implemented for the first time using SBS gain and loss spectra in 650 m of standard single mode fiber (SMF) as the OF. Impressive results in terms of filter performance were achieved, including high resolution of ~10 MHz, an ultrahigh stopband rejection of >60 dB, wide continuous frequency tuning of 1−30 GHz, and flexible bandwidth reconfigurability of 10–65 MHz. For the first time, key performance metrics of a bandstop filter (peak rejection, resolution, and central frequency tuning range) were simultaneously optimized.

Very recently, we implemented the filter concept using SBS in a compact ChG photonic chip [7]. Schematic of the experimental setup is shown in Fig. 1(b). Pump with tunable frequency was generated using a single-sideband suppressed carrier (SSB-SC) modulator driven by an RF tone from a signal generator (SG) [15]. In the signal arm, a dual parallel Mach-Zehnder modulator (DPMZM) driven through a quadrature hybrid coupler was used to generate RF signal sidebands with tunable phase and amplitude. The pump and the signal were launched into a 6.5-cm As_2S_3 optical rib waveguide using lensed-tip fibers. The

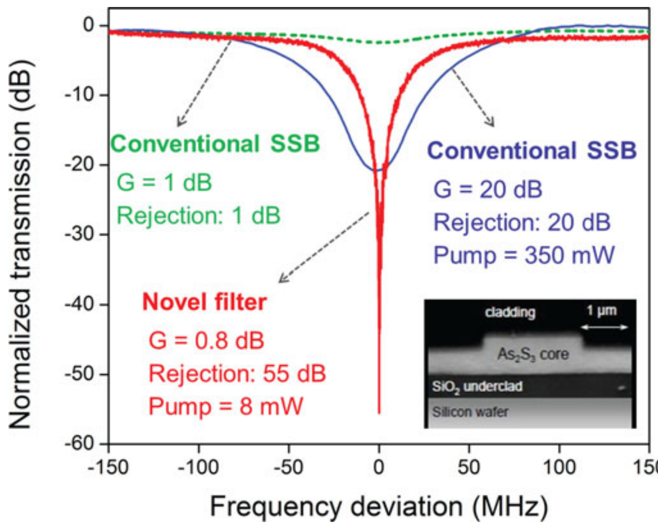

Fig. 2. Experimental result of MWP notch filter response using on-chip SBS with sub-1 dB gain. Blue trace indicates conventional filter using SSB modulation and SBS loss spectrum [14]. Red trace indicates notch response obtained from novel complex sideband processing [7] and SBS gain spectrum. The novel technique leads to an increase in filter resolution (47 MHz full-width at half maximum) and ultra-high enhancement of the peak rejection (>55 dB), achieved with only 8 mW of pump power.

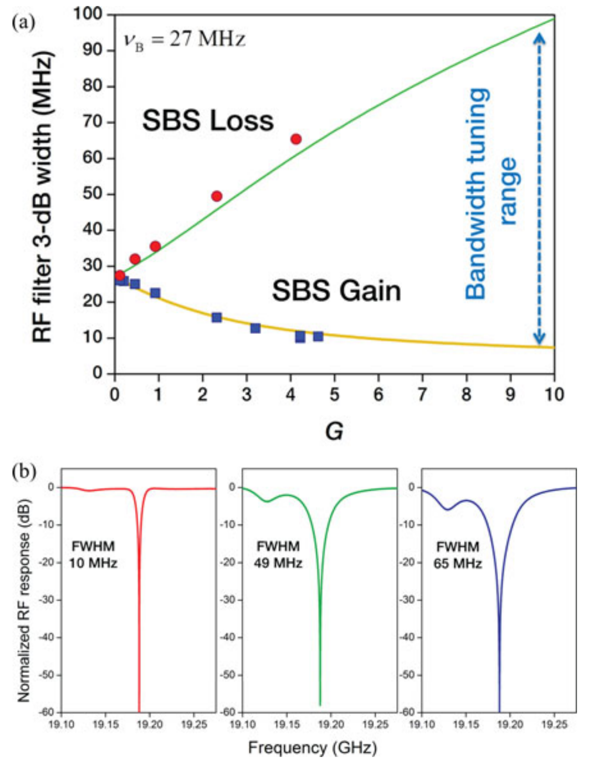

Fig. 3. (a) RF filter 3-dB bandwidth reconfigurability as functions of the SBS gain parameter, G. Solid lines represent simulation results with SBS linewidth of 27 MHz, while the scatter plots represent experimental data, for SBS filter in 650 m of SMF. In the experiments variation of G was obtained by changing the pump power. (b) The measured filter responses, showing optimized peak rejection independent of the bandwidth.

optical waveguide had a cross section of 0.85 × 2 μm, and a high SBS gain coefficient, due to high acoustic confinement and small effective area of 1.2 μm^2. The total waveguide insertion loss was measured to be 11 dB.

The measured filter response is shown in Fig. 2, together with filter responses obtained using conventional SSB modulation scheme. We achieved a filter with an ultra-high suppression of more than 55 dB, a high resolution of 47 MHz, and ultra-wide tunable central frequency of 1−30 GHz. Remarkably, this was obtained using an ultra-low SBS gain of 0.8 dB, and a very low pump power of 7 mW. This represents 50 times reduction in required pump power, relative to a conventional SBS notch filter generated using SSB modulation scheme [14], [15]. These results demonstrate that the sideband cancellation scheme can ease the implementation of low power nanophotonic devices as high performance RF notch filters.

While advantageous in terms of energy efficiency, using very low SBS gain can have an impact on the filter insertion loss and noise figure. Note that for very low gain, the cancellation condition in Eq. (2) and Eq. (3) can be partially met at frequencies other than the target notch frequency. In this case, signal cancellation and reduction in the filter pass-band occurs, which leads to an increase in the filter noise figure.

Recently [17], we proposed a technique to mitigate this passband signal reduction by means of precisely controlling the DP-MZM biases to create frequency notch which is slightly shifted from the central frequency of the SBS response. By introducing this frequency shift, the role of the SBS phase reponse to create the notch is more pronounced. As a result, away from the notch frequency, the phase condition for the cancellation is no longer met, and the passband insertion loss is significantly reduced.

C. Bandwidth Tunability

One of the strengths of the novel notch filter based on SBS is the dynamic reconfigurability of its 3-dB bandwidth. This advantage is a direct consequence of the fact that the sideband cancellation technique allows the use of both the SBS gain and loss spectra as the OF. Our analysis showed that these spectra have opposite spectral-width variations with increasing pump power. With increasing SBS gain parameter G, the gain spectrum tightens whereas the absorption spectrum broadens. The general expression of the notch filter bandwidth formed using SBS gain spectrum is given

$$B_{\text{Gain}} = \Gamma_B \sqrt{\frac{1}{x} - 1} \tag{6}$$

with the parameter x given by

$$x = \frac{1}{G} \ln \left[k \left(e^G - 1 \right) + 1 \right]. \tag{7}$$

The parameter k determines the type of bandwidth to calculate (i.e., 3-dB width or 10-dB width). For a 3-dB width, one would substitute $k = 10^{-3/10} \approx 0.5$ in the above expression. The bandwidth of the loss spectrum can be calculated by substituting $-G$ in these equations.

We plotted the calculated 3-dB widths of SBS gain and loss filters as functions of the SBS gain parameter, G. The results are shown in Fig. 3, where the green line indicates the bandwidth of the SBS loss spectrum, and the orange line the bandwidth of the gain. Here we have used the value of the SBS linewidth (Γ_B) of 27 MHz. As shown in this figure, the range of bandwidth reconfiguration of the notch filter increases significantly with increasing G, which can be achieved by increasing the pump power. For $G = 10$, which corresponds to SBS power gain of 43 dB, the bandwidth reconfiguration range is larger than 90 MHz. In the same figure, we plotted the measured 3-dB bandwidth of the notch filter implemented in 650 m of SMF [6]. The result showed very good agreement between experiments and simulations.

As shown in Fig. 3(b), the bandwidth tuning was obtained without sacrificing the filter peak rejection. Tuning the bandwidth from 10 MHz up to 65 MHz, the peak rejection was kept larger than 55 dB. Thus, using the novel filter topology, the trade-off between resolution and peak rejection optimizations is circumvented.

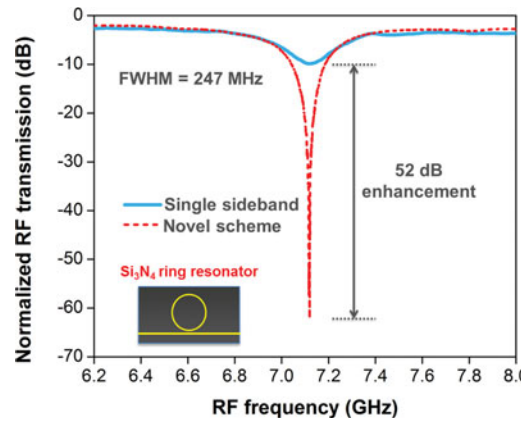

Fig. 4. Experimentally measured MWP notch filter response using a low loss Si_3N_4 ring resonator [8]. Implementing the complex sideband processing [6]–[8] led to a peak rejection enhancement of >50 dB relative to conventional SSB scheme.

D. Ring Resonator Implementation

One of the key advantages of the sideband cancellation notch filter scheme is its applicability to a wide range of OFs. For example, in [8] the technique was implemented using a reconfigurable silicon nitride ring resonator. Integrated ring resonators are very attractive as OF due to their high quality factors, compactness, and flexible tunability. These devices are tunable in terms of resonance frequencies and quality factors (tuned by varying the amount of light coupled to the resonator) and have widely been used in MWP signal processing for example as delay lines [18], filters [19], [20], and frequency discriminators [21].

Nevertheless, as an MWP notch filter, a ring resonator suffers from trade-off between resolution and peak rejection. This limitation can be seen from the transfer function of such a ring, given as [21]

$$H_R(\omega) = \frac{r - a\exp(-j\omega)}{1 - ra\exp(-j\omega)} \tag{8}$$

where r is the self-coupling coefficient to the ring and a is the round trip loss in the ring. Given a resonator loss (i.e. fixed a) but tunable coupling coefficient (variable r), the highest peak suppression is achieved at $r = a$. However, the highest resolution (i.e. smallest 3-dB width) is achieved for $r = 1$. Thus, in the context of using an optical ring resonator as a notch filter, the resolution and peak suppression of such filter cannot be optimized simultaneously.

By implementing sideband cancellation technique in such a notch filter, peak rejection enhancement of more than 50 dB can be achieved, relative to conventional SSB modulation scheme (Fig. 4). Such a high suppression would normally occur only when the resonator is critically coupled ($r = a$). But the novel technique allows one to achieve this high contrast independent of the ring coupling, thereby significantly relaxing the fabrication tolerance of such ring resonators.

III. On Chip FWM and XPM

On-chip ultrafast Kerr nonlinearity has also been exploited in the context MWP signal processing, for example for UWB signal generation [23] and reconfigurable multi-tap filtering [24]. In [23], Tan *et al.* combine the effects of XPM and birefringence in an As_2S_3 rib waveguide to generate polarity-inverted UWB monocycles with a single optical carrier. The high Kerr-nonlinearity of ChG in a chip platform enables efficient XPM in a short length of 7 cm. The combination of XPM and birefringence essentially acts as an all-optical differentiator that converts a train of Gaussian pulses into a train of monocycle electrical pulses after photo-detection process. Using this technique, Tan *et al.* demonstrated the generation of a wide variety of UWB pulses, including polarity-inverted monocycles and doublets. A key advantage in exploiting XPM was the chirp erasure of the input optical pulses, because XPM depends solely on the pulses intensity. Thus, shaped UWB optical pulses have a good tolerance to dispersion over fiber and are more suitable for long-distance transmission in UWB over fiber communication systems.

Recently, Chen *et al.* [24] have reported a step towards the integration of a reconfigurable MWP filter concept in [30], by exploiting an FWM process in a silicon nanowire, instead of using highly nonlinear fiber (HLNF). The silicon waveguide ($h = 220$ nm, $w = 650$ nm, length $= 12$ mm) was dispersion engineered to yield broadband FWM. They generated two idlers with measured conversion efficiency of -25 dB. These wavelengths taps were then modulated and amplitude controlled using a waveshaper. They used 4 km of SMF as the dispersive medium required to generate time delay between the taps. They measured the response of a four-tap MWP filter and demonstrated that the 12 mm silicon nanowire can be used to replace 1 km of silica highly nonlinear fibers (HNLF) without compromising the quality of the microwave photonic filter (MPF) response.

IV. Potential of Nonlinear Integrated MWP

In this section we discuss the potential of nonlinear IMWP and identify two key concepts that we believe will shape the field in the near future.

A. General Purpose Analog Processor

The exponential growth in bandwidth demand of radio communications has put unprecedented challenges in the RF signal processing chain. Traditionally, strong emphasis in such a chain is put on digital signal processing (DSP). However, for increasing operating frequencies and larger bandwidths, a reliable analog signal processor (ASP) that can match the flexibility of a DSP is desired [25], [26]. The aim here is to create a robust analog signal processing engine, which can be flexibly tailored in terms of group delay and amplitude responses, that works in millimeter wave or terahertz frequency range where DSP based systems are inefficient or inapplicable [25].

Due to its high bandwidth and potential reconfigurability, IMWP processor is an attractive candidate for such a flexible ASP. However, current state-of the-art IMWP processors were developed only for very specific tasks, for example beamforming and filtering, frequency discrimination, or pulse shaping. Thus, there is a lack of generality and multi-functionality of these processors. To emulate DSP, the IMWP processor has to be application agnostic, multi-purpose and programmable.

We believe that incorporating optical nonlinearities in an IMWP processor will open up the path towards a general purpose ASP. Gasulla and Capmany [27] have identified that a large number of MWP signal processing functions can be generalized as processing of a number of copies of RF modulated optical signals using reconfigurable OFs. Nonlinear optical processes that create new optical wavelengths such as FWM, SFG, or DFG are attractive candidates for generating such signal copies. In fact, this concept of wavelength multicasting has recently been implemented for MWP signal processing techniques such as channelization [28], [29] and reconfigurable filtering [30], [31]. In [28]–[30] FWM processes in HNLF were used, while SFG and DFG in periodically-poled lithium niobate (PPLN) have been exploited in [31]. In the view of the general processor, these wavelength copies will subsequently be processed by a reconfigurable OF. The typical signal processing tasks carried out by these filters include tunable time delay, carrier phase tuning, and complex (amplitude and phase) filtering. These processed optical signals will then be recombined or directed to separate dedicated outputs for a photodetection process.

The key challenge here is to create a monolithic photonic chip that hosts the nonlinear optics for wavelength multicasting and the reconfigurable linear optical filtering. Fig. 5 depicts an illustration of a possible design of such a photonic chip in Si_3N_4 technology [32]. The chip consists of three main sections: two long spiral waveguides for wavelength multicasting and multiplexing based on cascaded FWM processes, and a reconfigurable OF based on a network of ring resonators that can be tuned using thermo-optics effect. This ring network might host a mixture of all pass ring filters, add-drop rings, as well as Vernier (cascade of non-identical) rings which have been recently exploited for tunable delay lines in a multi-wavelength beamformer [33]. The programmability of the ring network will allow the chip to be reconfigured in real time, to synthesize different responses according to the user demand.

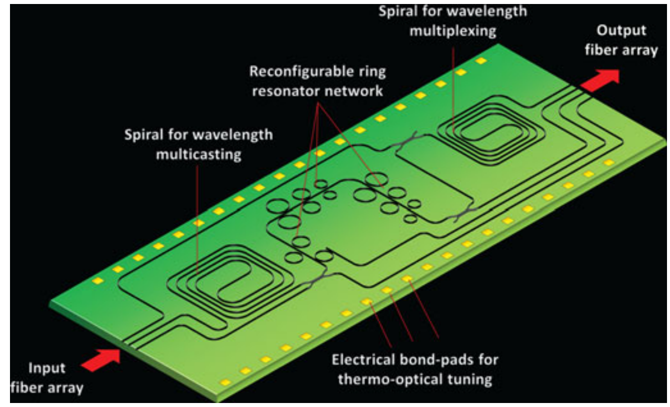

Fig. 5. Illustration of the envisioned general purpose ASP architecture combining ultrafast nonlinear optics for signal copies generation (for example wavelength multicasting via on chip FWM) and reconfigurable linear optical filtering (for example Vernier ring resonators tunable using thermo-optical tuning).

We believe that other material platforms such silicon and III–V materials such as indium phosphide (InP) can also be good candidates to construct this ASP. However, Si_3N_4 waveguides might be more suited for this purpose due to the following characteristics: ultra-low propagation losses (approx. 0.1 dB/cm [18]) which is very important for MWP systems, moderately high optical nonlinearity (ten times of silica) [34]–[37] and free from nonlinear losses such as two-photon absorption (TPA) and free-carrier effect (FCA) [35]. On top of this, Si_3N_4 waveguides have shown compatibility with efficient thermo-optics tuning and is a CMOS compatible material. While silicon also ticks some of the boxes and successful wavelength multicasting has been demonstrated in this platform [38], [39], the propagation loss of typical SOI nanowires is relatively high (2–3 dB/cm) [22] and they suffer from TPA and FCA [4], [35]. These losses might be prohibitive for creating an efficient nonlinear IMWP processor. As for InP, this material platform is more suited to create ASP without exploiting nonlinearities, for example a PIC with multiple lasers, modulators, and photodetectors, as described in [1]. AlGaAs is a more suitable III–V material for nonlinear IMWP processor due to its relatively high nonlinear coefficient [40].

B. Highly Integrated Tunable RF Filter

Harnessing SBS in nanophotonic devices has recently attracted significant interest due to its great potential for realizing tunable slow light, narrow-linewidth laser, optical frequency comb, and RF photonic signal processor in a compact footprint. Observation of SBS in a CMOS-compatible platform has recently been reported in a hybrid Si-Si_3N_4 photonic/phononic waveguide [41], but the amount of realized SBS gain was only in the order of 1 dB, which is far from sufficient for any actual application. While high gain and power efficient SBS nanophotonic devices are ultimately desired, elegantly harnessing the low SBS gain from current on-chip low-power devices to function in real-life applications represents a technological breakthrough.

As discussed in Section II, using the novel notch filter scheme one can create a high performance RF notch with an ultra-high

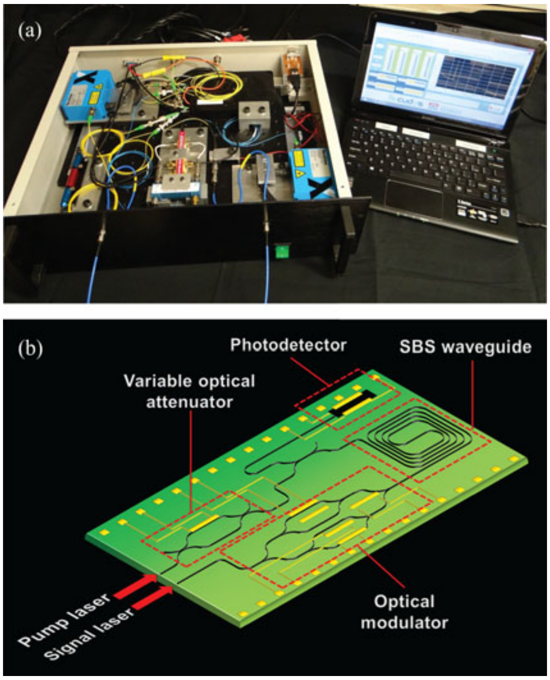

Fig. 6. Possible implementations of high performance RF notch filter using sideband cancellation and SBS. (a) Fiber based prototype consisting of two commercially available 100 mW DFB lasers, 40 GHz bandwidth DPMZM, high speed photodetector, and a spool of optical fiber. The filter is programmable via computer control. (b) Future vision of the same filter hybrid/monolithically integrated in a CMOS compatible photonic chip that consists of EOM, tunable optical coupler for pump tuning, a nanophotonic waveguide with high SBS gain, and a photodetector.

suppression using less than 1 dB of on-chip SBS and very low pump power. The ultimate goal for such filter is, however, to integrate more functionalities in a single photonic chip, together with the optical waveguides where SBS is induced. This vision in integration is illustrated in Fig. 6 together with a current prototype of the filter implemented using SBS in SMF and commercially available discrete components [Fig. 6(a)].

We believe that the realization of this integrated notch filter can go through two different paths: monolithic integration, or hybrid integration. Silicon for example, stands out as an ideal platform for monolithic integration of this filter. The fact that high speed modulators and photodetetcors are readily available in silicon is, indeed, a big advantage. However, thus far there is still no observation of SBS in silicon, due to a number of effects such as acoustic mode leakage [41]. Thus, the realization of monolithic integration of this SBS notch filter will depend strongly on the efforts in efficiently inducing SBS in silicon, or other CMOS compatible materials. A summary of this research activity can be found, for example, in Ref. [42]. It is worth to mention that monolithic integration can still be achieved with OFs other than SBS, such as silicon ring resonators [22], or silicon integrated Bragg-gratings [43]. We predict that some of these implementations will be reported soon.

The hybrid integration route, on the other hand, has recently seen some encouraging progress. Hybrid integration of chalcogenide and $LiNbO_3$ waveguides has recently been explored [44]. This is a very promising step to combine currently two best materials for SBS on chip (chalcogenide) and high speed EOM (lithium niobate).

V. Conclusion

In this paper we introduced nonlinear IMWP, which is an exciting new concept in MWP, where on-chip linear and nonlinear processes are combined to enable unprecedented RF signal processing capabilities. As an example, by exploiting SBS on chip and a novel sideband cancellation technique, an RF filter with ultra-high suppression and enhanced energy efficiency was achieved.

We believe that the growth of this new field will depend on two key factors: the efficiency of the associated on-chip nonlinear processes, and the integrability of the nonlinear platform of choice with other optical functionalities such as optical modulation, reconfigurable optical filtering, and photodetection.

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