Reconfigurable and Tunable Flat-Top Microwave Photonic Filters Utilizing Optical Frequency Combs

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***Abstract*—We demonstrate reconfigurable and tunable flat-top microwave photonic filters based on an optical comb source and a dispersive medium. Complex taps allowing flexible and tunable filter characteristics are implemented by programming the amplitude and phase of individual comb lines using an optical line-by-line pulse shaper. First, we implement a flat top filter by applying positive and negative weights across the comb lines, then tune the filter center frequency by adding a phase ramp onto the tap weights.**

***Index Terms*—Flat-top filters, microwave photonic filters, optical pulse shaping, reconfigurable filters.**

I. Introduction

MICROWAVE photonic filters offer potential attractive features such as low loss, low sensitivity to electromagnetic interference (EMI), and rapid tunability and programmability over a large bandwidth [1]. In contrast to recent work on microwave photonic filters based on coherent optical filters [2], [3], most microwave photonic filters are based on a multitap delay line scheme. Much of the early work used multiple physical delay lines, which is difficult to scale to large number of taps. Recently interest has arisen in new tapped delay line architectures based on broadband light sources and a single dispersive element. Because a single dispersive medium introduces a differential delay between optical frequencies, the multiple optical frequencies act as multiple taps. Light sources considered include multiple CW lasers [4], ASE [5], mode-locked lasers [6], and electrooptic (EO) frequency combs [7]. Our work employs an EO frequency comb, for which each individual optical frequency component becomes an independent tap. This approach can practically scale to much larger number of taps compared to multiple lasers, while providing optical frequency stability and coherence not available from ASE or typical harmonically mode-locked laser sources. The latter attribute enables line-by-line pulse shaping [8] in an interferometric configuration, which we adopt here to realize amplitude and phase control of individual taps. Complex taps have been implemented based on stimulated Brillouin scattering [4], a phase spatial light modulator used in a cross-polarized carrier-sideband geometry [9], a pulse shaper [10] capable of resolving and applying different phases to optical carriers and sidebands [11], and nonuniform tap spacing [12]. However, these techniques were demonstrated only for a small number of taps. A reconfigurable microwave photonic filter with high number of taps but fixed center frequency has been achieved via spectral shaping of an amplified spontaneous emission source [13]. In this letter we exploit the ability to program dozens of complex taps to demonstrate flat-top microwave photonic filters with reconfigurable bandwidth and tunable center frequency.

II. Theory

Tapped delay line microwave photonic filters are based on the concept of discrete time finite impulse response filter [14]. To implement arbitrarily shaped flexible filters, we need to apply complex tap weights. For this purpose we consider a configuration with a single sideband modulator placed into one arm of an optical interferometer. This is similar to a setup introduced in [7], in which a large number of positive taps was implemented, but with the position of the pulse shaper [10] moved to arm #2, as shown in Fig. 1, to give a programmable phase difference between the two interferometer arms. For this configuration, we can write the filter transfer function as

$$H(\omega_{\rm RF}) \propto \sum_{n=0}^{N-1} \sqrt{p_{1n}p_{2n}} e^{j\{n\Delta\omega(\Psi_2\omega_{\rm RF}+\tau)-\varphi_n\}} \tag{1}$$

where p_{1n} and p_{2n} is the power of the nth comb line in the two paths of interferometer, ψ_2 the fiber dispersion, $\Delta\omega$ the repetition frequency of optical frequency comb, τ the amount of relative delay between two interferometer paths, and φ_n the additional phase applied to the nth comb line by the pulse shaper. Tuning of the frequency response can be achieved by imposing phase shifts that are linear in tap number. According to (1), this can be achieved either by varying the optical delay τ of a delay stage [7] or by programming the φ_n for a linear phase function. In this letter we demonstrate the latter method, which allows

Manuscript received July 01, 2011; revised August 04, 2011; accepted August 07, 2011. Date of publication August 18, 2011; date of current version October 12, 2011. This work was supported by the Naval Postgraduate School under grant N00244-09-1-0068 under the National Security Science and Engineering Faculty Fellowship program. Any opinion, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the sponsors.

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Digital Object Identifier 10.1109/LPT.2011.2165209

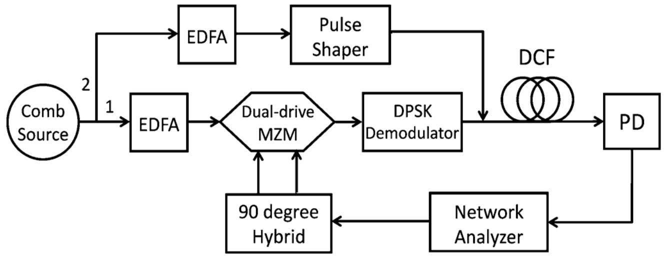

Fig. 1. Suggested microwave photonic filter architecture to implement complex tap weights.

both reconfiguration of the filter bandwidth and tuning of its center frequency under pulse shaper control.

Ideal rectangular filters have infinite impulse responses with sinc function envelopes consisting of both positive and negative tap values. As is well known in digital filtering, a flat top filter similar to an ideal rectangle filter can be obtained utilizing a finite number of taps by multiplying an infinite sinc function with a window function [15]. Here we use a Kaiser window [15] which offers desirable filter properties such as high sidelobe suppression and minimum passband ripple. For a baseband filter ($\tau = 0$), the positive and negative tap weights can be achieved by simply setting the φ_n to 0 and π, respectively. The resulting filter may then be shifted in frequency by superimposing an additional linear spectral phase.

III. Experiments

Our reconfigurable tunable complex tap microwave photonic filter configuration was shown schematically in Fig. 1. A comb with 9.95 GHz repetition rate and nearly flat power spectrum is generated by cascaded intensity and phase modulators of a CW laser [16] and is divided into two paths through a 3-dB optical splitter. After amplification through an EDFA (Erbium Doped Fiber Amplifier), path 2 passes through a commercially available fiber-pigtailed optical pulse shaper (Finisar WaveShaper 1000 s) in which we program the amplitude and phase of comb lines to control the complex tap weights. In path 1, the individual comb lines are single-sideband (SSB) modulated with a dual drive Mach–Zehnder (MZ) modulator excited by the input RF signal. The modulator output is connected to a periodic optical filter implemented by 9.95 Gb/s DPSK (differential phase-shift keying) demodulator which has deep nulls in its transmission response with 9.95 GHz periodicity. The nulls are tuned to remove the original comb lines, leaving only sidebands. The two paths are aligned in polarization, and combined in a 3-dB coupler, so that the shaped optical comb is mixed with a comb of sidebands without altering the amplitudes and phases. The coupler output is passed through a dispersion compensating fiber (DCF) that has -1259.54 ps/nm at 1550 nm, resulting in delay difference of 96 ps between adjacent 10 GHz comb lines. The free spectral range (FSR) of the filter is 10.4 GHz, equal to the reciprocal of the 96 ps delay increment. The optical signal is detected by a 22 GHz bandwidth photodiode (PD) and the transfer function (S21) is measured by a network analyzer.

The electrical signal generated after optoelectronic conversion is composed by a sum of beating terms between each of the RF sidebands from path 1 and the nearest shaped comb line from path 2. As a result, both amplitude and phase

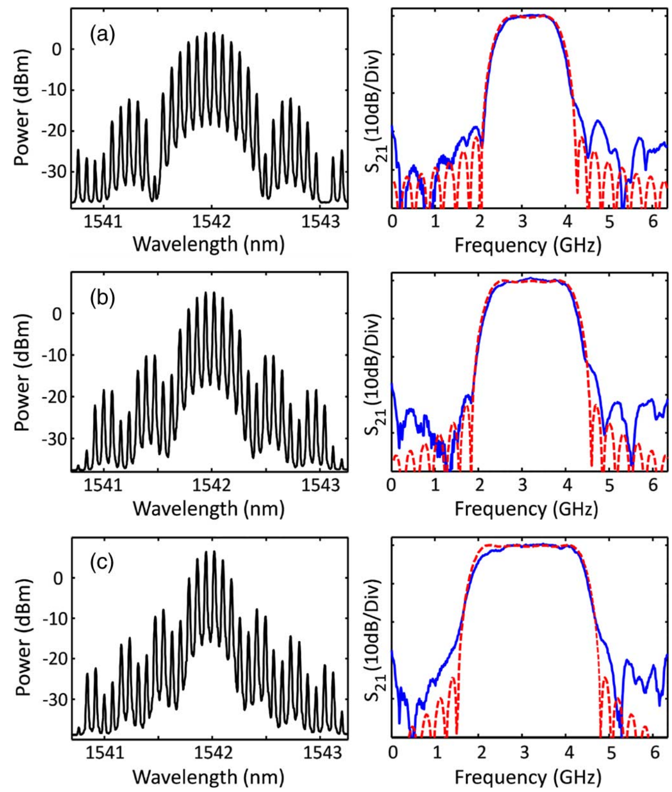

Fig. 2. Measured optical spectra at the PD input (left) and corresponding filter responses measured (solid) and simulated (dashed) (right) with 3-dB bandwidths of flat-top filter equal to (a) 1.5 GHz, (b) 2 GHz, and (c) 2.5 GHz, respectively.

for each individual tap can be controlled in a user-defined fashion. As seen from (1), both apodized negative and positive taps can be achieved by controlling tap amplitudes $\sqrt{p_{2n}}$ and phases φ_n via pulse shaper. Fig. 2(a) shows an optical comb (left) shaped for a 3-dB bandwidth of 1.5 GHz and measured using an optical spectrum analyzer when $\varphi_n = [0\,0\,0\,\pi\,\pi\,\pi\,\pi\,\pi\,\pi\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,\pi\,\pi\,\pi\,\pi\,\pi\,\pi\,0\,0\,0]$, as well as the measured and simulated filter responses (right). The amplitude and the phase are shaped to match an impulse response with a sinc function envelope apodized by a Kaiser window to limit the number of tabs to 32. Since for our 9.95 GHz comb spacing, the pulse shaper shows weak coupling between the amplitude and phase controls, we iteratively adjust both values in experiment. The simulated filter transfer function (dash line), obtained from (1) using the ideal sinc function multiplied by a Kaiser window impulse response, shows 31.5 dB sidelode suppression and 0.3 dB passband ripple. The measured response closely matches the predicted response with regards to 27.2 dB sidelode suppression and 0.45 dB passband ripple. Figs. 2(b) and (c) also show the apodized spectra and corresponding filter transfer functions when 3 dB bandwidths of flat-top filters are 2 GHz and 2.5 GHz. The comb of Fig. 2(b) is composed of 20 positive and 12 negative taps, and its measured filter response shows 27 dB sidelode suppression and 1.2 dB passband ripple. For Fig. 2(c) having 16 positive and 16 negative taps, the measured filter transfer function shows 27.4 dB sidelode suppression and 1.7 dB passband ripple. The measured and the simulated passband shapes are in relatively close agreement in all three cases, although the experimental

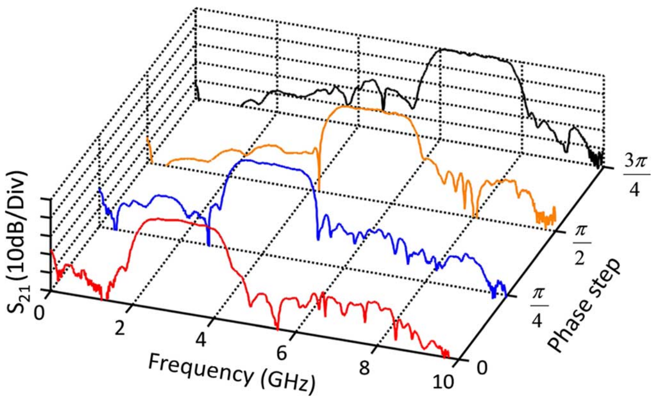

Fig. 3. Filter passband center shifts as the phase increases linearly at steps of 0 (not changed), $\pi/4$, $\pi/2$, and $3\pi/4$ per tap. Other comb parameters are fixed to have a 2-GHz 3-dB bandwidth flat-top filter.

sidelobe levels are increased. We will comment on reasons for these differences later.

As we notice in (1), there are two ways to tune the filter center frequency: controlling the relative delay between two arms [7] or applying linear spectral phase across the comb lines. Here we apply a linear phase to the comb using a pulse shaper to achieve filter tuning. Fig. 3 shows the measured filter transfer functions. When no additional phase is applied, the passband center is located at 3.2 GHz (corresponding to $\tau = 30.7$ ps). Then we program the pulse shaper to apply a linearly increasing phase (modulo 2π) in steps $\Delta\varphi = \pi/4, \pi/2$, and $3\pi/4$ per tap, respectively. The filter passband shifts to higher frequencies by 1.2, 2.3, and 3.6 GHz, which are close to the theoretical values of $\mathrm{FSR}/(2\pi/\Delta\varphi) = 1.3$, 2.6, and 3.9 GHz, respectively. The measured filter transfer functions, which show ~24.3 dB sidelobe suppression and ~1.3 dB passband ripple, remain approximately constant with relatively close agreement to the simulation result shown in Fig. 2(b). These results verify that we can achieve tunable microwave photonic filters, with selectable passband profile and essentially without changing filter shape, via line-by-line pulse shaping.

We do note that sidelobe suppression in the experiments is consistently several dB smaller than in simulation. This may be attributed to several practical issues. First, limited spectral resolution (comparable to the comb spacing) may introduce apodization and phase errors in pulse shaper control of the taps. Second, unwanted small reflections in the interferometer structure are known to give rise to low amplitude replicas of the filter passband, which are shifted in frequency according to the delay of the reflection [7]. Finally, imperfect SSB modulation due to amplitude and phase imbalances of the modulator and the 90 degree hybrid coupler results in a small double sideband (DSB) modulation component, which is also known to cause a small, frequency shifted, passband replica [17]. Achieving improved sidelobe suppression will require attention to all of these factors.

IV. Conclusion

We have demonstrated programmable and tunable flat top microwave photonic filters based on optical frequency comb shaping. The amplitude and the phase of each comb line were programmed by a pulse shaper to implement complex tap weights. The versatility of this scheme allowed programmable control of both the filter bandwidth and center frequency. Although in the current experiment we implement 32 taps (32 comb lines), our scheme may be extended to a larger number of comb lines [8] which may be helpful for improving arbitrary passband profile filter control. For example, it may be possible to achieve lower passband ripple, narrower transition bands, and stronger sidelobe suppression by increasing the number comb lines.

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