Signal interference RF photonic bandstop filter

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Abstract: In the microwave domain, signal interference bandstop filters with high extinction and wide stopbands are achieved through destructive interference of two signals. Implementation of this filtering concept using RF photonics will lead to unique filters with high performance, enhanced tuning range and reconfigurability. Here we demonstrate an RF photonic signal interference filter, achieved through the combination of precise synthesis of stimulated Brillouin scattering (SBS) loss with advanced phase and amplitude tailoring of RF modulation sidebands. We achieve a square-shaped, 20-dB extinction RF photonic filter over a tunable bandwidth of up to 1 GHz with a central frequency tuning range of 16 GHz using a low SBS loss of ~3 dB. Wideband destructive interference in this novel filter leads to the decoupling of the filter suppression from its bandwidth and shape factor. This allows the creation of a filter with all-optimized qualities.

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References and links

1. Introduction
Transmission and processing of radiofrequency (RF) signals through optical fibre has received considerable attention owing to the low-loss properties of optical fibres [1–3]. The emerging trend of multi-functional software-defined radio has led to an increasing need for adaptable RF communications hardware, including microwave filters [4]. In particular, a tunable, sharp-rejection, and wideband bandstop filter (BSF) is desired to block wideband interfering signals. There have been several approaches to synthesize microwave bandstop filters using optical filters which have been realized as microwave photonic filters (MPFs). Notch responses were achieved using optical filters resulting from ring resonators [5–7] or Lyot filters based on the birefringence of a polarization-maintaining fibre and a phase modulator [8]. Recently, the signal interference filter concept has been put forward to achieve wideband suppression in microwave BSFs. In such filters, destructive interference from two signal paths is used to create stopbands with high extinction and sharp rejection [9–11]. However, most electrical signal interference filters reported to date exhibit very limited tuning in terms of central frequency or bandwidth. It is thus enticing to implement the signal interference filter concept in the RF photonic domain, where multi-octave frequency tuning and flexible bandwidth reconfiguration have been demonstrated [12].

A similar concept of signal interference filters has been previously implemented in RF photonics through the so-called cancellation notch filter [12–14]. In this technique, a narrowband notch with ultra-high extinction was created through destructive interference of the signals resulting from mixing of two optical sidebands and an optical carrier. Implementation using various optical filters, including integrated ring resonator [13] or π-phase shifted Bragg gratings [14] have been demonstrated. In particular, cancellation filters based on stimulated Brillouin scattering (SBS) has resulted in unique and comprehensive performance. SBS is a strong third-order optical nonlinearity which is a result of coherent interaction between the optical and the acoustic modes within the material [15]. Nevertheless, the synthesized filtering function using this topology was limited to a notch, rather than a square and wideband BSF as which can be achieved through conventional microwave signal interference filters.

In this work, we show that RF photonic square and wideband signal interference BSF cannot simply be achieved through an extension of the cancellation notch filter. This is due to issues associated with the applied SBS phase response and the dispersion in the optical filter used in the topology. We then propose a new approach to realize signal cancellation over a wide range of frequencies achieved through precise synthesis of the SBS loss as the optical filter, with advanced phase and amplitude tailoring of RF modulation sidebands. In this technique, we experimentally demonstrate for the first time a sharp and square-shaped RF photonic BSF with 20-dB extinction, a tunable bandwidth of up to 1 GHz and a central frequency tuning range of 16 GHz using a low SBS loss of 3 dB. We then compare the unique performance of our BSF performance with the state-of-the-art electrical and RF photonic filters previously reported.
2. Principle of operation and theory

In a cancellation notch filter, the destructive interference at the notch frequency was achieved by satisfying the equal amplitude and opposite phase condition at the center of the optical filter resonance [12–14]. Figure 1 depicts a particular case where the SBS loss response is used as the optical filter. In a cancellation notch filter, phase and amplitude tailoring, via an optical modulator in the optical filter, are used to achieve a high extinction notch response. This is achieved through destructive interference between the mixing product of the optical sidebands with the optical carrier.

In this case, the equal amplitude and opposite phase conditions necessary for perfect cancellation were met upon photodetection, only at a specific point at the center of the SBS loss response. At only this specific optical frequency, the SBS loss matches the attenuation of the upper sideband, while the phase contribution of the filter is zero (Fig. 1(b)). Upon photodetection, the mixing products of these sidebands and the optical carrier at the intended frequency will perfectly cancel due to the $\pi$ phase difference obtained from the initial sidebands generation (quasi-phase-modulation) [13].

The same cancellation result applies when the broadening of the SBS pump profile is considered. Figure 2(a) shows the simulation results of the broadened-SBS-loss resonance (solid black curve) when applied to the upper sideband of a quasi-phase-modulated signal. Note that only amplitude matching can be achieved over the entire bandwidth of the SBS profile. The non-flat phase response of the SBS prevents the realization of a sharp-edged bandstop filter (see solid black curve in Fig. 2(b)). The $\pi$-phase difference condition, as expected from a single-resonance cancellation notch filter, can only be achieved at the center of the SBS response. Upon photodetection, the resulting RF response exhibits a maximum cancellation only at the center of the SBS response (see solid black curve in Fig. 2(b)) as opposed to a broadband cancellation.

To overcome this problem, one needs to compensate the SBS phase distortion by introducing an element with the opposite slope of the phase response. For example, the phase response of a tunable delay element will act to cancel out the SBS phase response, resulting in

Fig. 1. Operating principle of MWP cancellation notch filters. (a) An optical carrier generated from a laser (LD) is modulated by a phase modulator resulting in upper and lower sidebands with unequal amplitudes that are out-of-phase by $\pi$. An optical loss resonance is used to attenuate a band of the lower sideband spectrum, making its amplitude equal to the corresponding band in the upper sideband. (b) Corresponding phase responses of the sidebands after using the optical loss resonance. (c) The mixing product measured at the photodetector (PD). Beating these out-of-phase sidebands and the carrier results in a notch response.
Fig. 2. (a) The normalized SBS loss resonance (solid black curve) with the corresponding SBS phase response (solid red curve) and the lower sideband phase response (dashed red line) and amplitude (dashed black line), the modified phase of the lower sideband to compensate the phase difference applied by the SBS loss (dashed green line), and (b) the resulting microwave photonic filter responses before and after phase compensation indicated by the black and the red solid curves, respectively.

A flat-phase optical filter. When this flat-phase optical filter (dashed green line), opposite to the one generated by the SBS, is imparted on one of the optical sidebands, one can achieve a signal interference RF photonic filter with a broad bandwidth cancellation response and sharp edges (solid red line in Fig. 2(b)). In this case the nonlinear phase response of SBS is compensated by the linear phase response resulting from the tunable delay element. Such non-ideal phase compensation leads to limited filter extinction in the SBS bandwidth profile as shown in Fig. 2(b).

The principle of operation of signal interference that allows the phase slope and amplitude control of the optical sidebands is depicted in Fig. 3. This level of control can be achieved by using two optical carriers with different frequencies ($\omega_{s1}$, $\omega_{s2}$), each carrying an out-of-phase RF sideband generated by a phase modulator. By demultiplexing each carrier to different optical paths, tunable attenuation and phase slope that match the ones generated by the broadened SBS response can be imparted on one of the sidebands independently from the other (Fig. 3(IV)). Through precise tailoring, the mixing products generated from the beating of these carriers with their processed side bands will create broadband cancellation at the intended filter bandwidth (Fig. 3(V)).

For small-signal modulation, the optical field of the phase-modulated signal in general can be described as:

$$E(t) = E_0 \left[ J_0 e^{j\omega_{s}t} - J_1 e^{j(\omega_{s}-\omega_{RF})t} + J_1 e^{j(\omega_{s}+\omega_{RF})t} \right]$$

(1)

where, $E_0$ is the optical field of the laser, $J_0$ and $J_1$ are the zeroth and the first-order Bessel functions of the first kind, $\omega_{s}$, and $\omega_{RF}$ are the angular frequency of the laser and the injected RF signal, respectively. Note that the two first-order sidebands are out-of-phase. The upper sideband of the higher carrier frequency ($\omega_{s1}$) and the lower sideband of the lower carrier frequency ($\omega_{s2}$), are removed (see (I) and (II) in Fig. 3). Therefore, the optical fields given by $E_1(t)$ and $E_2(t)$ can be written as:

$$\begin{bmatrix} E_1(t) \\ E_2(t) \end{bmatrix} = E_0 \begin{bmatrix} J_0 e^{j\omega_{s1}t} - J_1 e^{j(\omega_{s1}-\omega_{RF})t} \\ J_0 e^{j\omega_{s1}t} + J_1 e^{j(\omega_{s1}+\omega_{RF})t} \end{bmatrix}$$

(2)
Fig. 3. The simplified setup and principle of operation of the reconfigurable and square-shaped bandstop MWP filter based on the signal interference technique. (I) and (II) are the phase modulated signals of two optical carriers filtered using a demultiplexer. (III) is the tailored SBS pump operating at the frequency $\omega_{pn}$ (where $n$ is the number of the pump line) to achieve a broadened SBS profile. (IV) Amplitude matching and phase engineering of both sidebands to fulfill the cancellation condition. (V) Destructive interference of the sidebands with the corresponding carriers at the photodetector resulting in a bandstop response over the SBS profile.

The remaining sidebands including the corresponding carriers, $E_1(t)$ and $E_2(t)$, are split and sent through two different paths to allow independent amplitude and phase control of each sideband. One of the sidebands is attenuated using the broadened SBS loss response resulting from a tailored SBS pump based on a feedback control loop approach [16,17]. When the SBS loss profile is applied to one of the sidebands (e.g., lower sideband of the corresponding higher frequency ($\omega_{s1}$) carrier), the amplitude of the unprocessed sideband is then adjusted using a variable optical attenuator (VOA) to fulfill the amplitude matching condition (see (IV) in Fig. 3). Therefore, the sidebands have the same amplitude over the bandwidth of the SBS response. The phase of the unprocessed sideband is fine-tuned using an optically tunable delay line (TDL) to maintain a $\pi$ phase-difference between the two sidebands. Consequently, the optical fields can be written as:

$$
\begin{bmatrix}
E_1(t) \\
E_2(t)
\end{bmatrix} = E_0
\begin{bmatrix}
J_0 e^{i\omega_0 t} - T(\omega) J_1 e^{i(\omega_0 - \phi_{\text{VS}}) t} \\
A e^{i\phi_{\text{VS}}} J_0 e^{i(\omega_0 + \phi_{\text{VS}}) t} + A e^{i\phi_{\text{VS}}} J_1 e^{i(\omega_0 + \phi_{\text{VS}}) t}
\end{bmatrix}
$$

(3)

where, $A$ is an attenuation factor ($A<1$) applied to the lower carrier frequency ($\omega_{s2}$) and its sideband to match the SBS loss amplitude, $\phi_{\text{VS}}$ is the phase applied by TDL and $T(\omega)$ denotes the single SBS loss profile

$$
T(\omega) = e^{-g(\omega)} e^{-i\phi(\omega)}
$$

(4)

here $g(\omega)$ is

$$
g(\omega) = G - \frac{\Gamma_g^2}{4\Delta\omega^2 + \Gamma_g^2}
$$

(5)

and $\phi(\omega)$ is

$$
\phi(\omega) = G \Gamma_g \frac{\Delta\omega}{4\Delta\omega^2 + \Gamma_g^2}
$$

(6)
where, $G$ denotes the SBS gain parameter and can be written as

$$G = \frac{g_0}{A_{\text{eff}}} P_{\text{p}}(0) L_{\text{eff}}$$

Here, $g_0$ is the Brillouin gain coefficient (m/W) depending on the material properties, $A_{\text{eff}}$ is the effective optical mode area, $P_{\text{p}}(0)$ is the pump power launched into the medium, $L_{\text{eff}} = \frac{\Delta}{\alpha}(1-e^{-\alpha L})$ is the effective length of the medium, $\alpha$ is the attenuation coefficient (in 1/m) of the medium and $L$ is the physical length of the waveguide. The $\Gamma_B$ is the Brillouin linewidth and $\Delta \omega = \omega_B - \Omega_B - \omega$ with $\Omega_B$ as the Brillouin frequency shift and $\omega_B$ as the pump frequency.

The beating signal between these sidebands and their corresponding carriers interferes destructively at the photodetector and hence, no signal appears in the RF spectrum over the broad SBS bandwidth. Outside the SBS profile, the signals do not completely cancel due to the amplitude difference between the sidebands [18].

To compensate the phase response of the SBS filter, here we use a TDL, which has a positive phase slope (i.e., slow light). For this reason, only optical profiles with negative phase slope (fast light or advancement) can be properly compensated by the TDL. This is illustrated by simulation results shown in Fig. 4. The RF photonic filter response corresponding to the SBS loss has a wide and squared-shaped response since its out-of-phase condition is satisfied (Fig. 4(c)). The level of suppression here is limited to ~15 dB because the phase matching condition is not satisfied everywhere in the stop band, as the phase applied by the SBS response is non-linear (as seen from the red curve in Fig. 4(a)), while the phase applied by the TDL is linear.

3. Experiment

We experimentally demonstrate the signal cancellation RF photonic filter using SBS in a 4.46 km-long spool of single-mode fibre (SMF). Such length allows for operation in a low-pump power regime, which is important in the wideband tailoring of the SBS response. Figure 5 illustrates the experimental setup. The concept is based on a pump-probe experiment where a seed probe is counter-propagated to the pump. The pump beam is generated from a tunable...
distributed feedback (DFB) laser (Teraxion Inc.) operating at 1550 nm with a maximum optical power of 80 mW. A broad pump profile is required in order to create a broad SBS response. This was achieved by modulating the SBS pump using an electrical comb signal generated from an arbitrary waveform generator (AWG - Keysight M8190A) generating a single sideband-suppressed carrier (SSB-SC) pump from a dual-parallel Mach-Zehnder modulator (DPMZM). The stopband response of the resulting filter is tailored based on a feedback control loop technique [16,17]. The pump is amplified using an Erbium doped fibre amplifier (EDFA1) and passed through a polarization controller (PC2) before being launched into the waveguide via a circulator.

Two different tunable DFB lasers (λ1 = 1548, λ2 = 1550 nm) are used to generate the optical carrier for the probe signal (DFB2, DFB3). The wavelengths of the carriers are deliberately tuned 2 nm apart to ensure that the beating frequency of these two frequencies fall outside the bandwidth of the photodetector. These optical carriers are then modulated using a phase modulator. A demultiplexer with a channel spacing of 100 GHz is then used to remove the upper sideband of the higher carrier frequency (ωs1) and the lower sideband of the lower carrier frequency (ωs2) (see (I) and (II) in Fig. 3). In this way, the probe signals are separated into two different optical paths, which is essential to allow freedom in the manipulation of the amplitude, phase and polarization of each probe signal individually. One of the probe signals experiences the tailored SBS loss response, while the other signal undergoes precise control of amplitude and delay using a tunable delay line (TDL) unit. The RF signal is detected by a high-speed photodetector (PD, u2t XPDV2120) with 0.6 A/W responsivity and 50 GHz RF bandwidth and measured by a vector network analyzer (VNA, Agilent PNA 5224A). About 2 m of fibre is added to the lower arm of the probe to match the length of the optical paths in order to avoid interferometer resonances after combining two optical paths [19].
Due to the SBS, the sideband corresponding to the higher frequency carrier \( (\omega_{s1}) \) is attenuated and imparts a phase shift to the RF signal. Subsequently, the phase of the unprocessed sideband is fine-tuned using the TDL to maintain the \( \pi \)-phase difference between the sidebands. Then, by adjusting the amplitude of the unprocessed sideband using EDFA2 and the VOA, cancellation conditions are fulfilled leading to extinction of the signal within the SBS response bandwidth.

The present setup is a proof-of-concept used to demonstrate the novel filtering capabilities. In principle, any noise resulting from the pump path (SBS noise or noise from EDFA1) should not result in the degradation of the SNR in the probe path. At present, the noise floor is dominated by EDFA2 and EDFA3 and it can be improved by incorporating components with lower losses, notably the phase modulator and the demultiplexer.

In the experiments, we observed that the precise tailoring of the SBS loss to match the amplitude ripple of the unprocessed sidebands is crucial for achieving higher extinction at the RF photonic filter stopband. Moreover, to achieve a sharp and nearly square filter profile, the SBS response is reconfigured with stronger response at the outer pumps, i.e. a “rabbit-ear” response. This is illustrated in Fig. 6, where three different cases were considered: imprecise matching of the flat-bottom SBS response with the unprocessed sideband, Fig. 6(a), precise matching with the unprocessed sideband, Fig. 6(b), and the optimized response with precise matching and a rabbit-ear profile, Fig. 6(c).

Figure 6(c) depicts the profiles of a 300-MHz bandwidth tailored SBS loss with higher loss on the edge (green curve) and the unprocessed sideband (black curve). The 10-dB shape factor defined as the ratio between the 10-dB bandwidth and 3-dB bandwidth and is found to be improved from 1.54 to 1.1 as shown in Fig. 6(d). The current signal interference filter suffers from the same insertion loss degradation characteristic of cancellation notch filters [12,13,18]. This is due to the anti-phase relationship between the mixing products at the photodetector, which causes them to partially cancel out even in the filter passband. In our experiment, this effect caused an 11 dB increase in the insertion loss of the filter. However, this degradation can be mitigated by using a stronger SBS resonance [18] at the cost of an increased SBS pump power. The RF insertion loss has not been optimized and was −55 dB. However, this can be improved by using a PD with higher saturation power.

The iterative pump tailoring through feedback control was carried out also for bandwidth reconfiguration of the RF photonic filter. As depicted in Fig. 7(a), the filter 10-dB bandwidth was tuned from 13 MHz to 1 GHz, resulting from single SBS pump to about 60 SBS pumps respectively. The electrically modulated pump using the AWG was set up to generate a broadened pump for bandwidth reconfigurability. First, 20 electrical spectral lines were generated with a frequency separation of the Brillouin gain bandwidth (34 MHz) to create an SBS loss profile with a 3-dB bandwidth of 300 MHz. Then, we increased the number of

![Fig. 5. Schematic of the bandstop MWP filter employing two probe arms for phase management.](image-url)
electrical comb lines to 40 and then to 60 to broaden the SBS bandwidth to 600 MHz and 1 GHz, respectively. It is important to stress that for wide bandwidths, the system was prone to four-wave mixing interactions between the multiple pump lines which led to generation and the buildup of unwanted tones. To mitigate this, we implement the technique proposed in [17].

![Figure 6](image1.png)

**Fig. 6.** Profiles of a 300-MHz bandwidth tailored SBS loss and the unprocessed sideband (black). (a) Imprecise matching of the flat-bottom SBS response with the unprocessed sideband, (b) SBS loss profile precisely matches the unprocessed sideband, (c) the optimized response with precise amplitude matching and a rabbit-ear profile, and (d) the corresponding VNA traces depicting the filter responses.

![Figure 7](image2.png)

**Fig. 7.** (a) Bandwidth reconfigurability of the bandstop filters from 0.013 to 1 GHz; (b) the 3-dB bandwidth (circle) and the 10-dB bandwidth (triangle) as a function of the central frequency.

where multiple electrical lines generated from the AWG were set to random frequency intervals around the natural SBS gain bandwidth. The difference in the rejection ratio between the notch filter and the broadened filter is due to the phase compensation between the nonlinear SBS phase response and the flat-phase resulting from the TDL. However in the case of broadening, the extinction is limited to about 15 dB due to imperfect SBS phase compensation. We then proceed with the demonstration of the frequency tunability of the filter as depicted in Fig. 7(b) showing the 3-dB and the 10-dB bandwidth as a function of
central frequency. The central frequency of the filter was tuned from 14 to 30 GHz by tuning of the pump laser, DFB1. At present the lower-end of the frequency tuning range is limited by the sharpness of the response of the demultiplexer used to remove the unwanted sidebands of the probe signals. This can be improved using a sharper optical filter to remove only one sideband from the phase modulator close to its carrier. On the other hand, the upper frequency range is limited by the operational bandwidth of the phase modulator. The shape of the filters remained almost the same throughout the frequency tuning. As can be seen from Fig. 7(b), the ratio of the 10-dB bandwidth to the 3-dB bandwidth remained almost constant.

To put this work into context of state-of-the-art filter technologies, we summarize and compare the filter performance with existing filter technologies, as indicated in Table 1. Here we compare various filter characteristics including the 10-dB bandwidth, the extinction ratio, the shape factor and the fractional tuning range which is defined as the ratio of the frequency tuning range to the lowest center frequency of the bandstop filter. Some of the notch filters have a relatively high extinction with a large shape factor and a small tuning range. The filter reported in reference [6] has an extinction of 45 dB for a 3-dB bandwidth of between ~4.66 to 8.56 GHz and a 10-dB bandwidth of 1.85 to 4.55 GHz. In another case reported in reference [7], the filter has an extinction of 40 dB with a 3-dB bandwidth of 6 GHz to 9.5 GHz and a 10-dB bandwidth of about 1.5 GHz. However, the filter profiles are not sharp. It is clear that the filter reported here has a superior overall performance including wide fractional tuning range (114%) and almost two decade bandwidth reconfigurability (13 MHz to 1 GHz) and a shape factor as low as 1.1. Such a filter can play an important role in the next generation wireless systems with wideband interference resulting from spectrum sharing.

### 4. Conclusions

In conclusion, we have demonstrated tunable-resolution rectangular-shaped microwave photonic filters with sharp edges and suppression of 20 dB using a low (~3 dB) Brillouin loss. We show the principle of operation for this new approach and experimentally implemented it in a spool of SMF fibre. The filter exhibited a unique performance including small shape factor that is comparable to state-of-the-art electronic filters. Furthermore, it provides GHz of bandwidth reconfigurability and a wide tuning range that is difficult to achieve simultaneously with any existing microwave filter technology.

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