Independent manipulation of the phase and amplitude of optical sidebands in a highly-stable RF photonic filter

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Abstract: Microwave photonic cancellation notch filters have been shown capable of achieving ultra-high suppressions independently from the strength of optical resonant filter they use, making them an attractive candidate for on-chip signal processing. Their operation, based on destructive interference in the electrical domain, requires precise control of the phase and amplitude of the optical modulation sidebands. To date, this was attainable only through the use of dual-parallel Mach-Zehnder modulators which suffer from bias drifts that prevent stable filter operation. Here we propose a new cancellation filter topology with ease of control and enhanced stability using a bias-free phase modulator and a reconfigurable optical processor as the modulation sidebands spectral shaper. We experimentally verify the long term stability of the novel filter topology through continuous real-time monitoring of the filter peak suppression over 24 hours.

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1. Introduction

Microwave photonic (MWP) filter [1–3] is a disruptive technology with a wide range of applications including radar, electronic warfare, wireless communications, and radio astronomy. The strengths of this technology include high bandwidth, wide (tens of gigahertz) frequency tuning, and flexible reconfiguration of the frequency response. These features are difficult to achieve with conventional radio frequency (RF) filter technologies. In addition to frequency agility, applications such as countermeasure and jamming require the use of filters with extremely large stopband rejection. While a high extinction is readily available with RF technologies, for example using absorption bandstop filters [4], achieving this while preserving frequency agility was not feasible until very recently, with the introduction of the cancellation MWP bandstop filter topology [5–8].

The cancellation MWP bandstop filter can be seen as the RF photonic counterpart of the RF absorption bandstop filter, in the way it achieves ultra-high extinction through precise phase and amplitude matching of two paths of the same signal to create signal cancellation at a desired bandstop, or notch, frequency. In the case of the MWP filter, the two cancelling signals are formed by the mixing of two optical sidebands with the optical carrier, hence putting a strong emphasis on proper tailoring of the phase and amplitude of these three spectral components. As previously reported, the most straightforward way to synthesize the required phase and amplitude of these components was through the tuning of a dual-parallel Mach-Zehnder modulator (DPMZM) bias voltages [5]. To achieve a high-suppression filter, the DPMZM was used to synthesize a double-sideband with carrier (DSB + C) optical spectrum with tunable ratio of sidebands amplitude and phase. This spectrum then acted as the input to a resonant optical filter such as an optical ring resonator [6], a fiber Bragg-grating [7] or the gain/absorption spectra of stimulated Brillouin scattering process [5,8]. The combination of the DPMZM and the optical filter was essentially used to create a signal cancellation at a specific frequency inside the resonance of the optical filter. This approach was successfully used to demonstrate a record performance MWP filter with simultaneously ultra-high suppression (>50 dB), high quality factor (Q = 375) and high fractional tuning range (2900%) from 0 to 30 GHz [8]. Nevertheless, a key point to consider in the actual application of the filter is the stability of the filter shape, notch depth, and the filter central frequency. To date, the long term stability of this filter operation has not been thoroughly investigated.

In this work, we show that the stability of the filter response is limited by the stability of the DPMZM transfer function. We then present a novel scheme for a cancellation filter, where the DPMZM is replaced by a simple bias-free phase modulator and the tailoring of the sidebands’ amplitude and phase is performed using a Fourier-domain optical processor (FD-OP) [10]. As a proof of principle, we compare the long term stability of the conventional DPMZM-based filter with the new scheme. We show that significant improvement in the filter stability can be achieved. Finally we show that the new scheme allows for active control of the filter extinction ratio, resulting in overall high extinction (>40 dB) for continuous operation over a 24-hour period.

2. Sideband spectral tailoring

Figure 1(a) shows the basic structure of the MWP cancellation notch filter. An input RF signal is up-converted to the optical domain through modulation of a continuous wave (CW) laser, which acts as the optical carrier. It is essential that the modulation process generates two optical sidebands about the carrier frequency, as shown in Fig. 1(b). The sideband spectra
are then tailored such that their phase difference relative to the carrier phase is 180°. This phase condition is more clearly expressed mathematically as

\[(\theta_c - \theta_u) - (\theta_u - \theta_l) = \pm \pi\,,\]

(1)

where \(\theta_c, \theta_u, \theta_l\) are the phases of the carrier, and upper and lower frequency sidebands, respectively. The sidebands are also tailored such that their magnitudes are unequal (i.e. one sideband is stronger than the other). This is done so that it is possible to equalize the amplitude of the sidebands over a narrow region through the use of an optical resonance. This, for example, could be provided by a fibre-Bragg grating, a ring resonator, or through SBS.

The resonance affects the signal by equalizing the magnitude of the sidebands only over the resonance linewidth. Such equalization could occur either by amplification of the weaker sideband (as in Fig. 1(b)), or by absorption on the stronger sideband, and is expressed mathematically as

\[E_l = GE_u\,,\]

(2)

where \(E_u, E_l\) are the amplitudes of the lower and upper frequency sidebands, respectively, while \(G\) denotes the peak magnitude response of the optical resonance, which can be attributed to either loss or gain.

Finally, the optical signal undergoes direct detection. The detection process generates two RF mixing products (due to the carrier beating with each of the two sidebands). Provided Eq. (1) is satisfied, these mixing products are in antiphase. Complete destructive interference thus occurs in the frequency range where the sidebands have equal amplitudes [i.e. where Eq. (2) holds true], resulting in zero signal output at that frequency only. At other RF frequencies, where the magnitudes of the optical sidebands are unequal, this does not occur, and a signal exists at the output. This process results in a notch filter response with a very high extinction ratio.

Fig. 1. (a) Structure and (b) operating principle of MWP cancellation notch filters. In steps B and C, note the antiphase relationship between the sidebands. In step C, an optical gain resonance is used to amplify a band of the upper sideband spectrum, making its amplitude equal to the corresponding band in the lower sideband.

The amount of suppression obtained in the notch response is directly related to how well Eqs. (1) and (2) are satisfied. It is clear that these conditions place very stringent requirements...
on the amplitude and phase relations of the optical sidebands. Furthermore, the stability of the notch depth depends on both equations being satisfied at all times.

In previous demonstrations, both the modulation and the sideband tailoring were achieved with a DPMZM, as shown in Fig. 2. Such modulators allow control over the phase and amplitude of the modulation sidebands and carrier, through adjustment of three bias voltages $V_A, V_B, V_C$. The next equations describe the amplitude and phase of each component at the DPMZM output, in the small-signal regime:

$$E_{\alpha}e^{j\theta_{\alpha}} = J_0(m_{RF1}V_{RF})\cos\left(\frac{\theta_\alpha}{2}\right)\exp\left(j\frac{\theta_\alpha}{2} + j\theta_c\right),$$

$$E_{\beta}e^{j\theta_{\beta}} = -J_1(m_{RF1}V_{RF})\sin\left(\frac{\theta_\beta}{2}\right)\exp\left(-j\frac{\theta_\beta - \pi}{2} + j\theta_c\right),$$

$$E_{\gamma}e^{j\theta_{\gamma}} = J_1(m_{RF2}V_{RF})\sin\left(\frac{\theta_\gamma}{2}\right)\exp\left(j\frac{\theta_\gamma - \pi}{2} + j\theta_c\right),$$

where $J_n(\cdot)$ is an $n$th-order Bessel function of the first kind, $m_{RF1}$ and $m_{RF2}$ are the modulation indices for the two Mach-Zehnder modulators present in the DPMZM, $V_{RF}$ is the amplitude of the input RF signal, and, $\theta_i = m_{DC}V_i$ where $i = A, B, C$ and $m_{DC}$ is the DC modulation index.

![Fig. 2. Structure of a MWP cancellation notch filter, with DPMZM used for tailoring the sidebands' spectra. At the input of the DPMZM, an RF hybrid coupler is used to split the input RF signal between the two arms of the modulator.](image)

By solving Eqs. (3-5), one can always calculate the biases required to synthesize an optical spectrum which satisfies Eqs. (1) and (2), and obtain a notch response. Due to their complexity, a solution if far from trivial, but could be obtained by using a lookup table. However, it is well known that the bias point of a lithium niobate modulator, such as a DPMZM, drifts over time due to charging effects, or due to ambient changes such as variations of temperature and polarization [9]. While in conventional operation, such as for the generation of differential quadrature phase shift keying (DQPSK) signals, the drift can be compensated with a bias controller, this is not the case when the desired output is a signal...
which satisfies Eqs. (1) and (2). To understand this, Fig. 3 shows the procedure for obtaining a high-suppression notch response by varying the DPMZM biases. This process requires all three bias voltages to be varied and, as shown in Fig. 3(b), not in the vicinity of points where a bias controller would be able to lock into (e.g. quadrature, null, or peak). Furthermore, the fact that the bias voltages do not always vary monotonically hinders the implementation of a feedback-based control mechanism.

![Fig. 3. (a) Simulation of a DPMZM-based cancellation notch filter. The different curves show the filter response for different DPMZM bias points, as shown in (b).](image)

This problem is exacerbated further by the fact that any fluctuations in the system (e.g. tuning of the notch frequency, or fluctuations in the optical resonance) need to be followed by proper adjustments of the DPMZM bias voltages, so that a high notch suppression can be maintained. Therefore, in most situations, the DPMZM bias voltages need to be continually adjusted, preventing the DPMZM response from stabilizing to a fixed point. This in turn introduces a time drift in the DPMZM transfer function, which comprises an additional source of instability.

![Fig. 4. Structure of a MWP cancellation notch filter, with a Fourier-domain optical processor (FD-OP) used for tailoring the sidebands' spectra. The enhanced functionality of the FD-OP means that the DPMZM can be replaced with a simple bias-free phase modulator.](image)

Here we propose to replace the DPMZM with a phase modulator, followed by a reconfigurable optical processor as shown in Fig. 4. The role of this optical processor is to independently manipulate phase and amplitude of the carrier and the optical sidebands generated by the phase modulator. While in general any optical processor with suitable resolution and functionality can be used, here we use a Fourier-domain optical processor (FD-OP) [10] for the phase and amplitude manipulation. There are two main advantages that follow from this novel configuration. The first is that a phase modulator does not need to be biased, hence removing the main source of instability. The second key advantage is that, by using a FD-OP composed of a two-dimensional liquid crystal on silicon (LCoS) array, the phase and amplitude relations can be independently controlled, greatly simplifying the process of satisfying Eqs. (1) and (2). To appreciate the simplified approach, we examine the field at the output of the phase modulator,
\[ E_C e^{j\theta} = J_0 (m_{RF} V_{RF}) \]
\[ E_L e^{j\theta} = -J_1 (m_{RF} V_{RF}) \]
\[ E_U e^{j\theta} = J_1 (m_{RF} V_{RF}) \]

Together with the frequency response \( H_{op}(\omega) \) of the FD-OP:

\[ H_{op}(\omega) = \begin{cases} 1 & \text{for } E_C, E_L, \\ Ae^{j\phi} & \text{for } E_U \end{cases} \]

where \( 0 < A < 1 \) and \(-\pi < \phi < \pi\) are parameters whose value can be independently controlled. Equations (6-8) show that the carrier and sidebands generated by the phase modulator automatically satisfy Eq. (1). Ideally therefore, the FD-OP need only be used to control the amplitude of one of the sidebands, with \( \phi = 0 \), to satisfy Eq. (2). The procedure for maximizing the notch suppression is shown in Fig. 5. It involves using the FD-OP to attenuate only one of the sidebands; as the attenuation approaches the value of the optical resonance, the notch suppression increases. The fact that the procedure requires control of a single variable (i.e. FD-OP attenuation), and that its value is changed monotonically, greatly simplifies the task of implementing automatic feedback control of the notch suppression.

Fig. 5. (a) Simulation of a cancellation notch filter using a phase modulator in combination with an FD-OP to sideband tailoring. The phase modulator causes Eq. (1) to be automatically satisfied. Equation (2) is satisfied by using the FD-OP to attenuate only one of the sidebands. (b) The different FD-OP attenuations, approaching the magnitude of the optical resonance, to maximize the notch suppression.

3. Experiment

An experiment was carried out to test the performance of the new filter configuration, and measure its stability. The optical resonance in this case was provided through SBS in optical fiber. In the setup, shown in Fig. 6, two DFB lasers in CW mode with 20 dBm output power, were used to generate the SBS pump and Stokes waves. The first laser wavelength was set to 1550 nm, and was sent through a phase modulator (PM), where it was modulated by an input RF signal supplied by a vector network analyzer (VNA). The phase-modulated signal then passed through the FD-OP (Finisar Waveshaper 4000s, denoted as WS in Fig. 6). As described in Section 2, the Waveshaper was used to attenuate one of the sidebands, without affecting the carrier, or the other sideband. Due to imperfections in the phase modulator, and to account for fiber dispersion, the Waveshaper response was also used to provide a small, yet nonzero, phase contribution, so that Eq. (1) could be satisfied. Finally, the signal was
launched in a 1.6 km length of single mode fiber (SMF) where the SBS interaction occurred, before being detected at the photodetector. The frequency of the laser used for generating the SBS pump wave was set such that the SBS gain resonance occurred on the attenuated sideband. In this way, the amplitudes of the sidebands were equalized only over a frequency range approximately equal to the SBS linewidth (~35 MHz), resulting in a narrowband notch response in the electrical domain. The operational bandwidth of the filter was from 0 to 30 GHz, limited by the bandwidth of the modulator. While the signal had to travel through more than 1 km of fiber, we note that fiber dispersion did not have a significant effect on the filter passband due to the modulation format used for the cancellation filter, where one of the sidebands is considerably stronger than the other. Effectively, the signal spectrum resembled that of a single sideband modulated signal, which is immune to fiber dispersion.

Initially, the system was optimized to achieve maximum notch suppression. This involved setting the WS attenuation to match the magnitude of the SBS resonance (5 dB). The system was then left running freely for a 24 hour period in an uncontrolled environment, subject to temperature and pressure fluctuations, and the filter response continually monitored. We then repeated the 24-hour measurement with a computer program monitoring the notch filter response over time, and actively adjusting the WS attenuation to maintain maximum notch suppression. This active control loop involved using the VNA to continuously measure the magnitude response of the filter. The VNA trace was then input to a computer program which measured the filter suppression (defined as the ratio of maximum to minimum transmission). If the measured value was found to be below a predetermined minimum suppression level, the program sent a control signal to the Waveshaper which adjusted its attenuation, and the corresponding ratio between the modulation sidebands. A hill climbing algorithm was used to determine whether the Waveshaper suppression had to be increased or decreased. The speed of the control process was mainly limited by the response time of the Waveshaper, in the order of 3 seconds.

Fig. 6. Experimental setup for the cancellation notch filter, with a phase modulator (PM) and a waveshaper (WS) used for tailoring the sidebands’ spectra. The filter response was measured with a vector network analyzer (VNA). The SBS interaction occurred in a 1.6 km spool of single-mode fiber (SMF). Polarization controllers (PC) were used to minimize losses, and to maximize the strength of the SBS interaction.

The long-term measurements were repeated also using the conventional filter topology (this is similar to Fig. 6, but with the PM and Waveshaper replaced by the DPMZM, as done in [8]). This allowed us to obtain a direct comparison between the stability of these two filter topologies. Figure 7 shows the measured filter responses at the start of the measurement (i.e. with optimized notch filter suppression), and after 12 and 24 hours of continuous operation, for all three sideband tailoring methods. The drift in the center frequency of the notch was due to free running arrangement of the lasers. Over the 24 hour measurement period, the maximum laser frequency drift was measured as 15 MHz. In the DPMZM measurements, shown in Fig. 7(a), the notch frequency drift is larger than this value due to the inherent instability of the DPMZM output. This instability causes the phase relations between the...
sidebands to deviate from the ideal antiphase state of Eq. (1), such that the destructive interference of the RF mixing products occurs at a frequency offset from the SBS line center, where its phase contribution is nonzero.

While the filter can be considered active due to the use of SBS (a gain mechanism) for obtaining the notch response, it is important to note that SBS has an effect solely in the filter stopband, and not in the passband. In the passband, no gain mechanism was utilized, and therefore the noise figure of the filter is similar to that of a standard microwave photonic link. In our experiments we measured a link gain level of $-35 \text{ dB}$ (as shown in Fig. 7), and the noise figure can be roughly estimate as the inverse of the link gain ($\sim 35 \text{ dB}$) [3].

Figure 8 shows the measurement of the notch filter suppression across the whole 24-hour period. The main source of instability during each 24-hour period was a drift in the SBS pump power and polarization. This caused fluctuations in the SBS resonance amplitude, which in turn caused Eq. (2) to no longer hold true. From the measurements however it is clear that the DPMZM implementation had an additional source of instability (due to bias drifts) which caused the filter response to deteriorate more rapidly. As stated in Section 2, the inherently unstable nature of the DPMZM, combined with the high complexity of its response, presented a major obstacle to realizing software control for filter stabilization. On the contrary, the simplicity of the PM and WS implementation enabled the realization of active software control, which greatly stabilized the filter response. While, on average, the filter suppression obtained with the active control method achieved higher suppression than the other two methods, it is clear that its value also experienced more fluctuations. It is important to note that any suppression beyond 50 dB was subject to the noise floor of the system, and therefore varied randomly. The fluctuations that occurred for suppression values lower than 40 dB however were due to the active control algorithm, which on average required multiple iteration steps to correct the Waveshaper attenuation to maximize the filter’s suppression. The correction algorithm itself was relatively simple, and designed only as a proof of concept.

![Fig. 7. Measurements of the notch filter response after 12 hour intervals of continuous operation. Sideband tailoring was performed using a (a) DPMZM; (b) PM in combination with waveshaper; (c) PM in combination with waveshaper, driven by software to actively control the waveshaper attenuation.](#)
Fig. 8. Measurement of the notch filter suppression over a 24 period of continuous operation. The three plots denote different methods for tailoring the sidebands' spectra.

We believe that the approach of independent tailoring of phase and amplitude of optical carrier and modulation sidebands will define the new waves of MWP processing, not only for filtering [11], but also for other signal processing such as phase shifting [12] and link gain optimization. We predict that in the near future approaches to integrate this tailoring functionality in a photonic chip will gain significant attention to redefine the field of linear and nonlinear integrated microwave photonics [13].

4. Conclusions

A novel concept in sideband processing has been implemented, making use of a simple, biasless phase modulator, in combination with a FD-OP. Tailoring of the modulation sidebands was used to demonstrate a high-suppression MWP cancellation filter. Compared to previous demonstrations, where a DPMZM was used for the sideband tailoring, the new implementation exhibited far greater stability, due to the elimination of the modulator biasing. Furthermore, the use of an FD-OP allowed independent control over the phase and amplitude of the sidebands, greatly reducing system complexity. This enabled the realization of a simple algorithm for controlling the filter suppression, and resulted in the first demonstration of a MWP notch filter with high 40 dB suppression, over a long 24-hour period.

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