Highly Programmable Optical Filters Integrated in InP-InGaAsP with Tunable Inter-Ring Coupling

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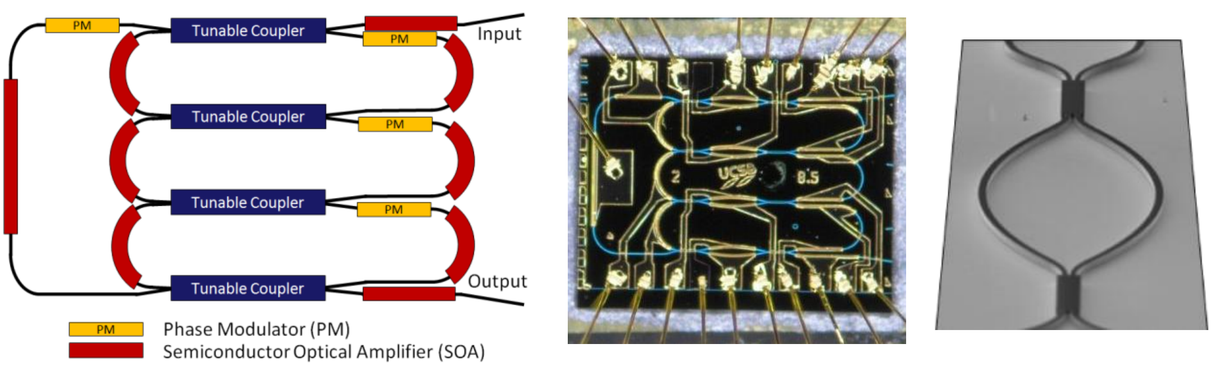
Abstract: A highly programmable optical filter architecture is designed and a unit cell building block is fabricated in InP-InGaAsP with tunable inter-ring couplers. Simulated and measured bandpass filter responses for the 3-ring structure are presented.

OCIS codes: 230.5750 Resonators, 250.5300 Photonic integrated circuits

1. Introduction

The all-optical and real-time filtering of an optical signal promises to reduce the power consumption, latency, and cost of electrical filtering approaches. Much progress has been made recently in the theory of constructing such optical filters [1-3], and results have been shown for wavelength-division-multiplexing (WDM) channel selection and add-drop filtering as well as RF signal filtering with limited tunability [4-7]. Specifically, RF channelizing filters require wide tunability in frequency, bandwidth, and extinction. We previously proposed a general integrated programmable filter lattice in the InP-InGaAsP material system consisting of a cascade of identical building blocks, or "unit cells" [8]. Work was also done on this design in the hybrid III-V/Si system [9]. By cascading unit cells, a general programmable filter architecture is possible. Here, we propose an improved unit cell design incorporating tunable couplers focused on the synthesis of flat-topped bandpass filters tunable in frequency and bandwidth and present preliminary results.



a) b) c)

Fig. 1. a) Schematic representation of the unit cell showing SOAs, PMs, MZI Tunable Couplers, and input and output waveguides. b) Picture of fabricated and wire-bonded unit cell. c) Scanning electron microscope (SEM) image of an MZI tunable coupler without contacts.

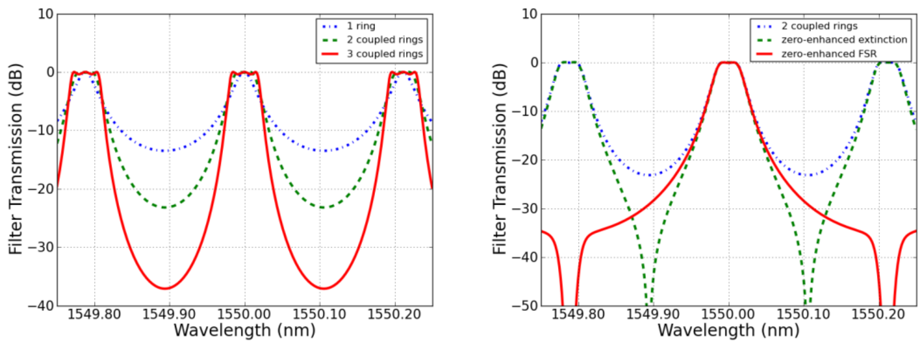
2. Unit Cell Design and Operation

The unit cell (figure 1a) consists of three rings, each connected by a 2x2 Mach-Zehnder Interferometer (MZI) tunable coupler, and all bypassed by a secondary waveguide path. The MZI tunable coupler design [reference?], consist of two 100µm long 2x2 restricted interference multi-mode-interference (MMI) couplers separated by a balanced MZI. The full range of coupler tuning is accomplished through phase modulation of one of the 300µm long MZI waveguides, demonstrated in figure 3a. Semiconductor Optical Amplifiers (SOAs) and Phase Modulators (PMs) within the unit cell provide tunability in amplitude and wavelength. The unit cell can be operated in two modes: the infinite-impulse-response (IIR) mode utilizing the rings, or the finite-impulse-response (FIR) mode, utilizing the bypass waveguide.

Shown in figure 2a, the "poles" created by each of the three rings in the unit cell provide the ability to synthesize first order, second order coupled, second order uncoupled, and third order coupled IIR filters of varying bandwidth. The order of the filter is determined by the number of rings that are utilized, and the resulting response is periodically repeated every free spectral range (FSR). The FSR is determined by the ring lengths, which are in this case 3mm giving an FSR of 0.22nm or 27.5 GHz. The IIR functionality of a unit cell is accomplished by applying a forward bias to the ring SOAs to achieve the desired extinction, and applying a forward bias to the ring PMs to tune the poles to the desired wavelength. A reverse bias is applied to the feedback SOA in any ring that is not to be used, preventing the signal from making a round-trip. A reverse bias is also applied to the bypass waveguide in order to operate the unit cell strictly in the IIR mode. By tuning the center wavelength of the filter, and by utilizing the periodically repeated response, filter synthesis is achieved across the c-band. Filter responses were simulated with a general 4-port scattering matrix technique.

The bypass waveguide creates the ability to synthesize a finite-impulse-response (FIR) filter with a free-spectral-range (FSR) twice that of the IIR filters. Shown in figure 2, this “zero” filter shape can be utilized to eliminate neighboring IIR bandpass filters to essentially double the FSR of a synthesized bandpass filter, or, placed between bandpass filters, to enhance their extinction. The FIR functionality of a unit cell is accomplished by applying a forward bias to the SOA in the bypass waveguide and the SOAs in the forward path through the rings in order to equalize the output magnitudes of these two “MZI” arms. The optical length difference between these two paths is half that of the rings (1.5mm), therefore producing an FSR that is twice as wide. A forward bias is applied to the PMs in each arm to tune the wavelength location of the zero. A reverse bias is applied to the feedback SOAs in each of the rings in order to operate the unit cell strictly in the FIR mode.

Unit cells are cascaded together on-chip to facilitate synthesis of a wide range of filter shapes. IIR Bandpass filters can be cascaded in this way to increase extinction and side-band roll-off, while the FIR functionality can be utilized as mentioned above to modify IIR filters synthesized in previous unit cells.



a) b)

Fig. 2. a) Example simulation of 1 ring, 2 coupled rings, and 3 coupled rings with 15% inter-ring coupling. The poles in the 1-ring and 2-ring filters have pole values of 0.65. In the 3-ring filter, the outer rings have pole values of 0.65, and the inner ring has a pole value of 0.85. b) Simulation of 2 coupled rings with zeros placed on neighboring filter orders to effectively double the filter FSR and placed in-between filter orders to enhance extinction.

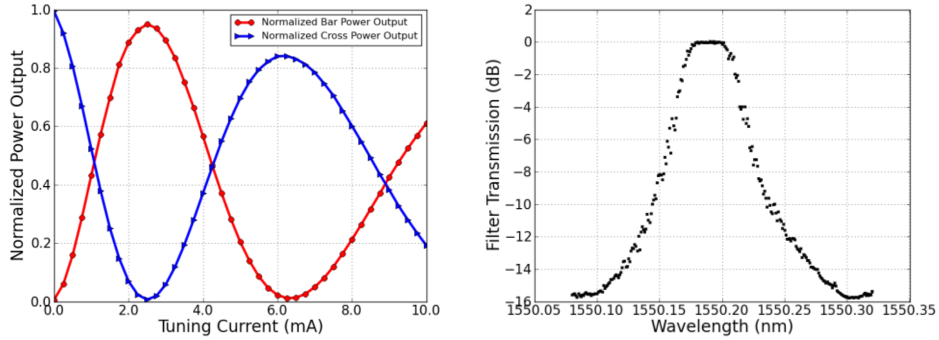
3. Fabrication

Individual unit cells were fabricated on an InP-InGaAsP offset quantum well platform which provides a simple and robust method for active and passive material integration. The quantum wells, which are grown on top of a 1.3Q InGaAsP passive waveguide layer, are selectively wet-etched to create low-loss passive waveguide sections. A blanket InP regrowth acts as the p-cladding. The waveguides are all deeply-etched structures created in an ICP dry etch. Details of this fabrication technique and results are outlined in [10]. A fabricated unit cell is shown in figure 1.

4. Results

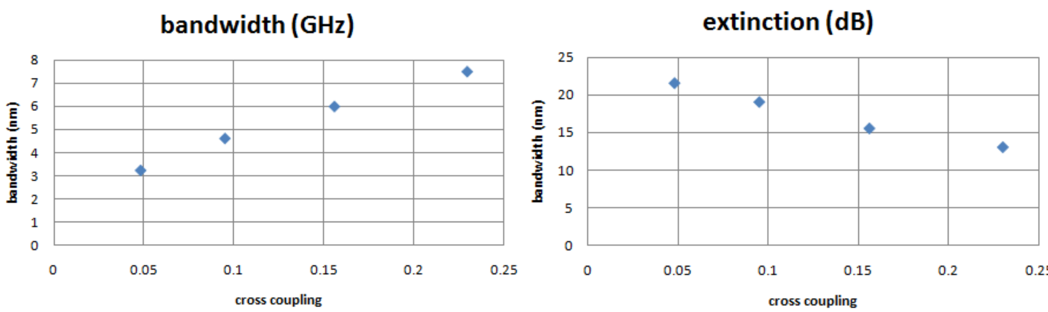
Successful operation of the MZI tunable couplers is crucial to the synthesis of coupled-pole filters. Figure 3 shows power splitting of a tunable coupler versus tuning current. Extinction of cross coupling to under 1% of total output power was achieved at 2.5mA tuning current, and 2π phase tuning was achieved at 6.25mA. Insertion loss for this structure was estimated to be 1dB.

To confirm operation of the unit cell, 2^{nd} order coupled pole bandpass filters of varying bandwidth were synthesized. Measurements were conducted with a locked-in tunable laser input and on-chip detection. The SOAs in the third ring were reverse biased and operated as detectors. The SOAs in the first two rings were forward biased and the PM in one ring was tuned until the poles from each ring were located at the same wavelength. By tuning the coupler between the two rings, the bandwidth of the filter was set by adjusting the inter-ring coupling ratio, and the filter pass-band ripple was optimized by adjusting the ring SOA gain. Figure 3 shows the filter transmission near 1550nm with XX power coupling between rings providing 15.5dB extinction and a bandwidth of 0.048nm or 6.0GHz. As the coupling was decreased, the bandwidth decreased and extinction increased. Figure 4 shows the relationship between coupling value and filter bandwidth and extinction.



a) b)

Fig. 3. a) Measurement of an MZI tunable coupler splitting values vs. phase modulator tuning current. Values are normalized to total output power with zero tuning current. Additional insertion loss is estimated to be 1dB. Cross coupling values of less than 1% of total output power were obtained at a 2.4mA tuning current. b) Measured response of a 2nd order coupled ring bandpass filter with inter-ring coupling ratio set at 15% and gain optimized to obtain a flat-topped filter. A bandwidth of 0.048nm or 6.0GHz was obtained with an extinction of 15.5dB.



a) b)

THESE FIGURES TO BE REPLOTTED Fig. 4. Measured a) bandwidth and b) extinction from 2nd order coupled ring filters vs. inter-ring coupling ratio.

5. Conclusions

A highly programmable filter architecture focusing on RF channelizing filters was proposed. The basic building block, or unit cell, was designed and fabricated. Consisting of three coupled rings with tunable inter-ring coupling, the unit cell is tunable in bandwidth, frequency, and extinction. The unit cell is also capable of producing an FIR zero response in order to enhance FSR and bandwidth. MZI tunable couplers and unit cells were evaluated and 2nd order coupled ring bandpass filters were measured.

Acknowledgements

This work was supported by DARPA through the PhASER project; a portion of the work was done in the UCSB nanofabrication facility, part of the NSF funded NNIN network.

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