High-suppression-ratio tunable optical filter using apodized sampled gratings in InP-based generic integration platform

Xiao Li
Address1: Eindhoven Hendrik Casimir Institute (EHCI)
Eindhoven University of Technology
Eindhoven, 5600MB, the Netherlands
Address2: Center for Optical and Electromagnetic Research, College of Optical Science and Engineering
State Key Laboratory of Modern Optical Instrumentation, Zhejiang University
Hangzhou 310058, China
x.li4@tue.nl

Kevin Williams
Eindhoven Hendrik Casimir Institute (EHCI)
Eindhoven University of Technology
Eindhoven, 5600MB, the Netherlands
K.A.Williams@tue.nl

Yuqing Jiao
Eindhoven Hendrik Casimir Institute (EHCI)
Eindhoven University of Technology
Eindhoven, 5600MB, the Netherlands
Y.Jiao@tue.nl

Sailing He
Center for Optical and Electromagnetic Research, College of Optical Science and Engineering
State Key Laboratory of Modern Optical Instrumentation, Zhejiang University
Hangzhou 310058, China
sailing@zju.edu.cn

***Abstract*—A high-suppression-ratio tunable optical filter is designed by using cascaded apodized sampled gratings on the generic InP integration platform, without the need for an optical circulator. The suppression ratio of non-adjacent and adjacent channels relative to the designed transmission mode bandpass filter are -21.5 dB and -41 dB, respectively. At the same time, the filter has a narrow 3 dB bandwidth and wide tuning range. It is fully compatible with active-passive integration technology, making it potentially be applicable to future densely integrated optical THz heterodyne systems.**

Keywords—InP generic integration platform, Foundry, Filter, Suppression ratio, Sampled grating, Apodization

I. Introduction

Optical communications is in the stage of explosive growth due to rapid expansion of the Internet [1]. To achieve ultra-high-speed communication beyond 5G, terahertz electromagnetic frequency band (from 300 GHz to 3 THz) that lies in the boundary region between optical frequency and radio frequency has been explored over the past few years [2, 3]. THz heterodyne systems are a promising method to achieve THz frequency output based on photonic integration circuit, within which a high performance optical filter with high channel suppression ratio, narrow bandwidth, and low insertion loss (IL) is required to realize single wavelength selection for stable and tunable heterodyne beating. Many studies have been performed for integrated tunable filters in recent years. High performance on-chip optical filter can be realized by various waveguide structures, such as cascaded Mach–Zehnder interferometers (MZI) [4, 5], ring resonators [6, 7], arrayed-waveguide grating (AWG) [8], and Bragg gratings (BGs) [9-11]. Most of them concentrate on high-index contrast platform, such as silicon-on-insulator (SOI) [4-7, 9, 15], and LN-on-insulator (LNOI) [10, 11].

InP generic photonic integrated platform can be based on butt joint active-passive epitaxy, which provides a compact means to flexibly achieve optical systems on one chip [12]. A big challenge for this platform is the low-index contrast layer stack, which makes it hard to achieve small size and compact passive devices. When considering general structures mentioned above to realize a high-performance filter on this platform, it is hard to implement. For cascaded MZI-based filters, researchers implement several different elements to achieve high suppression ratio and narrow bandwidth wavelength selection, which causes high optical loss simultaneously and brings complexity in system tuning [4]. The AWG-based filters need to combine several semiconductor optical amplifiers as channel switches to realize single wavelength selection [8], which increase the footprint, noise figure and control complexity for the optical system. The ring resonators with high suppression ratio and low IL are often used in high-index contrast platform with smaller sizes [6]. It utilizes the Vernier effect to enlarge the free spectral range (FSR). However high performance micro-rings have been challenging to achieve in conventional InP platforms. The reflection from BG needs an external device such as an optical circulator to extract the filtered light, and the tuning range is restricted by the limited effective index change [9]. Nowadays, the sampled gratings (SGs) with comb-like reflection spectrum have been attracting a lot of interests due to the wide tuning range using Vernier effect, and the narrow bandwidth with a low coupling strength of SGs. However, the adjacent suppression ratio of the sampled gratings is quite high, limiting its ability of single wavelength selection. This may be solved by apodization methods [13, 14].

In this paper, we present a high-suppression-ratio optical wavelength-tuning filter with low IL, narrow 3 dB bandwidth, and a wide tuning range on the InP-based generic integration platform. The transmission mode bandpass filter is composed of multiple cascaded multi-mode interferences (MMI) and sampled gratings without the need of an external circulator. We use Transfer Matrix Method to calculate the reflection spectrum of the filter. The sampled grating using Gaussian type apodization to modulate the duty ratio of SG periodically and can significantly increase the side-lobe suppression ratio (SSR) of the reflection spectrum. Following are the detailed introduction and simulation results of our designed transmission mode bandpass filter.

II. Theory and Results

A. Theory

The schematic diagram of the shallow-etched grating (above the substrate and below the top cladding) in the InP-based generic integration platform is shown in Fig. 1(a). The gratings have optical properties pre-defined by the platform technology, including the width of shallow waveguide w as 2 µm, coupling coefficient κ as 50 cm^{-1}, and effective index of grating n_{eff} as 3.266. The gratings are buried in the shallow-etched waveguide layer, with a 30 nm height of grating layer thickness T and the n-InP layer thickness D in the waveguide core [12].

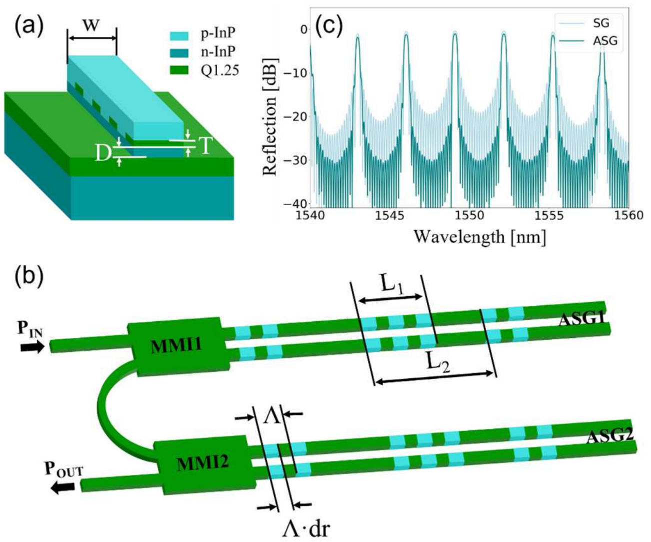

Fig. 1. (a): Schematic diagram of shallow-ecthed gratings in InP-based generic integration platform. The layer stack has been simplified, without showing doping differences in p-InP and n-InP layers. (b): Schematic diagram of the top view of tunable optical filter. (c): The reflection spectrums of Uniform sampled grating (SG) and Gaussian-apodized sampled grating (ASG).

Fig. 1(b) shows the schematic diagram of the tunable optical filter based on cascaded apodized sampled gratings (ASGs) with MMIs. The device consists of two 2*2 MMIs with two sets of ASGs. The two ASGs in each set are nominally identical. When light is injected into the 3-dB MMI coupler, the light will be equally divided into two output ports with a π/2 phase difference. Then the light reflected from ASG1 group will keep the same phase difference, and be injected into MMI again, which will be constructively imaged into the waveguide other than the input port. In this way, the transmission mode bandpass filter can guide the reflected and filtered light without the need of a circulator. By cascading such structures with slightly detuned ASGs, the Vernier effect can be achieved. By properly selecting the parameters of the two sets of ASGs, the FSR could be extended to cover the entire C band. At the same time, we could tune the optical filter by using current injection or reverse voltage bias to change the refractive index of the grating layer by putting electrodes on different sets of ASGs.

In the grating section, Λ denotes the period of the shallow-etched grating. Through the Bragg equation $\lambda_{\mathrm{Bragg}} = 2n_{\mathrm{eff}}\Lambda$, we could get $\Lambda = 237.3$ nm when selecting the Bragg wavelength λ_{Bragg} as 1550 nm. Meanwhile, the duty ratio of grating $dr = a/\Lambda$ is set to 0.5 for low IL and symmetrical reflection spectrum output. The sampled grating consists of several alternating shallow-etched gratings and straight waveguides arranged in sequence. The period, the shallow-etched gratings length in each periodic section, the total number, and the total length of sampled gratings are defined as L_2, L_1, N_{SG}, and L ($L = N_{\mathrm{SG}}{*}L_2$), respectively. To easily characterize the sampled grating, we set the duty ratio of the sampled grating as $dr_{\mathrm{SG}} = L_1/L_2$.

It is known that the sampled grating has a comb-like reflection spectrum, shown in Fig. 1(c). The spacing between the peaks in reflection spectrum can be calculated by the following equation:

$$FSR_{SG} = \frac{\lambda_{\mathrm{Bragg}}^2}{2n_{\mathrm{eff}}L_2} \qquad (1)$$

It is known that the reflection spectrum from sampled grating has a high side-lobe level around each peak, which leads to low suppression ratio when it is used as a filter. To overcome this problem, we use apodization method to modulate the refractive index difference in periodic structure of the sampled grating, which could greatly improve the suppression ratio of filter. This method has been widely used in Bragg grating structures [15] by modulating the coupling coefficient in each period of grating. However, for the InP-based generic integration platform, the coupling coefficient is fixed by the foundry. In this case, we choose to modulate duty ratio dr_{SG} in the sampled grating with Gaussian function to achieve an effective apodization. The apodization function used in this paper is shown as follow,

$$dr_{\mathrm{SG}}(i) = dr_{\mathrm{SGm}} * \exp\left(-\left(\frac{2.24\left(i-\frac{N_{\mathrm{SG}}}{2}\right)}{N_{\mathrm{SG}}}\right)^2\right) \quad i = [1, N_{\mathrm{SG}}] \qquad (2)$$

where dr_{SGm} is the maximum duty ratio in the center of the sampled grating. i is the section number for the sampled grating. After apodization, the dr_{SG} is changed symmetrically along the sampled grating, and the maximum dr_{SGm} is located at the center of the sampled grating.

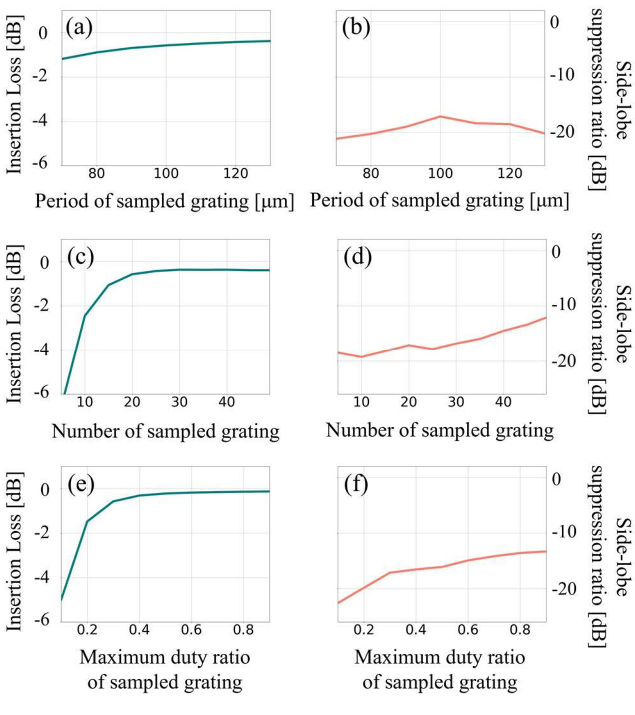

Fig. 2. The calculated IL curve (a) and SSR curve (b) under different period of sampled grating P_{SG}. The calculated IL curve (c) and SSR curve (d) under different number of sampled grating N_{SG}. The calculated IL curve (e) and SSR curve (f) under different maximum dutyratio of sampled grating dr_{SGm}.

The reflection spectrums of the Uniform sampled grating and the Gaussian-apodized sampled grating shown in Fig. 1(c) are calculated through Transfer Matrix Method, using parameters $N_{SG} = 20$, $dr_{SGm} = 0.2$ and $L_2 = 100$ µm. The FSR_{SG} can be calculated by (1) as 3.68 nm. The SSR and IL of the Uniform sampled grating are around 6.90 dB and 0.42 dB, which are 19.46 dB and 1.03 dB for Gaussian-apodized sample grating, respectively. By inducing the apodization method, the suppression ratio has been greatly reduced, however, this method will also bring a bit higher loss for Gaussian-type than the Uniform-type, which can be compensated by increasing the number of N_{SG}. Due to the low coupling strength of the shallow-etched grating, the 3 dB bandwidth is 0.3 nm. The distortion in the peaks far away from the central wavelength of Gaussian-apodized sampled grating are mainly because of the phase mismatch caused by the effective index changes along the sampled grating.

B. Results

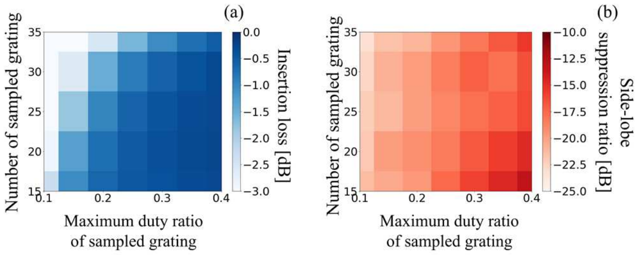

Fig. 3. The calculated IL parametric sweep diagram (a) SSR parametric sweep diagram (b) under different number and maixmum duty ratio of sampled grating (N_{SG} and dr_{SGm}).

The low IL and high SSR are two important parameters for high performance grating, which could be optimized by changing the parameters in sampled grating, like L_2, dr_{SGm} and N_{SG}. Fig. 2 show the IL curves and SSR curves of reflection spectrum from Gaussian-apodized sampled grating under different swept parameters (L_2 from 70 µm to 130 µm, N_{SG} from 5 to 50, dr_{SGm} from 0.1 to 0.9). The default parameters of the ASGs are set as $L_2 = 100$ µm, $dr_{SGm} = 0.3$ and $N_{SG} = 20$. When sweeping the period of the sampled grating L_2, the IL is slightly reduced to around 0.4 dB, but the SSR is kept at around -20 dB, shown in Fig. 2 (a-b), which indicates that the L_2 has little impact on the performance of the ASGs. In Fig. 2 (c-f), the IL is improved a lot with increased N_{SG} and dr_{SGm}, but the SSR will be highly degraded at the same time. Therefore, the N_{SG} and dr_{SGm} in the ASGs should be carefully selected by trading-off between IL and SSR.

TABLE I. THE OPTIMIZED PARAMETERS AND PERFORMANCES OF TWO DIFFERENT FILTERS BASED ON SAMPLED GRATINGS AND GAUSSIAN-APODIZED SAMPLED GRATING

Structure	***L_1 [µm]***	N_{SG}	dr_{SGm}	***FSR_{SG} [nm]***	***IL [dB]***	***SSR [dB]***
SG1	100	25	0.27	3.68	-0.23	-5.1
SG2	118		0.26	3.12	-0.22	-4.45
ASG2	100		0.27	3.68	-0.52	-18.32
ASG2	118		0.26	3.12	-0.47	-20.63

Fig. 3 show the parametric sweep diagrams of IL and SSR under different N_{SG} and dr_{SGm} of Gaussian-apodized sampled grating. When proposing a single ASG with IL lower than 0.5 dB and SSR higher than 15 dB, the N_{SG} and dr_{SGm} can be selected in the range of [15, 30] and [0.25, 0.35], respectively. In this work, we select N_{SG} as 25, and dr_{SGm} as around 0.26.

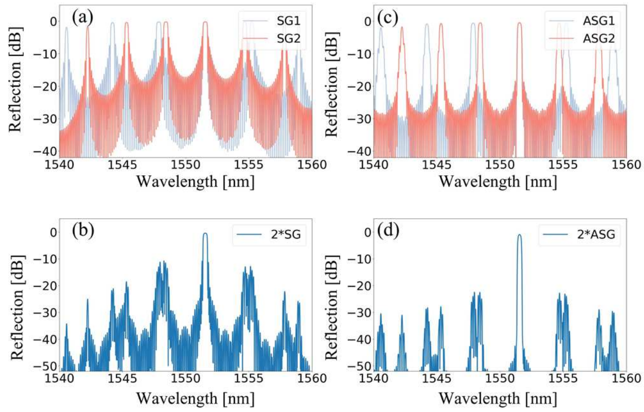

Fig. 4. The reflection spectrums of two Uniform SGs, separately (a) and two cascaded Uniform SGs (b). The reflection spectrums of two Gaussian type ASGs, separately (c) and two cascaded Gaussian type ASGs (d).

By using the Vernier equation to calculate the FSR of the filter, we could select the proper P_{SG} for two cascaded ASGs, which is defined as,

$$FSR = \frac{FSR_{SG1} * FSR_{SG2}}{FSR_{SG2} - FSR_{SG1}} \tag{3}$$

where FSR_{SG1} and FSR_{SG2} are the peak spacing in the reflection spectrum of ASG1 and ASG2 ($FSR_{SG1} < FSR_{SG2}$), respectively. The optimized parameters of the filters based on two cascaded Uniform SGs and two cascaded ASGs are listed in TABLE I.

Using these parameters, the reflection spectrums of two type filters are calculated in Fig. 4, and the IL and SSR of four sampled gratings are listed in TABLE I. It is clear that the Gaussian apodization method applied on sampled grating significantly improves the SSR from around -5 dB to around -19 dB, while having little impact on the IL. Fig. 4(b) and (d) depict the reflection spectrums of the filters based on Uniform SGs and ASGs. With apodization on the sampled grating, the adjacent channel suppression ratio has improved a lot from -10 dB to -41 dB, the non-adjacent channel suppression ratio has increased a lot from -10.35 dB to -21.51 dB as well, although the IL is slightly degraded from -0. 45 dB to -0.99 dB. The 3 dB bandwidth is calculated as 0.3 nm for both two cases, which is sufficiently narrow for laser wavelength selection purpose. When considering the loss of MMI (IL_{MMI} = 0.75 dB), we predict the total IL of the filter to be less than 3 dB.

III. CONCLUSION

In this paper, we propose a high-suppression-ratio tunable optical filter using cascaded apodized sampled gratings. Through Gaussian-type apodization on the duty ratio of the sampled grating periodically, the side-lobe suppression ratio can be highly reduced. The filter shows high performance, including low adjacent channel suppression ratio <-41 dB, low non-adjacent channel suppression ratio < -21.51 dB, low insertion loss > -3 dB, narrow 3 dB bandwidth < 0.3 nm, and wide FSR > 20 nm, which is a promising device on optical integration circuits for THz heterodyne system.

REFERENCES

[1] S. Cherry, "Edholm's law of bandwidth," IEEE Spectrum, vol. 41, no. 7, pp. 58-60, 2004.

[2] R. Piesiewicz, T. Kleine-Ostmann, N. Krumbholz, D. Mittleman, M. Koch, J. Schoebel, T. Kürner: "Short-Range Ultra-Broadband Terahertz Communications: Concepts and Perspectives", IEEE Antennas and Propagation Magazine, vol. 49, no. 6, pp. 24–39, 2007.

[3] T. Kleine-Ostmann, T. Nagatsuma: "A Review on Terahertz Communications Research", Journal of Infrared, Millimeter and Terahertz Waves, vol. 32, no. 2, pp. 143–171, 2011.

[4] Y. Ding, P. Minhao, L. Liu, P. Christophe, Z. Xinliang, H. Dexiu, O. Haiyan, "Bandwidth and wavelength-tunable optical bandpass filter based on silicon microring-MZI structure," Opt. Express, vol. 19, no. 7, pp. 6462-6470, 2011.

[5] H. N. Xu and Y. C. Shi, "Flat-Top CWDM (De)Multiplexer Based on MZI With Bent Directional Couplers," IEEE Photonics Tech. Lett. vol. 30, no. 2, pp. 169–172, 2018.

[6] S. Radosavljevic, N. T. Beneitez, A. Katumba, M. Muneeb, M. Vanslembrouck, B. Kuyken, et al., "Mid-infrared Vernier racetrack resonator tunable filter implemented on a germanium on SOI waveguide platform," Opt. Materials Express, vol. 8, no. 4, pp. 824-835, 2018.

[7] F. Xia, M. Rooks, L. Sekaric, and Y. Vlasov, "Ultra-compact high order ring resonator filters using submicron silicon photonic wires for on-chip optical interconnects," Opt. Express, vol. 15, no. 19, pp. 11934–11941, 2007.

[8] N. Kikuchi, Y. Shibata, H. Okamoto, Y. Kawaguchi, S. Oku, H. Ishii, et al., "Monolithically integrated 64-channel WDM channel selector with novel configuration," Electron. Lett., vol. 38, no. 7, pp. 331–332, 2002.

[9] P. Prabhathan, V. M. Murukeshan, Z. Jing, "Compact resonant Bragg-grating filters using submicron silicon-on-insulator (SOI) waveguide for optical communication network," In Optoelectronic Devices and Integration III, Vol. 7847, pp. 123-132, 2010.

[10] Y. Liu, X. Huang, H. Guan, Z. Yu, Q. Wei, Z. Fan, W. Han, and Z. Li, "C-band four-channel CWDM (de-)multiplexers on a thin film lithium niobate–silicon rich nitride hybrid platform," Opt. Lett. vol. 46, no. 19, pp. 4726–4729, 2021.

[11] J. He, D. Liu, B. Pan, Y. Huang, M. Zhu, M. Zhang, and D. Dai, "High-performance lithium-niobate-on-insulator optical filter based on multimode waveguide gratings," Optics Express, vol. 30, no. 19, pp. 34140-34148, 2022.

[12] L. M. Augustin, R. Santos, E. den Haan, S. Kleijn, P. J. A. Thijs, S. Latkowski, et al., "InP-based generic foundry platform for photonic integrated circuits," IEEE J. Sel. Top. Quantum Electron., vol 24, no. 1, pp. 1-10, 2017.

[13] X. Zou, W. Pan, B. Luo, Z. Qin, M. Wang, W. Zhang, "Periodically chirped sampled fiber Bragg gratings for multichannel comb filters," IEEE Photon. Technol. Lett., vol. 18, no. 12, pp. 1371-1373, 2006.

[14] T. Segawa, S. Matsuo, T. Ishii, Y. Oshiso, Y. Shibata, H. Suzuki, "High-speed wavelength-tunable optical filter using cascaded Mach–Zehnder interferometers with apodized sampled gratings," IEEE J. Quantum Electron., vol. 44, no. 10, pp. 922-930, 2008.

[15] A. D. Simard, N. Belhadj, Y. Painchaud, S. Larochelle, "Apodized silicon-on-insulator Bragg gratings," IEEE Photon. Technol. Lett., vol. 24, no. 12, pp. 1033-1035, 2012.