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RESEARCH ARTICLE

Q value analysis of microwave photonic filters

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Abstract This paper first presents the fundamental principles of the microwave photonic filters. As an example to explain how to implement a microwave photonic filter, a specific finite impulse response (FIR) filter is illustrated. Next, the *Q* value of the microwave photonic filters is analyzed theoretically, and methods around how to gain high *Q* value are discussed. Then, divided into FIR filter, first-order infinite impulse response (IIR) filter, and multi-order IIR filter, several novel microwave photonic filters with high *Q* value are listed and compared. The technical difficulties to get high *Q* value in first-order IIR filter and multi-order IIR filter are analyzed concretely. Finally, in order to gain higher *Q* value, a multi-order IIR microwave photonic filter that easily extends its order is presented and discussed.

Keywords microwave photonic filters, finite impulse response (FIR) filter, first-order infinite impulse response (IIR) filter, multi-order infinite impulse response (IIR) filter, high *Q* value

1 Introduction

Exploiting photonic devices and systems to generate, transmit, process, and detect microwave signals has been a subject of constant active research over the last 30 years and has crystallized in the new discipline known as microwave photonics [1]. One of the most important applications of this field is microwave photonic filters. Microwave photonic filters are attracting great interest because of their low loss, without the bottlenecks, immunity to electromagnetic interference (EMI), and inherent compatibility with optical fiber microwave systems [2–4]. Incorporating them with the optical fiber network, all-optical transmission and processing of the microwave signals to meet requirements of high-speed large-capacity wireless communications can be realized. With these advantages, microwave photonic filters will certainly take the place of the traditional microwave filters in future radio over fiber (ROF) systems and become the key part of the systems.

The traditional microwave filters process microwave signals in the electronic field by using electronic devices, while microwave photonic filters process microwave signals in the optical field by utilizing optical devices. The differences between them are shown in Fig. 1. For microwave photonic filters, if the light beams out of the optical signal processor are coherent, it is a coherence microwave photonic filter; otherwise it is an incoherence microwave photonic filter [5]. The researches on processing microwave signals by utilizing optical devices started from Wilner, who noted that the low loss and high bandwidth of single-mode optical fibers made them an ideal broadband delay line filter to process microwave signals in 1976 [6]. Such thinking aroused widespread attention immediately. From then on, microwave photonic filters using various optical devices, in various structures had been put forward in an endless stream. A common objective is to increase the *Q* value and frequency selectivity of these filters.

2 Fundamental principle of microwave photonic filters

2.1 Net topology

Microwave photonic filters process microwave signals by utilizing optical devices. First, the optical carrier is amplitude-modulated by a microwave signal. Then, the optical modulated signal is tapped to several beams. Each beam (or tap) is respectively weighted and delayed by using optical components. It must be ensured that the adjacent taps are delayed by an equal time space (*T*). Finally, all the delayed taps are mixed at the detector.

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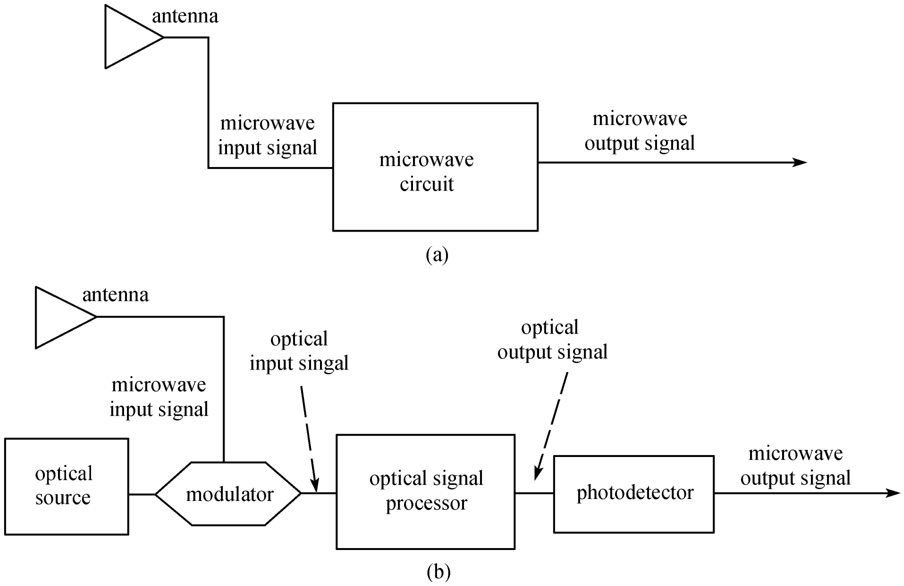

Fig. 1 Two approaches toward microwave filtering. (a) Traditional filters; (b) photonic filters

When the delayed time T between adjacent taps is much longer than the coherence time (τ_c) of the optical source, the taps are mixed in an incoherent way, so the interference does not exist and the light intensity of the mixed beam is the sum of the light intensity of all the taps. The optical detector is a square-law device that responds to the incident light intensity and is not fast enough to respond to the carrier frequency. After these steps, the microwave signal loaded on the light is tapped, delayed, weighted, and combined in the same way as the optical signal.

Similar to the classification of the digital filters, according to whether the number of the taps of the microwave signal is finite or infinite, microwave photonic filters are classified into finite impulse response (FIR) filters and infinite impulse response (IIR) filters. The net topology (parallel connected configuration) for microwave transmission of both filters is shown in Fig. 2. If $a_k = 0$ for all k, the filter is nonrecursive and is known as FIR filter, corresponding to the left half of Fig. 2. Otherwise, it is recursive and is known as IIR filter. Supposing $x(t)$ is the input signal at time t, $y(t)$ is the output signal at time t, and T is the delay time. The relation of the input signals and the output signals can be formulized as

$$\sum_{r=0}^{M} b_r x(t-rT) + \sum_{k=1}^{N} a_k y(t-kT) = y(t). \tag{1}$$

The transmission function is

$$H(w) = \frac{\sum_{r=0}^{M} b_r e^{-\mathrm{j}r\omega T}}{1-\sum_{k=1}^{N} a_k e^{-\mathrm{j}k\omega T}} \tag{2}$$

or

$$H(f) = \frac{\sum_{r=0}^{M} b_r e^{-\mathrm{j}r2\pi fT}}{1-\sum_{k=1}^{N} a_k e^{-\mathrm{j}k2\pi fT}}, \tag{3}$$

where ω is the angular frequency and f is the frequency. The above expression identifies a frequency response with a periodic spectral characteristic. The frequency period is known as the filter free spectral range (FSR) which is proportional to $1/T$. T is the time spacing between adjacent taps. So such filters are comb filters.

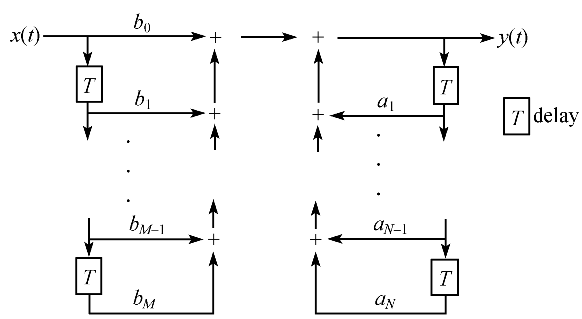

Fig. 2 Net topology of microwave photonic filters for microwave transmission

2.2 Implementation

When the microwave signal is tapped, weighted, delayed and summed in the optical field, a net for microwave processing as shown in Fig. 2 is built. An implementation

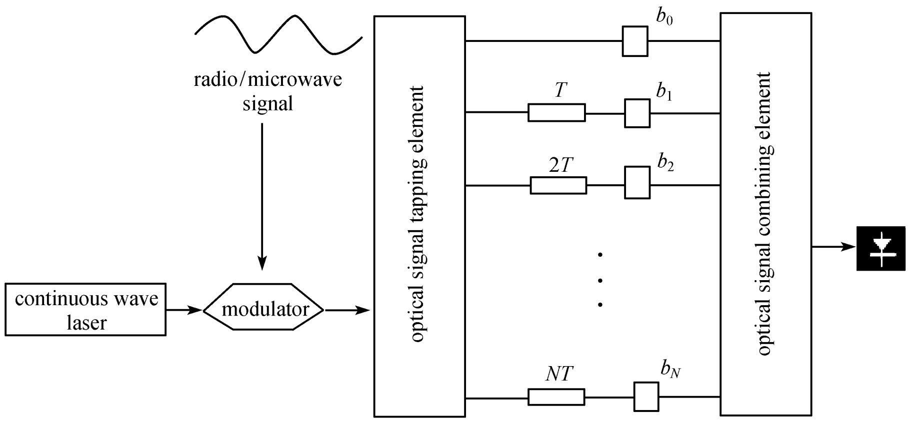

Fig. 3 Implementation layout of microwave photonic FIR filter

layout of a microwave photonic FIR filter is shown as Fig. 3 [5].

Supposing that an input microwave signal is given by

$$S_i(t) = A(t)\cos(\omega_s t), \tag{4}$$

where ω_s is the frequency of the microwave carrier; $A(t)$ is the envelope function. When the optical source is amplitude-modulated linearly by the microwave signal, the light intensity after modulating is given by

$$I' = \frac{1}{2}[1 + m(t)\cos(\omega_s t)]I, \tag{5}$$

where I is the output light intensity of the continuous wave laser; $m(t)$ is the modulation depth, which is proportional to the amplitude of the microwave signal, that is $m(t) \propto A(t)$. The amplitude of the microwave signal slowly changes over time relative to the optical carrier, so does the modulation depth. Then the function of the optical field after modulating can be expressed as

$$E_i(t) = \frac{1}{\sqrt{2}}[1 + m(t)\cos(\omega_s t)]^{1/2}\sqrt{I}e^{j(\omega_0 t+\phi)}, \tag{6}$$

where ω_0 is the frequency of the optical carrier and ϕ is the phase angle of the optical signal. After the optical signal is tapped, delayed and weighted, the optical field of the nth tap is expressed as

$$E_n(t) = \sqrt{\frac{b_n}{2}}\{1 + m(t-nT)\cos[\omega_s(t-nT)]\}^{1/2} \cdot \sqrt{\frac{I}{N}}e^{j[\omega_c(t-nT)+\phi_n]}. \tag{7}$$

Assuming that interference does not happen between any two taps, the light intensity at the photo detector input yields

$$I_0(t) = \sum_{n=1}^{N}\frac{b_n}{2}\{1 + m(t-nT)\cos[\omega_s(t-nT)]\}\frac{I}{N}. \tag{8}$$

After optical to electrical conversion and the direct current part being filtered, the output electrical signal is expressed as

$$S_0(t) = k\sum_{n=1}^{N} b_n m(t-nT)\cos[\omega_s(t-nT)] = k\sum_{n=1}^{N} b_n S_i(t-nT), \tag{9}$$

where k is a constant. From Eq. (9) it can be seen that once the optical modulated signal is tapped, delayed, weighted, and finally combined on a photo detector, the microwave signal loaded on the light is then tapped, delayed, weighted, and combined in the same way. Thus, a net for microwave processing as shown in Fig. 2 is built and the microwave signal filtered in the optical field is achieved. It shows that in order to constitute a microwave photonic filter, such devices as optical source, electro-optical modulator, optical signal tapping and combining element, time delay component, optical amplifier or optical attenuator, and photo detector are needed.

The microwave photonic filter described above is called an incoherent filter where the interference is lost and the light intensity at the photo detector is the sum of the light intensity of all the taps. Otherwise, if the light arising from each tap of the filter interferes with any tap of the rest, the light intensity at the photo detector has a relationship with the phase of the light of the taps, the filter is called a coherent filter. For coherent filters, any slight phase change in the propagation path of any tap drastically affects the filter response and their properties, which constitutes a very serious practical limitation for the implementation of these filters [3]. In this paper, only the incoherent filters are discussed.

3 Theory and methods around how to gain high *Q* value

In Sect. 2.1, it is shown that the frequency response of the microwave photonic filter has a periodic spectral characteristic. The frequency period is FSR. The amplitude-frequency characteristic curve of a certain microwave photonic filter is shown in Fig. 4. The frequency selectivity of the microwave photonic filter is denoted as quality or Q value which is expressed as

$$Q = \mathrm{FSR}/\Delta f_{-3\mathrm{dB}}, \tag{10}$$

where $\Delta f_{-3\mathrm{dB}}$ is the resonance full-width at half-maximum. The higher the Q value, the better the frequency selectivity.

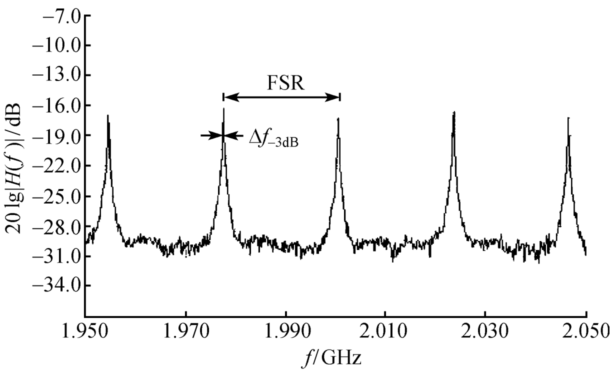

Fig. 4 Amplitude-frequency response curve of microwave photonic filter

The theory of the microwave delay filters is similar with that of the optical delay filters. As we know, optical delay filters get across the light-wave with a certain frequency which meets the conditions for enhanced interference but obstructs the light-wave with other frequency by employing interference between the various delay optical signals. Similarly, microwave delay filters get across the microwave with a certain frequency which meets the conditions for enhanced interference, while obstructing microwave with other frequency by employing interference between the various delay microwave signals. Thus, the comb-like spectra shown in Fig. 4 are formed.

Suppose that the number of taps is N, the amplitude of the signal of each tap is equal, and the central frequency of the pass band is f_{pass}. It is known that f_{pass} is the frequency point which meets the conditions for enhanced interference. At this frequency point, the amplitude of the output signal is the sum of the amplitude of all the input signals. Therefore, the value of the transmission function $|H(f)|$ at f_{pass} is given by

$$\left|H(f_{\mathrm{pass}})\right| = \frac{V_{\mathrm{out}}(f_{\mathrm{pass}})}{V_{\mathrm{in}}(f_{\mathrm{pass}})} = N. \tag{11}$$

The sharper the $|H(f)| \sim f$ curve at the central frequency f_{pass}, the higher the Q value. In other words, increasing the value of the $|H(f_{\mathrm{pass}})|$ can raise the Q value. Thus, in order to achieve higher Q value, the number of the taps N must be increased. For the FIR filter, the components and the cost of the filter will go up notably when the tap number is increased. If N tends to infinity, the Q value will also tend to infinity according to Eq. (11), which can be attained in IIR filters. In contrast with the FIR filter, the IIR filter can gain higher Q value using fewer components and then decrease the cost. The net topology of a first-order IIR filter is shown in Fig. 5. As shown, it has a recursive loop.

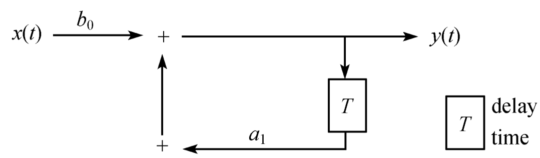

Fig. 5 Net topology of first-order IIR filter

Ideally, if the gain of the loop a_1 is equal to 1, the delay signals at the frequency of n/T meet the conditions for enhanced interference that the phase difference between the two adjacent signals is $2n\pi$. At these frequencies, the amplitude of the output signal is the sum of the amplitudes of all the delay signals whose number tends to infinity. In other words, the number of the taps N tends to infinity. Therefore, the Q value tends to infinity. On the other hand, if the gain of the loop a_1 is less than 1, the number of signals accepted at the photo detector N is a limited value because the weak signals whose amplitude less than the sensitivity of the photo detector are not accepted. Then the Q value is also a limited value.

Such conclusion also can be educed in the z field. The transmission function of a first-order IIR filter shown in Fig. 5 is given by

$$H(z) = \frac{b_0 z}{z - z_{\mathrm{p}}}, \tag{12}$$

where $z = e^{\mathrm{j}\omega}$, $\omega = 2\pi f/\mathrm{FSR}$, $z_{\mathrm{p}} = a_1$, z_{p} is the pole point of the transmission function in z field. The frequency period of the amplitude-frequency response curve of the microwave photonic filter is 2π when converting from z field to ω field. According to the definition of the Q value, the relationship between Q value and z_{p} can be deduced as

$$|H(\omega)| = \frac{b_0}{\sqrt{1 - 2z_{\mathrm{p}}\cos\omega + z_{\mathrm{p}}^2}}. \tag{13}$$

Assuming that in the region from 0–2π, the frequency at which the value of $|H(\omega)|$ decreases to the half-maximum is $\omega_{-3\mathrm{dB}}$, that is,

$$|H(\omega_{-3\mathrm{dB}})| = \frac{1}{2}|H(\omega)|_{\max}, \tag{14}$$

$$\frac{b_0}{\sqrt{1-2z_\mathrm{p}\cos\omega_{-3\mathrm{dB}}+z_\mathrm{p}^2}} = \frac{b_0}{2(1-z_\mathrm{p})}, \tag{15}$$

$$\omega_{-3\mathrm{dB}} = \arccos\frac{-3z_\mathrm{p}^2+8z_\mathrm{p}-3}{2z_\mathrm{p}}. \tag{16}$$

If the frequency period is 2π in ω field, the Q value can be expressed by

$$Q = \frac{2\pi}{2\omega_{-3\mathrm{dB}}} = \frac{\pi}{\arccos\frac{-3z_\mathrm{p}^2+8z_\mathrm{p}-3}{2z_\mathrm{p}}}. \tag{17}$$

It can be shown from Eq. (17) that the closer the pole point z_p to 1, the larger the Q value. That is, the closer the gain of the loop a_1 to 1, the larger the Q value. If a_1 tends to 1, the Q value tends to infinity.

As to IIR filters, increasing the order of IIR filters n can also increase the Q value. Suppose several same first-order IIR filters are connected in cascade whose number is n, the transmission function of this nth-order IIR filter is

$$H(z) = \frac{z^n}{(z-z_\mathrm{p})^n}. \tag{18}$$

In the same way shown from Eq. (14) to Eq. (17), the Q values at various z_p and n can be calculated, which are plotted as Fig. 6.

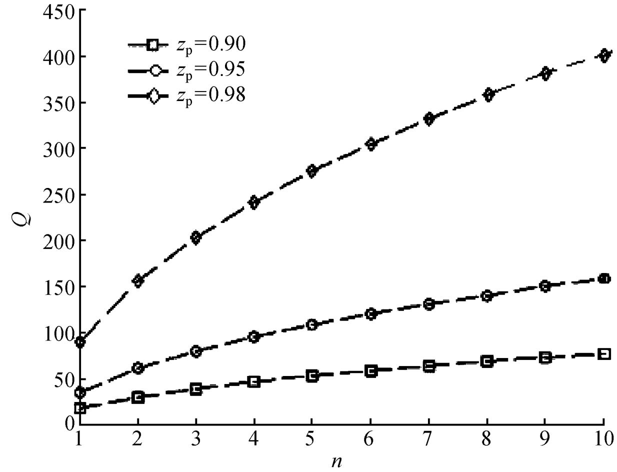

Fig. 6 Q values at various z_p and n

4 Several novel approaches to gain high Q value

4.1 FIR filters with high Q value

As to FIR filters, increasing the Q value demands increasing the tap number, then the components and the cost of the filters increase and the reliability reduces [7–12]. The layout of an FIR filter for making full use of all the components to effectively increase tap number while decreasing the cost is shown in Fig. 7 [12]. The signal light is split into two groups: the top one corresponds to positive weighting coefficients, while the bottom one corresponds to negative weighting coefficients. Each group is divided into N beams. The delay time between the two adjacent beams is set to τ by using fiber delay line. Then, each beam is divided into M elements employing an array Bragg grating at different wavelengths. The delay time between the two adjacent elements is set to T, which meets the relationship that $\tau = M\times T$. Finally, the tap number gets to $N\times M$ by using only $2\times(M+N)$ sets of delay components.

An FIR filter with high Q value based on n sets of $k\times k$ couplers connected in cascade is shown in Fig. 8 [10]. Where $n=3$, $k=3$, the number of taps is 9. By using $(k-1)\times(n-1)$ sets of delay components, the number of taps will get to k^n. In this configuration, the Q value is up to 256, which is the max Q value of FIR microwave photonic filters reported so far.

Overall, as to FIR filters, high Q value entails paying a high price for the increased cost and the reduced reliability. Therefore, FIR filters are not the ideal choice to get high Q value.

4.2 First-order IIR filters with high Q value

4.2.1 Configurations

For first-order IIR filters, their Q value can be increased by setting the gain of the loop close to 1. Similar to the loop cavity and the Fabry-Perot (F-P) cavity of the optical delay filters, the research group led by Hunter and Minasian at the University of Sydney put forward two kinds of structures of first-order IIR microwave photonic filters. One is a loop structure based on 2×2 coupler and active devices in the loop [13] (as shown in Fig. 9), the other is an F-P-like structure based on fiber Bragg grating (FBG) pair and active devices between them [14] (as shown in Fig. 10). The Q values obtained by these two methods can reach around 200.

In Fig. 9, the tapping and combining device is the 3 dB coupler. The route of the light signal is as follows. The signal of the first tap goes through the 3 dB coupler then reaches the output end. The signal of the second tap reflects off the right side of the FBG and goes through the 3 dB coupler and the erbium-doped fiber amplifier (EDFA), then reflects off the left side of the FBG and passes the same

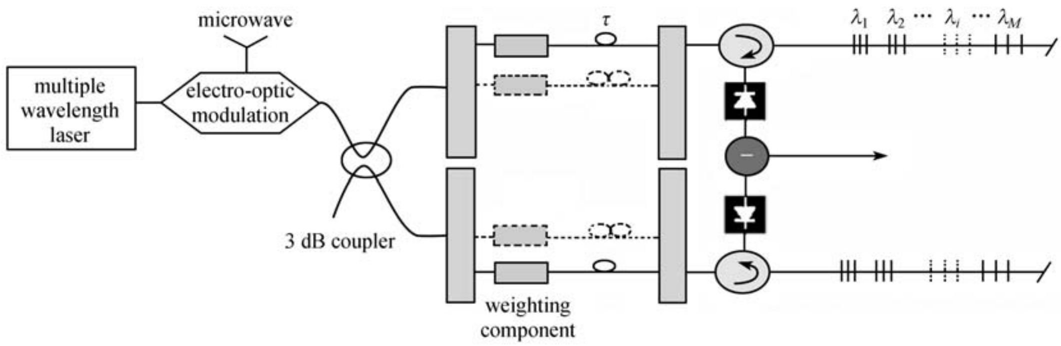

Fig. 7 Layout of FIR filter for $N\times M$ taps

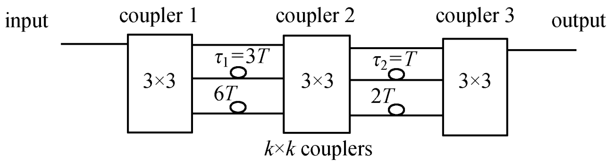

Fig. 8 Layout of FIR filter for k^n taps

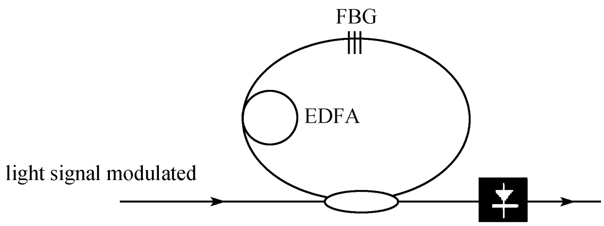

Fig. 9 Loop structure based on 2×2 coupler and active devices in the loop

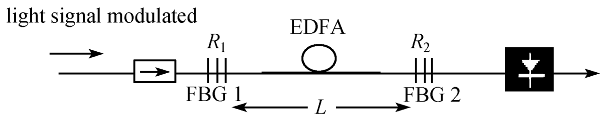

Fig. 10 F-P structure based on FBG pair and active devices between them

way between the FBG and the 3 dB coupler back and forth, then finally goes through the 3 dB coupler the second time and reaches the output end. The route amounts to going through the loop two times. Similar to the second tap, the route of the signal of the nth tap amounts to going through the loop $2n$ times. The delay time T between the adjacent taps is twice the time that takes the light signal to go through the loop. The function of the FBG is to act as an optical filter. Ideally, the EDFA compensates for the light coupled out of the loop and for other losses. In this case, the gain of the loop is equal to 1 and the signal light goes through the loop infinite times or the number of the taps N is infinite. Suppose the actual gain of the loop is G, the corresponding transmission function is given by

$$H(z)=\frac{z}{z-G^2}. \tag{19}$$

In Fig. 10, suppose that the reflectivity of the FBG 1 and the FBG 2 is R_1 and R_2, respectively. The light signal reflects off the FBG 1 and the FBG 2 and goes through the EDFA back and forth between the FBG pair. The EDFA compensates for the loss of the transillumination. A part of the light is output every time it reaches the FBG 2. The delay time T between the adjacent taps depends on twice the length L between the FBG pair. Assuming that the gain provided by the EDFA is g, the corresponding transmission function is

$$H(z)=\frac{g(1-R_1)(1-R_2)z}{z-g^2R_1R_2}. \tag{20}$$

On the basis of the configuration above, Hunter, Minasian and their group advanced their structure to gain higher Q value [15]. The improved structure is shown in Fig. 11. A first-order IIR filter in Fig. 10 is connected with a third-order FIR filter in cascade. The Q value of this hybrid filter is eight times that of the original IIR filter in Fig. 10.

Here the third-order FIR is made up of three first-order FIR filters in cascade. Suppose that the free spectral ranges of the three first-order FIR filters from left to right are FSR_1, FSR_2 and FSR_3, respectively. The free spectral range of the original IIR filter is FSR. The length of the EDFA is l_{act}. If the conditions are met that $l_1=l_{act}/8$, $l_2=l_{act}/4$, $l_3=l_{act}/2$, it can be deduced that $FSR_1=8FSR$, $FSR_2=4FSR$, $FSR_3=2FSR$, and the free spectral range of the third-order FIR is eight times that of the original IIR filter on the top. Thus, in the amplitude-frequency response curve, the peak of the hybrid filter corresponds to the eighth peak of the original IIR filter. That is, the hybrid filter selects one peak from the adjacent eight peaks of the amplitude-frequency response curve of the original IIR filter, and the other seven peaks are filtered out. Hence, the Q value of the hybrid filter is improved to eight times that of the original IIR filter. The amplitude-frequency response

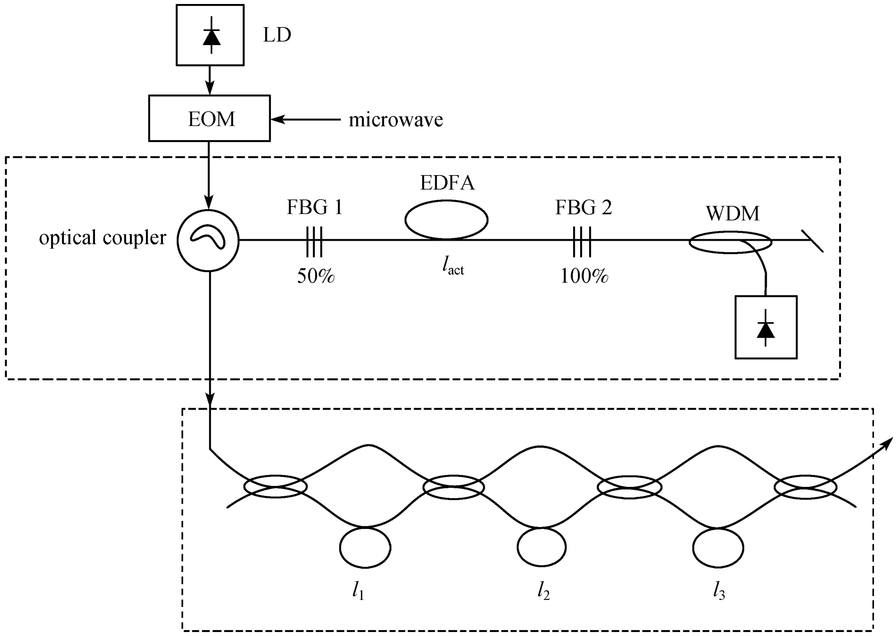

Fig. 11 Filter consists of a first-order IIR filter and a third-order FIR filter connected with it in cascade

curves of the original IIR filter and the hybrid filter are shown in Fig. 12. By this means, the max Q value reported reaches around 1000. The delay line l_1, l_2, and l_3 in this structure must be accurately adjusted to aim the peak of the third-order FIR at the eighth peak of the IIR filter in front. The shortage of this hybrid filter is the proportion of l_1, l_2, l_3 and l_{act} must be met rigorously.

4.2.2 Influence of characteristics of components on Q value [16]

Actually, the gain of the loop a_1 (in Fig. 5) for signal light is less than 1. Moreover, owing to the amplified spontaneous emission (ASE) noise of the active devices, the number N of the signals that can be detected is sometimes very small. In this case, the filters in recursive configuration are really FIR filters in spite of their looking like IIR filters.

In order to analyze the influence of the characteristics of the components on the Q value, we researched the first-order IIR microwave photonic filter based on semiconductor optical amplifier (SOA) in a loop. The experimental setup is shown in Fig. 13. The wavelength of the distributed feedback (DFB) laser diode (LD) is aimed at the central wavelength of the SOA. The swept microwave signal put out from the network analyzer modulated the intensity of the DFB LD optical light. The EDFA (the

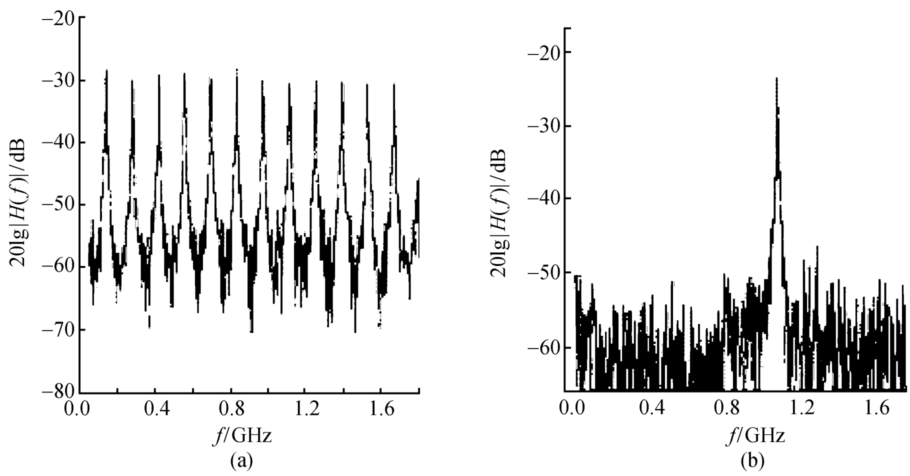

Fig. 12 Amplitude-frequency response curves. (a) Original IIR filter; (b) hybrid filter

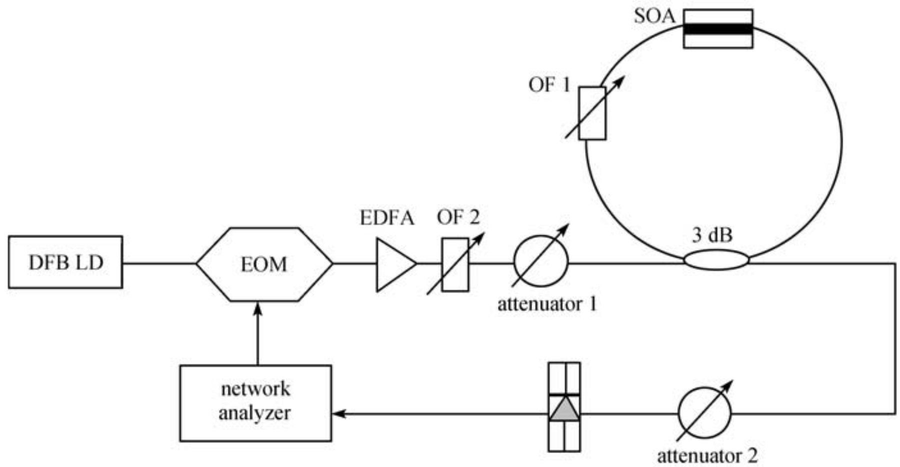

Fig. 13 Experimental setup for first-order IIR microwave photonic filter based on SOA in loop

amplification ratio is fixed) and the optical attenuator 1 are used to change the input optical power of the loop. The optical attenuator 2 is used to protect the optical detector. The optical filter 1 (OF 1) and the optical filter 2 (OF 2) are aimed at the wavelength of the DFB LD. The difference between Fig. 13 and Fig. 9 is that the delay time of the latter is half of the former.

The simulation and experiment results showed that increasing signal-to-noise ratio (SNR) and the gain of the signal light through the loop contribute to achieving higher Q value. The specific methods are as follows: using the SOA with smaller amplified spontaneous emission (ASE) power, adopting narrow-band optical filter in the loop, utilizing optical-electrical modulator with higher modulation coefficient, employing optical detector with lower SNR demands of input signal, and increasing the input optical power of the loop and the bump current of the SOA moderately. The transmission curve when setting the narrow-band optical filter in the loop and increasing the input optical power of the loop and the bump current of the SOA moderately compared with the curve not employing any methods are shown in Fig. 14. The Q values of the two curves are around 1.5 and over 150 respectively.

4.3 Multi-order IIR filters with high Q value

4.3.1 Technical difficulties to construct multi-order IIR filters

As has been noted, increasing the order of IIR filters can also increase the Q value. While as to the high-order filters in a cascade structure or in parallel structure, the interference between the light signals of various taps can hardly be avoided, and this leads to instability. For example, two same first-order IIR filters in a loop structure are connected in cascade as shown in Fig. 15. The light signal only going through the first loop will interfere with the light signal only going through the second loop at the

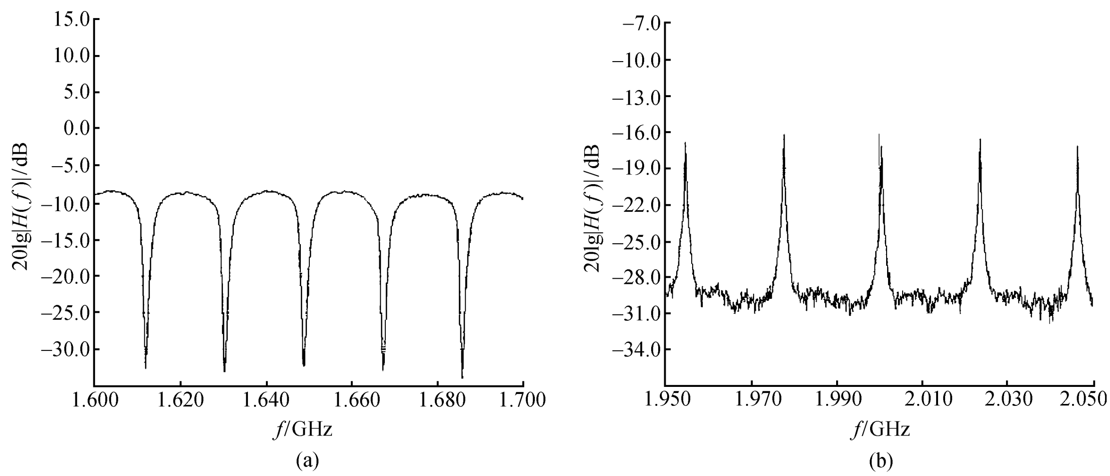

Fig. 14 Transmission curves. (a) Not using any methods; (b) using methods as setting narrow-band optical filter in loop, and increasing input optical power of loop and bump current of SOA moderately

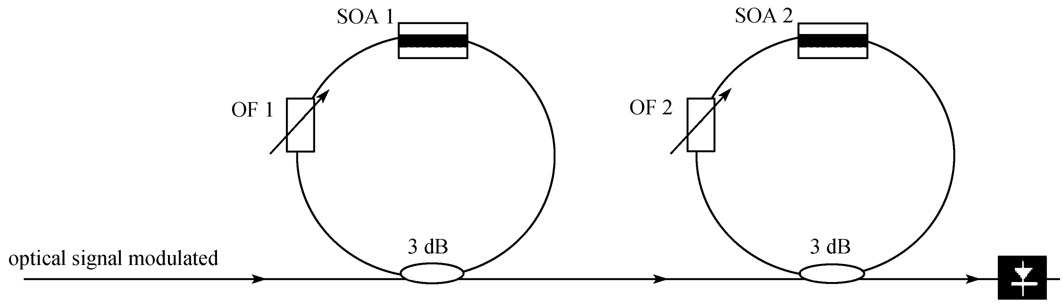

Fig. 15 Two same first-order IIR filters in loop structure are connected in cascade

output end. For the same reason, the light signal going through the first loop m times and the second loop n times will interfere with the light signal going through the first loop r times and the second loop s times, if the condition is met that $m+n=r+s$. The incoherent condition is not met. If the length of the loops change with the environment, the output light intensity will undulate at random and the stable transmission characteristic cannot be achieved.

For high-order filters in parallel structure, interferences cannot be avoided similarly. This is shown in Fig. 16. The length of the big loop is twice the length of the small one. Suppose the number of bypass of the light signal through the big loop is m and through the small loop is n, then the light beams will interfere with each other when the result of $m+2n$ is equal. For the same reason, the stable transmission characteristic cannot be achieved.

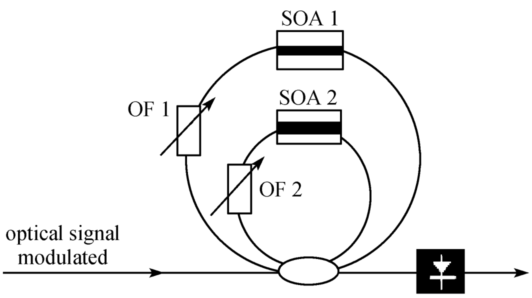

Fig. 16 Second-order IIR filter in parallel structure

4.3.2 Fixed third-order IIR filters

Chan constructed an artful third-order IIR filter to avoid the instability arising from interference which is shown in Fig. 17 [17]. This filter consists of a first-order IIR filter in a loop structure and an FBG connected with it. In this filter, the FBG makes a mirror image of the first-order IIR filter caused by reflection from it. The configuration corresponds to two same first-order IIR filters connected in cascade. The change of the length of the loop due to the changes in the environment is equal for the two loops. That is, the

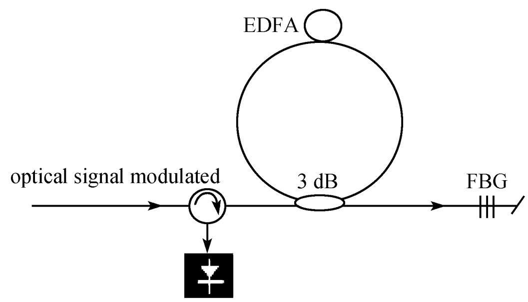

Fig. 17 Third-order IIR filter consists of a first-order IIR filter and an FBG connected with it

interferences at the output end are always enhancing interference. Thus, the changes in the environment will not cause the undulation of the output light intensity and the instability of the transmission characteristic. A third-order filter is realized owing to the interference term. The measured Q value is around 100. The drawback of this configuration is that it cannot be extended to higher order.

5 New multi-order IIR microwave photonic filter

It has been shown that in order to construct a multi-order IIR microwave photonic filter, the interference between the light signals of different taps must be avoided. In this part a second-order IIR microwave photonic filter which can be extended to higher order IIR filter is presented. The configuration of the filter is shown in Fig. 18. Supposing the optical length of the loop is ΔL, and the interference length is l. Compared with Fig. 15, the SOA 3 worked in saturate state with bump light at λ_2 is set between the two first-order IIR filters. The wavelength λ_1 of the signal lights in the first loop is conversed to the wavelength λ_2 after going through the SOA 3. Taking this change, the light signal only going through the first loop will not interfere with the light signal only going through the second loop at the output end if ΔL is larger than l. The optical path difference between two beams is ΔL and the interference condition cannot be met. Similarly, the light signal going

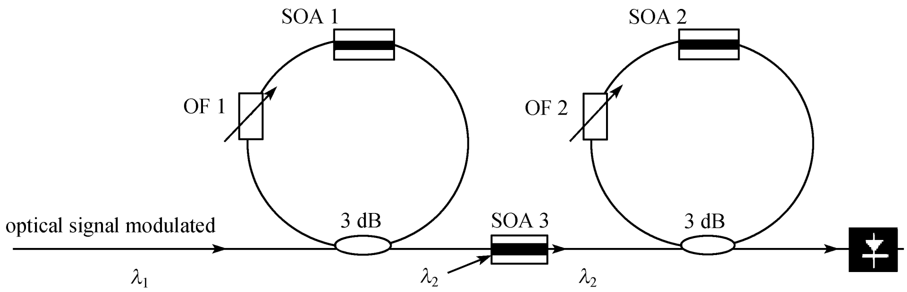

Fig. 18 Second-order IIR filter consists of two first-order IIR filters and an SOA between them

through the first loop m times and the second loop n times will not interfere with the light signal going through the first loop r times and the second loop s times again, even if the equation $m+n=r+s$ is met. The optical path difference between them is $\Delta L\times|n-r|$, which is larger than the interference length l. The advantage of this structure is it can be easily extended to higher order only by increasing the number of the loops connected in cascade, thus the Q value can be increased remarkably.

6 Conclusions

For microwave photonic filters, exploiting IIR configuration is easier to gain high Q value than FIR configuration, besides, it makes for lower cost and higher reliability. As to first-order IIR filters, achieving high Q value demands increasing the SNR and the gain of the signal light through the loop. As to multi-order IIR filters, raising the order results in high Q value. The technical difficulty in multi-order IIR filters is to avoid the interference between the taps. To get over this difficulty, we insert an SOA between two first-order IIR filters and construct a new second-order IIR microwave photonic filter. This filter is easy to extend its order, so the Q value of this IIR filter is expected to be significantly increased.

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