Programmable Photonic Lattice Filters in InGaAsP–InP

Erik J. Norberg, Robert S. Guzzon, Steven C. Nicholes, John S. Parker, and Larry A. Coldren, *Fellow, IEEE*

***Abstract*—A novel monolithic programmable optical lattice filter consisting of unit cell building blocks is proposed. Single unit cells incorporating a ring resonator in one arm of a Mach–Zehnder are fabricated in an InGaAsP–InP material system. Programmable poles and zeros are demonstrated and monolithically cascaded unit cells are used to synthesize a flat passband.**

***Index Terms*—Optical filter, photonic integrated circuits (PICs), programmable filter.**

I. Introduction

PROGRAMMABLE optical filters have the potential to improve latency in real-time signal processing applications compared to entirely electronic approaches. The optical filter can be programmed to create a channelizing prefilter, quickly tunable in bandwidth and frequency. Thus, massive amounts of incoming analog data can be prefiltered in nearly real time, identifying signal bands or signatures worthy of more detailed digital signal processing. This and other applications call for a general programmable filter. The idea of programmable optical filters was suggested over two decades ago, e.g., [1]; however, their complexity, control, and stability have all been limited by the inability to integrate the optical components on a single chip. More recently, channel selection and add–drop multiplexer filters have been shown for wavelength-division-multiplexing (WDM) applications using microring resonators as well as larger ring geometries [2]–[6]. In comparison, the programmable analog filter application is very challenging in that it requires much broader frequency and bandwidth tunability than channel selection filters. We propose a lattice-based filter, monolithically integrated using the InGaAsP–InP material system. The filter architecture is an array of identical unit cells that incorporate a ring resonator within one branch of a Mach–Zehnder interferometer (MZI). In this initial work, we have fabricated and characterized the basic building blocks of these filters consisting of one and two unit cells. Preliminary fabrication results have previously been reported [7]. Here we demonstrate improved results along with a more thorough characterization and discussion of these filters.

Manuscript received June 01, 2009; revised September 30, 2009; accepted November 04, 2009. First published November 20, 2009; current version published January 07, 2010. This work was supported by Defense Advanced Research Projects Agency (DARPA) under the PhASER Project. A portion of this work was done in the UCSB nanofabrication facility, part of the National Science Foundation (NSF) funded NNIN network.

The authors are with the Department of Materials and Department of Electrical Engineering, University of California Santa Barbara, Santa Barbara, CA 93116 USA (e-mail: norberg@ece.uscb.edu).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2009.2036448

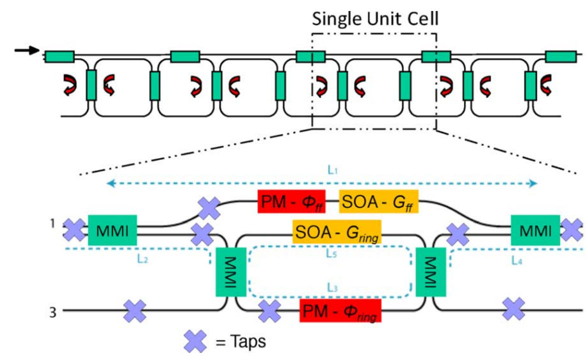


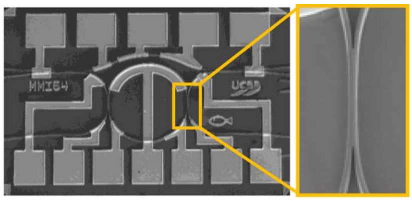
Fig. 1. Schematic drawing of the lattice filter built from unit cells. Key components in the single unit cell are highlighted: SOAs, PMs, MMIs, and Taps.

II. Filter Design

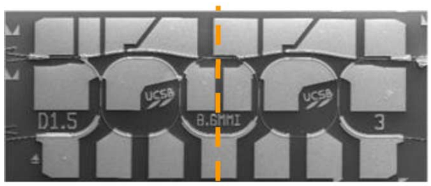
Fig. 1 shows the proposed lattice-based filter structure built from cascaded unit cells. The single unit cell itself consists of an asymmetrical MZI, in which one MZI-branch has an integrated ring resonator. Looking from port 1 to port 2, a first-order zero response is created by the MZI while a first-order pole response is provided by the resonator; these are the fundamental building blocks for both finite impulse response (FIR) and infinite impulse response (IIR) filters. The response from each single unit cell is tunable in amplitude and phase through active semiconductor optical amplifiers (SOAs) and phase modulators (PMs) incorporated in both the feed-forward MZI arm and the ring resonator. The single unit cell filter response can be described through the S_{21} scattering parameters, given here in a simplified form

$$S_{21} = AG_{\mathrm{ff}}e^{-j\beta L_1+\Phi_{\mathrm{ff}}} + \frac{Be^{-j[\beta L_2+L_3+L_4+\Phi_{\mathrm{ring}}]}}{1-CG_{\mathrm{ring}}e^{-j[\beta L_3+L_5+\Phi_{\mathrm{ring}}]}}. \tag{1}$$

The A, B, and C coefficients include the loss from various elements in the structure including waveguide, multimode interference (MMI) transmission, and MMI coupling loss. G_{ff}, Φ_{ff} and G_{ring}, Φ_{ring} are the gain and phase provided by the SOA and PM for the feed-forward and ring resonator, respectively. By reverse biasing the feed-forward SOA ($G_{\mathrm{ff}} \sim 0$) a pole response is isolated. Likewise a zero response is synthesized by reverse biasing the ring SOA ($G_{\mathrm{ring}} \sim 0$). The PMs that operate through carrier injection are used to tune the pole and zero responses in frequency. In addition to SOAs and PMs, a number of low quantum efficiency detectors (taps) are incorporated to provide real-time monitoring of the optical signal in the waveguide at many locations in the single unit cell, which, together with analog feedback circuitry and digitally implemented adaptive algorithms, can be used for control and stabilization.



(a)



(b)

Fig. 2. (a) Scanning electron microscope (SEM) picture of the single ring unit cell with the MMI coupler highlighted. (b) Two monolithically cascaded single unit cells make up a three-ring coupled system.

The single unit cell is naturally cascaded by connecting ports 2 and 4 with ports 1 and 3 of the next cell to realize the lattice filter. The programmability of this larger lattice filter is based on the flexibility of each individual unit cell. SOAs can "turn ON" and "turn OFF" rings by applying a forward bias and reverse bias, respectively. For example, high bandwidth flat-topped bandpass filters suitable for WDM add–drop applications [3] of any order can be synthesized by turning ON the SOAs in each ring, and turning OFF the feed-forward SOAs. Coupling rings in this fashion synthesizes bandpass filters without phase tuning as the bandwidth is determined by the coupling strength between rings. Filter rolloff and extinction are enhanced by the coupling via higher order poles.

If a narrower bandwidth response is desired, rings can be cascaded without coupling by turning ON every other ring. With the rings uncoupled, no higher order poles are synthesized, and each pole location and amplitude is independently tunable. Poles can then be located at the same frequency, decreasing full-width at half-maximum (FWHM) and enhancing extinction. The MZIs created by the unit cells can be used to eliminate neighboring poles to effectively enhance the free spectral range (FSR) of the filter. Furthermore, any filter configuration can be duplicated and cascaded without back-coupling to enhance extinction and roll-off and decrease the FWHM if desired.

We have fabricated single unit cells together with two monolithically cascaded unit cells shown in Fig. 2. An offset quantum well (OQW) InGaAsP–InP integration platform was used (quantum wells placed right above the waveguide layer). Low loss passive sections were realized by selectively wet etching away quantum wells in passive regions, followed by a single blanket InP regrowth of the p-cladding. An entirely deep etched waveguide design was utilized; the specific details of the fabrication have been described elsewhere [7].

III. Experiment and Discussion

Measurements of the filters were made 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). All testing was performed continuous wave (CW) at room temperature.

An isolated MZI response is shown in Fig. 3(a), this was generated between ports 1 and 2 by reverse biasing the ring SOA at -10 V, effectively shutting off the resonator. By varying the bias on the feed-forward SOA and hence balancing the MZI branches, the zero response is tuned in amplitude. However, while changing the current on the SOA, a parasitic phase shift is introduced (through current injection and heating) which unintentionally tunes the filter response in frequency. In our device, this is addressed by simultaneously utilizing the PMs, by injecting current the zero-frequency can be fixed. Fig. 3(b) displays the isolated pole response of the single unit cell using ports 3 and 4. The pole amplitude can be adjusted by varying the ring SOA bias, again utilizing the resonator PM to fix the filter in frequency. For the SOA biased at 33 mA ($I_{\rm th} = 35$ mA), an extinction ratio of $\sim$18 dB and a pole FWHM of 0.062 nm (7.9 GHz) corresponding to a resonator Q-value of 23 800 is obtained. The pole response was also measured with a lightwave component analyzer, and this verified the expected π-phase shift across the passband of this single-pole filter. A good fit of the experimental filter shapes with the S21 parameters in (1) are demonstrated by setting $AG_{\rm ff} = 1, B = 0.68, CG_{\rm ring} = 0$ and $AG_{\rm ff} = 0, B = 1, CG_{\rm ring} = 0.75$ in Fig. 3(a) and (b), respectively.

If a further enhancement of the filter extinction ratio is desired, both zeros and poles can be utilized simultaneously (i.e., forward biasing both the feed-forward and the resonator SOA). In Fig. 3(c), a zero has been placed in between two resonator poles, resulting in a total of 26.5-dB extinction.

The frequency tunability of the of the single unit cell is demonstrated in Fig. 4; the S_{21} MZI zero is continuously tuned over a 270-GHz range by utilizing phase pads in the feed-forward and the resonator arm. The FSR of the zero is 250 GHz, thus a zero can be placed anywhere in the C-band. The resonator poles allow for a 0.4-nm continuous tuning range, using the resonator phase pads. Wavelength tuning through current injection is associated with parasitic loss through the free-carrier-absorption effect; in our device design, the filter shape is preserved by manually adjusting the SOA bias. Future work includes using the passive taps as the input signal to adaptive algorithms that automatically control SOA and PM biases to maintain filter shapes while tuning or reprogramming the filter.

Drawing on the demonstrated tunability of the single unit cell it is predicted that by cascading several unit cells, higher order and more complex filter shapes can easily be synthesized by individually controlling each single unit cell. As a proof of concept, the fabricated cascaded unit cell filter is used to demonstrate a second-order coupled pole response shown in Fig. 5. This was created by turning OFF the feed-forward waveguides and the third ring by reverse biasing their respective SOAs. The remaining two rings were tuned using PMs to create a bandpass filter with a 0.302-nm (37.7 GHz) FWHM. Given the strong 3-dB inter-ring coupling in this filter, a relatively wide-bandwidth, low-extinction passband results.

In the current device configuration, we predict that the number of unit cells that practically can be cascaded is limited by the end to end loss of the individual unit cells; currently estimated to be around 7 dB which includes the 3-dB loss in the outer MZI-MMIs when operating the filter with cascaded poles. Given a $\sim$21-dB SNR in the first filter stage, a maximum of three unit cells can be cascaded. In future work, we, therefore,

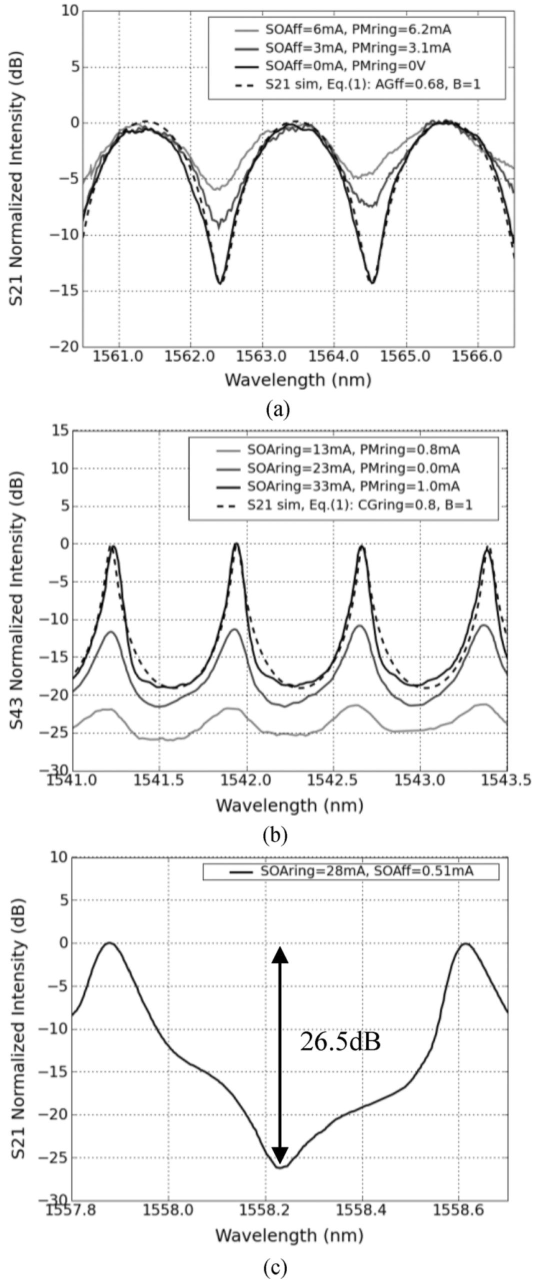


Fig. 3. (a), (b) Isolated pole and zero responses tuned in amplitude by varying bias on feed-forward SOA (SOAff) and ring SOA (SOAring), respectively, the ring PM (PMring) is used to fix the filter in frequency. (c) Zero and pole are utilizes simultaneously to enhance extinction ratio.

intend to achieve a zero insertion loss in every unit cell by incorporating an additional SOA in the ring-MZI arm (on L_2 or L_4 in Fig. 1), thus allowing a large number of filter stages to be cascaded. In addition, this also assists the balancing of the two MZI arms when a zero response is desired.

IV. Conclusion

We have proposed a novel monolithic programmable filter structure, constructed from cascaded unit cells. The single unit cells have the form of an MZI with a ring resonator integrated in one branch. Proposed programmability of the single unit cell was experimentally demonstrated through isolated zero and pole

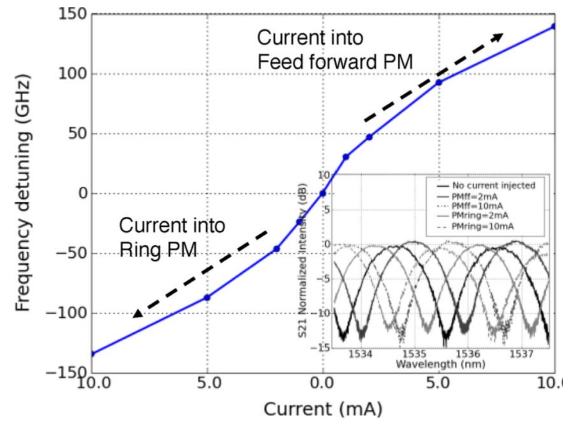


Fig. 4. Frequency detuning of the MZI zero response as a function of PM current; inset shows the actual filter response.

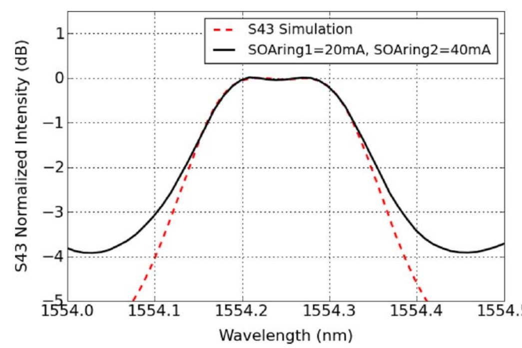


Fig. 5. Filter response from two-coupled-ring bandpass filter tuned to ~0.1-dB ripple with a 0.302-nm (37.7 GHz) FWHM.

responses with continuous amplitude and frequency tunability. Extinction ratios of 14 and 18 dB was shown for the zero and pole, respectively, simultaneously using the pole and zero the extinction was enhanced to 26.5 dB. From cascaded unit cells, a flat passband using a second-order coupled pole response was demonstrated.

References

[1] J. E. Bowers, S. A. Newton, W. V. Sorin, and H. J. Shaw, "Filter response of single mode fiber recirculating delay lines," *Electron. Lett.*, vol. 18, no. 3, pp. 110–111, Feb. 1982.

[2] S. Matsuo, Y. Ohiso, K. Tateno, T. Segawa, M. Kohtoku, and S. Oku, "A high-speed tunable optical filter using a semiconductor double-ring resonator," in *Proc. Int. Conf. Indium Phosphide and Related Materials*, Stockholm, Sweden, 2002, pp. 467–470.

[3] D. Rabus, M. Hamacher, U. Troppenz, and H. Heidrich, "Optical filters based on ring resonators with integrated semiconductor optical amplifiers in GaInAsP–InP," *IEEE J. Sel. Topics Quantum Electron*, vol. 8, no. 6, pp. 1405–1411, Nov./Dec. 2002.

[4] S. Choi, Z. Peng, Q. Yang, E. H. Hwang, and P. Dapkus, "A high-Q wavelength filter based on buried heterostructure ring resonators integrated with a semiconductor optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 17, no. 10, pp. 2101–2103, Oct. 2005.

[5] A. Agarwal *et al.*, "Fully programmable ring-resonator-based integrated photonic circuit for phase coherent applications," *J. Lightw. Technol.*, vol. 24, no. 1, pp. 77–87, Jan. 2006.

[6] Y. Ma, S. Chang, S. Chang, and S. Ho, "Improved optical filter responses in cascaded InGaAsP/InP microdisk resonators," *Electron. Lett.*, vol. 37, no. 9, pp. 564–565, Apr. 2001.

[7] E. J. Norberg, R. S. Guzzon, S. C. Nicholes, J. S. Parker, and L. A. Coldren, "Programmable photonic filters fabricated with deeply etched waveguides," in *Proc. Int. Conf. Indium Phosphide and Related Materials*, Newport Beach, CA, 2009, pp. 163–166.