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A Reconfigurable Microwave Photonic Channelized Receiver Based on Dense Wavelength Division Multiplexing Using an Optical Comb

Ze Li [a], Xianmin Zhang [a,*], Hao Chi [a], Shilie Zheng [a], Xiaofeng Jin [a], Jianping Yao [b]

[a] *Department of Information Science and Electronic Engineering, Zhejiang University, Hangzhou, 310027 China*
[b] *Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, K1N 6N5 Canada*

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ABSTRACT

A photonic approach to implementing a microwave channelized receiver based on dense wavelength division multiplexing using an optical comb is proposed. In the approach, a flat optical comb with 11 comb lines is generated using two cascaded Mach-Zehnder modulators. Frequency analysis of a microwave signal with multiple-frequency components is realized by using the optical comb together with an optical etalon with a periodic transfer function, a wavelength division multiplexer (WDM) and a photodetector array. The system is investigated numerically. Frequency measurement of a multi-frequency signal with a measurement range from 0.5-11.5 with an accuracy of ± 0.5 GHz is achieved. The reconfigurability of the system realized by tuning the comb-line spacing and the peak positions of the etalon is also evaluated. The improvement of the dynamic range of the system using an optimized periodic filter is also discussed.

1. Introduction

For modern radar and other electronic warfare (EW) systems, it is essential to perform signal analysis and identification over a wide bandwidth [1]. As the conventional electronic microwave frequency measurement techniques are thought to be slow, bulky, limited in bandwidth and vulnerable to electromagnetic interference (EMI), numerous photonic-assisted techniques have been proposed and demonstrated to achieve instantaneous microwave frequency measurement [2–15].

In [2–4], instantaneous frequency measurement (IFM) was realized based on a photonic scanning receiver, which was implemented using a tunable Fabry-Perot (F-P) etalon [2], an electrically-tunable fiber Bragg grating (FBG) [3] or a thermally-tunable echelle diffractive grating [4]. Although a scanning receiver could be used to analyze microwave signals with multiple frequencies, the scanning speed is usually slow, less than 1 kHz, which makes it difficult to analyze fast signals such as short-duration burst signals.

Recently, a technique to implement IFM of a single-frequency microwave signal based on the frequency-to-power mapping has been investigated due to the simplicity and relatively high measurement resolution [5–9]. The basic concept of this technique is to introduce the microwave signal with its frequency to be measured into two optical channels with two different transfer functions. Since there is a fixed relationship between the microwave frequency and the optical or microwave power ratio, the microwave frequency can be measured by monitoring the output powers [5–9]. However, this approach is not suitable for the EW applications where the microwave signals are embedded in a spectrally cluttered environment, where multiple microwave frequencies need to be measured simultaneously.

On the other hand, photonic-based channelized receivers are considered to be a promising solution for the instantaneous measurement of multiple microwave frequencies in a spectrally cluttered environment [10–12]. In [10], a channelized receiver based on a high-resolution free-space optical diffraction grating with a 1-GHz resolution was proposed and demonstrated. In [11], an array of phase-shifted chirped FBGs was employed to measure the multiple frequencies that lie in different channels. In [12], a microwave channelized receiver was realized based on an integrated optical Bragg grating F-P together with an integrated hybrid Fresnel lens system. In [13–16], the original multiple microwave frequencies were copied to the sidebands of an array of uniformly-spaced optical carriers and the sub-bands of each copy were sliced using a single periodic filter. By separating the sub-bands using a wavelength division multiplexer (WDM) and detecting the power of each sub-band using a photodetector (PD) array, frequency spectrum analysis of the intercepted microwave signal was realized. However, the use of the multiple laser sources in [13] would increase the complexity of the receiver. In addition, the measurement accuracy of the receivers in [13] and [14] is not tunable due to the fixed wavelength spacing between the optical carriers. Furthermore, the power ripples between different carriers were large in [15], which makes it difficult to set an appropriate threshold for the decision of a frequency.

In this paper, we propose a novel approach to realizing a reconfigurable photonic microwave channelized receiver based on an optical

* Corresponding author.
E-mail address: zhangxm@zju.edu.cn (X. Zhang).

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comb. The optical comb with flat comb lines is generated using two cascaded Mach-Zehnder modulators (MZMs) [16]. The microwave signal to be analyzed is then copied to the sidebands of the optical comb lines using a third MZM which is biased at the minimum transmission point (MITP). After slicing the sub-bands of each copy using an F-P etalon, the sliced copies are physically separated with a WDM. By detecting the output power of each of the WDM channel using a PD array, the frequency content of the microwave signal is analyzed. A simulation is performed to validate the proposed approach. Frequency measurement of a multi-frequency signal with a measurement range of 0.5-11.5 and an accuracy of ±0.5 GHz is achieved. The tunability of the measurement accuracy and the measurement range is discussed. The dynamic range of the system is also discussed. The proposed scheme offers two additional advantages compared with the approaches in [13–15]. First, the measurement accuracy is tunable compared with [13] and [14]. Second, the power ripples between different comb lines are less than 1 dB, which are much smaller than those in [15].

2. Operation Principle

The schematic of the proposed photonic microwave channelizer is shown in Fig. 1. A CW light wave from a laser diode (LD) is sent to two cascaded MZMs through a polarization controller (PC). An RF signal from a signal generator is divided into two copies and applied to the two cascaded MZMs through two high power microwave amplifiers. An RF phase shifter is applied between the two copies to adjust the phase difference between them. By adjusting the bias points and the amplitudes and phases of the two single-frequency modulation signal copies appropriately, an optical comb is generated, as shown at point (I) in Fig. 1, which is used as a multi-wavelength optical source [17]. The frequency spacing between the optical comb lines could be easily tuned by tuning the frequency of the RF signal. The optical comb is then modulated by an intercepted microwave signal using a third MZM, which is biased at the MITP. Under small signal modulation condition, the multi-wavelength optical carriers are suppressed and only multiple ±1st-order optical sidebands are generated, as shown at point (II) in Fig. 1. Then, an etalon with a periodic transfer function is used to filter out the fixed optical frequencies on one sideband of the modulated optical comb. The etalon is characterized by its free spectral range (FSR) and its finesse. The frequency spacing between the optical comb lines is slightly different from the FSR of the etalon. Fig. 2 shows an example of the frequency relationship between the transfer function of the periodic etalon and the uniformly-spaced optical comb lines. Assume that the optical carrier is aligned with the transmission peak of the etalon in channel 0. Then, there is a fixed, incremented frequency offset between the optical carrier and the transmission peak of the etalon from channel 1 to the last channel. Finally, a WDM is used at the output of the etalon to physically separate the multiple channels and the optical power of each channel of the WDM is monitored using a PD array. Thus, frequency channelization of the intercepted microwave signal is achieved.

Assume the FSR of the optical comb is FSR1 and the FSR of the etalon is FSR2. The measurement accuracy could be calculated as

$$\Delta = \pm\frac{|FSR1 - FSR2|}{2} \tag{1}$$

The measurement range is about

$$f_R = \frac{FSR1}{2} \tag{2}$$

For example, if a 0.5-19.5 GHz measurement range with ±0.5 GHz measurement accuracy is required, then FSR1 could be 40 GHz and FSR2 could be 41 GHz. If optical single sideband modulation is applied to the third MZM [18], the measurement range could be increased to as large as FSR1.

3. Numerical Results

To evaluate the performance of the proposed system, a simulation based on the setup shown in Fig. 1 is performed using the OptiSystem software. In the simulation, the optical power of the LD is set at 18 dBm and the frequency is set at 193.1 THz. The half-wave voltages of the two cascaded MZMs are both set at 3 V. The modulation frequency is set at 40.5, 41 or 41.5 GHz to achieve different measurement accuracy. The modulation indices are 3.36π and 4.7π, respectively, for the two MZMs and the phase shift between the two modulation signals is 97° [17]. The generated optical comb with 41 GHz spacing is shown in Fig. 3(a). As can be seen, 11 comb lines are generated and the power ripples between different comb lines are less than 1 dB. The generated optical comb is then sent to the third MZM, to which the intercepted microwave signal with its frequency spectrum to be analyzed is applied. The MZM is biased at the MITP to suppress the optical carriers and the extinction ratio is set at 50 dB. Fig. 3(b) shows the carrier-suppressed modulation result when the frequency components of the intercepted microwave signal are 2, 6, and 11 GHz. The powers of the three components are identical. It is seen that the optical carriers are about 22 dB lower than the ±1st-order sidebands.

Then, an F-P etalon with an FSR of 40 GHz and finesse of 160 is connected to the output of the third MZM to filter out the frequency components on one sideband of the modulated optical comb, leading to a measurement accuracy of ±0.5 GHz. As 11 comb lines are used in our system, the measurement range is 0.5-11.5 GHz. Note that if other techniques [19,20] are adopted to generate more optical comb lines, the measurement range could be greatly improved. Fig. 4(a) shows the optical spectrum at the output of the F-P etalon. As can be seen, the power of the second, the sixth and the eleventh channels are much higher than those of the other channels due to the filtering effect of the F-P etalon. A WDM with an FSR of 41 GHz is then used

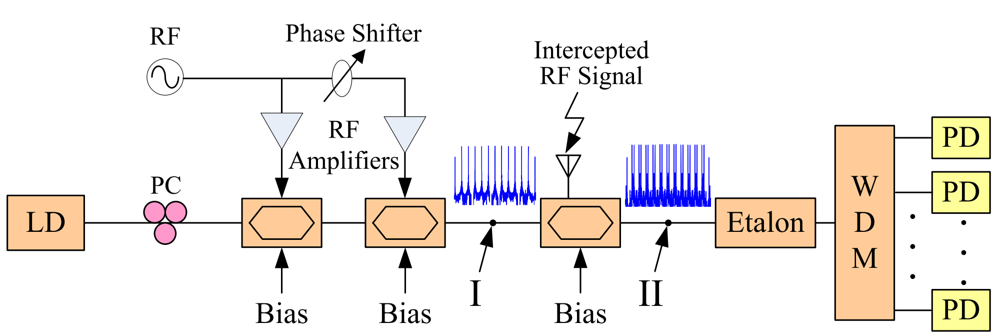

Fig. 1. Schematic of the proposed photonic microwave channelizer.

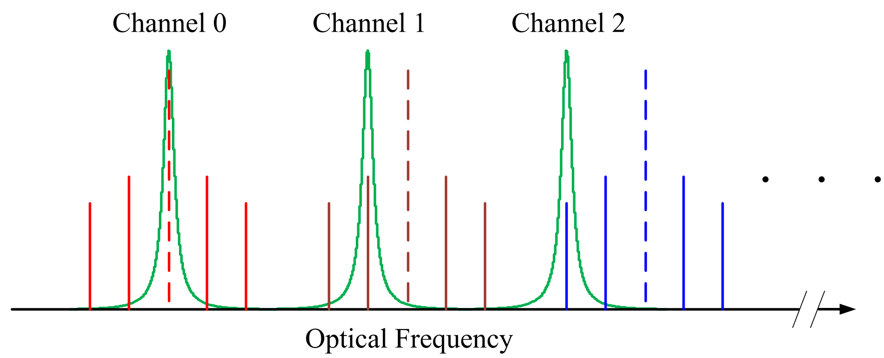

Fig. 2. Frequency relationship between the transfer function of the periodic etalon and the uniformly-spaced optical comb lines.

at the output of the F-P etalon to physically separate the different channels and a PD array with 11 PDs is used to detect the optical power of each channel of the WDM. Fig. 4(b) shows the detected optical powers of the 11 channels at the output of the PD array. It is seen that three frequency components falling in the second, the sixth and the eleventh channels are detected, which means that the estimated frequencies are 2, 6, and 11 GHz. Therefore, frequency channelization of the intercepted microwave signal is achieved. The adjacent channel rejection is about 15 dB.

The proposed system can be reconfigured such that the measurement accuracy can be adjusted. This is done by tuning the comb-line spacing and the central frequency of each peak of the F-P etalon. Two examples are given here. In the first example, the comb-line spacing is adjusted to be 41.5 GHz and the central frequencies of the corresponding peaks of the etalon are adjusted to match the 11 channels while the FSR of the F-P etalon is kept to be 40 GHz, which leads to an accuracy of ± 0.75 GHz. As 11 channels are used, the measurement range is increased to be 0.75-17.25 GHz. The frequency components of the microwave signal applied to the third MZM are set to be 1.5, 7.5, and 16.5 GHz. Fig. 4(c) shows the optical spectrum at the output of the F-P etalon and Fig. 4(d) shows the detected optical powers of the 11 channels. As can be seen, three frequency components falling in the first, the fifth and the eleventh channels are obtained, which demonstrates that the estimated frequencies are 1.5, 7.5, and 16.5 GHz. The adjacent channel rejection is about 20 dB. In the second example, the comb-line spacing is adjusted to be 40.5 GHz, leading to an accuracy of ± 0.25 GHz. The measurement range is decreased to be 0.25-5.75 GHz. The frequency components of the microwave signal to be analyzed are changed to be 1, 2.5, and 4 GHz. The optical spectrum at the output of the etalon and the detected optical powers of the 11 channels are shown in Fig. 4(e)-(f). It is seen that three frequency components falling in the second, the fifth and the eighth channels are obtained, which demonstrates that the estimated frequencies are 1, 2.5, and 4 GHz. The adjacent channel rejection is about 9 dB. Thus, according to the discussions above, there is a trade-off between the measurement range and the accuracy when the number of the optical comb lines is limited.

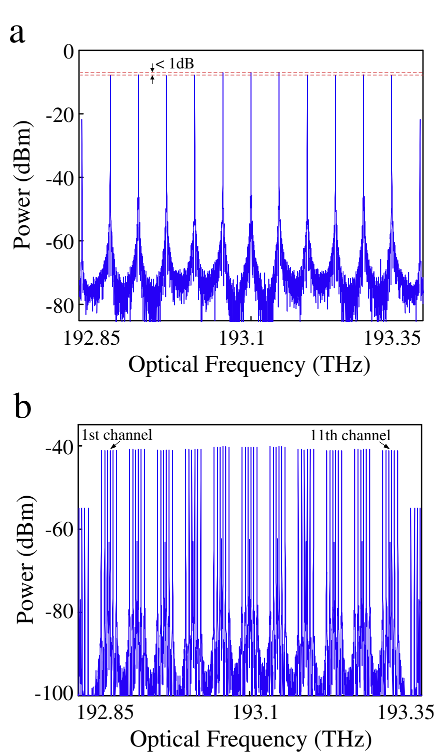

Fig. 3. (a) The generated optical comb with 11 comb lines. (b) The carrier-suppressed signal at the output of the third MZM.

The measurement range could be adjusted from 1–11 GHz to 6–16 GHz by simply tuning the peak position of the F-P etalon, while the measurement accuracy is kept to be ± 0.5 GHz. Fig. 5 shows the simulation result when the central frequency of the transmission peak of the F-P etalon is tuned to be 6 GHz smaller than the frequency of the optical carrier in the first channel (channel 0) and the FSR of the F-P etalon is kept to be 40 GHz. The frequency components of the microwave signal applied to the third MZM are set to be 6, 10, and 16 GHz. As can be seen from Fig. 5(a)-(b), the three frequency components have been successfully identified and the adjacent channel rejection is about 15 dB. As the frequency components are well separated from each other in the cases above, the influence from the adjacent channels is not well considered. Fig. 5(c)-(d) show the simulation results when the separations between the three frequency components are small. It is seen that the three frequency components can still be well identified and the adjacent channel rejection is above 16 dB, which indicates the influence from the adjacent channels could be ignored in our case. The simulation results above agree well with the prediction, which validates the effectiveness of the proposed system.

4. Discussion

In the section above, the three frequencies to be measured were aligned with the transmission peaks of the F-P etalon in the three channels, which could provide the maximum output optical power in each channel. However, if a frequency component locates near the boundary of two adjacent channels, the output power of the corresponding channel will be much smaller, which could influence the measurement of the frequency. Fig. 6(a)-(b) show the case when the modulation frequency components are adjusted to be 1.75, 6.8, and 11.2 GHz and the other conditions are kept identical to the case

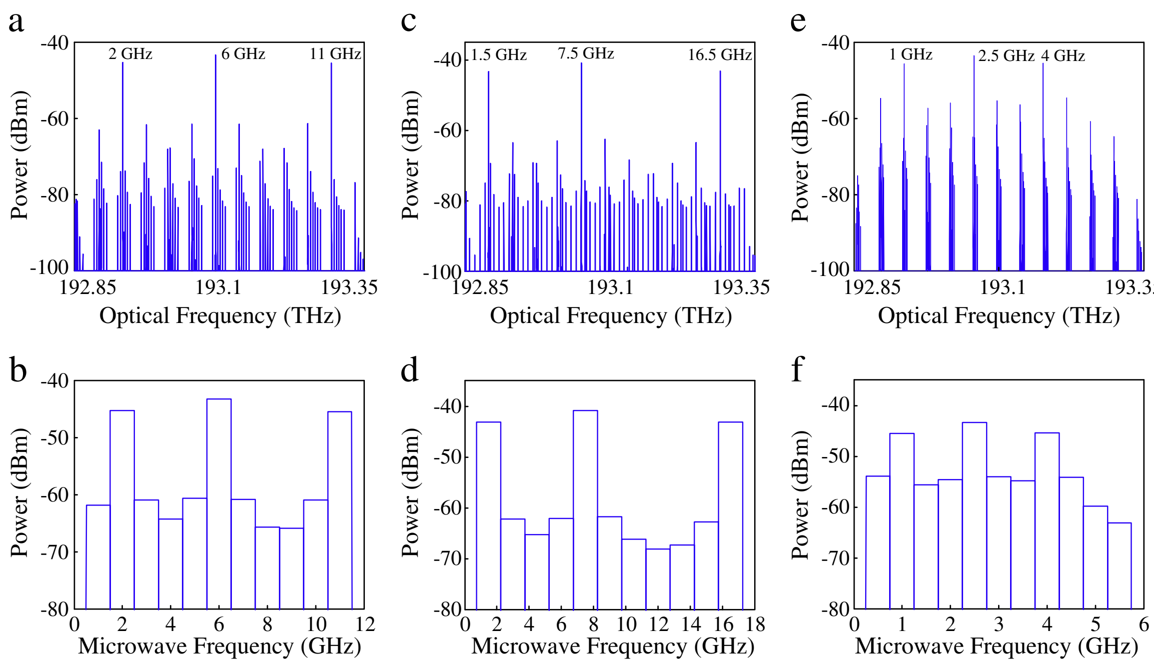

Fig. 4. Optical spectrum at the output of the F-P etalon and the detected optical powers of the 11 channels at the output of the WDM with different measurement accuracies. (a)-(b) ±0.5 GHz. (c)-(d) ±0.75 GHz. (e)-(f) ±0.25 GHz.

shown in Fig. 4(a)-(b). The three frequency components all locate at the "skirt" part of the F-P filter. It is seen that the optical powers in the three channels corresponding to the three frequencies are reduced by more than 5 dB and the adjacent channel rejection is about 9 dB.

In the example above, the powers of the microwave frequency components are set to be identical; however, for practical applications, the powers of different frequency components of an intercepted signal may vary greatly. Fig. 6(c)-(d) show the case when the power of the 11.2 GHz frequency component is tuned to be 12 dB lower and the other conditions are kept identical to the case shown in Fig. 6(a)-(b). As can be seen, the identification of the 11.2 GHz frequency component is more difficult. Thus, a large dynamic range is of great importance to the receiver system. In practical implementations, the dynamic range

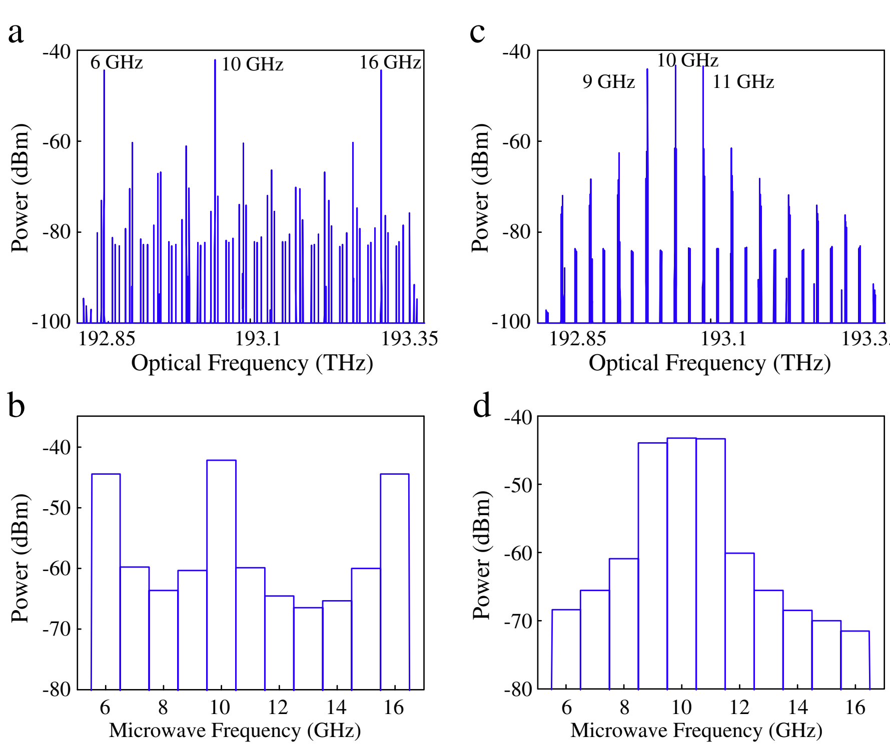

Fig. 5. Optical spectrum and the detected optical powers with 6–16 GHz measurement range and ±0.5 GHz measurement accuracy. (a)-(b) The case when the frequency components are well separated. (c)-(d) The case when the separations between the three frequency components are small.

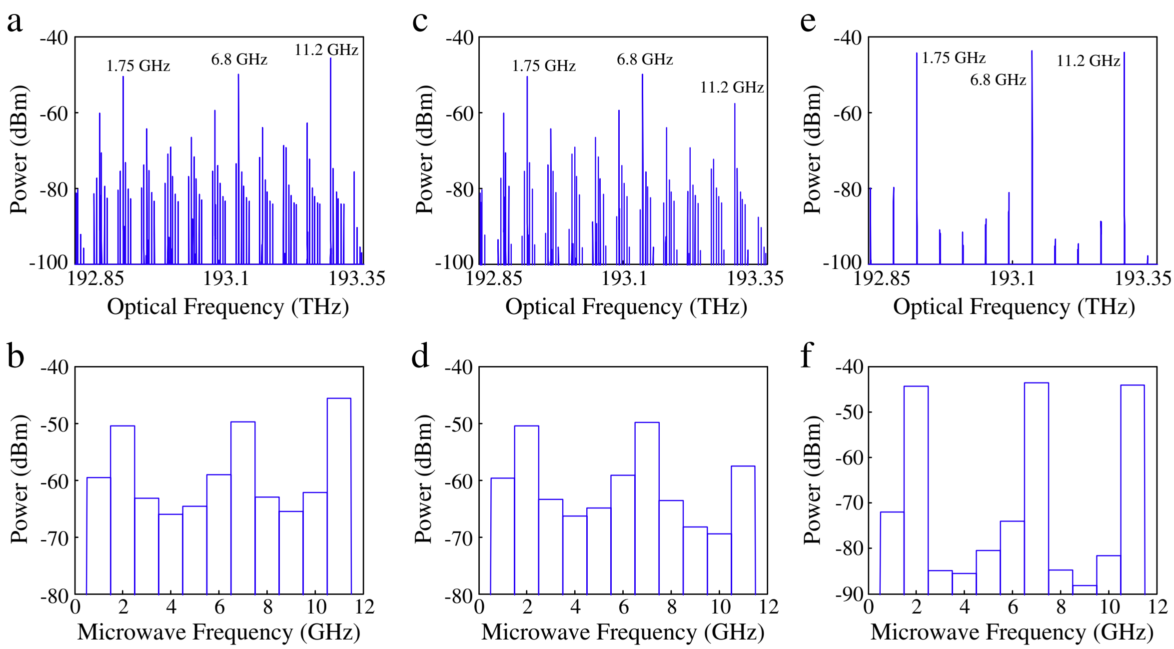

Fig. 6. (a)-(b) Three frequency components with identical power. (c)-(d) The power of the 11.2-GHz frequency component is 12 dB lower than the powers of the other two frequency components. (e)-(f) Three frequency components with identical power and the F-P etalon is replaced by an optimized filter with sharp edges.

could be improved by use of RF amplification and filter optimization [2,15]. The etalon used in the simulation is an F-P etalon (Lorentzian passband). For practical applications, an optimized filter with sharp edges should be adopted to minimize channel crosstalk [15]. Fig. 6(e)-(f) show the simulation results when the modulation frequency components are kept to be 1.75, 6.8, and 11.2 GHz and the F-P etalon is replaced by a flat-top periodic filter with a second-order super-Gaussian shape. The FSR of the filter is kept to be 40 GHz and the finesse is set at 50. As can be seen, the adjacent channel rejection has been greatly improved to be 28 dB, which could also greatly improve the dynamic range of the system. However, the use of a flat-top filter with sharp edges will reduce the reconfigurability of the system, which means the tunability of the measurement accuracy will be lost.

5. Conclusion

A novel approach to realizing a reconfigurable photonic microwave channelized receiver based on an optical comb has been proposed. A flat optical comb with 11 comb lines was generated using two cascaded MZMs. Frequency analysis of an intercepted microwave signal was achieved by using the generated optical comb together with an F-P etalon and a WDM. The reconfigurability of the system was shown by tuning the comb-line spacing and the peak positions of the etalon. The optimization of the periodic filter and the improvement of the dynamic range of the system were also discussed.

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