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Description of the Invention

Title: Photonic microwave filter with infinite impulse response

Applicants: Cheng Linghao, Sheel Aditya

FIELD OF THE INVENTION

The present invention relates to the field of filtering and in particular discloses a photonic method and apparatus for filtering RF or microwave signals.

BACKGROUND OF THE INVENTION

The huge bandwidth of photonic processors makes them attractive alternatives to process microwave signal to overcome the limitations of existing electronic approaches, such as the well-known “electronic bottlenecks” imposed by limited sampling speeds in conventional electrical signal processors. Moreover, photonic processors also provide excellent isolation, immunity to electromagnetic interference (EMI), wideband tunability and reconfigurability.

Considerable number of structures for photonic processing for applications in microwave signal filtering has been proposed over the years. A desired feature of these filters is to achieve high frequency selectivity, which then requires a large number of taps in the discrete time signal processor. Hence some schemes with infinite number of taps have been reported, which are known as infinite impulse response (IIR) filter. However, these schemes are realized entirely in the optical domain and hence to avoid coherent interference effects these have to use laser sources with coherence time less than the minimum delay difference in all possible paths of their filter structures. This limitation leads to some performance degradation, such as the limited range of tunability and the serious noise due to the optical interference. Besides, these schemes are lacking in reconfigurability to switch between bandpass and bandstop filter which is desired in some applications.

SUMMARY OF THE PRESENT INVENTION

This application describes techniques and devices to realize an opto-electronic filter for RF or microwave signal filtering with infinite impulse response. Implementations of this opto-electronic filter comprise opto-electronic circuits of a closed feedback loop. This closed feedback loop comprises:

- An optical modulator to modulate an optical signal using a feedback microwave signal;
- A photodetector to convert the optical signal to microwave signal;
- An optical delay line with some optical gain, feeding the optical output of the



optical modulator to the photodetector;

An electrical delay line with some electrical gain, feeding the electrical output of the photodetector back to the optical modulator as the modulating microwave signal.

The filter receives an optical signal modulated by a microwave signal. Alternatively, the input signal to the filter can be created via modulation of an optical signal by a microwave signal. The output of the filter is the microwave signal after filtering.

Alternatively, the filter can provide an output optical signal modulated by a microwave signal after filtering.

Alternatively, the filter can provide two outputs simultaneously: one is the microwave signal after filtering and the other is an optical signal modulated by a microwave signal after filtering.

In one embodiment, the optical modulator may be a Mach-Zehnder-Interferometer (MZI) based optical modulator, which enables the filter to switch the passband of the filter response to stopband.

Alternatively, the optical modulator may be a semiconductor based optical modulator, such as an electroabsorption modulator, which enables the filter to be integrated into a chip.

The gain of the optical delay line can come from an optical amplifier, such as a semiconductor optical amplifier (SOA) or an Erbium-doped fiber amplifier (EDFA).

The length of the optical delay line may be variable. This enables the free spectral range (FSR) of the filter to be tuned.

In one embodiment, the delay line may be highly dispersive. For example, the optical delay line may comprise a section of chirped fiber Bragg gratings (CFBG). This converts the filter into a hybrid filter: a finite impulse response (FIR) filter is inserted into the presented infinite impulse response (IIR) filter to shape the overall filter response further and enhance the filter performance for some applications.

The gain of the electrical delay line can come from an RF amplifier.

The length of the electrical delay line may be variable. This enables the free spectral range (FSR) of the filter to be tuned.

These and other implementations are described in detail in the attached drawings, the detailed description, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Notwithstanding any other forms which may fall within the scope of the present invention, preferred forms of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

FIG. 1 shows one example of a photonic microwave filter with infinite impulse response (IIR).

FIG. 2A shows the computed response of the photonic microwave filter with infinite impulse response (IIR) for positive feedback in the frequency range of one free spectral range (FSR).

FIG. 2B shows the computed response of the photonic microwave filter with infinite impulse response (IIR) for negative feedback in the frequency range of one free spectral range (FSR).

FIG. 3 shows the computed response of the photonic microwave filter with infinite impulse response (IIR) for different values of feedback efficiency in the frequency range of one free spectral range (FSR).

FIG. 4 illustrates one embodiment of the filter photonic microwave filter with infinite impulse response (IIR), which is also the experiment setup.

FIG. 5 shows the measured frequency response of the filter shown in FIG. 4 in the band of 0.04 – 1 GHz.

FIG. 6 illustrates the tunability of the filter shown in FIG. 4; FIG. 6A illustrates the tunability of the free spectral range (FSR) by varying the length of the optical delay line; FIG. 6B illustrates the reconfigurability to switch the passband to stopband.

FIG. 7 shows an alternative embodiment using an electroabsorption modulator to enable the integration of the filter on a semiconductor chip.

FIG. 8 shows another embodiment using a chirped grating in replacement of the optical delay line to expand the capability of the filter.

DESCRIPTION OF THE PREFERRED AND OTHER EMBODIMENTS

FIG. 1 shows one example of a photonic microwave filter **100** with infinite impulse response (IIR) described in this application for filtering RF or microwave signals. The filter **100** receives an optical input **101** modulated by an RF input **119**. The optical input **101** can be the output of an optical link or circuit and can be created by modulating the output of a laser **122** through an optical modulator **121** driven by an RF input **119** and a bias **120**. Inside the filter **100**, the optical input **101** is modulated by an RF feedback signal **105** through an optical modulator **102** with modulation efficiency **103** of R_1 . The RF feedback signal **105** is obtained by photo-detecting the output of the optical modulator **102** through a photodetector **112** with photodetection efficiency **113** of R_2 . An optical coupler **106** can be inserted between the optical modulator **102** and the photodetector **112** to provide an optical output **107** for the filter **100**. Between the optical modulator **102** and the photodetector **112** is a section of optical delay line **109**. The RF output of the photodetector **112** is split into two parts by an RF splitter **115**: one is the RF output **114** of the filter **100**; the other is the RF feedback signal **105** to drive the optical modulator **102** through a section of electrical delay line **118**. Therefore the filter **100** consists of a closed feedback loop where a part of the detected output signal of the optical modulator **102** is fed back to drive the optical modulator **102** itself. The signal gain in the loop can be controlled by using an optical amplifier **110** with an optical intensity gain **111** of G_o or an RF amplifier **116** with an electrical amplitude gain **117** of G_e . The optical amplifier **110** can be placed before or after the optical modulator **102**.

As one advantage, in the filter **100**, because the optical signal is terminated at the input of the photodetector **112** and the feedback signal is the RF feedback signal **105** which is an electrical signal, the filter **100** does not suffer from the problem of optical coherence. Therefore, there is no restriction on the coherence length of the laser **122** for the filter **100** to avoid the problems induced by the optical coherence such as the optical coherent interference and the excessive noise due to the optical phase-noise-to-intensity-noise conversion. The filter **100** can operate very well for laser sources at arbitrary wavelength and with arbitrary optical coherence length.

In the loop of the filter **100**, letting the optical intensity gain **111** of G_o include all the optical loss and letting the electrical amplitude gain **117** of G_e include all the electrical loss, when the average intensity of the optical input **101** is P_0 , the feedback efficiency of the loop is

$$\eta = G_e G_o P_0 R_1 R_2 \quad (1)$$

The feedback efficiency η stands for the amplitude ratio between the RF feedback signal **105** and the RF input **119**. Then, when $|\eta| < 1$, it can be shown that the RF power response of the filter **100** is

$$R_m = \left| \frac{1}{1 - \eta \exp(-j\omega_r T)} \right|^2 = \left| \frac{1}{[1 - \eta \cos(\omega_r T)]^2 + [\eta \sin(\omega_r T)]^2} \right| \quad (2)$$

$$= \frac{1}{(1 + \eta^2) - 2\eta \cos(\omega_r T)}$$

where T is the signal transmission time from the output of the optical modulator **102** back to the RF driving port of the optical modulator **102** to complete one cycle of the loop. ω_r is the frequency of the RF signal. It is then easy to find that the free spectral range (FSR) of the filter **100** is

$$FSR = \frac{1}{T} \quad (8)$$

FIG. **2A** and FIG. **2B** show the calculated response of the filter **100** for positive and negative η , respectively, in the frequency range of one FSR. The passband of the filter response for positive η becomes the stopband of the filter response for negative η and vice versa. Therefore, the passband and the stopband of the filter **100** can be switched simply by changing the sign of the feedback efficiency η .

FIG. **3** shows the calculated response of the filter **100** for different values of η in the frequency range of one FSR. It shows that the larger the $|\eta|$, the narrower the passband and the higher the rejection ratio of the response of the filter **100**. Therefore, the shape of the filter response can be tuned by changing the value of η , which, according to Eq. (1), can be changed by changing the average intensity of the optical input **101** P_0 , the optical intensity gain **111** of G_o , the electrical amplitude gain **117** of G_e , the modulation efficiency **103** of R_1 or the photodetection efficiency **113** of R_2 .

For correct operation of the filter **100**, the absolute value of feedback efficiency $|\eta|$ should be kept below 1. This can be ensured by employing some circuits in the feedback loop to control the value of $|\eta|$ automatically.

FIG. 4 illustrates one embodiment of the filter **100**, which is also the experiment setup. The embodiment uses a Mach-Zehnder modulator (MZM) **401** as the optical modulator **102** in the feedback loop of the filter **100**. The optical amplifier **110** is placed before the Mach-Zehnder modulator **401** in this embodiment. Through the RF splitter, 50% of the photodetector output is outputted as the RF output of the filter **100**.

The measured frequency response of the filter in the band 0.04 – 1 GHz is shown in FIG. 5. The spacing between the two adjacent peaks of the passband is the free spectral range (FSR) **501**, which is measured to be 42.6 MHz.

The FSR of the filter **100** can be tuned through changing the length of the optical delay line **109** or the electrical delay line **118**. FIG. 6 shows the measured frequency response of the filter in the band 0.5 – 1 GHz after shortening the length of the optical delay line **109**, which shows an increased FSR of 47.8 MHz.

In this embodiment, the Mach-Zehnder modulator (MZM) **401** can change the sign of the feedback efficiency η by tuning the bias **402** to let the Mach-Zehnder modulator (MZM) **401** work at the positive or the negative slope of its transfer function. Therefore, the passband of the filter response can be switched to the stopband by tuning the bias **402** to a bias point with opposite sign of the slope of the transfer function. This capability is shown in FIG. 6 clearly where the passband in FIG. 6A has been switched to the stopband in FIG. 6B and vice versa.

The rejection ratio of the filter response can be tuned through changing the value of $|\eta|$. FIG. 6B shows a smaller rejection ratio of about 25 dB compared to that of about 30 dB in FIG. 6A by decreasing the average optical intensity of the optical input **101** to lower the $|\eta|$.

As an alternative embodiment, the optical modulator **102** can be implemented using an electroabsorption modulator (EAM) **701** and the optical amplifier **110** can be implemented using a semiconductor optical amplifier (SOA) **702** as shown in FIG. 7. The critical components of this embodiment, including the optical modulator **102**, the photodetector **112**, the optical amplifier **110**, the RF amplifier **116**, the RF splitter **116** and the electrical delay line **118** can be integrated into a semiconductor chip for large

scale manufacture. For this embodiment, the optical delay line **109** can work as an accessory of the chip, which is variable to meet different requirements of various applications.

Another embodiment using a chirped grating in replacement of the optical delay line **109** is shown in FIG. 8. The insertion of the chirped grating can be realized by using an optical circulator **801** and a chirped grating **802**. The chirped grating introduces another filter with finite impulse response (FIR) before the filter with infinite impulse response (IIR), which therefore results in higher rejection ratio of the overall filter response due to the combination of two filters. This embodiment can accept an optical input **101** containing multiple wavelengths which can be realized by implementing the laser **122** by a multi-wavelength laser or a laser array. The response of the filter with finite impulse response can then be shaped by assigning different intensities to various wavelengths, which then shapes the overall filter response. The wavelength of the laser **122** can also be tunable; this can provide another means to tune the free spectral range of the filter.

The foregoing shows that the filter **100** exhibits substantial flexibility. The free spectral range (FSR) of the filter can be tuned continuously through changing the length of the delay lines; the rejection ratio of the filter response can also be tuned through tuning the gain in the feedback loop; the passband of the filter response can be switched to stopband easily and promptly through changing the sign of the feedback signal; and the filter response can also be shaped.

The filter **100** also provides ample capability for expanding and cascading. The filter **100** provides a pair of optical input **101** / output **107** and a pair of RF input **119** / output **114**. Therefore, the filter **100** can be used directly in combination with other optical components as well as other RF components. This capability enables the filter **100** to be able to be embedded in optical systems and RF systems seamlessly. Other photonic microwave filters and RF filters can be cascaded to the filter **100** directly to enhance the overall filter performance.

Only a few implementations are disclosed here. However, it would be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

What is claimed is what is described and illustrated, including:

1. A method:
Providing a photonic microwave filter device with infinite impulse response having a closed opto-electronic feedback loop;
the opto-electronic feedback loop comprises an optical section and an electronic section;
the closed opto-electronic feedback loop includes an optical modulator to receive an electrical feedback signal in order to produce an optical feedback signal;
a photodetector to receive the optical feedback signal in order to produce the electrical feedback signal and an electrical output.
2. The method as claimed in claim 1, further comprising amplifiers to compensate the signal loss and control the gain in the closed opto-electronic feedback loop.
3. The method as claimed in claim 1, wherein the optical section and/or the electronic section can be dispersive.
4. The method as claimed in claim 1, wherein the sign of the optical feedback signal can be switched between positive and negative so that the response of the photonic microwave filter can be switched between bandpass and bandstop.
5. The method as claimed in claim 1, wherein the propagation time of signals to complete one cycle of the closed opto-electronic feedback loop can be varied to tune the free spectral range of the photonic microwave filter.
6. The method as claimed in claim 1, wherein the power of the feedback signal can be tuned to tune the response of the photonic microwave filter.
7. A photonic microwave filter device, comprising:
a closed opto-electronic feedback loop which comprises an optical section and an electronic section, wherein the closed opto-electronic feedback loop includes an optical modulator to receive an electrical feedback signal to produce an optical feedback signal and a photodetector to receive the optical feedback signal to produce the electrical feedback signal and an electrical output.
8. A photonic microwave filter device as claimed in claim 7, further comprising optical amplifiers and/or RF amplifiers to compensate the signal loss and control the gain in the closed opto-electronic feedback loop.
9. A photonic microwave filter device as claimed in claim 7, wherein the optical section and/or the electronic section can be dispersive.
10. A photonic microwave filter device as claimed in claim 7, wherein the sign of the optical feedback signal can be switched between positive and negative so that the response of the photonic microwave filter can be switched between bandpass and bandstop.
11. A photonic microwave filter device as claimed in claim 7, wherein the

propagation time of signals to complete one cycle of the closed opto-electronic feedback loop can be varied to tune the free spectral range of the photonic microwave filter.

12. A photonic microwave filter device as claimed in claim 7, wherein the power of the feedback signal can be varied to tune the response of the photonic microwave filter.
13. A photonic microwave filter device as claimed in claim 7 wherein the said filter operates at microwave frequencies.
14. A photonic microwave filter as claimed in claim 13 wherein the input signal is optical carriers modulated by microwave signals and/or microwave signals.
15. A photonic microwave filter as claimed in claim 13 wherein the input signal is an optical signal which can be single wavelength, tunable wavelength or multi-wavelength.
16. A photonic microwave filter as claimed in claim 13 wherein the output signal is optical carriers modulated by microwave signals and/or microwave signals.
17. A photonic microwave filter device as claimed in claim 7, formed from optical fiber components.
18. A photonic microwave filter device as claimed in claim 7, formed from optical planar integrated circuits.
19. A photonic microwave filter device as claimed in claim 7, formed from semiconductor integrated circuits.

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