An Electrically-Tunable Microwave Photonic Filter Based on Polarization Modulation

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Abstract—A multi-tap microwave photonic filter (MPF) with its center frequency tuned by a single parameter is proposed and demonstrated based on polarization modulation. By simply adjusting the amplitude of a sawtooth wave signal to a polarization modulator, the MPF is tuned with the shape and the free spectral range (FSR) unchanged. The proposed system has advantages in terms of simple operation, fast tunability and large bandwidth.

Index Terms —microwave photonic filter, polarization modulator, analog signal processing, microwave photonics.

I. INTRODUCTION

Photonic processing of microwave or millimeter-wave signals has been intensively studied in the last few years due to the inherent features brought by optical technologies, such as broad bandwidth, low loss and immunity to electromagnetic interference. Microwave photonic filter (MPF) is one of the key components in microwave photonic signal processing. Previously, different kinds of MPFs have been reported [1-3]. Taking the popular finite impulse response (FIR) filters as example, there are MPFs with all-positive coefficients which implement only low-pass filtering, MPFs with one or more negative coefficients which perform bandpass filtering, and MPFs with complex coefficients which have tunable center frequencies. Among them, the last ones have the most flexibilities, which are highly desirable in many practical applications [4-7]. However, to adjust the center frequency of the MPF with complex coefficients, all the reported approaches have to control each tap independently, requiring complex driven circuits and sophisticated control algorithm. In addition, the adjusting resolution of the phase shifter in each tap would seriously affect the frequency response of the MPF after frequency tuning.

In this paper, we propose and demonstrate a MPF with its center frequency electrically tuned by a single parameter, i.e. the amplitude of a sawtooth wave signal. A proof-of-concept experiment is carried out. A two-tap MPF based on single sideband polarization modulation is constructed. By simply controlling the amplitude of the sawtooth wave signal to a second polarization modulator (PoIM), the center frequency of the MPF is tuned with the shape and the free spectral range (FSR) of the frequency response unchanged.

II. PRINCIPLE

The key component to realize a tunable MPF is the microwave photonic phase shifter, which was previously implemented based on slow light in semiconductor optical amplifier or stimulated Brillouin scattering, heterodyne mixing based on z-cut phase modulators, or vector sum method that combines two signals with different amplitudes and phases. If these phase shifters are applied to realize a MPF with complex coefficients [4-6], however, the coefficient of each tap has to be controlled independently. To overcome this problem, the microwave photonic phase shifter based on single sideband (SSB) polarization modulation [7] is adopted. Fig. 1 shows the schematic diagram of the proposed electrically tunable MPF based on polarization modulation, which consists of a tunable laser source (TLS), two PoIMs, a polarization controller (PC), a polarizer, three wavelength division multiplexers (WDMs), several tunable optical delay lines and a photodetector (PD). The PoIM equals to two phase modulators with complementary modulation indices connected parallel by a polarization beam combiner (PBC). The first PoIM (PoIM1) is driven by a RF signal to be filtered and the second PoIM (PoIM2) is driven by a sawtooth wave signal. The two signals are supposed to have expressions of $V_{\text{RF}} \cos(\omega_t t)$ and $V_{\text{SS}}(t)$, respectively. When a linearly polarized lightwave is inserted into PoIM1, two orthogonally polarized signals with complementary phase modulations are generated,

$$
\begin{align*}
F_{x} &= J_n(\beta) + j J_n(\beta) \exp(j \omega_t t) + J_n(\beta) \exp(-j \omega_t t) \\
F_{y} &= J_n(\beta) - j J_n(\beta) \exp(j \omega_t t) + J_n(\beta) \exp(-j \omega_t t)
\end{align*}
$$

(1)

where $\beta$ is the modulation index of PoIM1 and $J_n$ is the Bessel function of the first kind of order $n$. Then a PC is followed to...
control the polarization states of the output signal to be rotated by 45°, so the optical carrier and the ±1-st order sidebands are separated onto two different polarization directions. The two orthogonally polarized signals are incident into PolM2 to be modulated by a sawtooth wave signal. The signal at the output of PolM2 is expressed as:

\[
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix} = \begin{bmatrix}
J_1(\beta) \exp(-j2\gamma s(t)) \\
J_0(\beta) \exp(j(\omega_0 t + j\gamma s(t))) + J_1(\beta) \exp(-j(\omega_0 t - j\gamma s(t)))
\end{bmatrix}
\]

(2)

where \( \gamma \) is the modulation index of PolM2. Then a polarizer with polarization direction aligned of 45° to one of the principal axes of PolM2 is followed to combine the two orthogonally polarized signals. By setting the wavelength of the TLS at the edge of one passband of the WDM, single sideband modulated signal is obtained, when the combined signal is sent to a PD for square-law detection, the output current is given by

\( I(t) = J_1(\beta) I_1(\beta) \cos(\omega_0 t + j2\gamma s(t)) \) \hspace{1cm} (4)

As can be seen from (4), the phase of the generated current in the PD is a function of the modulation index \( \gamma \) which is expressed as \( \gamma = \pi V_s/2V_r \), where \( V_r \) is the half-wave voltage of PolM2 and \( V_s \) is the amplitude of the sawtooth wave signal. When the amplitude of the sawtooth wave signal changes, the phase of the generated signal would change accordingly.

To implement the MPF, \( N \) wavelengths are incident into the phase shifter and are split into \( N \) paths by a WDM. In each path, a time delay line is inserted to introduce a time delay. Then the \( N \) signals are combined by another WDM and are sent to the PD for square-law detection. The output signal from the PD is expressed as

\[ I_c(t) = \cos(\omega_0 t + 2\gamma s(t)) \cos(\omega_0 t - \tau + 2\gamma s(t - \tau)) \]

(5)

Representing \( (5) \) in the complex exponential form, it becomes,

\[ I_c(t) = \exp(j\omega_0 t) \sum_{n=1}^{N} \exp(-j\omega_0 \tau + j2\gamma s(t - n\tau)) \]

(6)

Since the time delay between the adjacent taps can be set to be \( mT + T/(N-1) \), where \( T \) is the rising time of the sawtooth wave signal and \( m \) is an integer, the phase difference \( \theta \) between the adjacent taps are the same. As a result, the transfer function can be written as,

\[ H(f) = \sum_{n=1}^{N} \exp(jn2\pi f/T) \] \hspace{1cm} (7)

From (7) we can see that the center frequency of the transfer function equals to \( \theta/2\pi \). Since \( \theta \) is related to the amplitude of the sawtooth wave signal and \( \tau \) is fixed, the only parameter that determines the center frequency is the amplitude. Therefore, by changing the amplitude of the sawtooth wave signal, the center frequency can be tuned with the shape and the FSR of the frequency response unchanged.

To verify the principle of the proposed electrically tunable filter, a two-tap MPF is built based on the setup shown in Fig. 1. Two lightwaves with wavelengths of 1549.66 nm and 1552.86 nm are emitted from a four-channel tunable laser source (TLS, Agilent N7714A) and introduced into two cascaded PolMs. Both the two PolMs (PolM1, PolM2, Versawave Inc.) have a bandwidth of 40-GHz and a half-wave voltage of 3.5 V, and are driven by an RF signal and a sawtooth wave signal, respectively. The RF signal is generated by a vector network analyzer (VNA, Agilent N5245A) with a power of 10 dBm. The sawtooth wave signal is generated by an arbitrary waveform generator (AWG, Tektronix AWG70000) and amplified by an electrical amplifier to have a peak-peak voltage of –6 V. The repetition rate of the sawtooth wave signal is about 170 MHz. A variable attenuator is connected to control the amplitude of the sawtooth wave signal into PolM2. A polarization beam splitter (PBS) with its polarization direction oriented to have an angle of 45° to the principal axis of PolM2 is followed to serve as a polarization. Two WDMs are incorporated to divide the two wavelengths into two paths and combine them again. The 3-dB bandwidth of each channel in the WDMs is 0.6 nm, and the edge slopes of the passbands are about 190 dB/nm. A tunable optical delay line is inserted into each path to introduce a time delay of about 5.62 ns. A PD with a bandwidth of 50 GHz and a responsivity of 0.65 A/W is used to perform the optical-to-electrical conversion. The frequency response of the proposed system is measured by the VNA and the waveform is observed by a digital real-time oscilloscope (Agilent DSO9404A).

Fig. 2 shows the waveforms of the generated sawtooth wave signal. As can be seen, the sawtooth wave has a rising time of about 5.88 ns which corresponds to a repetition rate of about 170 MHz. The peak-peak voltage of the sawtooth wave signal after amplification is ~6 V which can introduce a phase shift of ~1.714π according to (4). Since the time delay between the two paths is fixed with 5.62 ns, the maximum phase difference between the two paths is ~1.638π. By controlling the peak-peak voltage changed from 0 to 6 V, the phase difference between the two paths can change from 0 to 1.638π. As a result, the center frequency of the frequency response can be tuned. If the peak-peak voltage of the sawtooth wave signal is higher than 7 V, full-FSR tunable filter can be implemented.
Fig. 3. The frequency responses of the MPF with center frequencies around 13 GHz.

Fig. 4. The frequency responses of the MPF with center frequencies around 40 GHz.

Fig. 3 shows the frequency responses of the two-tap MPF with center frequencies around 13 GHz. The FSR of the filter is about 178 MHz, corresponding to a time delay of 5.62 ns. When the amplitude of the sawtooth wave signal is changed, the center frequency of the frequency responses can be tuned. The shape and the FSR of the frequency response are kept unchanged. To confirm the high frequency operation capability, frequency responses at high frequency regime are also observed, which are shown in Fig. 4. By adjusting the amplitude of the sawtooth wave signal, the frequency response can also be tuned. Thus, the proposed system has a large operation bandwidth, which is only limited by the bandwidth of the PolM and the PD, and the edge slope of the WDMs. Since the state-of-the-art PolM has a 3-dB bandwidth of more than 40 GHz [9] and the commercially available PD has a 3-dB bandwidth of more than 100 GHz, higher bandwidth can be obtained.

It is worth noting that the system has a fast tuning speed because of the fast tuning speed of the microwave photonic phase shifter [10]. Moreover, the proposed MPF is electrically tuned by a single parameter, simplifying the operation complexity. Last but not least, the system can be simplified if a dispersion compensation fiber (DCF) is used to replace the two WDMs and the time delay lines.

IV. CONCLUSION

A single-parameter electrically tunable MPF with complex coefficients was proposed and demonstrated. By simply controlling the amplitude of the driven sawtooth wave signal, the frequency response can be continuously tuned while maintaining the shape and the FSR unchanged. The proposed MPF features simple operation, large bandwidth and high tuning speed, and it may find applications in communication and channelized systems to suppress interference, and in microwave photonic signal processing systems to deal with broadband signals.

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