A Simple and Tunable Single-Bandpass Microwave Photonic Filter of Adjustable Shape

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***Abstract*—A simple and tunable single-bandpass microwave photonic filter of adjustable shape is proposed and experimentally demonstrated. The filter is based on multiple sources (spectrum-sliced by a Mach–Zehnder interferometer) and two cascaded incoherent optical structures, namely, a dispersion medium of 50-km single-mode fiber and a fiber ring delay line. In the experimental range from 1.0 to 3.8 GHz, a discretely tunable single-bandpass filter with a high Q-factor or a flat-top response is achieved by carefully matching the transfer functions of the two individual optical structures.**

***Index Terms*—Cascaded optical structures, microwave photonic filter, microwave photonics, photonic signal processing.**

I. Introduction

MICROWAVE photonic signal processing has been explored extensively for decades due to the inherent advantages of photonics such as high bandwidth, low loss, immunity to electromagnetic interference, etc. Microwave photonic filters are attracting more research attention recently as they provide a solution to the problem of the so-called electronic bottleneck and other sources of degradation of the conventional microwave filters [1]. However, some problems (such as spectral periodicity, positive-only coefficients, and tunability) arising in the optical domain limit their practical applications (see, e.g., [2]).

To overcome these problems, several configurations have been proposed to achieve microwave photonic filters of better performance. Bandpass filtering can be implemented using an electrooptic phase modulator combined with a dispersive device to eliminate the baseband resonance [3]. A single bandpass photonic transversal microwave filter was present based on a broadband optical source and a fiber Mach–Zehnder interferometer (MZI) [4], in which an optical variable delay line (OVDL) can be inserted to make its bandpass tunable [5]. To achieve a high Q-factor, a new structure based on a hybrid approach comprising both active and passive sections was reported [6]. Recently, an all-optical wavelength-division-multiplexing multitap microwave filter with flat bandpass was also realized based on two sets of optical carriers and dispersive media [7]. However, it still has the problem of spectral periodicity.

In this letter, we present a tunable single-bandpass (without spectral periodicity) microwave photonic filter of adjustable shape. In this proposed filter, a broadband optical source is transmitted through an MZI to obtain the optical samples as tunable multiple sources. Two incoherent optical structures in cascade are used to make the filtering shape variable. By carefully matching the transfer functions of the two individual optical structures, a measured Q of 95 is obtained and a microwave filter of flat-top shape (which is required in, e.g., millimeter wave and microwave frequency demultiplexing applications) is also observed in our experiment. The present microwave filter has good potential applications in the radio-over-fiber systems (e.g., [8]).

II. Principle

A complicated microwave photonic filter based on cascaded structures has been designed to provide high Q performance [6]. A time domain theoretical analysis was given in [9] on microwave photonic filtering properties of two incoherent cascaded structures. Each of the two cascaded optical structures [whose optical field transfer functions are $H_1(\omega)$ and $H_2(\omega)$] constitutes an independent microwave filter with the electrical domain transfer function $H_1(\Omega)$ or $H_2(\Omega)$. The overall electrical transfer function can be written as the product of the two individual constituents, provided that some special conditions are satisfied [9].

Fig. 1 shows the experimental setup of our proposed microwave photonic filter consisting of two simple incoherent cascaded structures. The light from the superluminescent light-emitting diode (SLED) is centered at 1550 nm, whose spectrum has a quasi-Gaussian shape as shown in the left inset of Fig. 1. The 3-dB bandwidth of the SLED is 41 nm (i.e., 21.5 THz). After passing through the isolator, the light is launched into an MZI structure composed of two 50 : 50 optical couplers (OCs) with an OVDL in one arm and a polarization controller in the other. An optical spectrum analyzer (Ando AQ6317, Resolution: 0.01 nm) is used to measure the transmission spectrum at one port of OC-2 from the MZI. The right inset of Fig. 1 shows the measured transmission spectrum from 1550 to 1556 nm after the MZI, from which one sees that the broadband SLED has been sliced uniformly and the dashed line block as a whole acts as the tunable multiple optical sources.

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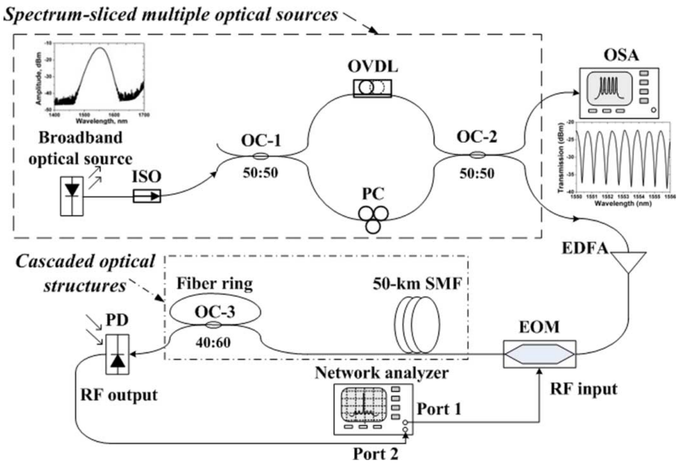

Fig. 1. Experimental setup of the proposed microwave photonic filtering system. The dashed line block shows the spectrum sliced multiple optical sources and the dashed-dotted line block shows the two cascaded optical structures.

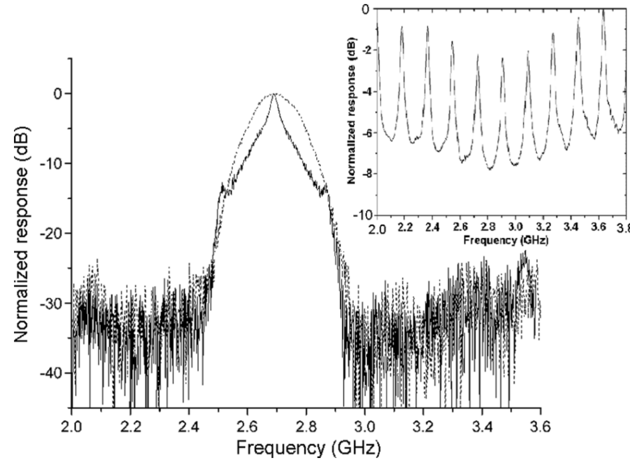

Fig. 2. Measured frequency response of the overall cascaded filtering system. For comparison, the frequency response $H_1(\Omega)$ of the filter based on the multiple sources and 50-km SMF (as the dispersive medium) is shown by the dashed line. Inset: measured frequency response $H_2(\Omega)$ of the filter based on the fiber ring structure.

The optical transfer function can be tuned with the inserted OVDL, and the intensity transmission can be written as [5],

$$T(\omega) = 1/\left[4 \cdot \left(1 + \gamma^2 + 2\gamma \cos(\beta_0 \Delta L)\right)\right] \quad (1)$$

where γ, β_0, and ΔL are transmission coefficient of the OVDL, the propagation constant [$\beta_0 = \omega/\nu$, where ν is the velocity of light propagating in the single-mode fiber (SMF)], and the length difference between the two arms of the MZI, respectively. Although additional noise and radio-frequency distortion may exist due to the spectrum slicing characteristic, it still provides a simple low-cost solution to generate a large number of taps required for a microwave photonic filter with a large frequency spectral range (FSR) [10], [11].

The erbium-doped optical fiber amplifier (EDFA) is used to amplify the multiple sources. The output of the EDFA is fed into an electrooptic modulator (EOM), which is driven by the microwave signal from Port 1 of the vector network analyzer (HP, R3765C).

The output of the EOM is then launched into the cascaded optical structures shown as the dashed–dotted line block in Fig. 1, which is composed of a 50-km SMF with dispersion $\beta = -20.3\ \mathrm{ps}^2/\mathrm{km}$ and dispersion slope $\chi = 0.0625\ \mathrm{ps}^3/\mathrm{km}$ (used as the first dispersive medium giving a transfer function $H_1(\Omega)$ with a single resonance) and a fiber ring structure (based on an OC with a coupling ratio of 40 : 60 for a better filtering response). The second optical structure gives a transfer function of $H_2(\Omega)$ with spectral periodicity and smaller rejection ratio. Different response shapes (such as high Q or flat-top shape) for the whole microwave photonic filter can be achieved by adjusting the relative spectral positions of the two transfer functions. Here we change the spectral position of $H_1(\Omega)$ by adjusting the OVDL. The central frequency of the bandpass of $H_1(\Omega)$ is defined as

$$f_0 = 1/(\beta L \Delta\omega) \quad (2)$$

where L is the length of the SMF as the dispersion medium, and the spectral spacing from MZI $\Delta\omega = 2\pi\nu\Delta L$. With the parameters chosen in our experiment, this central frequency f_0 can be up to 3.3 GHz without degradation caused by the dispersion slope [4]. In fact, although baseband response (<200 MHz) exists due to the only positive coefficients [2], the operation range of the filter (0.2–3.3 GHz) is mainly limited by the upper frequency (3.3 GHz). $\chi \cdot L$ (the dispersion slope) is the main reason for this, and serious degradation can be found at higher frequencies. However, the upper frequency limit can be higher if we shorten the fiber length L. A photodiode (PD) (Anritsu, MN4765A) converts the optical signal into an electrical signal, and the frequency response is measured by the network analyzer.

Accordingly, for two cascaded optical structures illuminated by multiple sources, the end-to-end electrical linearity will be preserved only if special conditions are satisfied (the coherent time of each source is less than the smallest delay imposed by either the first or second structure [9] and there is no time overlapping of impulsive optical path contributions to make sure that no coherent beating exists). Then the electrical transfer function of our proposed filter, whose optical field transfer function is $H_1(\omega)H_2(\omega)$, is given by

$$H_{\mathrm{Cas}}(\Omega) = H_1(\Omega)H_2(\Omega). \quad (3)$$

Note that in our case the very short coherent time of the used SLED makes the coherent beating negligible (even up to hundreds of gigahertz). This way we can achieve the desired filtering properties (using such a simple configuration) such as the single-bandpass, tunability, and adjustable shape, as demonstrated in Section III.

III. Experimental Results and Discussion

Fig. 2 shows the measured frequency response of the whole cascaded filtering system when the single bandpass of $H_1(\Omega)$ matches the peak position of response $H_2(\Omega)$. The delays of the two structures are 5.8 and 5.7 ns, respectively, which are much longer than the coherent time of each source (tens of femtoseconds). Thus, there is no time overlapping of impulsive optical path contributions and coherent beating does not occur. From this figure one can see easily that the transfer function of the two cascaded incoherent filters is the product of the transfer functions of their individual constituents. The inset of Fig. 2 is the measured frequency response of the filter based on

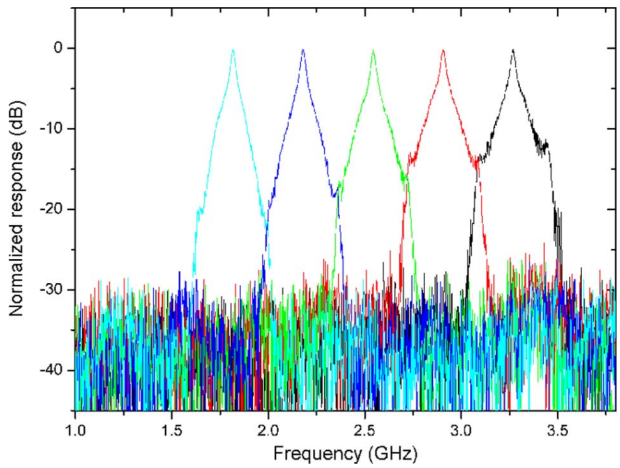

Fig. 3. Measured frequency responses when single-resonance response $H_1(\Omega)$ matches to the series of peaks of response $H_2(\Omega)$. The tunibility is achieved by adjusting the OVDL discretely.

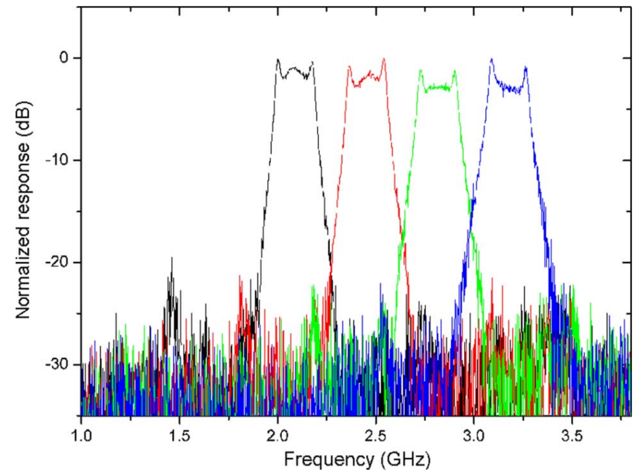

Fig. 4. Measured frequency responses when single-resonance response $H_1(\Omega)$ matches to the series of notches of response $H_2(\Omega)$.

the fiber ring structure (corresponding to the situation when the dashed–dotted line block of Fig. 1 contains only the fiber ring). This periodic filtering response has a small FSR of 175 MHz and a low rejection ratio of about 5 dB. The 1-dB fluctuation over the whole spectrum range may be caused by some nonflatness of the response of the PD or EOM. For comparison, the measured frequency response of the filter based on the multiple sources and the dispersive medium of 50-km SMF (corresponding to the situation when the fiber ring is removed in the dashed–dotted line block of Fig. 1) is also shown in the same figure by the dashed line, which has a single resonance with a 3-dB bandwidth of 170 MHz. Its central frequency is about 2.7 GHz when the wavelength spacing of the sliced spectrum is 0.675 nm (corresponding to $\Delta\omega = 0.365$ THz). From this figure one sees that the single-bandpass response of the cascaded filtering system has a much narrower 3-dB bandwidth (i.e., higher Q-factor).

As discussed before, transfer function $H_1(\Omega)$ of single resonance can be continuously tuned by adjusting the OVDL (so that the wavelength spacing of the sliced spectrum varies). By matching transfer function $H_1(\Omega)$ to different peaks of response $H_2(\Omega)$, a high-Q single-bandpass microwave filter which can be discretely tuned is achieved, as shown in Fig. 3. The Q-factor at the central frequency of 3.25 GHz is 95, and can be much higher (to hundreds) at a higher central frequency. In our experiment, the OVDL is tuned by 0.41 mm in one step, and the great linearity between the central frequency and the tuning step of the OVDL (see Fig. 3) is due to the spectral periodicity of $H_2(\Omega)$.

Fig. 4 shows the measured frequency responses when transfer function $H_1(\Omega)$ is matched to different notches of response $H_2(\Omega)$. The small fluctuation at the edge of the single bandpass could be eliminated with a better FSR matching. Neglecting this small fluctuation, we can consider this filtering system as a discretely tunable flat-top microwave photonic filter with a shape factor of about 1.72 (defined as the ratio between 20-dB bandwidth and 3-dB bandwidth).

IV. Conclusion

In summary, a simple and tunable single-bandpass microwave photonic filter of adjustable shape has been proposed and experimentally demonstrated. The filter configuration is based on multiple sources (spectrum-sliced by an MZI) and two cascaded incoherent optical structures (a fiber ring delay line and a dispersion medium of 50-km SMF). As examples, a discretely tunable single-bandpass filter with a high Q-factor or a flat-top response has been demonstrated by matching the single-resonance transfer function $H_1(\Omega)$ to different peaks or notches of periodic transfer functuion $H_2(\Omega)$. To the best of our knowledge, this is the first time implementation of a microwave photonic filter with a tunable single flat-top bandpass response. The present single bandpass microwave photonic filter has the advantages of simplicity, tunability, and partial reconfigurablility.

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