

A Compact Triplexer Based on InP/InGaAsP-MMI Coupler with Channel-Shaped Core Layer for 50G PON

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Abstract: A novel wavelength triplexer based on Channel-Shaped Multimode Interference (C-MMI) structures on the InP platform is proposed for multi-channel integration compatibility in a 50G passive optical network (PON) system. Performance analysis of the proposed device is carried out by using the 3D Beam Propagation Method (3D-BPM), which shows excellent properties with insertion loss < 0.5 dB and low crosstalk < −14 dB for the 1342 nm in the Original band (1260–1360 nm), 1490 nm in the Short wavelength band (1460–1530 nm), and 1577 nm in the Long wavelength band (1565–1625 nm), also known as the OSL wavelengths band. Furthermore, the passbands of the three downlink channels of 1342 nm, 1490 nm, and 1577 nm, reach 14 nm, 20 nm, and 64 nm, respectively, which is wide enough to meet the 50G PON optical line terminal (OLT) requirement. Additionally, the proposed device is extremely compact with a total length of only 448 μm, making it attractive in the monolithic integrated laser chip and OLT packaged module.

Keywords: multimode interference coupler; wavelength demultiplexer; beam propagation method



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1. Introduction

To meet the urgent demand for high-bandwidth services and applications such as cloud computing, ultra-high-definition video, virtual reality, and online gaming, bandwidth consumption will undoubtedly continue to accelerate in the next few years. At present, 10G Passive Optical Network (PON) architectures have been successfully commercialized on a large scale. The next generation of 50G PON technology, aiming to meet these new requirements, has been standardized and is expected to be commercially deployed around 2025 [1,2]. As the high performance and low cost have always been the key factors to determine the evolution of PON technology, 10G PON and 50G PON will coexist for a certain period in order to utilize the existing network resources as much as possible and save the cost of upgrading and evolution. The existing 10G PON Optical Line Terminal (OLT) module has two downlink channels: 1490 nm and 1577 nm. To ensure that the downlink wavelength channel of the 50G PON at 1342 nm is compatible with the 10G PON system without increasing the package size and cost of the optical module, the development of a monolithic integrated multi-wavelength laser chip capable of covering the three bands will be crucial for the 50G PON system. Therefore, a Wavelength Division (De)Multiplexer (WDM) should be introduced in the monolithic integrated laser chip to combine the 10G and 50G PON downlink channels.

Both silicon and InP platforms have been applied for fabricating WDM devices. Compared with InP-based structures, silicon-based WDMs have been extensively researched due to their high contrast refractive index ($\Delta n \approx 2.0$), which enables compact structures and compatibility with the Complementary Metal Oxide Semiconductor (CMOS) process. Heterogeneous integration of the silicon-based WDM devices with multiple InP-based laser

sources represents one possible route toward future PON system. However, the integration of heterogeneous components remains complex and costly, which are key factors in the evolution of PON systems [3]. Another route is the monolithic integration of InP-based WDM device lasers, which could effectively reduce the coupling loss, footprint, and cost of the 50G PON system.

Various approaches to WDMs have been proposed with structures based on Array Waveguide Gratings (AWGs) [4–6], Micro-Ring Resonators (MRRs) [7–12], Cascaded Mach-Zehnder Interferometers (MZIs) [13,14], Asymmetric Directional Couplers (ADCs) [15] and Multimode Interference (MMI) couplers [16–19]. Among these structures, the wavelength range of AWGs and MZIs is typically restricted by the Free Spectral Range (FSR). Covering a wide wavelength range from 1342 nm to 1577 nm in 50G PON is challenging, and the footprint is usually large, particularly on the InP platform, which has a very low refractive index contrast ($\Delta n \approx 0.2$) [6,14]. MRRs are common components for add/drop wavelength filters due to their small dimension and flexible scalability. However, a single MRR's response shape is Lorentzian-like, resulting in an extremely narrow -1 dB bandwidth. While cascading MRRs can produce a box-like function, the fabrication tolerance remains a challenge. Furthermore, the ring radius limits the FSR to the order of tens of nanometers [7]. ADC-based WDM has been demonstrated successfully on silicon platform, but its narrow waveguide gap and tight fabrication tolerance make this structure difficult to realize compact WDMs on InP platform [15]. For WDMs operating within a wavelength range exceeding 200 nm, which is required in a 50G PON system, MMI structures, which are based on the self-imaging principle [20], are attractive candidates due to their low insertion loss, large fabrication tolerance, and broad bandwidth [19]. An angled MMI-based WDM utilizing the wavelength dispersive nature of self-imaging has been experimentally demonstrated for coarse wavelength division multiplexing (CWDM) [21]. However, the total length of MMI structures exceeds 1000 μm , even when implemented on a silicon-on-insulator (SOI) platform. A wavelength triplexer utilizing cascaded MMI couplers, operating within a wavelength range exceeding 200 nm, was analyzed on an InP substrate. However, the total length exceeded 3000 μm [16]. Investigating a more compact wavelength triplexer is worthwhile to reduce the package size of the OLT module in a 50G PON system.

In this paper, we present a novel wavelength triplexer based on Channel-Shaped MMI (C-MMI) structures on InP platform for 50G PON system. The C-MMI is employed to impose a stronger constraint structure on the two sides of the multimode interference region. This approach effectively facilitates the separation of different wavelength bands. The proposed device shows very low loss, a low extinction ratio, and compact size, and it is capable of integrating with lasers monolithically, making it an attractive option for a 50G PON system. To the best of our knowledge, this is the first time that a C-MMI-based wavelength triplexer has been presented for multiplexing and demultiplexing the 1342 nm in the Original band (1260–1360 nm), 1490 nm in the Short wavelength band (1460–1530 nm), and 1577 nm in the Long wavelength band (1565–1625 nm), also known as the OSL wavelengths band.

2. Structure and Design

The operation of MMI couplers is based on the self-imaging principle. This principle allows the input field profile to be replicated, producing either direct or mirrored images alternately at intervals of every $3L_\pi$ along the propagation direction in general interference MMI couplers [20]. L_π is the beat length of the two lowest-order modes and is defined as:

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \cong \frac{4n_r W_e^2}{3\lambda_0} \quad (1)$$

where β_0 and β_1 are the propagation constants of the two lowest-order modes, respectively, $k_0 = \frac{2\pi}{\lambda_0}$, λ_0 is the free-space wavelength, and n_r is the effective refractive index of the

multimode interference region. W_e is the effective width of the MMI coupler; for TE mode, it is given by:

$$W_e = W + \frac{\lambda_0}{\pi} \left(n_r^2 - n_c^2 \right)^{-0.5} \quad (2)$$

where n_c is the cladding effective refractive index of the multimode interference region. When the two wavelengths of λ_1 and λ_2 are transmitted at the input waveguide, λ_1 can be coupled to one output waveguide, while λ_2 can be separated to the other output waveguide if the length of MMI coupler L_{MMI} are satisfied as:

$$L_{MMI} = p_1 \left(3L_{\pi}^{\lambda_1} \right) = p_2 \left(3L_{\pi}^{\lambda_2} \right) \quad (3)$$

where both p_1 should be either even or odd integers, while p_2 remains odd or even, different from p_1 .

As wavelength separation and the number of wavelength channels grow in a wave-length triplexer, the MMI's length must also extend to align with the propagation constants of waveguide modes across different wavelengths. To reduce the total device length, it is essential to reduce L_{π} , which can be realized by reducing W_e . The underlying physics minimizes the difference between the adjacent propagation constants β_0 and β_1 . Reducing the width of the MMI also decreases the number of supporting waveguide modes, which relaxes the requirement for phase matching conditions for all modes [22].

Figure 1c shows the simulation of a conventional MMI with narrowed multi-mode interference region using the 3D Beam Propagation Method (3D-BPM) with Transverse Electric (TE) polarization at an operating wavelength of 1342 nm. The MMI width is set to 2.4 μm , and the width of input waveguide is 1 μm . The cross-section of multimode interference region is plotted in Figure 1a with waveguide structure consisting of an InP buffer layer, a 300-nm InGaAsP core layer, and a 1.7- μm InP cladding layer, where the effective refractive index of InGaAsP and InP are 3.3822 and 3.167, respectively. It can be seen that the reproduction of the input field can be obtained at $L_{MMI} = 60 \mu\text{m}$. However, it can be observed that the image is confined to a very narrow length region along the transmission direction. When multiple-channel wavelengths operate simultaneously, aligning all the images at the same position along the transmission direction becomes a significant challenge.

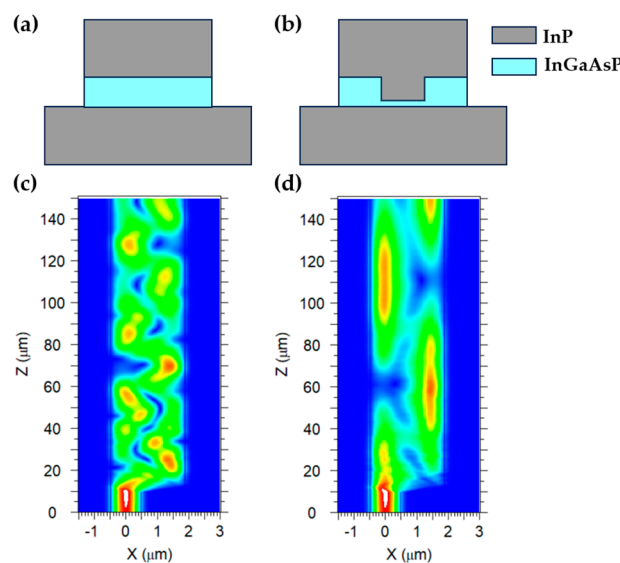


Figure 1. (a) Cross-section of common MMI coupler; (b) Cross-section of C-MMI coupler; (c) Simulated field profile of common MMI coupler; (d) Simulated field profile of C-MMI coupler.

To accommodate more wavelength channels, it is essential to develop a structure that allows the images from all channels to overlap and be confined within an extended region

along their propagation direction. Our approach is to create two mode guiding regions along the two sides of the MMI region, forming a channel-shaped core region, which is called C-MMI, and the cross-section is shown in Figure 1b. The two mode guiding regions work both as a multimode interference region to form the image, as well as a waveguide to confine the images. The C-MMI structure is simulated by using the 3D Beam Propagation Method (3D-BPM) with Transverse Electric (TE) polarization at an operating wavelength of 1342 nm. The effective refractive indexes of InGaAsP and InP are 3.3822 and 3.167, respectively, and the cover index is set to 1. The mode source is selected as the launch field, and the boundary condition is set to the full implementation of the Transparent Boundary Conditions (Full TBC) [23]. The grid sizes of the X, Y, Z directions are set to 0.02 μm , 0.01 μm , and 0.5 μm in order to have the highest mesh accuracy in the Y direction. Figure 1d shows the simulation of the proposed C-MMI design, with all the parameters kept the same with conventional MMI, except that a 1.1- μm wide channel-shaped region is etched out 200 nm at the center of the 300-nm InGaAsP core layer, which is different from the conventional MMI core layer. From the simulated results, we can see that the direct or mirrored self-images of the proposed C-MMI could be restricted effectively and maintained at larger length along the transmission direction of the proposed C-MMI due to the channel-shaped core layer enabling stronger constraints on the position of the two sides of the multimode interference region.

The proposed wavelength triplexer structure for the 50G PON system is composed of two cascaded MMI couplers with a channel-shaped core layer on the InP platform. Figure 2 shows the schematic diagram of a demultiplexing structure. In our scheme, the first MMI region (MMI 1) is designed to couple the wavelength of $\lambda_1 = 1342$ nm and $\lambda_2 = 1490$ nm into the second MMI region (MMI 2), while the wavelength of $\lambda_3 = 1577$ nm is demultiplexed by MMI 1 and exported from the Output3 directly. A channel-shaped core layer is used both in MMI 1 and MMI 2 regions to separate different wavelengths effectively and maintain the device sizes compact enough as well.

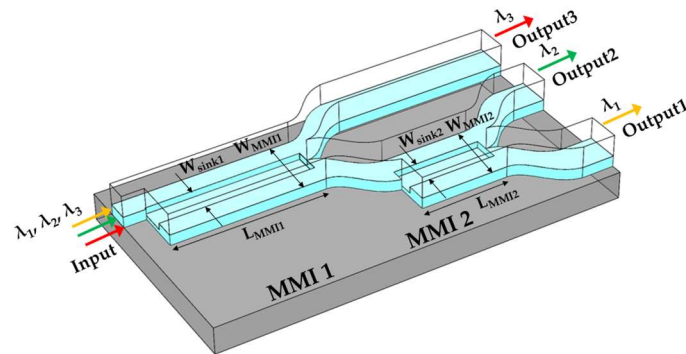


Figure 2. Schematic diagram of the proposed wavelength triplexer structure.

Firstly, the length of MMI 1 coupler L_{MMI1} is optimized, and the field distributions at the wavelengths of 1342 nm, 1490 nm, and 1577 nm are shown in Figure 3 with $W_{MMI1} = 2.4$ μm , $W_{sink1} = 1.1$ μm . As can be seen, the wavelengths of 1342 nm and 1490 nm will be collected at the right output port, while the wavelength of 1577 nm will be coupled to the left output port when L_{MMI1} is set to be 245 μm . Subsequently, the parameters of the MMI 2 coupler are optimized with $W_{MMI2} = 2.2$ μm , $L_{MMI2} = 103$ μm , and $W_{sink2} = 0.9$ μm to successfully separate the wavelengths of 1342 nm and 1490 nm.

The use of cosine-shaped S-bends with a length of 40 μm at the propagation direction facilitates the connection between MMI 1, MMI 2, and the output ports. The total length of the entire wavelength triplexer is 448 μm , which is notably shorter than previously reported InP-based triplexers. This compact InP-based wavelength triplexer is identified as a suitable solution for a 50G PON OLT module, as there is no need to increase the module's package size. Consequently, this approach significantly reduces the overall costs and implementation difficulties during the upgrade of the PON system.

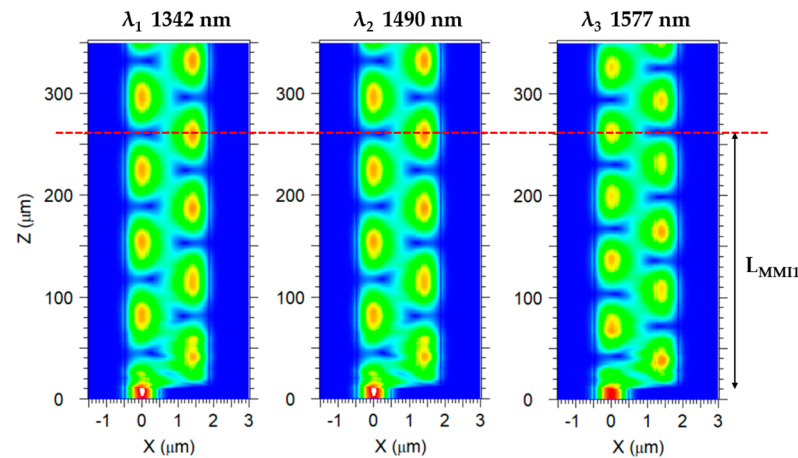


Figure 3. Field distributions of MMI 1 coupler at the wavelengths of 1342 nm, 1490 nm, and 1577 nm.

3. Simulated Results and Discussion

The simulated field distribution of the proposed wavelength triplexer for the three wavelength bands is shown in Figure 4a–c, respectively. When the fields of the 1342 nm and 1490 nm wavelengths are injected to the input port, they will be separated by the MMI 1 and MMI 2 couplers and be exported from Output1 and Output2, respectively, while the field of the 1577 nm wavelength will be separated by the MMI 1 coupler and directly coupled into Output3. The simulated insertion loss of the 1342 nm, 1490 nm, and 1577 nm wavelengths are as low as 0.23 dB, 0.29 dB, and 0.17 dB, respectively. The crosstalk for these three wavelengths are below -14.79 dB, -14.36 dB, and -14.27 dB, while the extinction ratios are as low as -14.06 dB, -13.06 dB, and -19.29 dB, respectively. The low insertion loss and high extinction ratio demonstrate the excellent performance for the device in transmitting and demultiplexing different wavelengths.

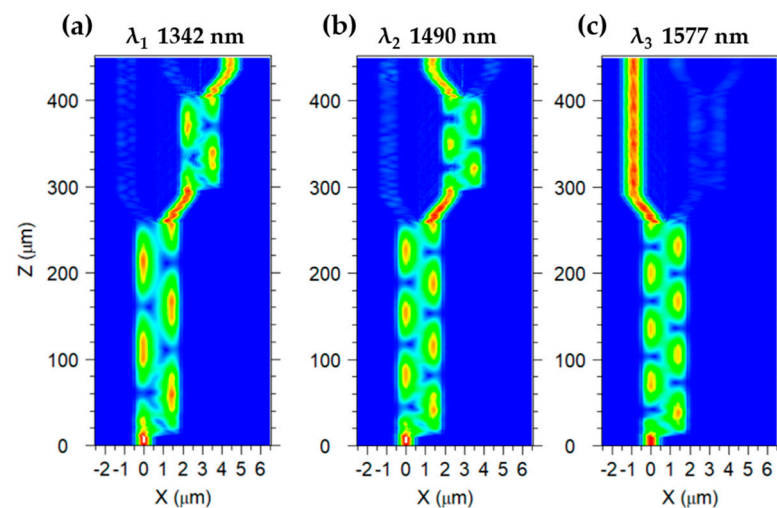


Figure 4. Simulated field distribution of the proposed wavelength triplexer for (a) 1342 nm, (b) 1490 nm, (c) 1577 nm.

Optical bandwidth is an extremely important parameter for the wavelength triplexer, as it determines whether or not the structure is accepted by the 50G PON application. Figure 5 shows the wavelength responses of Output1, Output2, and Output3 of the wavelength triplexer. The simulated data indicate that the insertion losses of 1 dB bandwidth for the 1342 nm, 1490 nm, and 1577 nm bands correspond to 14 nm (ranging from 1337 nm to 1351 nm), 20 nm (ranging from 1482 nm to 1502 nm), and 64 nm (ranging from 1555 nm to 1619 nm), respectively. Additionally, the extinction ratio in these bands remains below -10 dB. Therefore, the wavelength triplexer's operation bands are wide enough to cover

the bandwidths of all three downlink channels of 50G PON OLT with 2 nm at 1342 nm, 20 nm at 1490 nm, and 5 nm at 1577 nm.

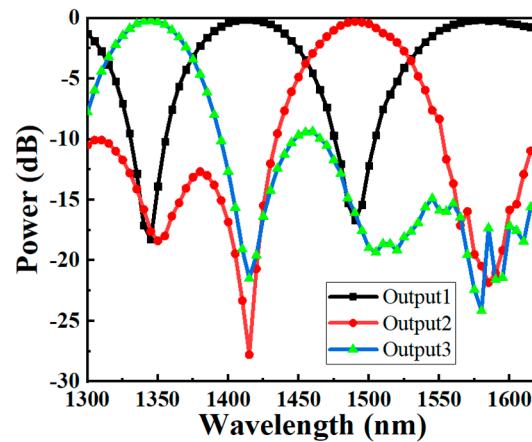


Figure 5. Wavelength response of Output1, Output2, and Output3 of the proposed wavelength triplexer.

The fabrication tolerance of the designed C-MMI based wavelength triplexer is also analyzed, and the widths of MMI couplers and their channel-shaped regions, which have the most rigorous fabrication requirements, are considered firstly. The simulated results of the ΔW_{MMI1} , ΔW_{MMI2} , ΔW_{sink1} , and ΔW_{sink2} are illustrated in Figure 6a–d, respectively. The acceptable window for triplexer performance is an insertion loss of less than 1 dB and an extinction ratio below -10 dB. It is evident that the fabrication error of ΔW_{MMI1} and ΔW_{MMI2} are the most critical design parameters, with a range of only ± 10 nm and -40 nm $\sim$ 15 nm. However, this can be compensated for by designing different lengths of the multimode interference regions. Fortunately, the widths of the channel-shaped regions in the MMI 1 and MMI 2 couplers have larger fabrication tolerances, ranging from -60 nm to 50 nm and -280 nm to 120 nm, respectively.

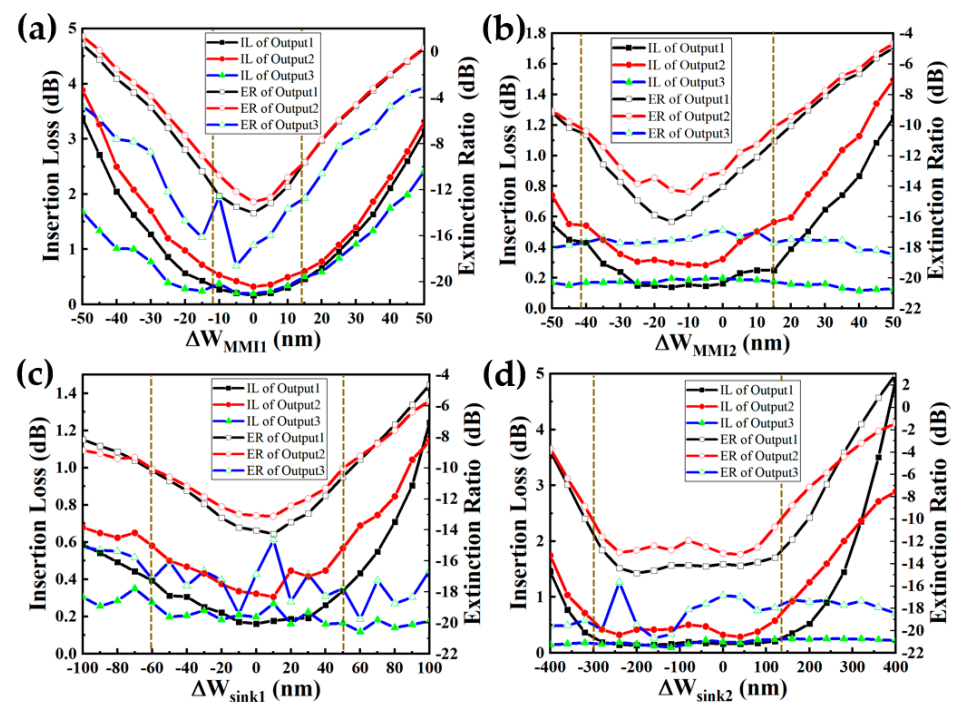


Figure 6. Fabrication tolerance of (a) MMI 1 width; (b) MMI 2 width; (c) MMI 1 channel-shaped region width; (d) MMI 2 channel-shaped region width.

Compared to the width of MMI couplers and their channel-shaped regions, the fabrication tolerance of the multimode interference lengths is more relaxed. The length errors of L_{MMI1} and L_{MMI2} are shown in Figure 7a,b, respectively. Simulation data show that when the insertion loss is less than 1 dB and the extinction ratio is below -10 dB, the length errors of MMI 1 and MMI 2 couplers from the optimal value are within the range of $\pm 4 \mu\text{m}$ and $-2.5 \mu\text{m} \sim 5.5 \mu\text{m}$, respectively, demonstrating a more relaxed fabrication tolerance.

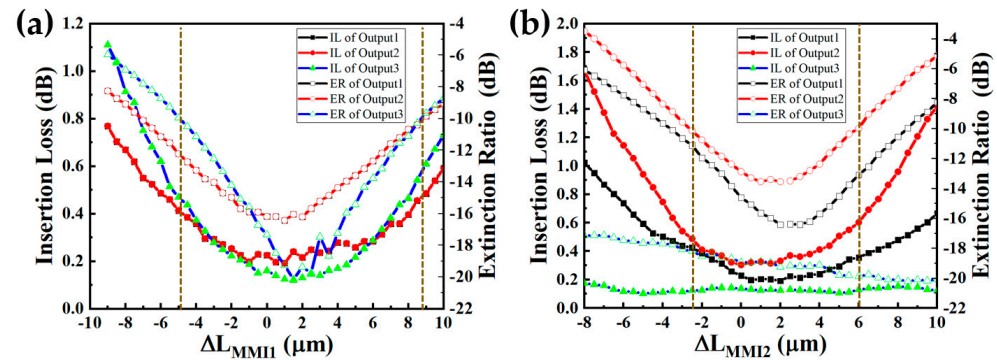


Figure 7. Fabrication tolerance of (a) MMI 1 length; (b) MMI 2 length.

Finally, the proposed structure of this work is compared with several existing MMI-based WDM for more than three channels on different platforms that have been previously published, and the key performance is summarized in Table 1. The proposed C-MMI structure demonstrates excellent performance with an extremely low loss of less than 0.5 dB and low crosstalk below -14 dB. Additionally, it has a very compact size even on InP platforms with a much smaller refractive index difference than silicon. In addition, the suggested WDM device can support other optical wavelength bands, such as the C-band, by combining two or more C-MMI structures. Therefore, it is possible to cover the entire optical communication band, making it suitable for widespread use in WDM systems as well.

Table 1. Comparison of MMI-based WDM for larger than three channels on different platforms.

Material	Wavelength Band	Crosstalk (dB)	Insertion Loss (dB)	Length (μm)	Channels	Ref.
SOI	C-	< -25	< 1	4700	4-channel	[24]
InGaAsP/InP	O-S-C	-	< 3	2933	3-channel	[16]
Silica	O-	< -19	< 1.6	17,480	4-channel	[25]
Silicon	980, O-S-C	-	< 2	712.6	4-channel	[18]
Silicon	O-S-C	< -14	< 3	800	3-channel	[19]
InGaAsP/InP(C-MMI)	O-S-L	< -14	< 0.5	448	3-channel	this work

4. Conclusions

In this paper, we propose a novel wavelength triplexer based on C-MMI structures on the InP platform for the 50G PON system. By etching a channel-shaped region in the center of a MMI coupler, direct or mirrored self-images could be restricted effectively and maintained at larger length along the transmission direction of the multimode interference region due to the channel-shaped core layer enabling stronger constraints on the position of the two sides of the multimode interference region. The proposed device shows excellent performance with an extremely low loss of less than 0.5 dB and low crosstalk below -14 dB for the OSL wavelengths band. The bandwidths of the three downlink channels of 1342 nm, 1490 nm, and 1577 nm can reach 14 nm, 20 nm, and 64 nm, respectively, which are wide enough to meet the 50G PON OLT requirement. More importantly, the length of the whole wavelength triplexer is only 448 μm , which is much shorter than many wavelength triplexers that were previously reported. Additionally, the fabrication tolerance of the

MMI width, the channel-shaped region width, and the MMI length is also analyzed. The proposed wavelength triplexer with its compact size, superior performance, and ability to integrate with lasers monolithically makes it a promising candidate to serve as a monolithic integrated laser chip in the 50G PON system.

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References

1. Bonk, R.; Geng, D.; Khotimsky, D.; Liu, D.; Liu, X.; Luo, Y.; Nettet, D.; Oksman, V.; Strobel, R.; Van Hoof, W.; et al. 50G-PON: The First ITU-T Higher-Speed PON System. *IEEE Commun. Mag.* **2022**, *60*, 48–54. [\[CrossRef\]](#)
2. Zhang, D.; Luo, Y.; Jin, J. Highspeed 50 Gb/s Passive Optical Network (50G-PON) Applications in Industrial Networks. In Proceedings of the 2022 IEEE 23rd International Conference on High Performance Switching and Routing (HPSR), Taicang, China, 6–8 June 2022; pp. 113–118.
3. Wei, W.-Q.; He, A.; Yang, B.; Wang, Z.-H.; Huang, J.-Z.; Han, D.; Ming, M.; Guo, X.; Su, Y.; Zhang, J.-J.; et al. Monolithic Integration of Embedded III-V Lasers on SOI. *Light Sci. Appl.* **2023**, *12*, 84. [\[CrossRef\]](#)
4. Chen, S.; Fu, X.; Wang, J.; Shi, Y.; He, S.; Dai, D. Compact Dense Wavelength-Division (De)Multiplexer Utilizing a Bidirectional Arrayed-Waveguide Grating Integrated with a Mach-Zehnder Interferometer. *J. Light. Technol.* **2015**, *33*, 2279–2285. [\[CrossRef\]](#)
5. Wang, J.; Sheng, Z.; Li, L.; Pang, A.; Wu, A.; Li, W.; Wang, X.; Zou, S.; Qi, M.; Gan, F. Low-Loss and Low-Crosstalk 8×8 Silicon Nanowire AWG Routers Fabricated with CMOS Technology. *Opt. Express* **2014**, *22*, 9395–9403. [\[CrossRef\]](#)
6. Lin, X.; Lang, T.; He, J.-J. Design Analysis and Experimental Verification of Cross-Order AWG Triplexer Based on Silica-on-Silicon. *J. Light. Technol.* **2011**, *29*, 1407–1413. [\[CrossRef\]](#)
7. Uddin, M.R.; Yazid, M.; Law, F.K.; Rashidi, C.B.M. Characterizations of Cascaded Micro-Ring Resonators. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *767*, 012028. [\[CrossRef\]](#)
8. Chen, P.; Chen, S.; Guan, X.; Shi, Y.; Dai, D. High-Order Microring Resonators with Bent Couplers for a Box-like Filter Response. *Opt. Lett.* **2014**, *39*, 6304–6307. [\[CrossRef\]](#)
9. Carvalho, W.O.F.; Mejía-Salazar, J.R. Magneto-Optical Micro-Ring Resonators for Dynamic Tuning of Add/Drop Channels in Dense Wavelength Division Multiplexing Applications. *Opt. Lett.* **2021**, *46*, 2396–2399. [\[CrossRef\]](#)
10. Cohen, R.A.; Amrani, O.; Ruschin, S. Response Shaping with a Silicon Ring Resonator via Double Injection. *Nat. Photon* **2018**, *12*, 706–712. [\[CrossRef\]](#)
11. Neto, J.V.S.; Carvalho, W.O.F.; Mejía-Salazar, J.R. Magnetically Tunable Micro-Ring Resonators for Massive Magneto-Optical Modulation in Dense Wavelength Division Multiplexing Systems. *Sensors* **2022**, *22*, 8163. [\[CrossRef\]](#)
12. Seifouri, M.; Fallahi, V.; Olyaei, S. Ultra-High-Q Optical Filter Based on Photonic Crystal Ring Resonator. *Photon Netw. Commun.* **2018**, *35*, 225–230. [\[CrossRef\]](#)
13. Horst, F.; Green, W.M.J.; Assefa, S.; Shank, S.M.; Vlasov, Y.A.; Offrein, B.J. Cascaded Mach-Zehnder Wavelength Filters in Silicon Photonics for Low Loss and Flat Pass-Band WDM (de)Multiplexing. *Opt. Express* **2013**, *21*, 11652–11658. [\[CrossRef\]](#)
14. Xu, H.; Liu, L.; Shi, Y. Polarization-Insensitive Four-Channel Coarse Wavelength-Division (de)Multiplexer Based on Mach-Zehnder Interferometers with Bent Directional Couplers and Polarization Rotators. *Opt. Lett.* **2018**, *43*, 1483–1486. [\[CrossRef\]](#)
15. Zhu, L.; Sun, J. Silicon-Based Wavelength Division Multiplexer by Exploiting Mode Conversion in Asymmetric Directional Couplers. *OSA Contin.* **2018**, *1*, 92–103. [\[CrossRef\]](#)
16. Chack, D.; Kumar, V.; Raghuvanshi, S.K.; Singh, D.P. Design and Analysis of O-S-C Triple Band Wavelength Division Demultiplexer Using Cascaded MMI Couplers. *Opt. Commun.* **2017**, *382*, 324–331. [\[CrossRef\]](#)
17. Truong, C.D.; Tran, T.A.; Tran, D.H. A Design of Triplexer Based on a 2×2 Butterfly MMI Coupler and a Directional Coupler Using Silicon Waveguides. *Opt. Commun.* **2014**, *312*, 57–61. [\[CrossRef\]](#)
18. Khalilzadeh, H.; Bahrami, A.; Badri Ghavifekr, H. MMI-Based All-Optical Four-Channel Wavelength Division Demultiplexer. *Photon Netw. Commun.* **2018**, *36*, 217–223. [\[CrossRef\]](#)

19. Truong, D.C.D.; Nguyen, D.H. A Compact Triplexer Based on Cascaded Three Tilted MMI Couplers Using Silicon Waveguides. In Proceedings of the 2017 4th NAFOSTED Conference on Information and Computer Science, Hanoi, Vietnam, 24–25 November 2017. [[CrossRef](#)]
20. Soldano, L.B.; Pennings, E.C.M. Optical Multi-Mode Interference Devices Based on Self-Imaging: Principles and Applications. *J. Light. Technol.* **1995**, *13*, 615–627. [[CrossRef](#)]
21. Hu, Y.; Jenkins, R.M.; Gardes, F.Y.; Finlayson, E.D.; Mashanovich, G.Z.; Reed, G.T. Wavelength Division (de)Multiplexing Based on Dispersive Self-Imaging. *Opt. Lett.* **2011**, *36*, 4488–4490. [[CrossRef](#)]
22. Li, Z.; Huang, X.; Liu, Y.; Kuang, Y.; Guan, H.; Tian, L.; Li, Z.; Han, W. Ultra-Compact Low-Loss Variable-Ratio 1×2 Power Splitter with Ultra-Low Phase Deviation Based on Asymmetric Ladder-Shaped Multimode Interference Coupler. *Opt. Express* **2020**, *28*, 34137–34146. [[CrossRef](#)]
23. Yevick, D.; Hermansson, B. New Formulations of the Matrix Beam Propagation Method: Application to Rib Waveguides. *IEEE J. Quantum Electron.* **1989**, *25*, 221–229. [[CrossRef](#)]
24. Hu, Y.; Gardes, F.Y.; Thomson, D.J.; Mashanovich, G.Z.; Reed, G.T. Coarse Wavelength Division (de)Multiplexer Using an Interleaved Angled Multimode Interferometer Structure. *Appl. Phys. Lett.* **2013**, *102*, 251116. [[CrossRef](#)]
25. Zeng, G.; Yin, Y.; Ding, Y.; Yang, J.; Yan, J.; Sun, X.; Zhang, D. Temperature-Insensitive and Fabrication-Tolerant Coarse Wavelength Division (de)Multiplexing on a Silica Platform Using an Angled Multimode Interferometer. *Opt. Express* **2023**, *31*, 21161–21171. [[CrossRef](#)] [[PubMed](#)]

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