

Key technologies on microwave photonic filter

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Abstract Microwave photonic filter (MPF) as one of the key devices in the radio-on-fiber (ROF) system has attracted much interest recently. Some key technologies of MPF including the coherence, quality factor (Q) and reconfigurability are introduced. The difference between the incoherent and coherent MPF (ICMPF and CMPF) is given, and the methods to realize an ICMPF are also introduced. Higher Q factor MPF can be developed with more taps, and it is proved by simulation. Then the methods of finite and infinite impulse response MPF (FIRMPF and IIRMPF) are both given. At last, the reconfigurability is verified by four kinds of window functions.

Keywords microwave photonic filter (MPF), radio-on-fiber (ROF), coherent, Q value, reconfigurability

1 Introduction

With the needs of wideband and wireless increasing gradually, the increase in capacity is required imminently, with the development of technologies such as broadband wireless access networks from universal mobile telecommunications system (UMTS) to fixed access pico-cellular networks and wireless local area network (WLAN), worldwide interoperability for microwave access (WIMAX), local multipoint distribution service (LMDS), etc. A feasible method to obtain this objective is the radio-on-fiber (ROF) system [1]. In the ROF system, the use of optical fiber filters to carry out microwave signal processing in the optical domain has attracted significant interest. The microwave photonic filter (MPF) as one of the key parts of the ROF system is come into being. The objective of an MPF is to replace a standard microwave

filter used in an RF system, bringing a series of advantages such as tunability, reconfigurability, electromagnetic immunity, etc. [1]. In the last few years, extensive efforts have been directed to the design and implementation of MPF with different architectures to fulfill different functionalities at the incoherent, tunability, negative coefficient, bandpass response, reconfigurability and high quality value (Q).

In this paper, some key technologies of MPF are introduced, including the coherence, coefficient, Q value, tunability and reconfigurability. Some basic concepts and theory to verify the conclusion are also provided.

2 Key technologies of MPF

2.1 Incoherent and coherent

Figure 1 shows the principle layout of MPF. The RF signal is directly modulated by the light carrier from laser which realizes the RF to optical conversion. Then the modulated signal is conveyed by the light carrier and fed to the sample unit where the taping and delay are finished. At last, the combined signal is optically RF-converted by the photo detector (PD), and the RF signal is produced.

Supposing the input RF signal and the light carrier are given by

$$S_i(t) = A_s(t)\cos(\omega_0 t), \quad (1)$$

$$E = A_e e^{j(\omega_c t + \phi)}. \quad (2)$$

After modulating, tamping and delay, the combined signal before PD is

$$E_{\text{pdin}} = \sum_{n=1}^N \sqrt{\frac{a_n}{2}} \{1 + \beta_{\text{AM}}(t - n\tau)\cos[\omega_0(t - n\tau)]\}^{1/2} \cdot \sqrt{\frac{A_e}{N}} e^{j[\omega_c(t - n\tau) + \phi(t - n\tau)]}, \quad (3)$$

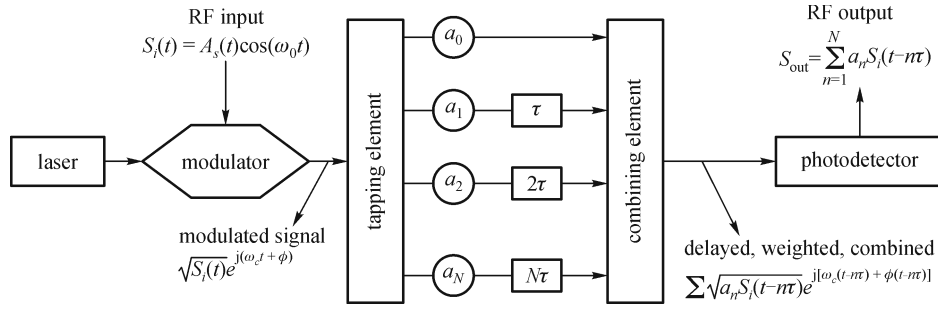


Fig. 1 Principle layout of MPF

where $\beta_{AM}(t) = mA_s(t)$, which is free from the amplitude of the RF signal, and m is a constant.

Supposing the coherent exists between the adjacent taps; the current after PD is

$$\begin{aligned}
 I_{\text{out}} &= \langle |E_{\text{pdo}}|^2 \rangle \\
 &= \sum_{n=1}^N \sum_{r=1}^N \sqrt{k} \sqrt{a_n} \sqrt{S_i(t-n\tau)} \sqrt{k} \sqrt{a_r} \sqrt{S_i(t-r\tau)} \\
 &\quad \cdot \langle e^{j[-\omega_c n\tau + \phi(t-n\tau) + \omega_c r\tau - \phi(t-r\tau)]} \rangle \\
 &= k \sum_{n=1}^N a_n S_i(t-n\tau) + \sum_{n=1}^N \sum_{r \neq n}^N \sqrt{a_n} \\
 &\quad \cdot \sqrt{S_i(t-n\tau)} \sqrt{a_r} \sqrt{S_i(t-r\tau)} \Gamma((n-r)\tau), \quad (4)
 \end{aligned}$$

where $\Gamma((n-r)\tau) = \langle e^{j[-\omega_c n\tau + \phi(t-n\tau) + \omega_c r\tau - \phi(t-r\tau)]} \rangle$ is a stochastic process which stands for the light source phase noise, $k = \frac{mA_e}{2N}$. In Eq. (4), the first part is incoherent, and the second part is coherent. The MPF will be worked at incoherent, when the second part is set to be zero.

In fact, $\Gamma((n-r)\tau)$ can be simplified as

$$\Gamma((n-r)\tau) \propto e^{-\frac{|(n-r)\tau|}{\tau_{\text{cohere}}}}, \quad (5)$$

where τ_{cohere} is the laser coherent time, and it is directly proportional to the laser line width. If MPF works at incoherent which means $\Gamma((n-r)\tau) = 0$, then

$$\tau \gg \tau_{\text{cohere}}. \quad (6)$$

So from Eq. (4),

$$I_{\text{out}} = k \sum_{n=1}^N a_n S_i(t-n\tau). \quad (7)$$

Compared with Eqs. (1) and (7), the output signal is the sampling, weighting and delay of the RF signal. And the signal process is realized by the light carrier.

From Eq. (7), we can see that the incoherent MPF (ICMPF) is a kind of stable filter which is free from the

light source phase noise. Much kind of schemes have been proposed to realize an ICMPF. At the beginning, a single incoherent light source with coherent time smaller than the minimum delay time is mainly used to ensure stable filter operation. For example, a long chirped fiber Bragg grating (CFBG) and a tunable laser source were used to realize an incoherent continuous tuning capability ICMPF [2]. Due to the limit of the laser coherent time (see Eq. (6)), the ICMPF using single light meets the bottleneck. But several methods were put forward to overcome the problem, such as multiple sources, wide source slicing, laser array, etc. Previous works in this direction include the use of independent lasers operating at different wavelength and dispersion media [3], multi-wavelength erbium-doped fiber laser [4], spectrum slicing the output of a broadband source by uniform fiber Bragg grating (UFBG) or arrayed waveguide grating (AWG) [5,6], and the use of laser arrays and the periodicity of AWG or linearly CFBG [7–11].

MPF under incoherent operation has traditionally suffered from the positive nature of the coefficients due to the linearity in optical intensity, which limited the range of attainable transfer functions and the resonance place at the baseband [1]. Complex-coefficient filter with enhanced tuning of its frequency response is proposed to solve these limitations since 1980s, such as phase modulator and CFBG [12], phase inversion in an electro-optic modulator [13], stimulated Brillouin scattering [14], single-sideband modulation and narrow-band optical filtering [15], and single laser diode [16], etc.

As shown in Eq. (4), if $\Gamma((n-r)\tau) \neq 0$, the output current includes two parts, and the second part is coherent. So the MPF with the transfer function is coherent MPF (CMPF). Compared with the ICMPF, CMPF is unstable and sensitive to the circumstance due to the light phase in the second part of Eq. (4). So CMPF is not conducive to the practical applications.

ICMPF has been a hot research spot in the MPF researches. Considering the coherent time and the minimum delay time, multisource structures are proposed and widely used. At present, ICMPF is not a key bottleneck with more and more schemes put forward.

2.2 Q value

For an MPF, it is important to develop a structure that can produce a large number of taps in order to realize sharp frequency response characteristics and high resolution in the frequency domain. A key factor that limits the performance of a high-quality-value (Q) MPF, which is defined as the ratio of the free spectrum range (FSR) and the 3-dB bandwidth, is the number of the taps. MPF can be classified into finite impulse response microwave photonic filter (FIRMPF) and infinite impulse response microwave photonic filter (IIRMPF) according to the number of the taps.

For an FIRMPF, more taps can bring not only better response but also higher cost and more complex structure. So it is not appropriate to obtain a considerable volume of taps by constructing an FIRMPF. Figure 2 shows a different response with three and eight taps. We can see that when the number of the taps increased, the FSR, depth and side-lobe suppression ratio are stable, but the 3-dB bandwidth is narrower, which means that the Q value can be increased. In 1998, five taps FIRMPF was proposed by Capmany et al. using four tunable lasers and one distributed feedback (DFB) laser [11]. The fast reconfiguration of the transfer function by proper adjustment of the output powers of the lasers in the array and tunability of the filter resonances by controlling the spectral separation between the center wavelengths of the sources were both obtained in this structure.

Compared with the limitation of FIRMPF, substantial taps can be obtained easily for an IIRMPF by setting a feedback loop in the structure. In theory, the number of the taps for an IIRMPF can be infinite. But it is difficult to realize in practice. Some theories have been proposed to prove that a higher Q value can be obtained by setting the gain and the coefficient of the feedback loop equal to 1 in a one-order IIRMPF. At present, much research has been devoted to get a high Q value structure by realizing an IIRMPF. A single-bandpass MPF with high Q factor being 95 was reported by Zhu et al. [17]. Through spectrum-sliced by a Mach-Zehnder interferometer as the multiple source, a fiber ring delay line and a dispersion medium of 50-km SMF as the cascaded optical structures, the flat response was also realized. The typical one-order IIRMPF realized by a feedback loop was presented by the research group led by D. B. Hunter and R. A. Minasian in the University of Sydney in 1997. A loop structure based on a coupler and active devices and a structure based on FBG pair and some length active fiber [18] were put forward according to the loop cavity and the Fabry-Perot (F-P) cavity of the optical delay filters. The Q value around 200 was obtained both in the two methods.

It can be seen that FIRMPF is easier to be structured, but the Q value is limited by the finite number of the taps which will prevent it from the great performance

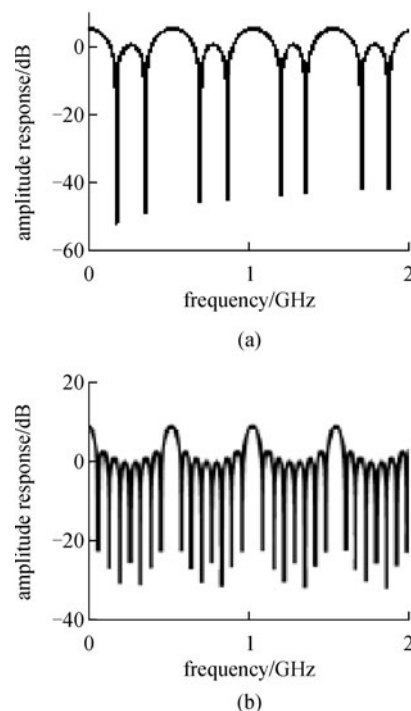


Fig. 2 Different responses with different number of taps. (a) Three taps; (b) eight taps

improvement. In addition, the more the number of the taps, the higher cost and the more complexity the structure. It is not a good choice for the communication system. In contrast with it, IIRMPF has more advantages because IIRMPF can gain a high Q value using fewer components and then decrease the cost. By far, a Q value as high as 237 for an FIRMPF using a tuned modulator [19] has been reported. Recently, a Q value of more than 3000 has been reported by Ortega et al. [20]. The filter is based on a modified gratings and erbium-doped fiber-based structure. Q factors over 3000 are demonstrated when a tuned modulator is used in combination with the recirculating approach.

2.3 Reconfigurability

The reconfigurability of MPF can be achieved by modulating the power or adding a different weighting coefficient on the taps. Figure 3 shows the different weighting function, and Fig. 4 shows the reconfigurability of the MPF with the above function of eight taps. It can be seen that MPF in the Hamming window has the best response, and the side-lobe suppression ratio is the highest. In general, passive structures are in capable of this feature. Several solutions have been proposed to overcome this limitation, such as the use of multiwavelength erbium-doped fiber laser [4], broadband optical source sliced by UFBG [5], linearly CFBG fed by a laser array [9,11], single laser diode [16], and so on.

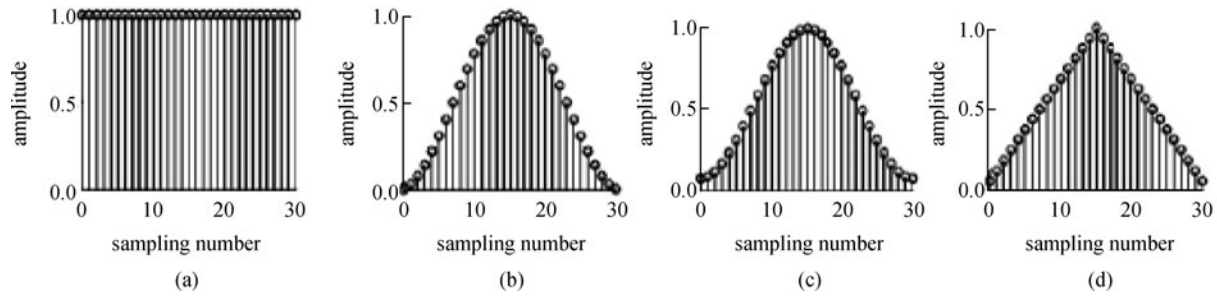


Fig. 3 Different weighting functions. (a) Rectangle; (b) Hamming; (c) Hanning; (d) triangle

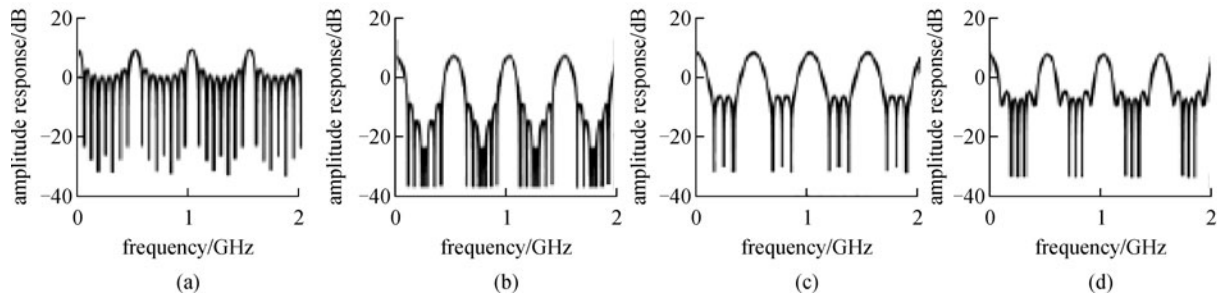


Fig. 4 Reconfigurability of MPF with different weighting functions of eight taps. (a) Rectangle; (b) Hamming; (c) Hanning; (d) triangle

3 Conclusions

Some key targets of MPF are discussed including the coherence, Q factor and the reconfigurability. For a CMPF, the unstable character is the main limitation for using it. Nevertheless, ICMPF as one of the hot spots is free from the phase noise of the source and is immune to the circumstance. An ICMPF structure contains two methods. One is the single sources which need the coherent time smaller than the minimum delay line. And the other is multiple sources which are realized by laser arrays, tunable laser or broadband source slicing by optical devices or FBG. In the practical system, sharp response is needed to filter the noise, and as far, IIRMPF has become the main method to obtain a high Q factor response. The reconfigurability for MPF is to tune the weight of the taps. One method is to change the power of every output of the laser arrays. FBG is a very constructive device to realize the reconfigurability due to the different reflectivity of different wavelength. Despite many schemes proposed to achieve the better performance, there are still some highlights of the main current technological challenges such as developing new techniques to obtain stable filters with high Q values, more compact methods to obtain negative and complex coefficient MPF and new techniques leading to the tunability.

There is an increasing interest in MPF; on one hand, emerging communication system requires an increase in the capacity by reducing the coverage area. On the other

hand, MPF can find applications in specialized fields such as radar and photonic beam steering of phased array antennas. Practical applications require the ability to work at incoherent, to generate multiple taps, to produce both positive and negative taps. So the research on MPF is developing. We believe that MPF will play a more and more important part in the future communication system.

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