Tunable microwave-photonic filter using frequency-to-time mapping-based delay lines

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Abstract: A new implementation of microwave-photonic filters (MPFs) based on tunable optical delay lines is proposed and demonstrated. The variable delay is based on mapping of the spectral components of an incoming waveform onto the time domain, the application of linearly-varying temporal phase offsets, and an inverse mapping back to the frequency domain. The linear phase correction is equivalent to a frequency offset, and realized though suppressed-carrier single-sideband modulation by a radio-frequency sine wave. The variable delay element, controlled by the selected frequency, is used in one arm of a two-tap MPF. In a proof-of-concept experiment, the free spectral range (FSR) of the MPF was varied by over a factor of four: between 1.2 GHz and 5.3 GHz.

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References and links

1. Introduction

The processing of radio-frequency (RF) and microwave signals using optical means, or microwave photonics, has drawn much attention in recent years. Microwave photonics provides numerous potential advantages, such as low propagation loss in optical fibers, ultra-broad transmission bandwidth, immunity to electromagnetic interference, availability of high-bandwidth electro-optic modulators and detectors, and potential for light-weight and small-footprint modules [1–4]. One potential application of microwave photonics is the implementation of broadband tunable filters in arbitrary waveform generation [5], radio over fiber systems [6], and wireless access networks and radars [7].

Many microwave photonic filter (MPF) architectures rely on splitting an RF-modulated optical signal among multiple paths of different lengths, and their recombining prior to detection [1–7]. Tuning the free spectral range (FSR) of such delay-and-sum filters requires optical delay variations. Several mechanisms for tunable optical delay lines have been proposed in the literature. Examples include switching among fiber paths of different lengths [8], dispersive elements in conjunction with variable wavelength sources [9], and combinations of the above methods [10]. Other techniques employ reconfigurable integrated devices [11], and group velocity modifications (‘slow light’) [12, 13].

In [14], delays were implemented through optical single sideband (OSSB) modulation, together with cascaded, phase-shifted fiber Bragg gratings (FBGs). In another demonstration [15], large FSR variations were obtained through sliding a couple of bare fibers within a cladding-mode coupler. ‘Slow light’ delay variations based on stimulated Brillouin scattering (SBS) [16], and reflections from multiple, movable dynamic Brillouin gratings [17] were also employed within tunable MPFs. However, the above methods either require specialty photonic devices and complicated setups [14, 15], and/or involve high power levels and provide a restricted tuning of the FSR [16, 17].

In this work, we propose and demonstrate a simple scheme for the implementation of widely tunable MPFs. As described in detail in the next section, delay variations within the filter are based on frequency-to-time mapping, the application of a temporally-varying phase correction term, and an inverse, time-to-frequency conversion [5, 18–21]. The results extend our earlier work, in which FSR variations were restricted to ± 9% [5]. Here, we report and
experimentally demonstrate a two-tap MPF whose FSR is varied from $-39\%$ to $+163\%$, or by over a factor of four, between 1.2 GHz and 5.3 GHz.

2. Tunable delay line

A tunable group delay is analogous to a spectral phase modification that scales linearly with frequency. However, the realization of this transfer function directly in the frequency domain is susceptible to severe delay-bandwidth product limitations. Here, tunable optical delays are achieved through phase variations in the time domain instead [5, 18–20] (see Fig. 1). First, the different spectral components of the processed waveform are spread in time through propagation in a second-order dispersive medium. A one-to-one linear frequency-to-time conversion (FTTC) is obtained. Then, a phase correction that is linear in time is implemented. Finally, the waveform is recompressed in a time-to-frequency conversion (TTFC) step, carried out in propagation through a medium of opposite dispersion. The process is analogous to the spatial Fourier-domain processing that is commonplace in free-space optics [21].

In principle, ramp-shaped signals can be used in temporally-linear phase modulation [5, 19]. However, the bandwidth of such waveforms is restricted, eventually limiting FSR variations of the MPF [5]. In this work, following the FTTC block the signal is amplitude-modulated by a sine wave of radio-frequency $\Omega$ [18]. The modulation introduces multiple sideband replicas of the signal spectrum, which are separated by $\Omega$. A tunable optical band pass filter is used to select either the upper or the lower first-order spectral sideband. At the output of the filter, the time-mapped signal is effectively multiplied by $\exp(\pm j\Omega t)$, where $t$ stands for time. The combined transfer through modulator and filter is therefore analogous to a frequency offset by $\pm \Omega$, or a linearly-varying temporal phase of $\pm \Omega t$.

Following TTFC, the reconstructed waveform is relatively delayed or advanced by $\pm \tau = \beta_2 L \Omega$, where $\beta_2$ is the group velocity dispersion parameter of the TTFC medium [ps$^2$/km] and $L$ is its length. Therefore, a primary requirement of the TTFC module is a $\beta_2 L$ product that is as large as possible. In addition, in order to avoid distortions of the delayed signal, the dispersions of the FFTC and TTFC modules should cancel out each other as fully as possible. We therefore chose modules with large $\beta_2 L$ values that are equal in magnitude and of opposite signs. The proper filtering of a single sideband requires that $\Omega$ must exceed twice the bandwidth of the incoming waveform. If a suppressed carrier single sideband modulation (SCSSM) is used instead of the AM in Fig. 1, the tunable optical filter is not required and there is no lower limit for $\Omega$. However, a SCSSM modulator was not available for the experiments. The upper limit on modulation frequency is set by the microwave generator and the electro-optic modulator. Unlike ramp waveforms [18, 20], sine-wave modulation frequencies readily reach tens of GHz [19].

3. Experiments

A two-tap MPF structure shown in Fig. 2 was realized in a proof-of-concept experiment. The MPF consisted of two optical paths. Delay in the lower arm was fixed, whereas that of the
upper branch was tuned as described above. Each path was connected to the output of a separate laser diode source. Light in both branches was modulated by a separate electro-optic modulator. Both modulators were driven together by the RF output of a vector network analyzer (VNA). Following the fixed or variable delay, the two paths were combined by an optical coupler and connected to a photo-detector. The wavelengths of the laser diodes were 1 nm apart, to guarantee incoherent summation of the two paths upon detection [1]. The output of the detector was connected to the VNA input port, for the analysis of the MPF transfer function. Within the tunable delay element, the FTTC and TTFC blocks consisted of a 75 km long standard fiber and a dispersion compensating module, respectively, both having $\beta_2 L \approx 1590$ ps$^2$.

With no frequency modulation taking place in the tunable delay element, the delay imbalance between the two arms was about 500 ps, corresponding to a FSR of approximately 2 GHz at the MPF output. The 3 dB bandwidth of the MPF periodic pass bands was 1.33 GHz, as expected in a two-tap filter. The FSR can be tuned by changing $\tau$ in the upper branch. Figure 2(b) shows the expected and measured FSR for different relative delays or advancements. The maximal modulation frequency $\Omega$ achievable with our equipment was 38 GHz, corresponding to delay variations of more than ± 300 ps. As can be seen from Fig. 2(b), the corresponding FSR tuning range was between 5.291 GHz (or + 164%) for maximum advancement and 1.218 GHz (or −39%) for the maximum delay. The frequencies of the electrical signal at the MPF input varied between 0 and 10 GHz. Correspondingly, the frequency modulation $\Omega$ was restricted to at least 20 GHz or higher. The lower frequency limit in the practical setup was 22 GHz, due to the finite transition bandwidth of the optical band pass filter used inside the tunable delay element. Therefore, delay or advancements of less than 200 ps could not be obtained, and not all FSR values could be reached. Given the bandwidth of the input RF signal and the initial path difference between the two arms in our setup, a 1.5 GHz-wide range of FSR values could not be implemented (see Fig. 2(b)). This range of unattainable FSRs decreases with the bandwidth of the input RF waveforms and with the initial path difference between the arms. Please note that with a SCSSM instead of the AM and the optical filter in Fig. 1 there would be no gap in the delay and all FSR values could be reached.

Lastly, the RF transfer functions of the MPF, for the maximum and minimum delay and advancement values, are shown in Fig. 3. The experimental transfer functions agree well with
the expected form of two-tap filters. The differences between calculation and experiment are attributed to the frequency response of the amplitude modulators, and thermal variations of the long FTTC fiber path length.

The proposed MPF architecture is scalable to a larger number of taps. Each additional tap would require its own laser light source, RF sine-wave generator and electro-optic modulator. However, different taps can share common FTTC and TTFC modules. An illustration of a higher-order filter is provided in Fig. 4. The cost of components and power consumption of the MPF would scale linearly with the number of taps. Increase in footprint could be marginal, depending on implementation.

Fig. 3. Simulated (dashed) and experimental (solid) results for the MPF transfer function for several different FSR adjustments. (a) $\Omega = 22$ GHz, red: FSR = 1.462 GHz, FSR change = $-27\%$ for delay and blue: FSR = 3.105 GHz, FSR change = $+51\%$ for advancement}, (b) $\Omega$ = 38 GHz, brown: FSR = 1.218 GHz, FSR change = $-39\%$ for delay and green: FSR = 5.291 GHz, FSR change = $+164\%$ for advancement}. The black trace shows the MPF transfer function without either delay or advancement [{FSR = 2 GHz}].
4. Conclusions

A 2-tap MPF with a FSR that is tunable between 1.2 GHz and 5.3 GHz was demonstrated experimentally. Compared with other MPF implementations, the proposed setup is simple, based on readily available standard components, and allows for a broad tuning range of the FSR. The upper limits of the delay or advancement, and therefore the MPF tuning range, are defined by the bandwidth of available equipment. The use of an optical bandpass filter to select only a single modulation sideband results in a power loss. Careful adjustment of the modulator driving voltage, or choice of a single-sideband modulator, would reduce this loss. Relative drawbacks of the proposed architecture are the relatively large size of the FTTC and TTFC fiber-based modules, and the relatively high propagation losses associated with them. The electrical power consumption of the filter is elevated by the need for optical amplification. However, other methods such as chirped FBG’s, arrayed waveguide gratings, photonic crystal structures, or coupled ring-resonators which produce a high dispersion can be used for the FTTC and TTFC modules instead of fibers. Some of these methods have much lower power loss and footprint, which could open the way to a possible integration. The architecture is scalable to the implementation of finite impulse response MPF with a larger number of taps.