Programmable Photonic Filters from Monolithically Cascaded Filter Stages

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Abstract: A monolithic programmable photonic filter structure is constructed from cascaded single filter stages individually capable of producing poles or zeros. Flat-topped 2nd and 3rd order filters with pass-band rejection exceeding 30 dB are demonstrated.

OCIS codes: 230.5750 Resonators, 250.5300 Photonic integrated circuits

1. Introduction

A programmable photonic filter is capable of synthesizing a variety of filter shapes and rapidly tune in both bandwidth and center frequency. Such a filter can be used as a channelizing filter to prefilter massive amounts of incoming analog data in nearly real time, thus having the potential to reduce latency in signal processing applications compared to entirely electronic approaches. The idea of this kind of filter was suggested almost three decades ago [1], however the complexity, control and stability have all been limited by the inability to integrate on a chip. Compared to channel selection and add/drop filters for WDM applications which have been successfully realized in recent years [2,3], the analog RF-filter application is more challenging as it requires much broader tunability in bandwidth and frequency. Lattice type filter structures can provide theses necessary characteristics [4]. We have previously proposed a lattice building block capable of producing both IIR (infinite-impulse-response) and FIR (finite-impulse response) filter shapes, and experimentally demonstrated it in the InP-InGaAsP material system [5]. Similar work was done in parallel on a hybrid Si-III/V platform [6]. At this time, we focus on the cascading of multiple filter stages and construction of more complex higher order filters. In order to improve the stability and control of the overall filter structure, the single filter stage has been modified to an uncoupled filter scheme.

2. Filter design and fabrication

Each filter stage consists of two nested rings of different lengths. Thus, the design also incorporates an asymmetric Mach-Zehnder interferometer (MZI), figure 1. The single stage filter response has two poles and a zero; however, the intention of the single stage design is to generate either a single pole or zero. This is achieved by utilizing the SOAs as on-off switches for different paths through the filter. Eq. (1a-c) gives the S21 scattering parameters for the single stage in the different configurations, with $G_{1,2,3}$ and $\varphi_{1,2}$ representing gain and added phase from the SOAs and the phase modulators (PM) respectively, and A,B,C representing propagation and coupling losses. By reverse biasing either SOA_1 or SOA_2 one of the poles is isolated, Eq. (1a),(1b). If SOA_2 is reversed biased, a longer resonator remains than if SOA_1 is reversed biased. A longer resonator translates into a narrower full width half max (FWHM), so depending on which ring configuration is utilized a narrower or wider bandwidth filter is synthesized. The MZI zero filter response is isolated by reverse biasing SOA_3, Eq. (1c). In each bias configuration, the filter response is tuned in amplitude by forward biasing the remaining two SOAs, providing ring gain or balancing the MZI arms in the pole or zero configurations respectively. Frequency tunability of the filter is provided through the PM.

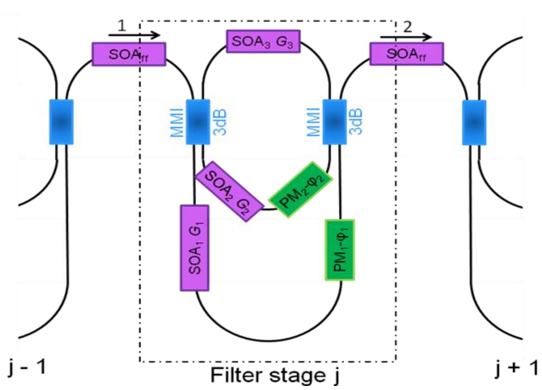

Fig.1 Schematic drawing of the filter structure highlighting the single filter stage with functional components labeled, SOAs, MMI couplers and PMs.

$$S_{21} = \frac{AG_1 e^{-j(\beta L_1+\varphi_1)}}{(1 - AG_1 C G_3 e^{-j(\beta(L_1+L_3)+\varphi_1)})} \qquad (1a)$$

$$S_{21} = \frac{BG_2 e^{-j(\beta L_2+\varphi_2)}}{(1 - BG_2 C G_3 e^{-j(\beta(L_2+L_3)+\varphi_2)})} \qquad (1b)$$

$$S_{21} = AG_1 e^{-j(\beta L_1+\varphi_1)} + BG_2 e^{-j(\beta L_2+\varphi_2)} \qquad (1c)$$

$$\left|S_{21}^{tot}\right| = \prod_j \left|S_{21}^{j}\right|, \quad \angle(S_{21}^{tot}) = \sum_j \angle(S_{21}^{j}) \qquad (2)$$

When designing cascaded filter structures, there are two main design schemes: coupled or uncoupled. In the coupled case, there is feedback between filter stages. For resonators this means that the poles are coupled and higher order poles are created. While this scheme has certain advantages in e.g. providing larger pass band rejection through the higher order poles, the inter stage couplings becomes extremely critical in order to reach the desired filter shape. In addition, a coupled system with active phase and gain controllers has more parameters and thus becomes inherently harder to control and stabilize in a real system application. This is the main reason we have in this work instead focused on a completely uncoupled approach, i.e. there is no feedback between filter stages. This is most easily seen through the single waveguide connecting neighboring stages in figure 1. This linear system approach implies that the overall transfer function of the filter is simply the product of the individual single stage transfer functions; or in S-parameters, the magnitude and phase response multiplied and added respectively, Eq. (2). With a pole or a zero synthesized by each filter stage, higher order filters are subsequently constructed by programming the individual stages with the desired pole and zero magnitudes and phases. In contrast to the coupled approach, the overall filter shape in the uncoupled scheme is completely independent of the coupler values, allowing for more fabrication tolerance and flexibility in coupler choice.

In order to monolithically integrate this type of filter we utilize the InP-InGaAsP material system, which has the advantage of providing on-chip optical gain and fast phase tuning through current injection. An offset quantum well (OQW) integration platform was employed with low loss passive waveguides realized by selectively removing quantum wells in passive regions followed by a blanket InP p-cladding regrowth. In order to avoid radiation loss from bends while keeping the fabrication complexity to a minimum, deeply etched waveguides created with a single ICP-dry etch step was used for the entire device design. For ring coupling, 3dB-2x2 restricted interference multi-mode-interference (MMI) couplers were used throughout; the insertion loss was measured to be 0.5-1dB/coupler. Specifics of the fabrication and the integration platform have been reported elsewhere [7]. In this work a total of five single filter stages were monolithically cascaded; figure 2 shows a device with four filter stages which have been wire bonded to a carrier.

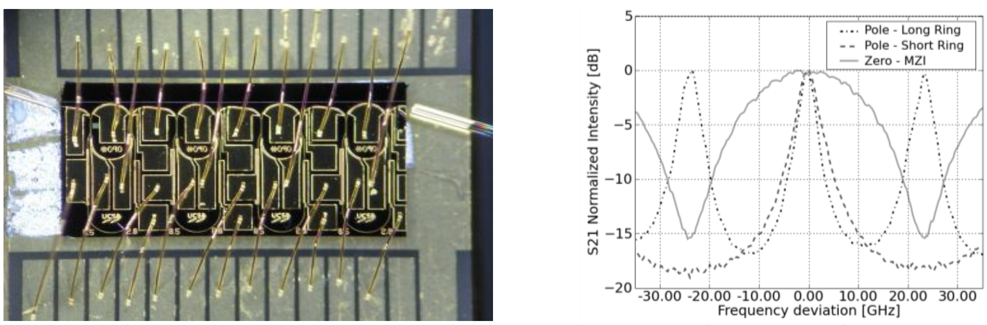

Fig.2 a) Optical image of wire bonded device with 4 cascaded filter stages. b) Experimental filter responses from a single stage filter, normalized in frequency and intensity.

3. Single filter stage

In order to construct higher order filter shapes that are useful to an application, careful consideration needs to be given to the design of the individual filter stages. The bandwidth and FSR of the overall filter is ultimately determined by the individual ring length and difference in MZI path lengths. For microwave photonic applications we are mainly interested in filters with bandwidths ~10 GHz and less, this translates into resonator lengths in the mm to cm range. In this work the two resonators lengths are 1,750 and 3,500 mm. Thus, having a relative difference in free spectral range (FSR) by a factor of two (45 and 22.5 GHz), the difference in MZI path length was designed to be 1,750 mm (45 GHz) as well. Experimental filter responses of these filter configurations are presented in figure 2. The single stage filter responses are tunable in both amplitude and frequency by tuning the SOA and PM currents. All experimental data was measured by fiber coupling broadband light from an amplified spontaneous emission (ASE) source into the chip and fiber coupling the output into an optical spectrum analyzer (OSA) with a 10 pm (1.25 GHz) resolution. All testing was performed continuous wave (CW) at room temperature.

4. Cascaded filter stages

When the single filter stages are cascaded, the transfer functions of the individual stages are multiplied together, Eq. (2). By controlling the individual filter stages separately, higher order filter shapes are easily synthesized. In order to synthesize a band-pass filter, two or more stages are programmed as poles and offset in frequency using the phase modulators. The bandwidth and ripple of the filter is set by the pole value (i.e. SOA gain) and the amount of frequency offset between the stages. For a narrower bandwidth filter the long ring configuration is advantageous (SOA_2 reversed biased, G_2~0). In this configuration, by introducing zeros, the FSR of a band-pass filter response can effectively be doubled since the FSR of the zero is twice that of the resonator, figure 2. For wider bandwidth filters, the shorter ring configuration is utilized (SOA_1 reversed biased, G_1~0). The zero can now be used to enhance the pass-band rejection of the filter if placed half way between the pass-bands, see figure 2. In figure 3a) a 2nd order flat-top band-pass filter is experimentally demonstrated utilizing two cascaded filter stages in the short ring configuration, with the flattop achieved by injecting 0.65 mA into the PM of one stage. The filter has a 0.4 dB ripple, FWHM of 7.68 GHz and a maximum pass-band rejection of 25 dB. By adding one more filter stage, a 3rd order filter is demonstrated in figure 3b). Two poles are used to create a flat-top pass-band and a zero is placed half way in between the pass-bands to further enhance the extinction ratio. Again, the flat-top was created by injecting 0.31 mA into the PM of one stage while 5.1 mA was injected in the MZI stage PM to position the zero. The resulting filter has a 0.2 dB ripple and a FWHM of 5.5 GHz with 33 dB of maximum pass-band rejection. The reduced bandwidth for this filter is due to a slightly higher pole value (0.775 in figure 3b) versus 0.75 in figure 3a)) together with the smaller ripple.

The center frequency of the filter can be tuned continuously over one FSR using the phase modulators in each filter stage. This implies we can filter anywhere in the c-band as the filter response repeats every FSR over the gain bandwidth (~1530-1575 nm).

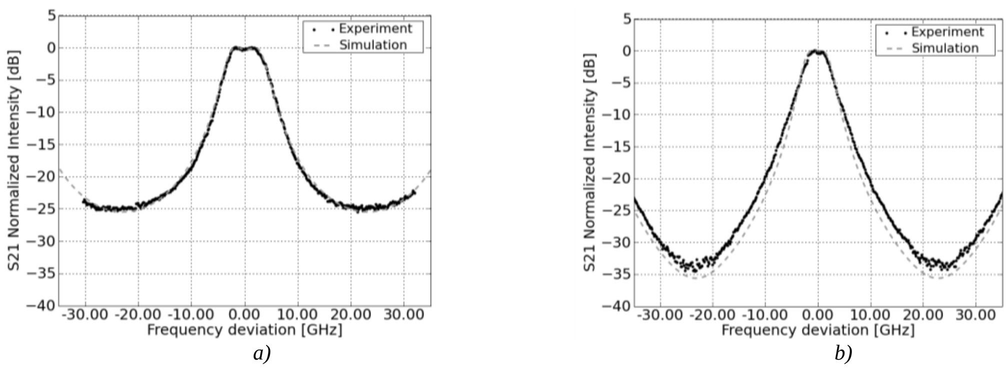

Fig.3 Experimentally measured filter responses from cascaded filter stages, simulations using Eq.(1) and (2) are superimposed. a) 2nd order flattop band-pass filter response and b) 3rd order filter - 2nd order flattop band-pass filter with a zero placed half way in between the pass-bands. Data was normalized in frequency and intensity.

5. Conclusions

A programmable photonic filter was constructed from monolithically cascaded filter stages. The single filter stages independently synthesize poles and zeros thus providing a versatile platform to create higher order filters. With increasing number of filter stages, extinction, filter roll-off, tunability in bandwidth etc., naturally improves. Band-pass filters with varied bandwidth and extinction were experimentally demonstrated utilizing two and three cascaded filter stages.

Acknowledgements
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