Flat-top bandpass microwave photonic filter with tunable bandwidth and center frequency based on a Fabry–Pérot semiconductor optical amplifier

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We propose a flat-top bandpass microwave photonic filter (MPF) with flexible tunability of the bandwidth and center frequency based on optical nonlinearities in a Fabry–Pérot semiconductor optical amplifier (FP-SOA). Phase-inverted modulation induced by cross-gain modulation (XGM) and optical spectral broadening induced by self-phase modulation (SPM) are exploited to achieve flat-top and bandwidth tuning, respectively. Wideband and continuous tuning of the center frequency is achieved by altering the bias current of the FP-SOA. Experimental results demonstrate a flat-top single-passband MPF with its center frequency tunable from 6.0 to 18.3 GHz by adjusting the bias current from 54.05 to 107.85 mA. The 3-dB bandwidth of the passband when centered at 10.0 GHz is shown to be variable from 680 to 1.43 GHz, by increasing the injected optical power from -1 to +5 dBm. During the bandwidth tuning, the amplitude ripple within the passband is maintained at less than ±0.5 dB. Excellent main to secondary sidelobe ratio exceeding 45 dB is achieved when the MPF is centered at 18.3 GHz. © 2016 Optical Society of America

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Advantageous features inherent to photonics such as low loss, high bandwidth, immunity to electromagnetic interference (EMI), tunability, and reconfigurability have aroused increasing interest in the microwave photonic filter (MPF) as a versatile substitute for its electronic counterpart in both broadband wireless access networks and modern radar systems [1,2]. As the bandpass MPF with flat-top can maintain the fidelity of the processed radiofrequency (RF) signal, approaches to achieve MPFs with flat passband have been proposed. Superimposing two RF bandpass responses [3,4] has been proved to be a convenient option, while the tunability is relatively limited. Directly transforming the flatness of the optical filter to the obtained RF filter is verified as feasible as well [5,6], with efforts devoted to finely engineering the fiber Bragg gratings (FBGs). Elaborately programming the tap coefficients of a multi-tap finite impulse response (FIR) MPF can also construct the desired flat-top passband [7–11]. However, in this case the system would get increasingly complex with increased taps. Optical nonlinearity is expected to be a good candidate to realize agile control over the obtained MPF passband [1]. Stimulated Brillouin scattering (SBS) in fiber has been proposed to implement an ultra-flat rectangular MPF by digitally controlling the multiple frequency components in the pump [12]. Since a long span of fiber is used as the gain medium, making such a system compact is not easy.

In this Letter, we propose and demonstrate a flat-top passband MPF with flexible tunability of the bandwidth and the center frequency based on nonlinear effects in a Fabry–Pérot semiconductor optical amplifier (FP-SOA). Linear amplification by the FP-SOA has been used to realize the phase modulation to intensity modulation (PM-IM) conversion in our previously proposed single-passband MPF scheme [13]. Furthermore, the resonant gain of an SOA assisted with distributed feedback (DFB) grating has been used to selectively amplify the optical signal [14] and further employed to generate an MPF [15]. In these three Letters [13–15], only selective linear amplification process was exploited. However, in this proposed scheme, besides the mapping technique by selectively amplifying the optical sidebands, the self-phase modulation (SPM) of FP-SOA is used to control MPF bandwidth while the cross-gain modulation (XGM) is used to realize flat-top passband. Here by driving the FP-SOA into saturation with strong enough incident optical power, the XGM effect is intentionally aroused [16]. Then an inverted copy of the input modulated signal is directly applied onto the output comb spectrum of the FP-SOA. After photodetection an extra amplitude-scaled and phase-inverted RF response [17] is thus generated in addition to the RF passband generated by the input modulated signal. A flat-top MPF is therefore obtained after the subtraction between the two anti-phase RF passbands. Meanwhile, optical spectral broadening induced by the SPM effect [18] is employed to adjust the
The bandwidth of the obtained RF response by controlling the injected optical power. The tuning of the center frequency is realized by altering the bias current. In the experiment, a flat-top single-passband MPF with its center frequency tunable from 6.0 to 18.3 GHz is demonstrated. The 3-dB bandwidth of the MPF when centered at 10.0 GHz is variable from 680 to 143 GHz by increasing the optical power injected into the FP-SOA from −1 to +5 dBm. Excellent main to secondary side-lobe ratio (MSSR) exceeding 45 dB is obtained when the center frequency of the MPF is tuned to half of the free spectral range (FSR) of the FP-SOA, for instance, 18.3 GHz.

The operation principle is schematically illustrated in Fig. 1. Figure 1(a) displays the formation principle of the bandpass MPF based on phase modulation and an FP-SOA. The input phase-modulated signal and the characteristic comb gain spectrum of the FP-SOA [19] are represented by the green-arrowed lines and the magenta comb line, respectively. The frequency separation of the gain spectral peaks equals the FSR of the FP-SOA, which is determined by cavity length. When located near one spectral peak of the FP-SOA, the phase-modulated signal will experience the PM-IM process, and a bandpass RF filter can be achieved [13]. The center frequency of the filter is equal to the frequency interval between the carrier and the nearby spectral peak. Therefore, the center frequency of the MPF can be tuned by shifting the gain spectrum of the FP-SOA or by altering the carrier wavelength.

Figure 1(b) shows the bandwidth adjustment of the MPF by exploiting the SPM effect in the FP-SOA. The bandwidth of the MPF is determined by the linewidth of the laser source and the spectral width of the nearby gain spectral peak of the FP-SOA. If a continuous wave (CW) laser with narrow linewidth is used as the light source, the bandwidth of the MPF is almost determined by the nearby gain spectral peak of the FP-SOA. However, when the optical power injected into the FP-SOA is strong enough, carrier consumption-induced nonlinearities will become significant, and the spectrum of the input signal will be broadened due to the SPM effect. Stronger SPM can be generated by increased input signal power and leads to larger spectral broadening. The broadened optical spectrum (represented by the green curve in Fig. 1(b)) will induce MPF bandwidth to increase (represented by the red curve). Therefore, the bandwidth of the MPF can be controlled simply by adjusting the input signal power.

The XGM effect is used to flatten the microwave passband, as shown in Fig. 1(c). When the input intensity modulated power is high enough to drive the SOA into saturation, the gain of the SOA will be modulated by the input signal [16]. Therefore when the FP-SOA is saturated by the PM-IM converted signal, the obtained output comb spectrum of the FP-SOA will be intensity modulated as well. After photodetection, the counter-phase-modulated comb spectrum of the FP-SOA will generate an extra RF response (represented by the blue-dashed curve in Fig. 1(c)), which is weaker in amplitude and inverted in phase compared to the RF response generated by the input signal (represented by the black-dashed curve). After subtraction, the top part of the RF response induced by the PM-IM conversion will be rightly offset by the XGM-induced response. Thus, the passband of the obtained MPF can be flattened as indicated by the red solid curve.

The effectiveness of the proposed MPF is experimentally verified with the setup illustrated in Fig. 2. A CW light emitted from a laser source (LS, Koheras BasiK E15) is launched into a phase modulator (PM) and phase-modulated by the RF signal emitted by a vector network analyzer (VNA). A polarization controller (PC1) is used to adjust the polarization state of the signal injected into the PM. After power adjusted by a variable optical attenuator (VOA), the modulated signal is injected into the FP-SOA through an optical circulator (CIR). PC2 is placed before the FP-SOA for polarization adjustment. The phase-modulated signal is then processed by the FP-SOA and launched into a photodetector (PD) with large bandwidth via the CIR. The frequency response of the MPF is measured by the VNA (Anritsu MS4647B) with a typical intermediate frequency bandwidth (IFBW) of 1 kHz being set. The fundamental functional element within the setup is the FP-SOA, a customized product from INPHENIX. For both the input and output sides, the facet reflectivity is 30%, and the maximum output power is about 10 dBm. With a multi-quantum-well active region and a cavity length of 1200 μm, the FP-SOA shows an FSR of 36.6 GHz. To ensure stable performance of the FP-SOA, bias and temperature controllers with high stability are preferred.

The output optical spectrum from the FP-SOA is characterized via an optical spectrum analyzer (Yokogawa AQ6370C) with the resolution bandwidth (RBW) set at 0.02 nm. Figure 3 demonstrates the optical spectra at the output of the FP-SOA and the corresponding MPF responses when the laser wavelength is closer to one gain spectral peak of the FP-SOA and exactly in the middle of two gain spectral peaks.

**Fig. 1.** Schematic illustrations of (a) the forming of the MPF, (b) the broadening of the bandwidth, and (c) the flattening of the passband top.

**Fig. 2.** Experimental setup of the proposed microwave photonic filter.
resonant states. The carrier signal is phase-modulated by a 10.0-GHz RF signal prior to injecting into the FP-SOA. These spectral peaks are intensity modulated as indicated by their modulation sidebands. Figure 3(b) demonstrates the corresponding MPF responses. As analyzed in Fig. 1(c), a flat-top bandpass MPF centered at 10.0 GHz is obtained with the participation of the inversely modulated comb spectral peaks (in the red solid curve). According to the inset, only ±0.5 dB amplitude ripple is within the 3-dB bandwidth of 1.43 GHz. The MPF shows an MSSR of 20 dB. The secondary sidelobe centered at 26.6 GHz is generated by the carrier signal and the next nearest comb peak on the left. As predicted in Fig. 1, by increasing the optical input power and stimulating proper nonlinear effects in the FP-SOA, the passband top of the MPF is flattened and the bandwidth is broadened compared to the case of linear amplification (the blue-dashed curve).

For Fig. 3(c), the bias current of the FP-SOA is 107.52 mA. Now the injected optical carrier locates exactly in the middle of two adjacent comb spectral peaks and is phase-modulated by an 18.3-GHz RF signal. When the input optical power is increased to +5 dBm, the modulation sidebands of the comb spectral peaks induced by the XGM effect can be clearly seen from spectrum in the magenta solid curve. The corresponding MPF response is shown in Fig. 3(d). Since the passband formed by the carrier and the left nearest spectral peak is now overlapped with the passband formed by the carrier signal and the right-nearest spectral peak, a single passband centered at 18.3 GHz is obtained with an improved MSSR exceeding 45 dB. According to the inset, the amplitude ripple is about ±1.5 dB within the 3-dB bandwidth of 1.28 GHz. The flatness of the passband is deteriorated since now the MPF passband is concurrently determined by two adjacent comb spectral peaks. When the carrier signal is slightly deviated from the center, a flat microwave passband centered at FSR/2 can also be obtained [4].

Figure 4 demonstrates the bandwidth tunability based on the SPM-induced optical spectral broadening. Keeping the bias current of the FP-SOA the same as that in Fig. 3(b), we alter the input signal power from −1 to +5 dBm with a step size of 1 dBm. The corresponding MPF responses are shown in Fig. 4(a). It can be observed that when the optical power is increased from −1 to +5 dBm, the 3-dB bandwidth of the...
flat-top MPF is linearly increased from 680 to 1.43 GHz, correspondingly. An averaged bandwidth tuning coefficient of 126 MHz/dBm is obtained. Then we repeat the power tuning process when the MPF is centered at 18.3 GHz and plot the measured results in Fig. 4(b). Now the 3-dB bandwidth of the flat-top MPF is increased from 620 to 1.28 GHz, which corresponds to a slightly different bandwidth tuning coefficient of 113 MHz/dBm. Considering that the input power variation also results in the spectral drift of the FP-SOA and thus the center frequency drift of the MPF, proper adjustment of the bias current is necessary to compensate for the power-induced drifting during bandwidth tuning. Note that the input optical power should be neither too high nor too low. Too-low input optical power cannot arouse strong enough XGM to flatten the top of the MPF, while too-high input optical power will deteriorate the stability of the MPF because of the possible injection locking and high-order modulation sideband. In the experiment, the input optical power is controlled between −1 and +5 dBm so that within the whole frequency tuning range the MPF can have flat-top, tunable bandwidth and stable frequency response.

Continuous tunability of the center frequency for the proposed MPF is shown in Fig. 5(a). The center frequency of the MPF is adjusted at 7.0, 7.5, 8.0, 8.5, and 9.0 GHz when the bias current is set at 59.60, 61.69, 64.73, 67.38, and 69.16 mA, respectively. With the incident optical power kept at −1 dBm, a center frequency tuning coefficient of 200 MHz/mA is obtained. The stability of the center frequency is determined by the stability of laser wavelength as well as the stability of the gain spectrum of the FP-SOA, because the relative wavelength drift between the carrier wavelength and the gain spectrum of FP-SOA will result in the spectral drift of the MPF. Owing to the high stability of the employed laser source and the bias and temperature controllers for the FP-SOA, no obvious drifting of the frequency response is observed. During the tuning process, the 3-dB bandwidth of about 1 GHz and the amplitude ripple of about ±0.5 dB are maintained. The wideband tunability of the proposed MPF is demonstrated in Fig. 5(b). By adjusting the bias current from 54.05 to 107.85 mA, the center of the MPF is tuned from 6.0 to 18.3 GHz. The lower limit of the center frequency of the MPF (i.e., the minimum frequency separation between the optical carrier and the nearest comb spectral peak of the FP-SOA) is observed to be 6.0 GHz in the experiment. When the optical carrier gets too close to the resonant comb peak of the FP-SOA, the FP-SOA easily gets injection locked to the optical carrier and no desired MPF will be achieved. The upper frequency limit (i.e., 18.3 GHz) equals to half of the FSR of the FP-SOA.

In conclusion, we have proposed and demonstrated a flat-top MPF with flexible tunability of the bandwidth and the center frequency based on an FP-SOA. Phase-inverted XGM on the output comb spectrum of the FP-SOA is exploited to flatten the passband top of the MPF. Convenient bandwidth tuning is realized by controlling the SPM-induced optical spectral broadening through the input optical power. This method provides a novel approach to realize bandwidth tuning by controlling the intensity of phase modulation, which can easily be controlled in various nonlinear media. Moreover, by shifting the gain spectrum of the FP-SOA by adjusting the bias current, wideband and continuous tuning of the center frequency is realized. To construct the proposed MPF with agile tuning of the passband, only a single CW laser source, a single PM, a single FP-SOA, and a single PD are demanded. With a simple structure a monolithically integrated version of the system can be implemented based on the InP/InGaAsP platform.

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**Fig. 5.** Tuning of the filter center frequency by adjusting the bias current of the FP-SOA: (a) continuous tuning of the center frequency from 7.0 to 9.0 GHz; (b) wideband tuning of the center frequency from 6.0 to 18.3 GHz.