



Tunable optical-microwave filters optimized for 100 MHz resolution

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Abstract: New continuously tunable RF-spectrum analyzers, RF receivers, and RF signal generators are proposed and analyzed for the silicon-on-insulator integrated-photonics platform at the ~ 1550 nm wavelength. These RF system-on-a-chip applications are enabled by a new narrowband 2x2 Mach-Zehnder interferometer (MZI) tuned filters for reconfigurable multiplexing, demultiplexing and RF channel selection. The filter can be optimized for ~ 100 MHz 3-dB bandwidth (BW) by utilizing N closely coupled Bragg-grating resonators to form one effective waveguide resonator in the single-mode silicon nanowire used for each MZI arm. The number of periods M within each individual resonator is selected to engineer BW in the 0.1 to 1 GHz range. Butterworth design is employed. Continuous tuning of the 100 MHz-BW devices over 18.6 GHz has been simulated by using local micron-scale thermo-optical heater stripes on the MZI arms with a temperature rise from 0 to 48K. For the case of $N = 3$ and 100-nm silicon side teeth, some representative performance predictions are: insertion loss (IL) = -10.7 dB, BW = 80.5 MHz and $L = 113$ μm for $M = 58$; while IL = -0.74 dB, BW = 1210 MHz and $L = 86$ μm for $M = 44$.

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OCIS codes: (230.4555) Coupled resonators; (250.6715) Switching; (130.7408) Wavelength filtering devices; (230.1480) Bragg reflectors.

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1. Introduction

Microwave Photonics is a powerful technology for optical processing of microwave signals. It enables complex, challenging and novel RF functionalities on an integrated-optical chip with savings in size-weight-and-power along with lithographic fabrication that overcomes many limitations of the conventional all-electronics solution. Although the conventional solution is supported by industrial maturity, the integrated microwave photonics approach responds very well to demands for enhanced performance in bandwidth, tunability, power consumption, low electromagnetic interference and efficiency [1]. Generally speaking, the system architecture that connects the RF and photonic domains comprises four basic building blocks: light source, electro-optical modulator, optical signal processor, and optical detector [2]. In this context, the recent advances of electro-optical modulators allow RF modulation frequencies up to 100 GHz, inducing modulated optical spectra such as double sidebands (DSB), asymmetric sidebands (ASB), single sideband (SSB), and optical carrier suppression (SC). All these modulated optical spectra are manipulated by the optical signal processor inducing signal processing such as filtering, splitting, combining, phase shifting, and delay. Finally, optical detection by means of a single-end detector, or balanced detector, retrieves the processed RF output signal. Therefore, advances in this approach are related to progress in the integrated-optical processors for implementing RF functionalities. In this context, several architectures have been proposed in recent works [3–12] as narrowband microwave photonic filters. Narrow band 2×2 Mach-Zehnder interferometer (MZI) crossbar switches that are actuated by thermo-optical (TO) means are newcomers compared to the established broadband MZIs [13–22]. The resonant 2×2 s find application in datacom/telecom [23–24] where such 2×2 s would often be interconnected to form an $N \times N$ matrix switch within a

wavelength-multiplexed system. But the applications-scope of these resonant MZIs when they are deployed as filters is much wider than switching and extends to numerous microwave functions as is spelled out in this paper. The tunable 2×2 represents a key device for realizing reconfigurable on-chip microwave processing because the optical spectral profiles (peaks, notches, etc.) are readily shifted along the wavelength axis by means of thermo-optical (TO) heater stripes [25].

Overall, the 2×2 resonant approach, guaranteeing compactness, stability, robustness and low fabrication cost, represents a highly attractive platform for several important RF applications such as measurement of the unknown frequency of an RF input [26], and for microwave satellite communications that demand high-speed and broad-band capacity. Indeed, the trend in Fixed Satellite Service (FSS), Broadcasting Satellite Service (BSS) and Mobile Satellite Service (MSS) is towards larger frequency bands and accommodation of more transponders [27]. Other potential applications include RF spectrum analysis and RF signal generation by the optical-microwave chip.

In the microwave context, the novel features of the very narrowband tunable 2×2 Bragg-grating filters investigated in this paper are: (1) the choice of an optical bandwidth of 0.1 to 5 GHz with high rejection on the sidewalls of the band profile; (2) the creation of compact chips enabled by “simple” small-footprint replicated filter devices; (3) applicability to at least five monolithic RF-system-on-a-chip applications including spectrum analysis, satcomm receiving, variable-frequency generation, frequency measurement and time-delay beamsteering of a phased-array antenna; (4) capability of cost-effective manufacture in a foundry; (5) easy reconfiguration of filters by low-power TO inputs; (6) applicability to all integrated-photonics platforms; (7) the possibility of ultrafast tuning using electro-optical injectors.

For achieving the above goals, this theoretical simulation paper deals with the engineering of major improvements in the performance of narrowband 2×2 Mach-Zehnder filters. In particular, an optimization of tunable optical-microwave filters for 100 MHz resolution is proposed. In this paper we have focused on a new type of resonant MZI structure in which each of two identical waveguided MZI “arms” consists of N Bragg-grating resonators (waveguide Bragg resonators, WBRs) that are closely coupled to each other within a strip channel to form one effective resonator. As discussed below, this allows a good trade-off between the very narrow bandwidth, the very steep side walls (fast rolloff) and the acceptable optical insertion loss (IL). The photonics platform assumed here is the foundry-compatible and CMOS-compatible silicon-on-insulator (SOI) platform operating around the 1550 nm wavelength. The paper is organized as follows. RF Spectrum Analysis and RF signal generation are presented and discussed in Section 2. Then, in Section 3, parametric simulations are reported for the optimization of 2×2 MZI filters, focusing on the engineering of 100 MHz passbands. Finally, Section 4 summarizes the conclusions.

2. On-chip Rf spectrum analysis and RF generator

In microwave communication systems, such as satellite communications, it is often important to change from one RF channel to another; or it could be important to detect unwanted RF “threats” that enter certain RF channels in order to reject those interfering signals and/or to seek other RF signal channels. As we shall show here, these important microwave functions can actually be performed in the optical domain, entirely on one integrated-photonics chip such as SOI, and the chip size could be around 0.2 cm^2 . The basic idea in the microwave-photonics approach is to use the incoming RF spectrum to amplitude-modulate an optical carrier (at 1550 nm for example), producing typically an RF double-sideband-plus-carrier optical signal on the optical chip. After that, this composite signal is tunably filtered with an extremely narrow optical filter, and subsequently, using a fast, square-law photodetector, the filtered signal is down-converted to RF baseband (which is the chip’s electrical output) using the difference frequency generated between two optical signals impinging upon the

photodiode. Figure 1 shows schematically the approach proposed in this paper for spectrum analysis (and for tunable RF receiver). The basic idea is to employ our previously described Mach-Zehnder interferometer filter devices [22] for the functions of optical demultiplexing (demux), narrowband tunable filtering, and optical multiplexing (mux).

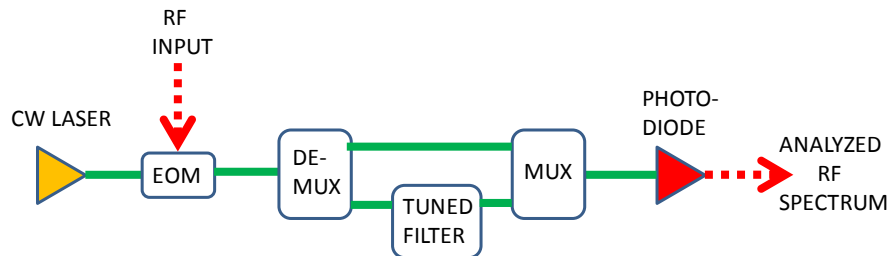


Fig. 1. System-on-a-chip for RF/microwave spectrum analysis or for the tunable RF receiver function.

Now we can show in more detail how this is done [Fig. 2] where each of the three MZIs is in effect a reconfigurable add-drop multiplexer, and where each contains (in both of its arms) an identical N-fold group of coupled Bragg-grating standing-wave resonators, illustrated schematically by the lateral-lines. The DSB + C input is assumed.

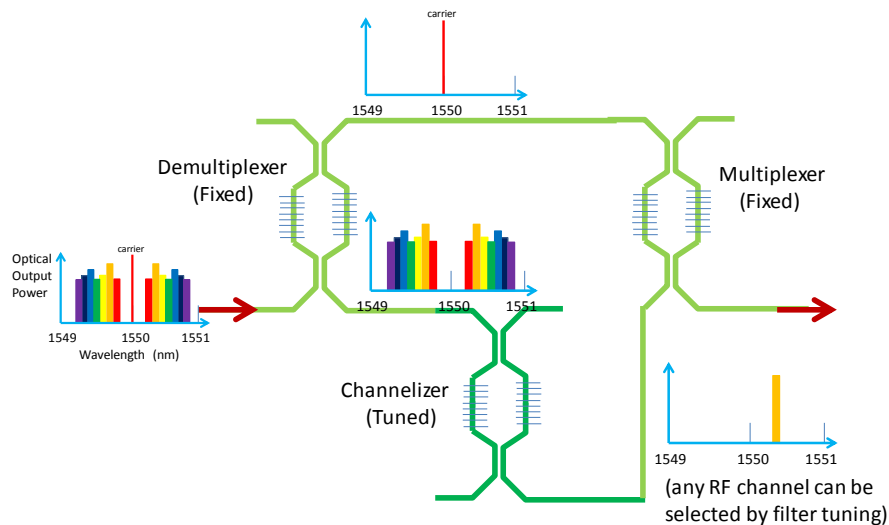


Fig. 2. Detailed explanation of the system function using fixed and tuned MZI Bragg-grating coupled-resonator filters that can serve, if desired, as ROADMs.

The demux and mux in Fig. 2 are fixed (not tuned) and we shall abbreviate these as optical demultiplexing-or-multiplexing filters (ODMFs), while the third device has an extremely narrow optical-filter passband that is continuously tuned via the TO effect, a device known as a microwave spectrum-analysis filter (MSAF). For Fig. 2, we might envision that each identical RF sideband has a span from 1 GHz to 20 GHz, for example. Then, to attain a detailed spectral analysis at baseband, we could impose the high-resolution requirement of a ~ 0.1 GHz passband for the tuned MSAF as illustrated in Fig. 3(a). As a result of scanning the channelizer in Fig. 2, an analog spectrum profile is found. However, the demux that splits off the optical carrier from the sidebands, and the mux filter that combines that carrier with the chosen sideband “slice,” can have a wider passband such as the ~ 1 GHz band shown in Fig. 3(b). An advantage of the MZI architecture in Fig. 2 is that the same “topology” can be used to attain the mux/demux functions and the tuned filtering. Returning to Fig. 3(a), when the

two MZI resonant regions in the Fig. 3(a) MSAF are not heated, the 100 MHz passband is designed to be centered at 1550 nm.

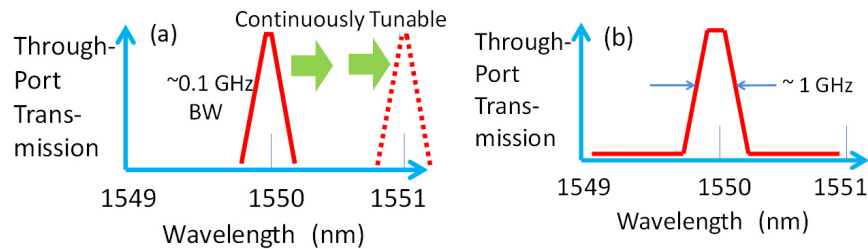


Fig. 3. Spectral transmission of the 2 x 2 MZI devices: (a) the mux and demux devices; (b) the RF channelizer device.

Our simulations show that when the temperature of both resonator-arms is raised identically by microheaters, the passband center wavelength shifts towards longer wavelengths as illustrated by the tuning to 1551 nm in Fig. 3(a).

The RF generator utilizes both sidebands instead of the single sideband employed in Fig. 2. Beneficially, the waveguide connections between the three MZI filters proposed in Fig. 2 enable this significant on-chip optical-microwave application—the generation of a variable-frequency microwave signal by suppressing the carrier and by then choosing (via tuning) a region in the left side band (LSB) to be mixed in the fast photodiode with a different chosen region in the right sideband (RSB). The system-on-a chip diagram is quite similar to the previous RF spectrum analyzer system, except here we have two tunable filters, and we are going to combine a selected RF-optical channel from LSB with a different selected RF-optical channel from RSB to attain an optical difference frequency (at baseband) at the photodetector output. The proposed architecture of this RF generator is illustrated in detail in Fig. 4.

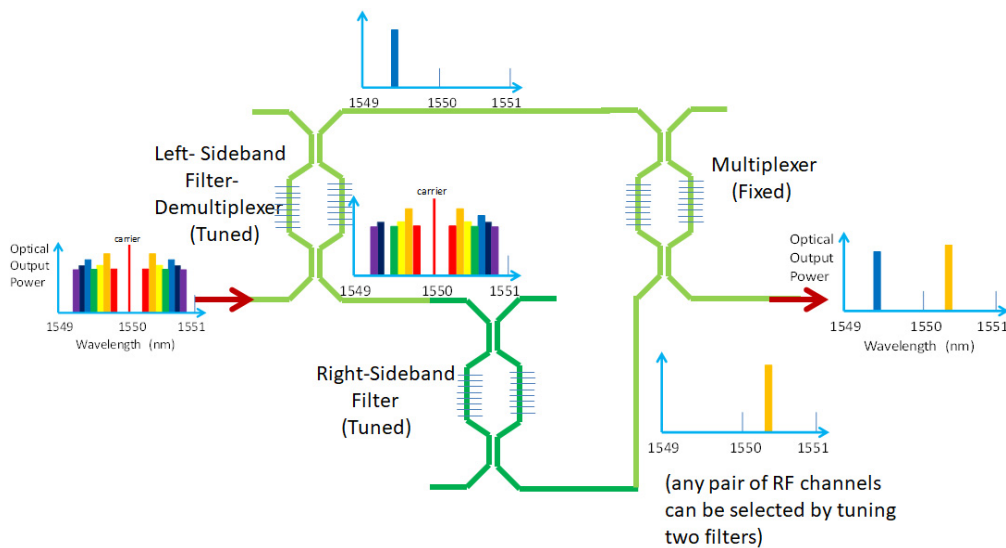


Fig. 4. Selectable-frequency RF signal generator architecture using fixed and tunable MZI Bragg-grating coupled-resonator filters to induce an optical frequency difference signal (microwave or millimeter wave) at the photodetector output.

Figure 4 shows how one RF channel is first tunably stripped out of the LSB (via tuned demux) and is sent forward to the fixed mux while another RF channel is stripped from the RSB by the “tuned channelizer filter” and is then sent forward to the mux; both of these

narrow optical signals being “spectrally added” in the mux and routed into the photodiode where the desired, selected difference-frequency signal (left-optical frequency minus right-optical frequency) is generated for use in the microwave system. The advantage of the Fig. 4 chip is its ability to increase the RF output frequency up to twice the maximal frequency of that generated in Fig. 2. The Fig. 4 frequencies available depend upon the RF frequencies that are sent into the broadband EO modulator. The Fig. 4 output frequency can be changed smoothly by tuning the LSB and RSB filters. The features of the three RF filters for this generator are illustrated in Fig. 5 where the LSB channel/demux and the RSB channel selectors both require high resolution in the range of 0.1 to 0.5 GHz, for example, as shown in Fig. 5(a) (LSB channel centered at 1549 nm before tuning) and in Fig. 3(b) above (RSB channel centered at 1550 nm before tuning).

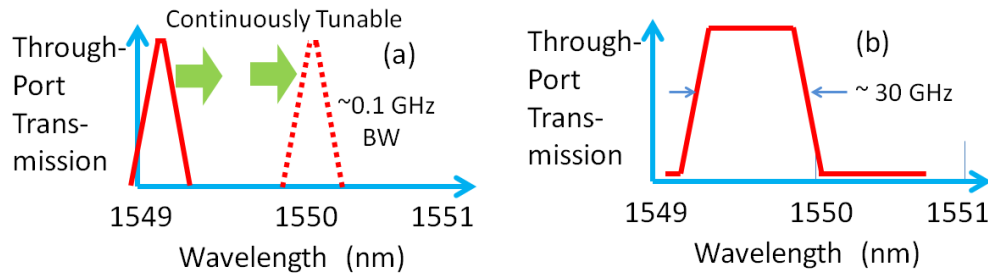


Fig. 5. Spectral transmission of the 2 x 2 MZI devices: (a) the left-sideband filter devices; (b) MUX filter.

The untuned mux filter is different in the sense that its passband of this fixed MZI filter device should be wide enough to accommodate the entire LSB (such as 20 GHz BW) as indicated in Fig. 5(b) in order to allow choice of any spectral slice within that LSB. For the example of the 1 to 20 GHz span mentioned for Fig. 2, the Fig. 4 generator could provide an RF output signal frequency varied continuously (by TO temperature choices) to be anywhere within the 2 to 40 GHz range. The highest electrical frequency available at the chip output is limited by the photodiode bandwidth.

3. Numerical results

The goal of this section is to engineer the 2 x 2 MZI filters for the on-chip applications described here above. Each arm of the waveguided MZI is a special resonator [22]. As mentioned above, this resonant structure consists of N waveguide Bragg-grating resonators closely end-coupled to each other in one strip waveguide. One of the N grating resonators is shown in Fig. 6(a).

The filter is physically realized with WBRs in a single-mode SOI wire waveguide having an unperturbed cross section of $W = 450$ nm width and $H = 250$ nm thickness. The Bragg grating sections are created by introducing along the nanowire, sidewall corrugations having width extension (W_t), that is in the range from 50 to 150 nm. The period is chosen to be $\Lambda = 315$ nm in order to operate at the central wavelength of 1550 nm. Moreover, the phase-shift sections each with a length $L_p = 315$ nm (at $W_t = 100$ nm) are included in the middle of each WBR in order to induce a narrow transmission-filter behavior with a 3-dB bandwidth (BW). The separation between individual resonators is zero in our work. Hereafter, we focus the design and analysis on the TE polarization, specifically the TE_{00} fundamental optical mode [Fig. 6(b)].

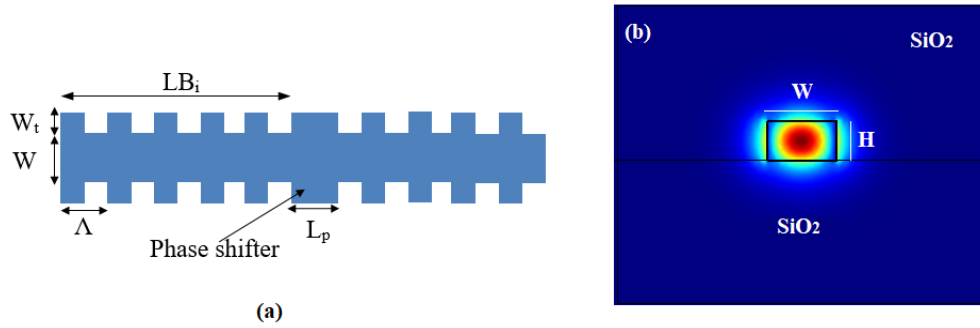


Fig. 6. (a) The i -th waveguide Bragg resonator; (b) Electric field x component of TE_{00} modal distribution.

In addition, we assume the length of the first WBR (LB_1) as a degree of freedom and express the subsequent lengths LB_i ($i = 2 \dots N$) as a function of LB_1 in order to induce a maximally flat filter response. The parameters listed in Table 1 have been used to obtain the Butterworth filter response, and the $N = 2$ case, not shown, has $LB_1 = LB_2$. Indeed under the hypothesis of 3-dB directional couplers, the outputs at the drop and through ports of the MZI are equal to the reflection and transmission of the N -coupled WBRs, respectively. In the WBR, the phase-shifted Bragg grating acts as an optical resonator storing electromagnetic energy and communicating to the outputs through either port constituted by the two Bragg grating sections. In particular, this power escape can be characterized by a decay rate $1/\tau_i \propto e^{-2|\kappa_c|LB}$, where κ_c is the coupling coefficient between the forward and backward modes inside the Bragg grating. Thus, the N -coupled resonators can induce a specific spectral response by designing opportunely the decay rates for each optical resonator. In this context, the lengths LB_i can be evaluated as:

$$LB_i = \frac{1}{2\kappa_c} \log\left(\frac{g_i}{g_1}\right) + LB_1; \quad i > 1 \quad (1)$$

where the terms g_i are normalized coefficients, as listed in Table 1.

Hereafter, the length of the first Bragg resonator is given as $LB_1 = M \times \Lambda$, where M is the number of periods in the Bragg section of the first WBG. Moreover, all simulations are performed using a mixed full-vectorial mathematical model based on the FEM, CMT and Transfer Matrix approaches (see Ref [22]. for details). In particular, determination of the MZI output spectra is obtained using the transfer matrix approach. Thus, using terms b_i and a_i to indicate the outgoing and the incoming field amplitudes at the generic MZI port ($i = 1(2)$ for Input(Add) port, and $i = 3(4)$ for Drop (Through), the 2×2 MZI filter is fully described by Eq. (2):

$$\begin{bmatrix} b_2 \\ a_2 \\ b_4 \\ a_4 \end{bmatrix} = \mathbf{T}_{MZI} \begin{bmatrix} b_1 \\ a_1 \\ b_3 \\ a_3 \end{bmatrix} = \begin{bmatrix} \mathbf{E} & \mathbf{F} \\ \mathbf{G} & \mathbf{H} \end{bmatrix} \begin{bmatrix} b_1 \\ a_1 \\ b_3 \\ a_3 \end{bmatrix} \quad (2)$$

where the $\mathbf{T}_{MZI}$ is the 4×4 transfer matrix of the 2×2 MZI filter. The 2×2 matrices $\mathbf{E}$, $\mathbf{F}$, $\mathbf{G}$ and $\mathbf{H}$, are dependent upon the transfer matrices of the DCs and WBRs. Therefore, the filters outputs are expressed as a particular combination between the $\mathbf{T}_{MZI}$. However, it is

worth noting that the spectrum simulations are carried out by means of the implementation of a mixed numerical approach based on (1) the finite-element method (FEM), for the evaluation of the electric field distribution and overlap integrals, (2) the full vectorial coupled-mode theory (CMT) for the calculation of the optical features such as DC coupling factor and WBR reflectivity and transmittivity, and (3) the transfer matrix for the system analysis.

Table 1. Coefficients g_i .

Values	Butterworth response							
	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8
N = 2	1.4142	1.4142						
N = 3	1	2	1					
N = 4	0.7654	1.8478	1.8478	0.7654				
N = 5	0.6180	1.6180	2	1.6180	0.6180			
N = 6	0.5176	1.4142	1.9318	1.9318	1.4142	0.5176		
N = 7	0.4450	1.2470	1.8019	2.0000	1.8019	1.2470	0.4450	
N = 8	0.3902	1.1111	1.6629	1.9615	1.9615	1.6629	1.1111	0.3902

The insertion loss (IL) and bandwidth (BW) are plotted in Fig. 7 as a function of the number N of coupled WBRs in each arm of the MZI, assuming $M = 50$.

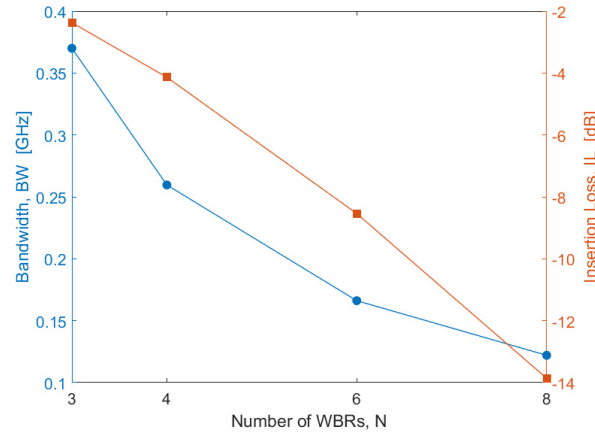


Fig. 7. Insertion loss and bandwidth as a function of the number N , assuming $M = 50$. The simulations are performed by considering: $W = 450$ nm, $H = 250$ nm, $W_t = 100$ nm, $A = 315$ nm, and $\alpha_t = 0.2$ dB/cm.

In the simulations, we have assumed the corrugation width (W_t), and the propagation loss coefficient (α_t) of 100 nm and 0.2 dB/cm (the smallest experimental value reported in the literature), respectively. Similarly, Fig. 8 shows the IL and BW versus M for $N = 3$, and 4, and assuming $W_t = 100$ nm. Figures 9(a) and 9(b) show the IL and BW versus M for $N = 3$, and changing W_t from 100 to 150 nm.

It is important to compare this result with that for different narrow filter topologies. An immediate comparison can be made with the narrow filter based on stimulated Brillouin scattering (SBS) in a silicon nanowire. A 1.25 cm silicon nanowire with a cross section of 220 by 480 nm which was supported by a silica pillar of 50 nm width has been proposed in [11] in order to realize an RF photonic notch filter with 48 dB of suppression, 98 MHz linewidth and SBS gain saturation at 30 mW.

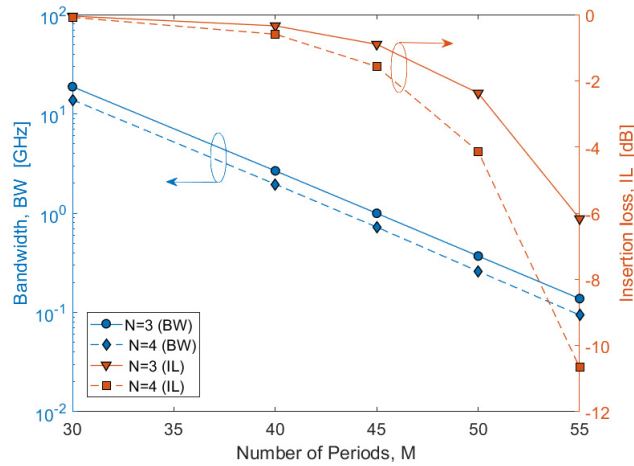


Fig. 8. Insertion loss and bandwidth (Log scale) as a function of the number of periods M , assuming $N = 3$ and 4. The simulations are performed by considering: $W = 450$ nm, $H = 250$ nm, $W_t = 100$ nm, $A = 315$ nm, and $\alpha_l = 0.2$ dB/cm.

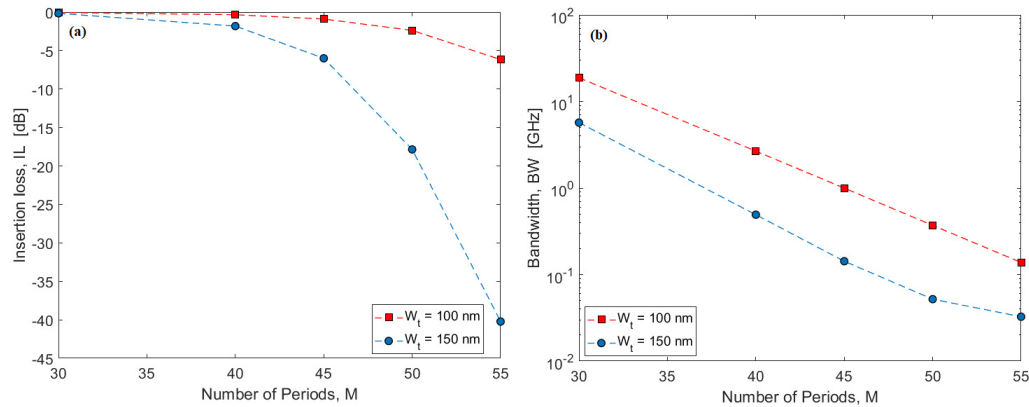


Fig. 9. (a) Insertion loss as a function of the number of periods M , for different values of W_t ; (b) Bandwidth as a function of the number of periods M , for different values of W_t .

The simulations are performed by considering: $W = 450$ nm, $H = 250$ nm, $N = 3$, $A = 315$ nm, and $\alpha_l = 0.2$ dB/cm.

Moreover, the center frequency of the notch in the RF domain has been tuned simply by changing the frequency of the SBS pump over a 6 GHz range, while maintaining the notch suppression above 48 dB. In the context of the architectures of Figs. 2 and 4, we think that the narrow filters based on the SBS approach present the following drawbacks. The waveguide needs to be larger than 1 cm inducing very high footprint. In addition, to induce an efficient SBS effect, air-suspended silicon waveguides are required, prohibiting the realization of any kind of modulation. In this sense, the filter tuning obtained by means of the tunable laser pump could represent further disadvantage. Recently, a Nyquist-filtering optical (de)multiplexer using a ring resonator-assisted interferometer circuit has been proposed in [12]. A near-rectangular passband spectrum, scalable port count, spectral resolution smaller than 1-GHz, FSR of 25 GHz and tuning by means of thermo-optical mechanism has been designed using ordinary passive photonic-integrated circuit building blocks such as multiple ring resonators, MZIs and delay lines. In addition, the chip has been fabricated in a

commercial low-loss, high-index-contrast Si_3N_4 waveguide technology, since a very low coefficient loss was required by the architectural constraints. However, although the circuit proposed in [12] shows very interesting potential, we guess that it is very challenging to convert the architecture in the SOI platform and obtain BW around 100 MHz. In addition, the ring resonator-assisted interferometer filter presents a periodic series of passbands, representing a limitation in the behaviour of the on-chip RF spectrum analysis and RF generator presented in this work. Thus, we think that the filters designed through our Figs. 7-9 can represent good candidates to realise efficiently the architectures of Figs. 2 and 4.

Choosing now some filters for practical application, we show in Fig. 10 the MZI Through-port spectra for Microwave Spectrum-Analysis Filters (MSAFs). In the simulations two different values of M (54, and 58), $N = 3$, and $W_t = 100$ nm have been assumed. The overall length L of the N grating region is 105.0 and 112.6 μm , respectively.

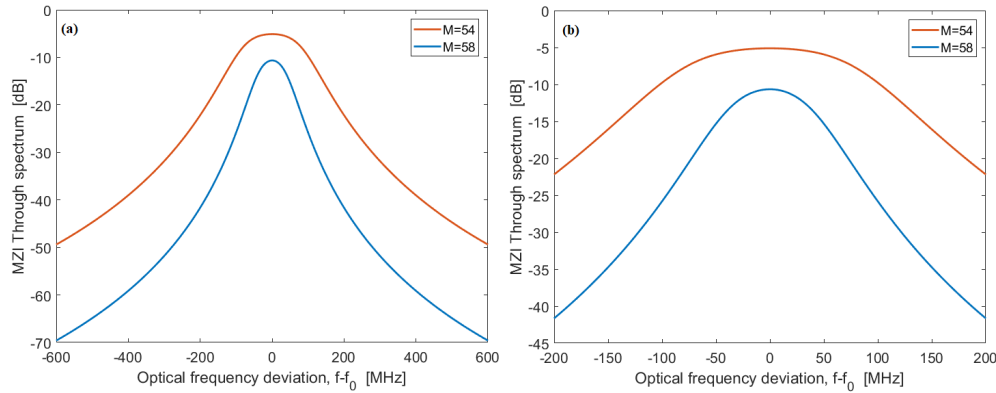


Fig. 10. MZI Through spectrum for $M = 54$, and 58 : (a) Zoom out; (b) Zoom in. The simulations are performed by considering: $W = 450$ nm, $H = 250$ nm, $N = 3$, $A = 315$ nm, $W_t = 100$ nm, and $\alpha_t = 0.2$ dB/cm.

The simulations record an insertion loss and a bandwidth of $\text{IL} = -5.1$ dB, and -10.7 dB, and $\text{BW} = 167.3$ MHz and 80.5 MHz, for $M = 54$ and 58 , respectively. In this context, the MZI Drop-port spectra for MSAFs are shown in Fig. 11.

Figure 11(a) shows that the rejection ratio is strongly dependent upon the value of M . Indeed for a given N value, the decay rate from each WBR resonator, $1/\tau_t$, decreases by increasing the Bragg section length LB_t and then by increasing M . As a result, the notch in the drop spectrum becomes more and more deep as the energy stored inside the phase shifter regions is increased.

Similarly, Fig. 12 shows the MZI Through-port spectra for the Optical Demultiplexing or Multiplexing Filter (ODMF) application which allows a somewhat wider bandwidth than of the Fig. 10 RF channelizer devices. The curves have been obtained under the assumptions of: $M = 44$, and 47 , $N = 3$, and $W_t = 100$ nm. Here, the length L is 86.1 and 91.8 μm , respectively.

The plot of Fig. 12 indicates $\text{IL} = -0.74$ dB, and -1.32 dB and $\text{BW} = 1.21$ GHz, and 0.67 GHz, for $M = 44$ and 47 , respectively. Finally, in Fig. 13 we show the MZI Drop-port spectra for the ODMF operating in the same conditions.

At this point in the paper, we shall change the focus to examine the tunable-filter opportunities. The narrowband MSAFs are tuned by means of TO heater strips deposited on the top of the WBRs.

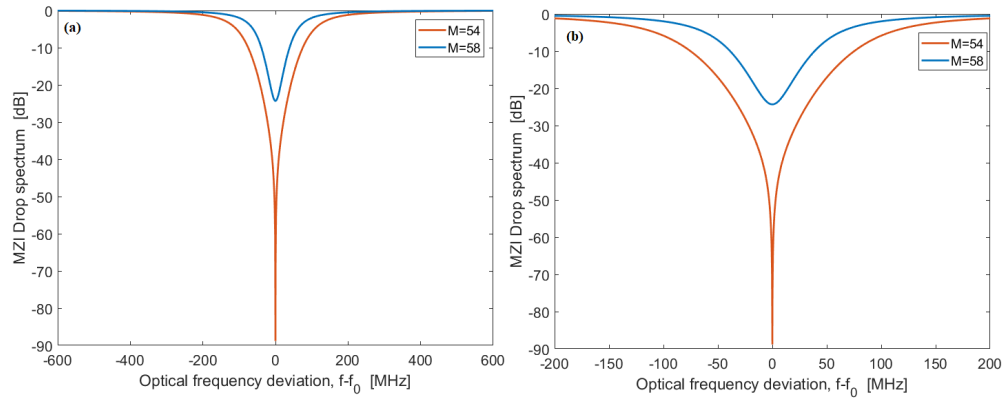


Fig. 11. MZI Drop spectrum for $M = 54$ and 58 : (a) Zoom out; (b) Zoom in. The simulations are performed by considering: $W = 450$ nm, $H = 250$ nm, $N = 3$, $A = 315$ nm, $W_t = 100$ nm, and $\alpha_t = 0.2$ dB/cm.

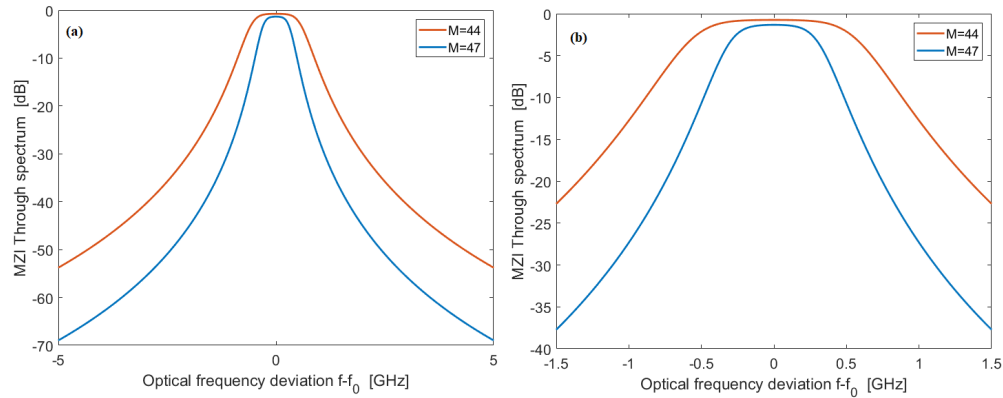


Fig. 12. MZI Through spectrum for $M = 44$, and 47 (a) Zoom out; (b) Zoom in. The simulations are performed by considering: $W = 450$ nm, $H = 250$ nm, $N = 3$, $A = 315$ nm, $W_t = 100$ nm, and $\alpha_t = 0.2$ dB/cm.

As outlined in [19], the TO technique can be considered as an efficient tool to induce refractive index changes (Δn) with low-power consumption. Indeed, due to silicon's thermo-optic coefficient $dn/dT = 1.86 \times 10^{-4} \text{ K}^{-1}$, an effective refractive index change Δn can be induced in both WBRs –either over the phase-shifter length-zones, or over the entire WBR length. Our simulations indicate that for a local heating of $\Delta n = 0.0009$ in the phase shifter regions (the three micron-scale locations in our $N = 3$ case), which corresponds to a local $\Delta T = 4.84$ K, we obtain a shift of about 2 GHz in the MSAF spectral profile. In this context Fig. 14 shows the tuning mechanism in the case of MSAFs with $M = 54$, and 58 , and assuming the local Δn changing with a step of 0.0009.

If we consider the geometric features of the filters discussed in this paper, we see that all of the constituent MZIs have nanometer-scale features that require high precision in the fabrication of the MZI. If an error $\Delta L_p / L_p$ is made in fabricating the length of the phase shifter, the resonance of the single resonator will be affected. Indeed, each resonator in the N -coupled WBR has its individual resonance wavelength which must be aligned to attain optimum performance, in terms of metrics and spectral profile. However, in practice, errors in fabrication can induce misalignments in resonance wavelengths.

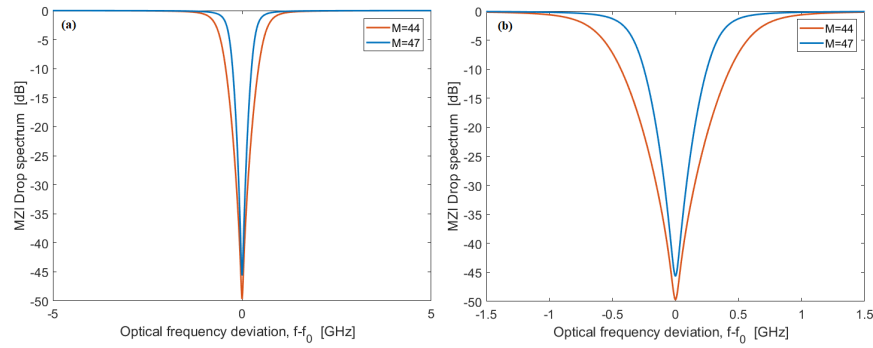


Fig. 13. MZI Drop spectrum for $M = 44$, and 47 (a) Zoom out; (b) Zoom in. The simulations are performed by considering: $W = 450$ nm, $H = 250$ nm, $N = 3$, $\Lambda = 315$ nm, $W_t = 100$ nm, and $\alpha_t = 0.2$ dB/cm.

In this context, we have performed a number of simulations evaluating the resonance wavelength misaligned $\Delta\lambda$ for the single WBR, as induced by fabrication error $\Delta L_p / L_p$. We have quantified that effect and have found with simulations that the actual resonance wavelength will experience a deviation from λ_0 (1550 nm) by an amount $\Delta\lambda = \pm 0.41$ nm/% error. The likely scenario is the one in which errors occur in the same direction and value within the phase shift regions of the the N -coupled WBRs. In this context, two cases could be verified. First case: the same error is present also within the two MZI arms, and then the switch's passband center-wavelength shifts away from the design wavelength λ_0 . In this scenario, the behavior device keeps its validity but for opportunely shifted input light. The second case takes place if the errors within the two MZI arms are different. In this context, the mismatch between the resonance wavelenths of arm-1 and arm-2 in the MZI induces a reduction of the IL and CT in the cross state by an amount that depends upon the switch BW. However, this problem could be minimized by hypothesizing the presence of a second heater placed on the overall arm length (except for the phase shift regions, used for the device tuning, see Fig. 14 in the following). The approaches available to do this were discussed in [19]. The techniques include employing micron-scale direct-current TO heaters on the arms to “trim” their response on a constant basis, and/or to deposit atomic-layer films on the arms to offer permanent trimming of any imbalances. Our numerical investigations indicate that an error of about 5% between the phase shifter lengths placed in the two MZI arms could be compensated by $\Delta n \approx 0.007$.

The Fig. 14 plot illustrates a discrete step-wise scan, with the filter tuning covering the range from 0.0 GHz to 18.6 GHz. Step-wise tuning might be used to pick a specific RF channel, but in other applications such as determining the RF band profile, the TO-induced temperature of the waveguided phase-shifters would be increased smoothly as a function of time so as to move the filter profile continuously along the wavelength axis.

Thereby, the to-be-analyzed RF spectral profile would be determined with an “analog shape” at the Fig. 1 detector output. However, this local-heating scan has a temperature limit because a frequency shift larger than 18.6 GHz requires $\Delta n > 0.009$ locally ($\Delta T > 48$ K) which might not be acceptable. There is nevertheless an RF filter scanning strategy that is viable for larger scanning ranges such as 40 GHz, and that would be to heat the entire grating length L with one TO stripe. That global heating makes it easy to scan the range. However, in that approach, the issue becomes the very small values of ΔT (min) used to scan the filter over a given “minimal” optical-frequency increment. The full-grating solution could be modified to an $L/2$ or $L/3$ heating in order to alleviate the small- ΔT requirement by making the new increment ΔT (mod) two or three times larger than ΔT (min).

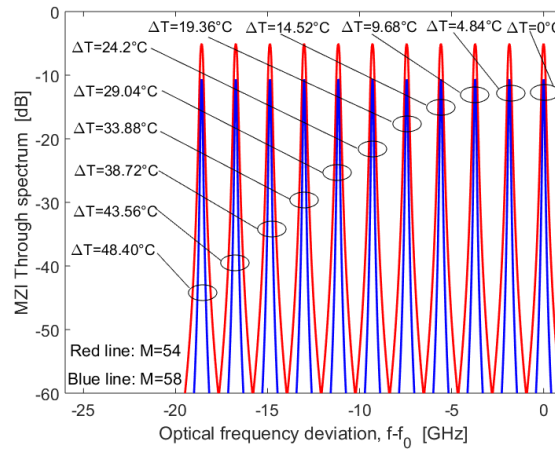


Fig. 14. MZI Through spectrum for $M = 54$, and 58 , changing Δn with a step of 0.0009 (local heating approach). The simulations are performed by considering: $W = 450$ nm, $H = 250$ nm, $N = 3$, $A = 315$ nm, $W_f = 100$ nm, and $\alpha_f = 0.2$ dB/cm.

Looking at the “big picture” of filter tuning, it is important to recognize that electro-optical tuning, such as PIN injection of free carriers into our phase-shifter regions, could be very effective and practical in the present RF application. That is a topic for further research.

4. Conclusions

In this paper a mixed full-vectorial mathematical model based on the FEM, CMT and Transfer Matrix approaches has been implemented for engineering the performance of integrated-photonic 2x2 Mach–Zehnder optical filters, where each arm of the interferometer is composed of N -coupled Bragg resonators deployed in one single-mode SOI waveguide that operates around 1550 nm. Taking a TE_{00} polarization for the input light, the filter optimization has been performed for on-chip applications such as an RF analyzer and an RF generator. An opportune interconnection between three different MZI filters is required for both architectures. For the RF receiver, the demultiplexing-or-multiplexing filters have a passband of ~ 1 GHz, while the very narrow (BW ~ 0.1 GHz) channelizer filter is continuously tuned via the thermo-optical (TO) effect—so that the electrical RF output of the chip tunes in correspondence across the total RF spectral input to the EOM. Practical trade-offs between bandwidth requirements and insertion loss are found for both Mux and Channelizer filters. For MSAFs in the 1550-nm SOI platform, the $N = 3$ performance predictions when $M = 54$ or 58 are: IL = -5.1 dB, and -10.7 dB, respectively, and BW = 167.3 MHz and 80.5 MHz, respectively, for a overall resonant-structure length of 105 and 113 μm , respectively. Taking $M = 44$ or 47 in the $N = 3$ ODMFs, our simulations indicate IL = -0.74 dB and -1.32 dB and BW = 1.21 GHz and 0.67 GHz, for $L = 86.1$ and 91.8 μm , respectively. Using the aforementioned MSAFs, specific predictions about tuning were made. Step-wise TO-heater scan simulations have demonstrated the possibility of realizing filter tuning covering the range from zero up to 18.6 GHz, by means of local heating of the phase shifter regions with a ΔT limit of 48K. Moreover, larger scanning ranges such as 40 GHz, can be obtained by increasing the length of the TO strip.

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