Photonic microwave finite impulse response filter using a spectrally sliced supercontinuum source

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A novel photonic microwave discrete-time finite-impulse response filter is created by spectrally slicing a supercontinuum source, generated from a mode-locked laser. We experimentally demonstrate a four-tap filter with a 28.16 dB extinction ratio. Comparison between measured and predicted magnitude responses shows an excellent match in the performance of the notch filter across the entire bandwidth. The small amount of individual deviation points from the predicted response shows the stability of the amplitude fluctuations between each of the individual, spectral sliced filter taps. © 2012 Optical Society of America

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1. Introduction

Considerable interest has been shown in the field of photonic signal processing for microwave filtering applications [1]. Microwave photonic filters offer many advantages, including wide bandwidth, low loss across the entire bandwidth, compactness, lightweight, and immunity to electromagnetic interference. Moreover, photonic microwave filters are easily tunable and reconfigurable in real time, allowing for filtering with adaptive capability. Microwave photonic filters have many important applications, including broadband processing of radio frequency (RF) signals. Much research has been done in the field of microwave photonic filtering, and several novel components for developing reconfigurable filters have been proposed, such as fully tunable delays and negative weighting [1].

In order to scale filters to multiple taps, the use of one optical source per tap becomes inefficient. The Q-factor (or quality factor) defines the resolution of the filter and the selectivity of the filter regarding a certain frequency, and the greater the number of taps, the higher the Q-factor [1]. While many photonic filter schemes have been built with arrays of optical sources, they become hard to scale when a high Q-factor or many taps are needed. Thus of particular interest, photonic filters utilizing spectral slicing of one optical source for the entire architecture have been realized to build incoherent filters [2–8]. Many techniques for slicing a broadband optical source have been proposed, such as using a Fabry–Perot filter comb [2], fiber-Bragg gratings (FBGs) [3], and optical filters [4]. Unfortunately, these methods lack control over tap weights and reconfigurability. Other techniques using spatial light modulators (SLMs) [5] and liquid crystal on silicon (LCoS) [6] can provide weighting as well. However, these methods spectrally slice a broadband source generated from an amplified spontaneous emission (ASE) noise source, which has random fluctuation of phase and amplitude that contributes to noise and instability in the system [7]. A spectrally sliced continuous-wave supercontinuum has been proposed [8]. This approach also relies on slicing an ASE source, with

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the disadvantages outlined previously, and, further, is limited to a maximum of 125 taps [8].

In this paper we propose a novel photonic finite impulse response (FIR) microwave filter using a mode-locked laser (MLL) source. Our approach offers the advantages of using a single broadband optical source (the MLL) that is not based on using an ASE source so that it is stable across the entire spectrum. The pulses from the MLL are compressed using dispersion decreasing fiber such that a supercontinuum source with a broad spectrum is generated. The supercontinuum source gives our approach high scalability as well. Spectral slicing of the broadband pulses to achieve incoherent summing is performed so that only a single laser source is needed for the entire system. Moreover, by using optical amplifiers and fiber delay lines, our architecture offers the advantages of full tunability and reconfigurability as well.

Unlike an ASE source, an MLL does not generate random fluctuations across the spectral bandwidth. Spectral slicing based on supercontinuum generation is stable and generates very little noise with the standard deviations (and spectrum) uniform across all channels [9]. Reference [10] presents BER measurements for a communication system using a spectrally sliced supercontinuum source and shows error free transmission for all channels with a maximum power penalty of 2 dB for the channels furthest away from the center [10]. Finally, supercontinuum generation can be spectrally broader than traditional ASE sources based on erbium-doped fiber amplifiers (EDFAs) and a spectrum of >250 nm can easily be generated [9], making our approach highly scalable.

2. Theory

Using discrete-time sampling theory, we can express the transfer function for the proposed architecture. The discrete difference equation of an $N+1$ tap FIR filter is given by

$$y[n] = b_0 x[n] + b_1 x[n-1] + \ldots + b_N x[n-N], \qquad (1)$$

where $x[n\text{-}N]$ represents the input signal, $x[n]$ delayed by N time samples and weighted by a scalar coefficient of b_N. $y[n]$ represents the filtered output signal. An FIR filter simply represents the sum of delayed and weighted samples. The transfer function for an FIR filter with pulsed sampling becomes

$$H(\omega) = g \sum_{m=0}^{N} b_m \exp(-j\omega m\tau), \qquad (2)$$

where g is gain, given by [11] as

$$g = 1/t_s \int_{-t_s/2}^{t_s/2} p(t)\mathrm{d}t, \qquad (3)$$

where τ represents the delay increment between successive taps, tap m is associated with a specific weight b_m and delay $m\tau$, and $p(t)$ is defined as the pulse shape.

3. Experimental Setup

The configuration for the discrete-time photonic FIR filter is shown in Fig. 1. An MLL, driven by an RF sinusoidal signal from a signal generator, acts as the optical carrier. The pulse width of the source is 1.8 ps with a repetition rate of 9.95328 GHz, tunable over 1530 to 1565 nm. The original spectrum has a FWHM of 1.18 nm. The RF signal that we would like to process with the photonic FIR filter is modulated onto the optical carrier using a Mach–Zehnder modulator (MZM). Ultrafast discrete-time sampling of the RF signal is achieved by using a train of pulses as the optical carrier. In order to allow for correct reconstruction and to avoid aliasing, the sampling rate of the pulses must be greater than twice the highest frequency component of the RF signal, according to the Nyquist–Shannon sampling theorem.

To avoid optical beat noise, incoherent summing, by providing each tap with its own wavelength, is required. The modulated optical signal is inserted into a pulse compressor for supercontinuum generation, with the output signal amplified by an EDFA. The pulse compressor uses a 190 m piece of off-the-shelf, proprietary dispersion compensating fiber. The supercontinuum is generated by the pulse compression, and broadening of the spectra is achieved in the spectral domain [9]. The pulse width is compressed from 1.8 ps to 1.1 ps. The spectrum is sufficiently broadened for the frequency of interest, as shown in Fig. 2.

The modulated, compressed pulses are sent to a filter box, which spectrally slices the spectrally broadened signal, the upper curve in Fig. 2, into four spectral components shown by the lower curve, to create a four-tap filter for optical incoherent summing. The filter box is an optical wavelength filter (not a RF frequency filter such as our architecture), which slices the broadband signal into individual wavelengths.

The four filtered signals are split, and each is sent through a series of weights and delays. Optical amplifiers in the form of EDFAs in the filter box are used to control the weight of each of the signals. Each tap represents a discrete-time sampled version of the input RF signal that is weighted and delayed. The tap weights and delays of the FIR filter are designed to match the desired filter response. The four taps are then combined using a 4×1 coupler and then detected using a photodetector. Spectral slicing of

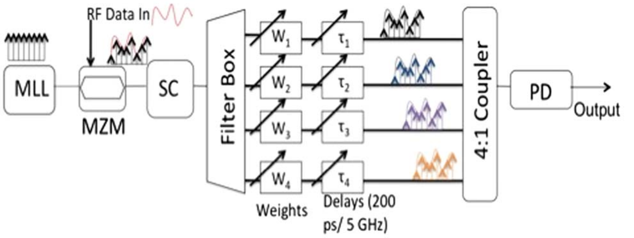

Fig. 1. (Color online) Proposed architecture for four-tap FIR filter. MLL, mode-locked laser; MZM, Mach–Zehnder modulator; SC, supercontinuum generator; PD, photodetector.

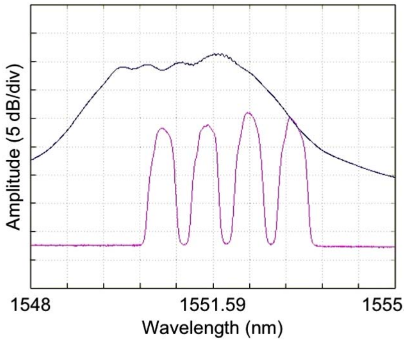

Fig. 2. (Color online) Spectral slicing (lower curve) of SC-broadened spectra (upper curve).

a spectrally broadened signal to obtain different wavelengths for each of the taps serves to ensure incoherent summing of the taps at the coupler. Thus, a photonic discrete-time FIR filter is realized.

Our filter is both tunable and reconfigurable. Since delays are controlled by fiber delay lines, we can splice the fiber to match any range of delays of interest. Once the fiber has been spliced, we have 200 ps of range in order to fine-tune and control the delays using simple tunable fiber delay lines. Weighting is performed by EDFAs within the filter box, in which we can control the output power by adjusting current with a max current of 500 mA corresponding to a maximum power of 18.92 dBm.

4. Experimental Results and Discussion

The predicted magnitude of the frequency response of a four-tap FIR filter is shown in Fig. 3, indicated by the dark blue curve. The MLL has an optical pulse repetition rate of 10 GHz, equal to the inverse of the sampling interval, ts, of 100 ps. The four spectral components are centered around 1550.535, 1551.396, 1552.272, and 1553.141 nm. The tap weights are chosen to be .5, .5, 1, 1 (corresponding to optical power of −2.68, −2.68, .32, and .32 dBm), and tunable delays lines are chosen to be 0 ps, 200 ps, 400 ps, and 600 ps, respectively. To measure the data, a single tone sinusoidal RF signal from a signal generator is used. The signal sweeps from 10 KHz to 5 GHz, linearly in 10 KHz steps. The filtered output is received by a photodetector and analyzed by an RF spectrum analyzer. The transfer function of the system is experimentally measured using the setup as described in Fig. 1, and the measured magnitude response is shown by the light green data points in Fig. 3.

To show reconfigurability, we created a second filter, this time with two taps offset in amplitude. We also wanted to show extreme delay between the two taps. We set tap weights to be 1, .7 (corresponding to .32, .224 dBm) with a delay set to be 8000 ps. The spectral components are centered around 1550.535 and 1552.272 nm. Data is measured the same way by sweeping a sinusoid from 100 to 600 MHz, showing four complete periods of 125 MHz.

There is a close match between the predicted and measured responses. The accuracy of the magnitude and frequency of the notches are of particular interest. The deep notch in Fig. 3, with maximum extinction ratio of 28.16 dB, at 2.5 GHz and the shallower notches at 1.25 GHz and 3.75 GHz show that accurate weighting of tap coefficients has been achieved. The bandwidth of the overall response of Fig. 3 is 5 GHz, equal to the inverse of the delay spaced at 200 ps, and shows the precision of the optical delay lines. Similarly, the notches at 187.5 MHz, 312.5 MHz, 437.5 MHz, and 562.5 MHz in Fig. 4 show the periodicity of the filter, which is only possible with very accurate delaying. There are only a small amount of individual points that deviate from the predicted response line for both Figs. 3 and 4. Since our data is gathered by sweeping through the bandwidth, this small deviation shows the stability of amplitude fluctuation noise between each of the individual, spectral sliced filter taps.

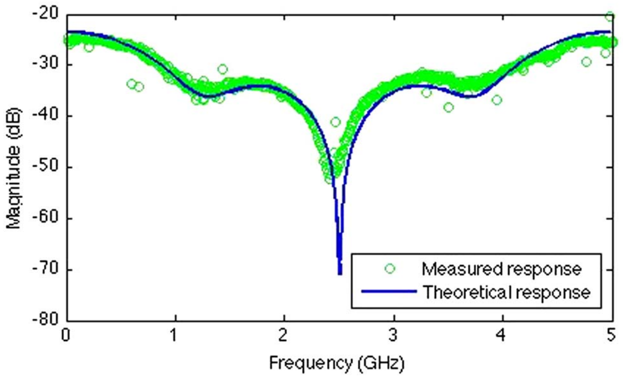

Fig. 3. (Color online) Measured (dot) and predicted (line) magnitude response of four-tap FIR filter.

The general shape of the filter is near perfect, except for the fact that the deepest notch of the magnitude response at 2.5 GHz does not approach the negative infinity of the theoretical response. This is due to the imperfect matching of the individual filter tap amplitudes to theoretical values, and a slight mismatch in the coefficients of the taps can produce a noticeable decay in the notch. Moreover, we see specific isolated points of magnitude response that differ from the predicted response. While small, both

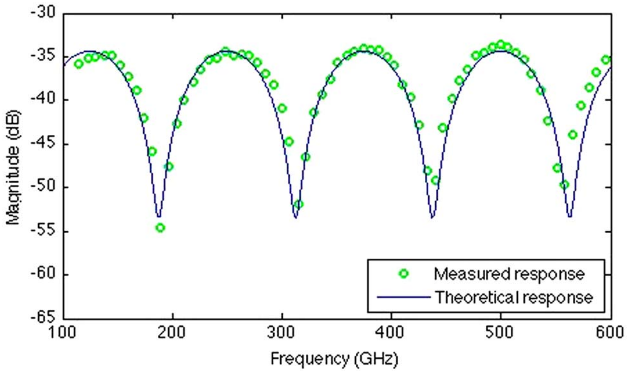

Fig. 4. (Color online) Measured (dot) and predicted (line) magnitude response of two tap FIR filter.

these imperfections arise from amplitude fluctuations of the spectrally sliced compressed pulses.

5. Conclusion

A novel discrete-time photonic microwave FIR filter has been proposed and demonstrated experimentally. The photonic FIR filter is designed to replace electronic analog-to-digital converters and standard RF filters. The proposed architecture implements fast discrete-time sampling at 10 GHz using an MLL source. Furthermore, by compressing the pulses using a supercontinuum source, spectrally broadband scalable slicing for incoherent summing of tap outputs can be achieved. A major advantage of the architecture is that it is able to use only a single laser source to implement multiple taps and is easily scalable to larger N-tap filters.

A practical four-tap filter was developed with fixed delays. Close agreement between predicted and measured magnitude response was observed, evidence of accurate matching of tap coefficients and delays. Excellent stability and low noise were shown by the system.

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