Low-power, chip-based stimulated Brillouin scattering microwave photonic filter with ultrahigh selectivity

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Highly selective and reconfigurable microwave filters are of great importance in radio-frequency signal processing. Microwave photonic (MWP) filters are of particular interest, as they offer flexible reconfiguration and an order of magnitude higher frequency tuning range than electronic filters. However, all MWP filters to date have been limited by trade-offs between key parameters such as tuning range, resolution, and suppression. This problem is exacerbated in the case of integrated MWP filters, blocking the path to compact, high-performance filters. Here we show the first chip-based MWP bandstop filter with ultrahigh suppression, high resolution in the megahertz range, and 0–30 GHz frequency tuning. This record performance was achieved using an ultralow Brillouin gain from a compact photonic chip and a novel approach of optical resonance-assisted RF signal cancellation. The results point to new ways of creating energy-efficient and reconfigurable integrated MWP signal processors for wireless communications and defence applications. © 2015 Optical Society of America

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1. INTRODUCTION

The explosive growth in mobile communications demands radio-frequency (RF) technologies with exceptional spectral efficiency such as cognitive radios, which can adapt their frequencies to exploit the available spectrum in real time [1,2]. Such frequency-agile systems will benefit hugely from RF filters that can be tuned over many gigahertz whilst keeping high megahertz-scale resolution and high selectivity to prevent severe interference due to spectrum sharing. While this is difficult to achieve with all-electronic filters [3–7], integrated microwave photonic (IMWP) filters [8] can readily achieve a multigigahertz tuning range without significant degradation in their frequency response. However, these filters typically exhibit limited resolution (gigahertz instead of megahertz linewidths) and are plagued by trade-offs between key parameters, such as between the frequency tuning range and the resolution for multitap filters [9–13], or between the peak rejection and the resolution for resonator-based filters [14–18].

Stimulated Brillouin scattering (SBS) [19–22] offers a route to megahertz-resolution IMWP filters. Although SBS has been widely studied in optical fibers, recently there has been growing interest in harnessing SBS in nanophotonic waveguides [22–27]. The ability to control the coherent interaction of photons and acoustic phonons in chip-sized devices (as...
opposed to in optical fibers many kilometres long) not only promises fascinating new physical insights, but also opens the path to realizing key technologies on chip including slow light [28,29], narrow linewidth lasers [30], optical frequency combs [31,32], RF signal processing [33–35], and filtering [36–40]. In particular, SBS filters can exhibit linewidths of the order of 10–100 MHz. Such a high resolution is unmatched by most on-chip devices because it requires extremely low material losses and impractically large devices [41].

Although IMWP filters exploiting SBS on chip have been demonstrated, they require relatively high SBS gain and high pump powers to achieve moderate filter suppression. In [40], Morrison et al. demonstrated a bandstop filter with 20 dB suppression in a 6.5 cm As2S3 waveguide using 350 mW of pump power. From a broader perspective, this need for high power is unattractive for on-chip signal processing with particularly stringent requirements for energy efficiency. More importantly, this prevents implementation of integrated RF signal processing in low-gain SBS devices, such as the ones recently reported in CMOS-compatible platforms [26,27]. By harnessing SBS in silicon, these devices are highly attractive due to the potential to integrate RF signal processing in a single compact monolithic chip [42]. Nevertheless, they currently exhibit very low gain, of the order of 1–4 dB, which is far from sufficient for any MWP signal processing if one relies on conventional techniques.

Here, we demonstrate experimentally a highly selective SBS IMWP bandstop filter in a centimeter-scale chalcogenide glass waveguide that operates with a low pump power (8–12 mW) and a low SBS gain (1–4 dB), while maintaining high, reconfigurable resolution (32–88 MHz) and high stopband rejection of >55 dB. We further show that the filter can be tuned over a wide frequency range of 0–30 GHz, leading to a unique performance combination difficult to match with any existing filter technology. We achieved this performance through on-chip SBS filtering of a phase- and amplitude-tailored RF-modulated optical spectrum [43–45], resulting in precise RF signal cancellation at a resolution comparable to state-of-the-art RF filters. We further show that for a given SBS gain, this approach allows the flexibility to redistribute the pump optical power into modulated optical power, thereby reducing the filter insertion loss. The results presented here point to new possibilities for creating high-performance SBS-based reconfigurable MWP filters that will play a key role in modern RF systems for next-generation radar [46] and high data rate wireless communication [47], with the potential for monolithic integration in silicon chips [Fig. 1(a)].

2. Enhancing Filter Suppression by Spectral Tailoring

The chip-based SBS filter topology is illustrated in Fig. 1(b). An electro-optic modulator is used create RF sidebands from an optical carrier. The modulated signal is injected into a nonlinear chalcogenide optical waveguide [48,49] as the probe of an SBS process, while an SBS pump is injected from the opposite end. Our filter relies on precise phase and amplitude tailoring of the RF-modulated optical spectrum at the input of the SBS filter [Fig. 1(c)]. The desired spectrum contains a dual-sideband (DSB) modulation where the optical sidebands are out of phase but have unequal amplitudes. The SBS gain spectrum is used to amplify the weaker sideband to achieve the same amplitude as the stronger sideband only at the peak of the gain resonance. The sidebands along with the optical carrier are then sent into a high-speed photodetector for direct detection that results in RF mixing between these components. At the RF frequency where maximum sideband amplification occurs, the mixing products between sidebands and the optical carrier have equal amplitudes but opposite phase.
and thereby cancel leading to very high signal suppression [43,44]. Outside the SBS resonance, the signals do not completely cancel due to the amplitude difference between the sidebands [50]. This filtering technique contrasts with the conventional SSB approach [Fig. 1(d)], where the SBS loss/absorption resonance is used to attenuate the sideband in a single-sideband (SSB) optical spectrum. While simple, this approach suffers from a lack of suppression and low resolution due to inherent limitations in the SBS loss resonance [44].

It is important to stress that the tailored spectrum required for the filter operation is very different from spectra generated and used in conventional MWP signal processing so far, such as intensity modulation (IM), phase modulation (PM), or SSB modulation. Ideally, the spectrum should contain an optical carrier and sidebands that can be tailored independently in amplitude and phase. A good approximation of this ideal spectrum can be generated using a dual-parallel Mach–Zehnder modulator (DPMZM). In the small signal approximation this electro-optic modulator can create an optical carrier with two sidebands whose relative amplitude and phase difference can be sufficiently tunable [42,50].

3. ON-CHIP FILTER EXPERIMENTS

Figure 2(a) depicts the experimental setup to demonstrate the filter operation. An SBS pump at 1550 nm was generated, amplified, and injected into a 6.5-cm-long As$_2$S$_3$ rib optical waveguide via a lens-tipped optical fiber. A frequency-detuned RF-modulated probe generated using a DPMZM was launched from the opposite end. The typical insertion loss of the photonic chip was measured to be 9.5 dB. The rib waveguide has a cross-sectional area of $4 \times 0.85 \, \mu$m$^2$, and it exhibited a large Brillouin gain coefficient, $g_B = 0.74 \times 10^{-9} \, \text{m/W}$, due to its high acoustic confinement and small effective area [23].

For the SBS pump we used a distributed feedback (DFB) laser (Teraxion Pure Spectrum $\lambda = 1550$ nm) with 100 mW of optical power, connected to an electronically controlled variable optical attenuator (VOA, Kotura), and an erbium-doped fiber amplifier (EDFA, Amonics) with maximum output power of 1 W. The VOA was used to control the pump power, and subsequently the SBS gain, with a high precision of 0.5 dB. For the SBS probe we used a DFB laser (Teraxion) to generate the optical carrier, which was modulated using a DPMZM (EOSPACE IQ-0D6V-35). The half-wave voltage, insertion loss, and 3 dB bandwidth of the modulator were 5 V, 5 dB, and 35 GHz, respectively. The RF input ports of the DPMZM were driven by an RF signal through a quadrature hybrid coupler with frequency range of 1.7–36 GHz (Krytaz). The three bias voltages of the DPMZM were adjusted using a programmable multichannel voltage supply with 1 mV voltage accuracy (Hameg HM7044G). The signal was detected using a high-speed photodetector (PD, u2t XPDV2120) with 0.6 A/W responsivity and 50 GHz RF bandwidth. For filter response measurements, a frequency-swept RF signal with 0 dBm power was supplied from and measured on a 43.5 GHz vector network analyzer (VNA, Agilent PNA 5224A).

Using the experiment setup we demonstrated and compared the filtering performance of the conventional SSB approach and the novel cancellation-based filter. The conventional filter generated a SSB RF-modulated optical spectrum as the input to the optical filter. Typically, the measured extinction ratio of the suppressed optical sideband with respect to the unsuppressed sideband was 20 dB [Fig. 2(b)]. The cancellation filter requires a near-phase modulation signal as input [see Fig. 1(c)]. The measured optical spectrum of the generated sidebands with opposite phase and 1 dB amplitude difference is shown Fig. 2(c).

Figure 2(d) shows the measured RF magnitude responses of both the conventional and the cancellation approaches. In the conventional approach, a bandstop filter with moderately high suppression (20 dB) can only be achieved by pumping the optical waveguide with a high pump power (350 mW), as shown as the blue trace of Fig. 2(d). When very low pump power, in the order of 8 mW, was used instead, the filter suppression was very shallow, of the order of 0.8 dB (green dashed trace). On the other hand, with the same low pump power, and a sub-1-dB SBS gain, the cancellation filter can achieve 55 dB of suppression and a higher resolution compared to the conventional...
This result illustrates the superiority of the novel filter, which exhibited impressive peak suppression and a high resolution while using only low SBS gain and very low pump power. This massive 43-fold reduction in required pump power (8 mW versus 350 mW) highlights the energy-efficiency enhancement of the novel cancellation filter.

4. FREQUENCY TUNING AND BANDWIDTH RECONFIGURABILITY

We demonstrate the frequency agility of the MWP filter by tuning the central frequency of the RF bandstop response and its 3 dB bandwidth. Central frequency tuning with a resolution of 12.5 MHz was achieved by adjusting the frequency difference between the pump and the probe waves by temperature tuning the probe DFB laser. For all measurements, the pump wavelength and power at the facet of the photonic chip were kept at 1550.43 nm and 24 dBm, respectively. The chip insertion loss was 8.5 dB. The result is depicted in Fig. 3(a), where central frequency tuning from 1 to 30 GHz was achieved. Critically, the filter suppression was maintained above 51 dB for the entire tuning range.

Reconfiguration of the filter bandwidth was achieved by switching between SBS gain and loss responses, and the variation of pump power for each case. The RF bandwidth of the bandstop filter is equivalent to that of the SBS process, given by:

$$\Delta \nu_{RF} = \Gamma_B \sqrt{\frac{G}{\ln(e^G + 1) - \ln 2}} - 1,$$

where \(\Gamma_B\) is the Brillouin linewidth, and the \(G\) parameter is proportional to the SBS pump power. Here, \(G > 0\) corresponds to SBS gain, while \(G < 0\) corresponds to SBS loss. Figure 3(b) shows the calculated filter bandwidth as a function of \(G\), for \(\Gamma_B = 58\) MHz, together with the experimental data. For the SBS gain, we tuned the SBS pump to achieve gain variation from 0.8 to 11.6 dB and obtained an increase in filter resolution from 56 MHz down to 32 MHz. As for the SBS loss, we tuned the peak absorption from −0.8 to −8.1 dB to expand the filter bandwidth from 61 to 88 MHz. In total, we achieved a 56 MHz tuning range in the experiment. For each measurement we kept the stopband suppression beyond 50 dB by changing the balance between the sidebands to maintain cancellation at the center of the SBS resonance. The normalized frequency response of the filter at the extreme points of the bandwidth tuning range is shown in Fig. 3(c).

5. DEMONSTRATION OF RF FILTERING

Here we demonstrate what is to our knowledge the first high-resolution RF filtering experiment using a chip-based MWP filter. We consider a scenario in which two RF signals, one of interest and the other an unwanted interferer, were supplied to the input of an optical modulator (see Fig. 4). The signal of interest was band-limited with a width of 1 MHz, while the unwanted interfering signal was a single frequency tone. These were separated in frequency by 20 MHz, and the power of the unwanted signal was 21 dB higher than the signal of interest. To generate the signal of interest, we created a frequency modulated signal with unity modulation index from an RF tone with a frequency of 11.982 GHz and power of −9 dBm. The modulation signal was a triangular waveform with 30 kHz frequency and 1 V peak-to-peak amplitude generated using an arbitrary waveform generator (Tabor Electronics WW5061). This created a band-limited signal.
with 1 MHz width and peak power of -21 dBm. The unwanted tone at 12.002 GHz and power of 0 dBm was generated using the signal source of an Agilent Fieldfox N9918A microwave handheld combination analyzer. The two RF signals were combined and supplied to an electro-optic modulator using a 1.7–36 GHz microwave combiner (Krytar). We analyzed the filter output RF spectrum using the N9918A microwave combination analyzer with a span of 50 MHz and 100 Hz resolution bandwidth.

We compare the filtering performance of this input spectrum between a conventional SSB filter and the novel cancellation filter. The SSB filter was generated using SBS loss with 28 dBm pump power at the chip facet creating 17 dB of peak suppression. The cancellation filter was created using 4 dB of SBS gain from 21 dBm of pump power at the chip facet. The chip insertion loss in these measurements was 8.8 dB. In both measurements the filter response was aligned to have maximum suppression at the unwanted tone frequency of 12.002 GHz.

The measured output RF spectra with and without the SBS pump in the conventional SSB filter are depicted in Fig. 4(a). As expected the unwanted tone power was reduced by 17 dB, but the signal attenuation was as high as 9 dB, which indicated that the conventional filter resolution was below 20 MHz. This clearly demonstrates the limitation of the conventional approach, which cannot simultaneously achieve high-resolution and high-suppression filtering. In contrast, this can be achieved using the cancellation filter, as shown in Fig. 4(b). The measured interferer suppression in this case was 47 dB, limited by the noise floor of the measurements. The signal underwent a low attenuation of 2 dB, indicating that the half-width at half-maximum of the filter was below 20 MHz.

### 6. INSERTION LOSS REDUCTION EXPERIMENT

For various reasons, such as photosensitivity [48], heating [39], or intensity-dependent losses [27], many on-chip devices are not suited to handle high optical power. These devices are thus expected to work with a stringent optical power budget. Here, we investigate and compare the overall performance of the conventional SSB filter and the cancellation filter under a total optical power budget of the order of 400 mW at the facets of the chip. Such a power was chosen to optimize long-term operation and stability of the chip-based filter. We quantify the filter performance in terms of peak suppression, resolution, and RF-to-RF filter insertion loss.

In the case of the conventional SSB filter we distributed the optical power as follows: 25 dBm (316 mW) as the SBS pump and 20 dBm (100 mW) as the (probe) modulated optical carrier power. Higher pump power was chosen to maximize the suppression of this filter. The insertion loss of the photonic chip in these experiments was 9.3 dB. We generated an RF filter with 13 dB suppression and a resolution of 100 MHz. The measured RF insertion loss was -37.7 dB, obtained using 3 mA of detected photocurrent. The measured response centered at frequency of 24.5 GHz is shown in Fig. 5 (blue trace).

We then reversed the optical power distribution between the pump and the probe in the case of the cancellation filter. With 100 mW of pump power we generated 4 dB of SBS gain. The filter response exhibited 55 dB of peak suppression and a...
resolution of 40 MHz. The detected photocurrent increased to 10 mA due to higher optical carrier power, and an RF filter insertion loss of $-31.3$ dB was measured, which is a 6.3 dB improvement compared to the conventional SSB filter.

The results of these experiments demonstrate that in the case of limited power budget, the cancellation filter allows redistribution of optical power from pump to probe waves, thereby reducing the insertion loss of the filter, with improved peak suppression and resolution compared to the conventional filtering approach. Combined with a higher power handling photonic chip and a photodetector that can handle higher photocurrent, the cancellation filter can potentially achieve very low insertion loss in addition to the high suppression, high resolution, and wide frequency range—a combination that is very difficult to achieve using any existing RF or MWP filtering approach.

7. DISCUSSION

We compared the overall performance of the SBS-on-chip cancellation filter to other state-of-the-art integrated filter technologies. This is summarized in Table 1. First, the SBS-based filter uniquely combines salient features of two different MWP filter classes: high rejection levels typical of a multitap filter, and wide frequency tuning typical of resonance-based filters. In terms of linewidth, our filter is unmatched by any other integrated MWP approach, achieving nearly two orders of magnitude higher resolution. In fact, such a high resolution is more akin to low-loss electronic filters [3–7]. However, for the same resolution and rejection level, the SBS filter achieves 36 times wider tuning range compared to the best-performing electronic RF filter reported very recently [7]. Overall, our filter showed the highest quality factor ($Q = 375$) and fractional tuning range (2900%) compared to any integrated filter technology to date. Here, the $Q$-factor is defined as the ratio of the filter’s 3 dB bandwidth to the central frequency of the resonance, while the fractional tuning range is defined as the ratio of the frequency tuning range to the lowest center frequency of the stopband. Note that this measured $Q$ value is higher than previously reported values ($Q = 134$) in a fiber-based SBS MWP filter [38].

The lowest insertion loss measured in our filter was $-30$ dB, which is lower than typical losses in integrated MWP filters [11,12] but is high compared to electronics solutions. This loss can be recuperated using two approaches: reducing chip-coupling loss and reducing the loss in the underlying photonic link. Lower chip-coupling loss, of the order of 1.1 dB per facet, can be achieved in optical waveguides with inverse tapers [51]. Photonic link loss can be minimized by using an RF modulator with lower half-wave voltage ($V_{\pi}$), a higher-power laser source, and a higher-power handling detector [52,53]. Realistically, the insertion loss figure can be improved by 28 dB using the waveguide with inverse tapers, a modulator with half the $V_{\pi}$, and a high photodetector current of 40 mA. This will lead to $-2$ dB insertion loss, which is comparable to electronic RF filters, and is crucial to realize a filter with low noise figure and high spurious-free dynamic range (SFDR) [54,55]. Such an improvement in the insertion loss will lead to a filter technology with all-optimized properties that is essential in modern RF systems and applications.

The filter central frequency stability in our setup is presently limited by the wavelength drifts of the pump and probe lasers. On the other hand, the stopband suppression stability is limited by the bias drifts of the electro-optic modulator. Stability improvement can be achieved by using a single laser as both pump and probe [37,39] and to operate the modulator using a bias control circuitry.

We note that the approach introduced in this paper can be generalized to schemes that use SBS for bandpass filters, such as the recent demonstrations reported in [37,39,56,57], offering better extinction and more energy-efficient operation in photonic integration platforms. The technique can also be extended to multichannel notch filters with ultrahigh extinction using multiple SBS pumps [58].

8. CONCLUSION

In conclusion, we have reported a miniaturized highly selective MWP bandstop filter using SBS in a centimeter-scale chalcogenide glass waveguide. The filter exhibited a unique performance combination of tuning range, reconfigurability, resolution, and rejection that is difficult to match with any existing filter technology. Implementing the key concept of sideband phase and amplitude tailoring led to significant improvement in the energy efficiency of this active filter, therefore opening the path toward monolithic integration in silicon chips. Future work will address the tailoring of the...
SBs pump to create a square-shaped bandstop and bandpass filter as well as banks of filters. Combined with higher-resolution sideband spectral shaping of the probe light, these approaches would enable ultrahigh suppression and reconfigurable-resolution channelizers that are essential in modern RF signal processors, systems, and applications.

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