Ultrahigh-Q microwave photonic filter with tunable Q value utilizing cascaded optical-electrical feedback loops

Jie Liu,[1] Nan Guo,[1] Zhaohui Li,[2] Changyuan Yu,[3] and Chao Lu[1]

[1]*Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China*

[2]*Institute of Photonics Technology, Jinan University, Guangzhou 510632, China*

[3]*Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117576*

**Corresponding author: li_zhaohui@hotmail.com*

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A microwave photonic filter with the highest reported quality factor (Q) value of 4895.31 is proposed and experimentally demonstrated by using two cascaded infinite impulse response (IIR) filters. Each IIR filter comprises both optical and electronic signals in a feedback loop and thus the loop length can be reduced without the need to consider the light coherence length. The Vernier effect enables a significant improvement of the free spectral ranges and Q values of the cascaded filter. The Q value of the proposed microwave photonic filter can be changed when the loop lengths of two cascaded filters are carefully adjusted. In addition, for a fixed Q, the frequency response of the filter can also be tuned by adjusting the bias of the Mach–Zehnder modulator in each loop. © 2013 Optical Society of America

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Microwave photonic filters, which are photonic subsystems carrying out equivalent functions to those ordinary microwave filters within a radio frequency (RF) system or link, have attracted great research interest in the past few decades. Their advantages include high bandwidth, excellent isolation, immunity to electromagnetic interference, and wideband tunability and reconfigurability [1–5]. A desired feature of a microwave photonic filter is its ability to offer high frequency selectivity with high quality factor (Q) value. Recently, several methods have been proposed and successfully demonstrated aiming at increasing the Q value of both finite impulse response and infinite impulse response (IIR) microwave photonic filters [6–11]. However, microwave photonic filters with single-stage feedback structures, especially those based on optical fiber delay elements, often have low free spectral ranges (FSRs), which limits the Q values of the filters. This drawback can be overcome using cascaded multistage structures [12–16]. Two demonstrations of cascaded structures have enabled the realization of microwave photonic filters with Q value of more than 3000. In [15], a RF photonic filter based on a tuned modulator and a recirculating cavity is implemented to realize a Q factor of more than 3000. However, only single resonance can be generated at a time using an IIR filter cascaded with a tuned electrical filter. In [16], a scheme with two cascaded IIR filters is demonstrated to realize an IIR microwave photonic filter with Q value of 3338. Wavelength conversion in one filter can help to avoid the interference between the optical signals of different taps from the two cascaded IIR filters. Only those frequency components matching both IIR filters can be chosen due to the Vernier effect and thus the FSR of the cascaded filter is significantly increased. However, in order to avoid coherent interference effects within one loop, the loop length of each IIR filter has to be more than the coherence length of the laser source, which has restricted the further improvement of the FSR and Q value of the filter.

In [17] an IIR filter with both optical and electronic signals in a feedback loop is proposed to overcome the problem of optical coherent interference. In this Letter, we extend this concept to an IIR filter with two cascaded optical-electrical feedback loops. Lengths of the two cascaded IIR loops can be decreased without considering the coherence length of the light source. In addition, the Vernier effect can help to select the frequency components passing through both cascaded loops of the proposed filter and therefore largely increase the FSR of the filter. As a result, a highest reported Q value of 4895.31 is achieved in our experimental demonstration of the proposed IIR filter. In particular, Q value of the proposed microwave photonic filter can be varied when the lengths of the two cascaded loops are carefully adjusted. In addition, for a fixed Q, the frequency response of the filter can be tunable by adjusting the bias of the Mach–Zehnder modulator (MZM) in each loop.

Figure 1 shows the experimental setup of the proposed microwave photonic filter with cascaded optical-electrical feedback loops. A directly modulated laser

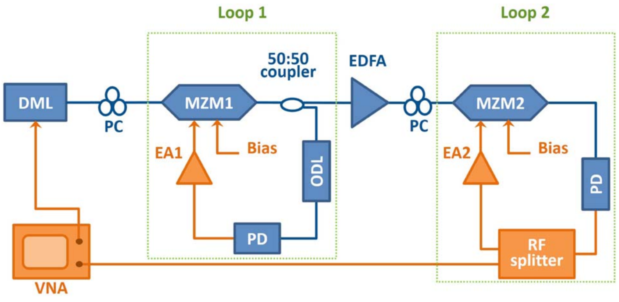

Fig. 1. Experimental setup of the proposed IIR filter with cascaded optical-electrical feedback loops.

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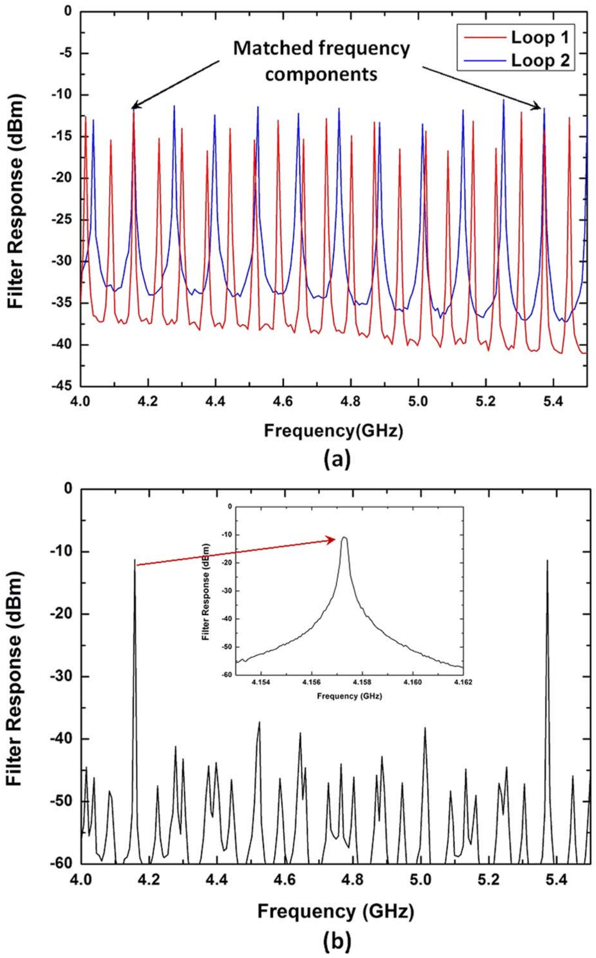

Fig. 2. (a) Frequency response of the IIR filters with one loop (Loop 1, the one with smaller FSR; Loop 2, the one with larger FSR). (b) Frequency response of the IIR filter with two cascaded loops.

(DML), whose central wavelength is ~1557.71 nm and output optical power is ~7 dBm, is driven by microwave signals from a vector network analyzer (VNA). It is noted that a DML rather than an external modulated laser is used in our experiment in order to simplify the experimental setup as well as eliminate the large insertion loss of the external modulators and the ASE noise due to optical amplification. The generated optical signals are then launched into a MZM in the first loop (Loop 1). Before the MZM, a polarization controller is utilized to control the polarization state of the input light. A 50:50 optical coupler is employed to split the optical signal to two parts: One part is converted to an electrical signal at a 10-GHz photo detector (PD), amplified by an electrical amplifier (EA) and then looped back to drive the MZM in Loop 1. The other part of the optical signal is amplified by a low-noise gain-tunable erbium-doped fiber amplifier (EDFA) and injected into Loop 2, which has a similar structure as Loop 1. After passing through both optical-electrical feedback loops, part of the electrical signal is split out by a RF splitter and transmitted back to the VNA for analyzing the transfer function of the filter.

According to the theoretical analysis in [17], high selectivity (3 dB bandwidth and rejection ratio) of the single-loop filter can be realized when the feedback efficiency of the loop is close to one (but less than one). In order to increase the loop feedback efficiency, three-stage broadband RF amplifiers (Centellax UA0L30VM) with gain of ~30 dB, PIN-TIA detectors with responsivity of 0.8 A/W, and MZMs with Vpi of around 3.5 V are utilized in both loops. There is no EDFA inserted in either of the two loops, because the erbium-doped fiber will increase the loop length and thus reduces the FSR of the single-loop filter. In addition, in order to decrease the intermodulation distortion, the modulators and RF amplifiers used in the experiment are all with high nonlinearity. Because of the relatively high noise figure of the broadband RF amplifiers (frequency range: 100 kHz–30 GHz) at low frequency as well as the limited bandwidth of the PDs (~10 GHz), the frequency response of the filter is measured in a moderate frequency range (from 4 to 5.65 GHz).

By carefully adjusting the tunable optical delay line (ODL) in Loop 1, FSR of the first single-loop filter is tuned to match that of the second one. Then the frequency response peaks, whose FSR is the least common multiple of the FSRs of the individual single-loop filters, can be selected due to the Vernier effect. As shown in Fig. 2(a), the FSR of the IIR filter with Loop 1 is exactly 10/17 times that of the one with Loop 2. Only one peak of every 17 peaks of the filter with Loop 1 can match one peak of every 10 peaks of the filter with Loop 2. Then the matched peaks of the cascaded filter are enhanced while others are suppressed, as shown in Fig. 2(b). Thus the FSR of the cascaded filter is significantly increased. Frequency response peaks of the cascaded filter are sharpened along the leading and trailing edges [13]. Therefore, the 3 dB bandwidth (BW) of the cascaded filter is reduced, compared with that of the single-loop filters (seeing Case I in Table 1). Since the FSR is increased and 3 dB bandwidth is decreased, an ultrahigh Q value of 4895.31 of the cascaded filter is realized, as shown in Fig. 2(b).

Since the optical-electrical feedback loops have fairly short loop lengths in our scheme, FSR of the single-loop filter can be easily changed as the ODL is tuned within a limited range. As a result, different FSRs and Q values of the cascaded filter can be achieved by adjusting lengths of the two cascaded optical-electrical feedback loops.

Table 1. Measured Parameters of the Individual Filters (Loop 1 & Loop 2) and the Cascaded Filter

		Loop 1		Loop 2		Cascaded Filter			
	Time Delay (ps)	FSR (MHz)	3-dB BW (kHz)	FSR (MHz)	3-dB BW (kHz)	FSR (MHz)	3-dB BW (kHz)	Q	Rejection Ratio (dB)
Case I	44.88	71.79	471.69	122.05	811.45	1220.45	249.31	4895.31	~25
Case II	118.82	71.19	463.12	122.05	811.45	854.32	228.49	3738.98	~26
Case III	299.64	69.73	448.13	122.05	811.45	488.12	198.64	2457.31	~29

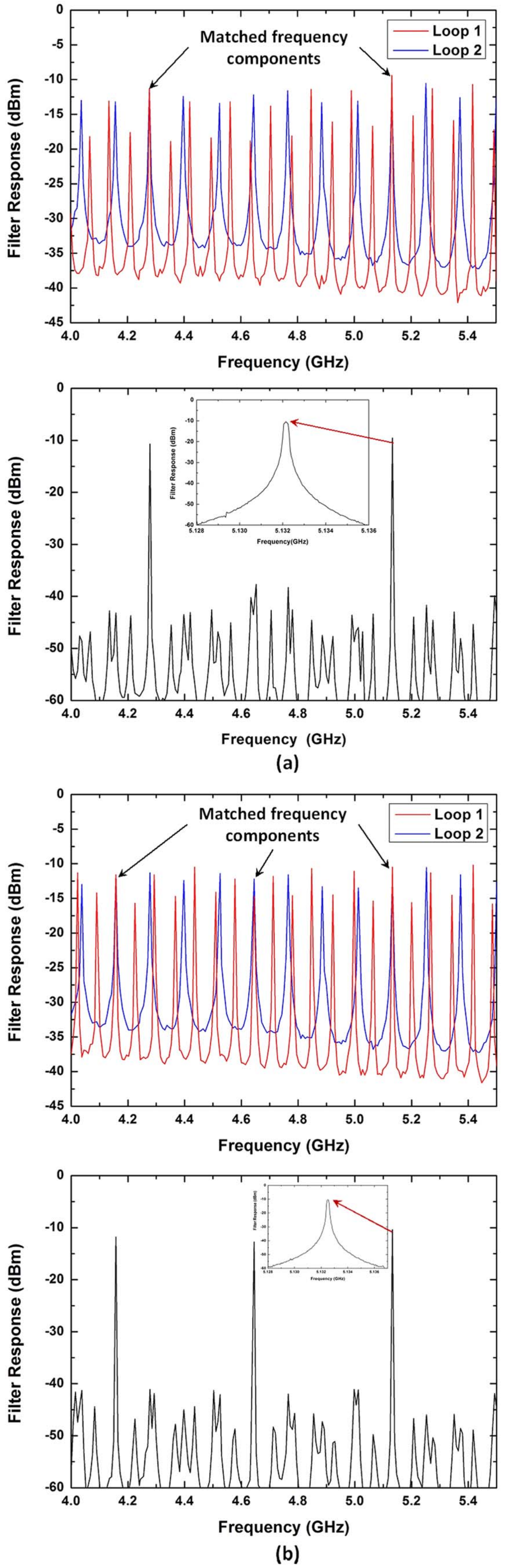

Fig. 3. Frequency response at different FSRs and Q values. (a) Case II. (b) Case III. (Case I is shown in Fig. 2. For the single-loop-filter frequency response: Loop 1, the one with smaller FSR; Loop 2, the one with larger FSR.)

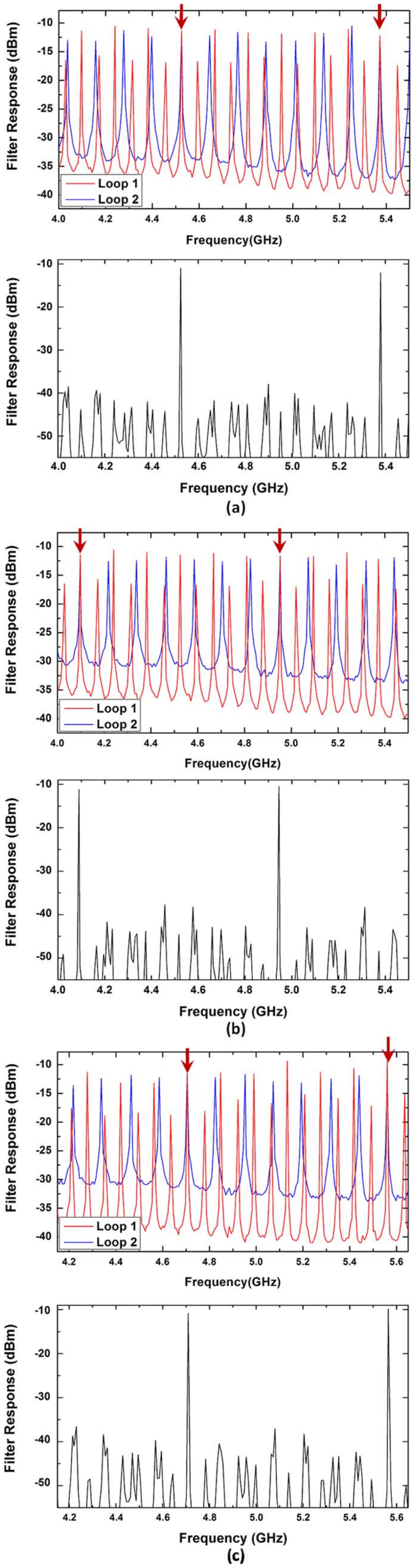

Fig. 4. Frequency response with Q of 3738.98 in the case of (a) MZM1: 3Vpi/2, MZM2: Vpi/2; (b) MZM1: 3Vpi/2, MZM2: 3Vpi/2; (c) MZM1: Vpi/2, MZM2: 3Vpi/2. [The case of “MZM1: Vpi/2, MZM2: Vpi/2” is shown in Fig. 3(a). For the single-loop-filter frequency response: Loop 1, the one with smaller FSR; Loop 2, the one with larger FSR.]

Here in our experiment, only one ODL is employed in Loop 1 due to the device limitation. In addition to Q value of 4895.31 (Case I in Fig. 2), the other two Q values of 3738.98 and 2457.31 (Case II and Case III) are also realized in our experiment demonstration, as shown in Fig. 3. In practical implementation, when ODLs with high precision are used in both cascaded loops, we believe Q value can be varied substantially by carefully adjusting the loop lengths of the two cascaded filters.

From the measured results in Table 1, it can be seen that the rejection ratio of the cascaded filter is limited to around 25 dB when FSR is 1220.45 MHz. This is because of the relatively broad 3 dB bandwidths of the single-loop filters, which make it difficult to suppress some of the closely spaced frequency response peaks efficiently. However, as the FSR of the cascaded filter decreases to 854.32 and 488.12 MHz, there is around 1 and 4 dB improvement of the rejection ratio, respectively (seeing Table 1). The main reason is that the 3 dB bandwidth of the first filter is decreased with the decrease of its FSR. For single-loop filters, when the loop gain and input optical power remain fixed, 3 dB bandwidth of the filter is proportional to the FSR [17]. As a result, there should be a trade-off between the rejection ratio and the FSR for the proposed filter.

In addition to the ability to vary Q values, frequency response tunability for a fixed Q value can also be realized in our scheme. When a MZM is used in the loop, the polarity of the slope of the MZM transfer function can be switched to a positive or negative value simply by switching the bias point at $\mathrm{Vpi}/2$ or $\mathrm{Vpi} * 3/2$, respectively (here Vpi is the modulation voltage that is required to change the phase in one MZM arm by π). Consequently, with this capability, the single-loop filter is reconfigurable and the passband and stopband of the frequency response can be easily interchanged [17]. As for the two cascaded loop scheme, the filter frequency responses can be varied within four different states, as the bias points of the MZM in each loop can be either $\mathrm{Vpi}/2$ or $\mathrm{Vpi} * 3/2$. Figures 3(a) and 4(a)–4(c) show the experimentally measured four different states of the filter frequency response when the Q value of the cascaded filter is fixed at 3738.98. Unlike the two interchangeable states of the single-loop filter, which are with frequency response difference of around half of the filter FSR [17], the four states of the two-cascaded-loop filter are with frequency response difference of around one fourth of the filter FSR, which is relatively more flexible.

Another issue that should be considered is the stability of the cascaded filter, which is mainly affected by the polarization of the optical light and the bias applied to the MZM. Since the MZMs with polarization preserving fiber pigtails and voltage sources with high stability are utilized in the experiment, the filter can be kept stable during the measurement period of tens of minutes. In the practical implementation, integrated optical devices [18] and auto bias control module (e.g., Fujitsu FMM3951) might be employed to enhance the filter stability.

In summary, a microwave photonic filter with Q value up to 4895.31 has been proposed and experimentally demonstrated. The proposed filter consists of two cascaded IIR filters, which comprises both optical and electrical signals in a feedback loop to overcome problems due to optical coherent interference and thus the loop length can be decreased without considering the light coherence length. The Vernier effect enables a significant improvement of FSR and Q value of the cascaded filter. In addition, the ability to vary the Q value of the proposed microwave photonic filter can be achieved by carefully adjusting loop lengths of the two cascaded filters, and the frequency response of the filter with a fixed Q can also be changed by tuning the bias of the MZMs in the two loops.

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