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Low-Power-Consumption and Broadband 16-Channel Variable Optical Attenuator Array Based on Polymer/Silica Hybrid Waveguide

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Abstract: A variable optical attenuator (VOA) is a crucial component for optical communication, especially for a variable multiplexer (VMUX) and reconfigurable optical add-drop multiplexer (ROADM). With the capacity increasing dramatically, a large-port-count and low-power-consumption VOA array is urgent for an on-chip system. In this paper, we experimentally demonstrate a 16-channel VOA array based on a polymer/silica hybrid waveguide. The proposed array is able to work over C and L bands. The VOA array shows an average attenuation larger than 14.38 dB with a low power consumption of 15.53 mW. The low power consumption makes it possible to integrate silica-based passive devices with a large port count on-chip.

Keywords: integrated optics; polymer; optical switch; VOA; ROADM



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1. Introduction

With the application of cloud computing and the Internet of Things (IoTs), the demand for high capacity, flexible, and power-efficient optical networks is increasing. A reconfigurable optical add/drop multiplexer (ROADM) [1], an effective tool for multiplex signals along with wavelengths in one channel, has been widely researched, and it urgently needs to be extended to more channels. To achieve dynamic control and preserve power uniformities across all signal channels, a variable optical attenuator (VOA) array is always integrated with arrayed waveguide grating (AWG) [2] to conduct variable attenuator multiplexer/demultiplexer (VMUX/VDMUX), which is a crucial component of ROADM. Recently, significant progress has been made regarding VOA arrays based on different material platforms, including silicon-on-insulator (SOI) [3–5], silicon nitride (SiN) [6,7] and silica-based planar lightwave circuits (PLCs) [8,9]. Benefiting from a large index difference between the core and cladding, silicon photonic (SiPh) with a compact footprint is suitable for large-scale integration. However, the nanoscale waveguide geometry contributes a low coupling efficiency and low fabrication tolerance. Silicon nitride, as a candidate of silicon, shows low loss and high fabrication tolerance. Combining the high-efficiency modulation of silicon and the excellent passive property of SiN, the SiN-on-SOI platform, a three-dimensional (3D) photonics integration circuit (PIC), has been widely accepted for optical phase array and optical interconnection. This complex fabrication requires expensive equipment, making it difficult to use for commercial purposes. Low propagation loss, polarization independence, and a high coupling efficiency make silica-based PLC available commercially. However, a lot of effort have been made to reduce silica-based VOA power consumption. Due to the low thermo-optical coefficient (TOC) of silica, silica-based devices

need to consume a lot of power to achieve reconfiguration [10]. However, optical devices, such as a microring resonator [11], AWG [12], and waveguide bragg grating [13], are easily influenced as the temperature of the chip increases. To realize a power-efficient and large-scale integration optical device, low power consumption is necessary and important to prevent central wavelength shifts and power consumption in a thermo-electric cooler (TEC) [14,15]. Polymer-based PLCs with TOCs one order higher than silica-based ones have been considered to solve the issues of high port count VOA and switch array [16,17]. To integrate AWG, the operating wavelength range of the VOA must be wide enough for wavelength-division multiplexing (WDM) scenarios [18,19]. In this paper, we propose a 16-channel VOA based on a polymer/silica hybrid waveguide with low power consumption and a broadband property. The VOA unit consists of two broadband conventional multimode interferences (MMIs) and connecting waveguides. A Mach-Zehnder interferometer (MZI)-based VOA shows an attenuation exceeding 14.38 dB at 1550 nm for each channel and power as low as 15.53 mW over a C + L communication band.

2. Design and Simulation

Figure 1a shows the schematic of the waveguide cross section. The refractive index of the upper cladding on polymethyl-methacrylate (PMMA) is 1.4761 at 1550 nm, and the down cladding with a refractive index of 1.4456 at 1550 nm is made of SiO₂. The core layer, SU-8 (Microchem Corporation, Newton, MA, USA), with a refractive index of 1.5802, is commercially available. The simulation result obtained using the three-dimensional beam propagation method (3D-BPM) algorithm indicates that waveguides with dimensions of 3 $\mu\text{m} \times 3 \mu\text{m}$ can support fundamental and one-order mode propagation. Taking fabrication tolerance into consideration, we choose these dimensions as the core geometry. Additionally, SiO₂ possesses a high thermal coefficient ($1.4 \text{ W} \times \text{K}^{-1} \text{ m}^{-1}$), which can enhance the response speed of the device. A 15 μm thick silica buffer layer is grown through thermal oxidation on a silicon substrate. Then, SU-8 film is spin-coated and developed to form waveguides. After that, a PMMA upper cladding covers the cores. At last, the aluminum (Al) microheater is fabricated above the PMMA cladding. The VOA is diced and polished. The cross section is smooth and clear, as shown in the scanning electron microscopy (SEM) image in Figure 1b.

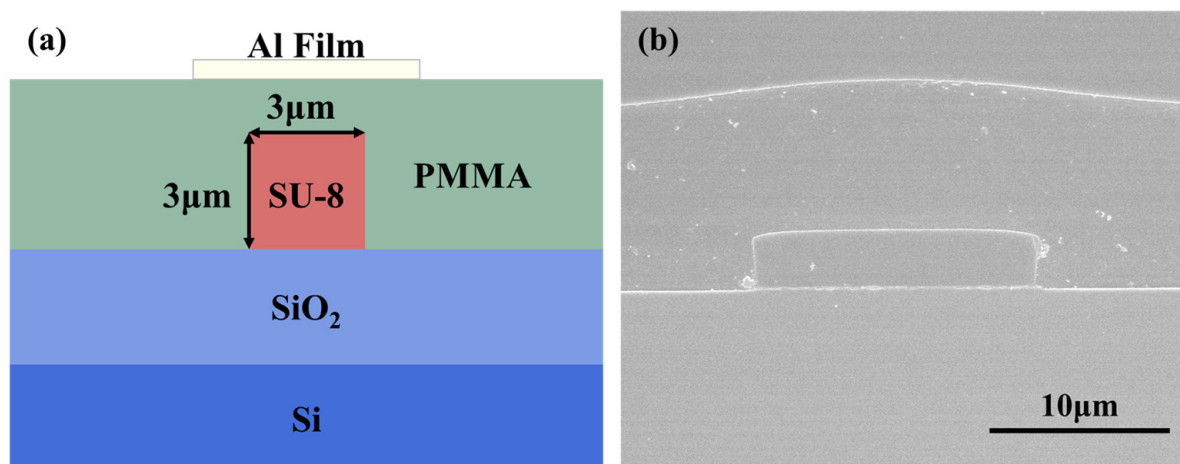


Figure 1. (a) The schematic of the cross section of the polymer/silica hybrid waveguide. (b) A scanning electron microscopy (SEM) image of the waveguide (2300 $\times$).

A schematic of the optimized MMI is shown in Figure 2a. The width of the MMI (W_{MMI}) is 25 μm . To achieve a 3 dB splitter, the length of the MMI (L_{MMI}) is optimized to 332 μm . To decrease the loss caused between the coupling region and single waveguide, linear tapers are introduced between the input and output waveguides from 3 μm (W_1) to 4.6 μm (W_2) with a length (L_{taper}) of 5.5 μm . The gap (W_3) between two output tapers is

8.3 μm . The simulated spectra are shown in Figure 2b. Balance between the two output ports ensures high attenuation and low loss for VOA. The excess loss of MMI is 0.05 dB. The simulated spectra of the MMI show an ability to operate over a wide bandwidth of wavelengths.

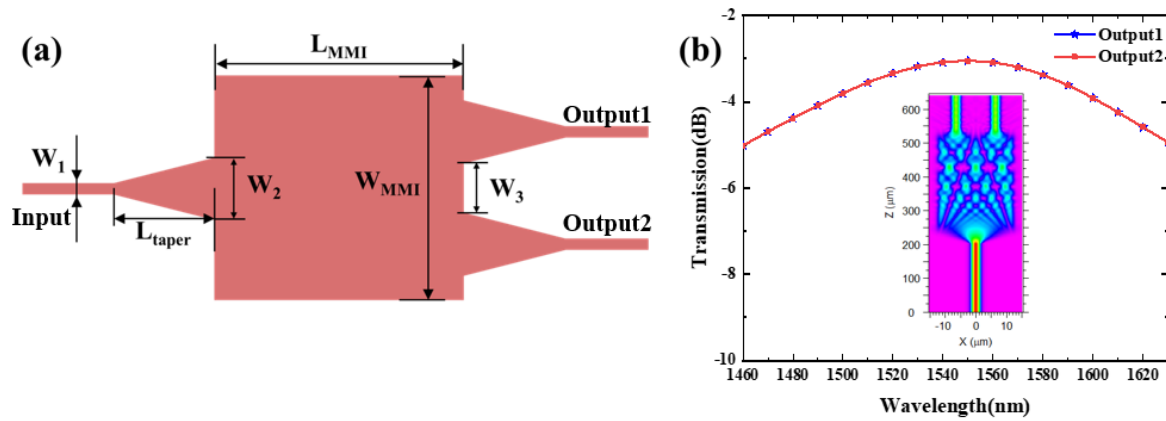


Figure 2. (a) A schematic of the MMI; (b) the simulated spectra of the MMI insert with a simulated light distribution at 1550 nm.

Figure 3a presents a simulation relationship between transmission and temperature change on the left arm. The simulation, conducted at a wavelength of 1550 nm, reveals that the maximum optical attenuation occurs at a temperature change of 2.2 K. The simulated light distributions are depicted in the insert of Figure 3a. Subsequently, simulated spectra under temperatures at 0 K and 2.2 K are depicted in Figure 3b. The simulation indicates that the proposed structure achieves a minimum extinction ratio of 18.56 dB across the entire S + C + L band. The largest attenuation of 69 dB occurs at 1558 nm. Due to limitations in testing conditions, subsequent tests are conducted only within the range of 1500 nm to 1630 nm. Nonetheless, the operating wavelength range is able to span the entire C + L band.

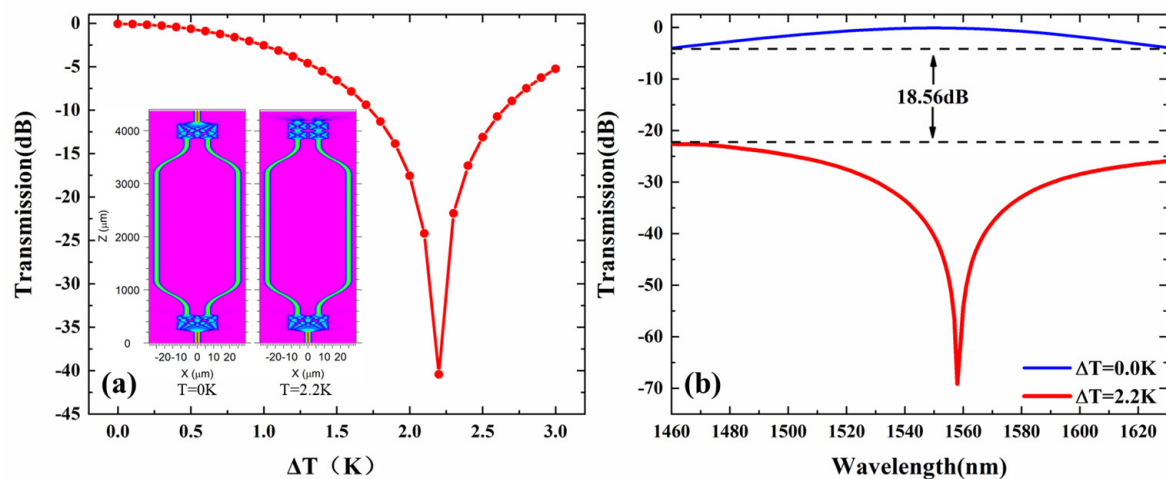


Figure 3. (a) Simulated transmission versus modulation arm temperature change; insert: simulated field distributions of VOA while temperatures of arm are 0 and 2.2 K. (b) Simulated spectra of VOA; temperature changes in modulation arm are 0 and 2.2 K.

3. Fabrication and Characterizing

Figure 4 shows the process flow diagram of the VOA array. After cleaning, using acetone, ethanol, isopropanol, and deionized water (DI water), the silicon wafer with a 15 μm thick layer of silicon dioxide is baked to remove residual moisture. Subsequently, an air plasma treatment is performed for one minute to enhance surface adhesion, followed

by spin-coating a 3 μm thick layer of SU-8 2002 on the wafer. Soft bake at 100 $^{\circ}\text{C}$ for 3 min is conducted to dry the solvent in the photoresist, and the photoresist is then exposed using a lithography machine (peak emission wavelength: 365 nm; irradiance: 15 mW/cm², ABM-USA, Inc., San Jose, CA, USA) with an energy of 70 mW/cm². Post-exposure baking at 100 $^{\circ}\text{C}$ for 3 min is carried out to induce a crosslinking reaction. Subsequently, development is performed for one minute using PGMEA (from Microchem Corporation, Newton, MA, USA), and then the developed photoresist is cleaned with isopropanol. Following a hard bake at 120 $^{\circ}\text{C}$ for 30 min, a 7 μm thick PMMA cladding is spin-coated and thermally cured. A 500 nm thick Al film is thermally evaporated over the upper cladding. After completing the on-wafer processing, edge polishing is performed. Initially, 353ND thermosetting glue is used to attach 0.3 mm thick glass cover plates to both ends of the chip, preventing the deformation of the waveguides due to fixture-induced stress during subsequent polishing processes. The poorly shaped waveguides at the chip's edge are cut using a dicing saw (NANO 150 g dicing saw, NDS, Taichung, Taiwan), reducing the subsequent grinding time. Grinding is carried out for 10 min at 15 rpm on a glass plate with the addition of alumina powder and water as abrasives. Polishing with silicon dioxide polishing liquid on a polyurethane pad for one hour is followed by rinsing and wiping both ends with ethanol-dipped lint-free cotton swabs. Edge polishing removes edge defects and scratches, improves surface quality to minimize coupling losses, and reduces the appearance of resonance peaks [20]. The performance of the fabricated devices is characterized by using single-mode optical fibers (SMFs) in edge-coupling configuration. The signal light from a laser (TSL-550, Santec, Komaki, Japan) is input into the device through a polarization controller, and the output is split into a photodetector (PD) and an optical power meter (MPM200, Santec, Komaki, Japan) using a 3 dB splitter. The PD is connected to the data acquisition (DAQ) system to observe the variation in optical power with modulation voltage, providing a straightforward method to test the extinction ratio of the device. Modulation is achieved using heaters above arms by applying voltages using a source (Keithley 2450, Tektronix, Beaverton, OR, USA).

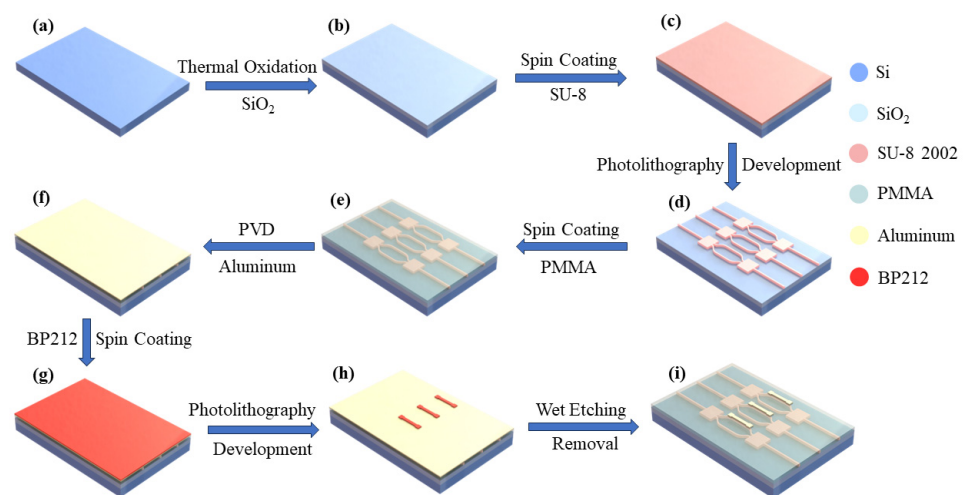


Figure 4. (a–i) The process flow diagram of the VOA array.

Figure 5a presents a top view under a microscope, offering a clear depiction of the MMI-MZI structure, with Al heaters fabricated on the single arms of the MZI. The VOA consists of two symmetric 8-channel sub-VOA arrays. An edge coupler linearly enlarges the width from 3 μm to 16 μm with a 200 μm length taper. The waveguide spacing is set to 127 μm to be packaged with the fiber array (FA). The final dimensions of the device are 5 mm $\times$ 2 mm. For illustrative purposes, the spectra from the VOA array of channel 4 is presented in Figure 5b. More than 15 dB of optical attenuation is realized over the whole testing length, reaching 17.96 dB at 1550 nm with a minimal voltage requirement of 2.3 V. The voltage–current (V-I) curves of the device are shown in Figure 5c. Well linear fitting

indicates a calculated resistance of 348 Ω . According to the current shown in Figure 5c, the power consumption of VOA is 15.53 mW. Figure 5d summarizes the measurement result for all channels. The device exhibits an average extinction ratio (ER) of 19.63 dB and an average insertion loss of 15.2 dB across all 16 channels. An ER exceeding 14.38 dB is achieved across all channels at 1550 nm. The insertion loss and uniform can be improved with angle adjustment and the packaging of FA.

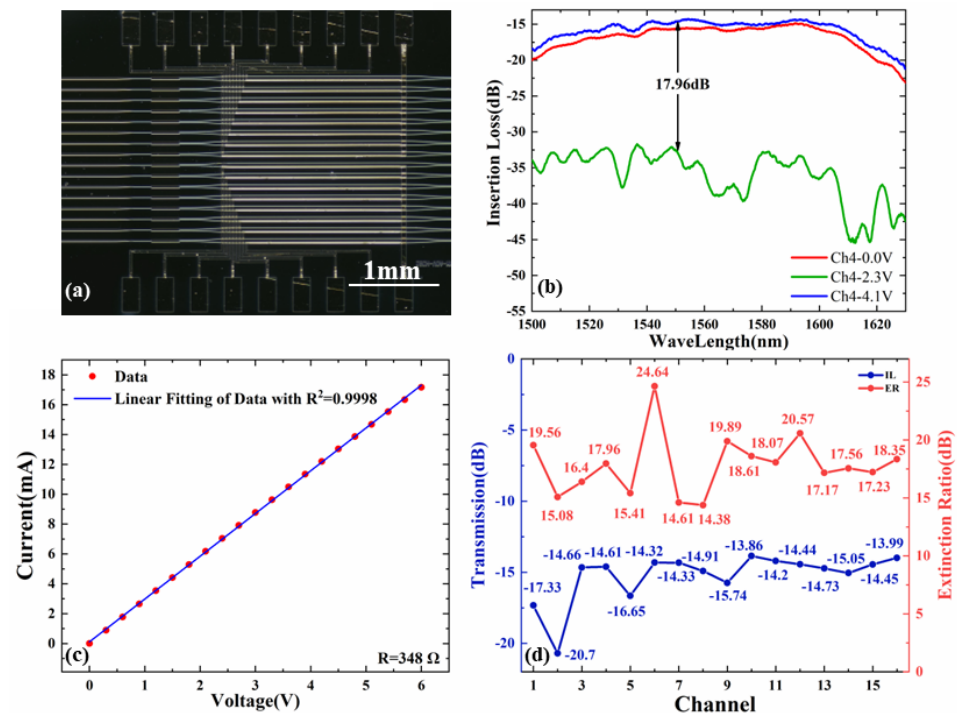


Figure 5. (a) A picture of the VOA array from the top view; (b) the spectra of the single VOA; (c) the voltage–current (V-I) curves; (d) a parameter summary of all channels.

4. Discussion

In recent years, the rapid development of photonics has led to notable advancements in VOA and VOA arrays, characterized by reduced insertion loss and power consumption, an increased channel count, and enhanced integration capabilities. The development of a commercial VOA [21] has played a crucial role in advancing polymer photonics. This development not only highlights the growing significance of VOA devices but also showcases their substantial commercial potential. However, owing to the inherent characteristics of different material platforms, each one exhibits distinct advantages in device performance. A comparative analysis of recent developments in VOA is shown in Table 1.

A large difference between the core and cladding contributes to the nano-scale geometry waveguide on the silicon photonics platform [3,22]. The low coupling loss and high polarization dependence make the SOI far from being able to be used commercially. In ref. [3], two types of electro-absorption (EA) VOAs are demonstrated. It should be noted that the theory of EA VOA based on SOI is different from what we proposed in this paper. The SOI-based VOA shows a compact footprint and can be integrated with microelectronics devices for short-term communications, such as high-performance computers and optical interconnections. A high extinction ratio (ER) can be achieved. However, hundreds of mW and tens of voltages are hard to accept.

As a commercially available platform, a silica-based PLC is well optimized to realize a low-power-consumption VOA array [10,18,23,24]. Mature fabrication and package technology make a silica-based VOA array uniform and stable. The uniform and low coupling loss of 0.4 dB/point by the periodically segmented waveguide (PSW) make the VOA promising for commercial use. However, even with the air isolation and bent waveguides introduced

in [10], the power consumption is around 100 mW due to the material's TOC. In [25,26], all polymer VOAs with low power consumption and low coupling loss are demonstrated. To achieve a high coupling efficiency, the difference between the polymer core and cladding should be small enough to enlarge the waveguide geometry, which leads to a large bent radius and footprints, limiting its potential for monolithic integration with AWG. In our previous work [15], a broadband and low-power-consumption VOA was demonstrated on an O band. A large difference between the core and cladding makes the VOA compact. Unfortunately, a large channel count is not achieved. In this work, we demonstrated a 16-channel VOA array based on a polymer/silica platform. The wavelength range and channel number make it possible to integrate it with a dense wavelength division multiplexing (DWDM) system. The power consumption is one order magnitude lower than silica, which makes it attractive for a large port count.

Table 1. A comparison of the VOA and VOA array.

Ref.	Platform	IL (dB)	ER (dB)	PC (mW)	Work Range (nm)	Size	Ch
[3]	SOI	4.54 4.87	59.08 (3.2 V) 60.11 (33 V)	292.6 mW (29.71 dB) 486 mW (29.77 dB)	1550	N.A.	1
[22]	SOI	0.5	20	60.74 mW	1544–1556	2.9 mm × 1 mm (With AWG)	16
[18]	Silica	0.04 (Sim)	20–26	6–8 V	1536.5–1560.5	N.A.	16
[23]	Silica	3.2–3.9	20	110	1530–1560	25 mm × 25 mm	40
[10]	Silica	0.8	15	98	N.A.	N.A.	24
[24]	Silica	1.6	10	160	1520–1620	15 μm × 10 μm	24
[25]	Polymer	0.7–0.9	41	17	1550	10 mm × 7 mm	10
[26]	Polymer	~1	25	25	1525–1560	220 mm × 135 mm (With ROADM)	40
[15]	Polymer/Silica	12.43	23.65	8.72	1260–1360	N.A.	1
This work	Polymer/Silica	15.2	15.5 (C + L)	15.53	1500–1630	5 mm × 2 mm	16

IL, insertion loss; ER, extinction ratio; PC, power consumption; N.A., not applicable; Ch, channel.

The polymer we used has a large refractive index difference ($\Delta = 6.37\%$), contributing to the compact geometry of the waveguide and devices. However, the compact size results in a large mismatch with a normal single fiber. A silica-based spot size converter (SSC) with PSW achieved a low loss of 1.59 dB [27]. We believe using a polymer-based SSC with a high amount of NA fiber will solve the coupling loss problem. Another issue of high loss is caused by the polymer material itself. Fluorinated polymer, with the C-F bond replacing the C-H bond in the molecular structure, effectively reduces the absorption loss of the material in the near-infrared wavelength band [28]. Additionally, we can replace the propagation waveguide with silica or silicon nitride to achieve a hybrid integration switch with low loss and low power consumption [29]. In brief, integrating PLC foundry with silica is a good choice to make the polymer fabrication process stable and mature.

Furthermore, in Figure 5b, it can be observed that at a voltage of 4.1 V, the insertion loss of the device is lower than that at 0 V. This discrepancy is attributed to the non-zero initial phase caused by process tolerances, presenting a challenge that needs to be addressed in the future development of this structure. Ref. [30] proposes a straight polymer waveguide with a perpendicular carbon nanotube (CNT) trench, which may solve the problem, but its uniformity is not enough for arrays. In addition, structures with a large refractive index difference can improve process tolerance, but this inevitably increases the device's size, contradicting the vision of integration. In order to reduce power consumption, optimizing electrodes is one of the future research directions. However, according to ref. [31], the length of the electrodes has a negligible effect on the power consumption of the device, and the main influencing factors are the electrodes and the material used in the device itself. The costs and processing advantages of polymer systems are evident. The low cost and simplicity of the manufacturing process make polymer-based devices economically efficient. Looking forward, advancements in polymer platforms could benefit from meticulous

polishing, the incorporation of air isolation slots, and the adoption of PSW structures to enhance the device's performance.

5. Conclusions

In conclusion, this paper demonstrates a 16-channel VOA array based on a polymer/silica waveguide platform. By enabling optical signal attenuation and equalization for 16 channels, the device achieves high integration coupled with low power consumption and a wide operational wavelength range. The power consumption is 15.53 mW, with each unit achieving an extinction ratio exceeding 14.38 dB at 1550 nm, covering the entire C+L band, and only occupying a size of 5 mm × 2 mm. The device exhibits excellent uniformity and low costs and holds significant application prospects and commercial value.

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References

1. Sgambelluri, A.; Izquierdo-Zaragoza, J.-L.; Giorgetti, A.; Gifre, L.; Velasco, L.; Paolucci, F.; Sambo, N.; Fresi, F.; Castoldi, P.; Piat, A.C.; et al. Fully Disaggregated ROADM White Box with NETCONF/YANG Control, Telemetry, and Machine Learning-based Monitoring. In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 11–15 March 2018; OSA: San Diego, CA, USA, 2018; p. Tu3D.12.
2. Yuan, P.; Wang, Y.; Wu, Y.; An, J.; Zhu, L. Monolithic integration of a wavelength division multiplexer/demultiplexer and electro-absorption VOAs based on 3 μm -SOI. *Infrared Laser Eng.* **2019**, *48*, 818004. [[CrossRef](#)]
3. Huang, Y.; Lu, L.; Chen, G.; Xu, Y.; Zhu, L. Design and optimization of an SOI-based electro-absorption-type VOA. *Appl. Opt.* **2023**, *62*, 6316. [[CrossRef](#)] [[PubMed](#)]
4. Zhao, Y.; Liu, S.; Shi, Y.; Hao, L.; Ma, Y.; Dai, P.; Liu, G.; Ni, Y.; Chen, X. Compact mode converter on SOI based on a polygonal subwavelength grating structure. *Opt. Lett.* **2024**, *49*, 834. [[CrossRef](#)] [[PubMed](#)]
5. Wu, S.; Su, Y.; Zhang, L.; Gu, X.; Feng, T.; Xiao, J.; Yao, X.S. Local-field engineering in slot waveguide for fabricating on-chip Bragg grating filters with high reflectivity across a flat broadband. *Opt. Express* **2024**, *32*, 4684. [[CrossRef](#)] [[PubMed](#)]
6. Ai, X.; Zhang, Y.; Hsu, W.-L.; Veilleux, S.; Dagenais, M. Broadband 2 × 2 multimode-interference coupler on the silicon-nitride platform. *Opt. Express* **2024**, *32*, 9405. [[CrossRef](#)] [[PubMed](#)]
7. Pita, J.; Nabki, F.; Ménard, M. Inverse-designed silicon nitride reflectors. *Opt. Lett.* **2024**, *49*, 786. [[CrossRef](#)] [[PubMed](#)]
8. Sato, T.; Wada, M.; Mori, T.; Sakamoto, T.; Imada, R.; Matsui, T.; Nakajima, K.; Saitoh, K. Broadband design of silica-PLC mode-dependent-loss equalizer for 2LP-mode transmission systems. *Opt. Express* **2023**, *31*, 39965. [[CrossRef](#)] [[PubMed](#)]
9. 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. [[CrossRef](#)] [[PubMed](#)]
10. Wu, X.; Liu, W.; Yuan, Z.; Liang, X.; Chen, H.; Xu, X.; Tang, F. Low Power Consumption VOA Array with Air Trenches and Curved Waveguide. *IEEE Photonics J.* **2018**, *10*, 7201308. [[CrossRef](#)]
11. Hu, C.; Shi, Y.; Zhou, T.; Xu, C.; Zhu, A. A Small Size On-chip Temperature Sensor Based on a Microring Resonator. *Silicon* **2022**, *14*, 5847–5854. [[CrossRef](#)]
12. Li, J.; Mao, B.; Xu, B.; Shen, C.; Xu, R.; Wang, L.; Wang, D.; Zhao, C. PDMS-filled Fabry–Perot interferometer-based multipoint temperature measurement using an array-waveguide grating. *Appl. Opt.* **2020**, *59*, 9773. [[CrossRef](#)] [[PubMed](#)]
13. Ning, N.; Huang, Q.; Zhang, Q.; Wei, Z.; Xia, P.; Wang, Y.; Yang, J.; Yu, H. Narrow-band Add-Drop Filters Based on Silicon Nitride Multimode Waveguide Bragg Grating. *IEEE Photonics Technol. Lett.* **2024**, *1*, 1. [[CrossRef](#)]

14. Sato, H.; Miura, H.; Qiu, F.; Spring, A.M.; Kashino, T.; Kikuchi, T.; Ozawa, M.; Nawata, H.; Odoi, K.; Yokoyama, S. Low driving voltage Mach-Zehnder interference modulator constructed from an electro-optic polymer on ultra-thin silicon with a broadband operation. *Opt. Express* **2017**, *25*, 768. [\[CrossRef\]](#)
15. Yin, Y.; Yao, M.; Ding, Y.; Xu, X.; Li, Y.; Wu, Y.; Zhang, D. Polymer/Silica Hybrid Waveguide Thermo-Optic VOA Covering O-Band. *Micromachines* **2022**, *13*, 511. [\[CrossRef\]](#)
16. Gaso, P.; Pudis, D.; Seyringer, D.; Kuzma, A.; Gajdosova, L.; Mizera, T.; Goraus, M. 3D Polymer Based 1x4 Beam Splitter. *J. Light. Technol.* **2021**, *39*, 154–161. [\[CrossRef\]](#)
17. Shang, Y.; Zhou, J.; Jiang, H.; He, X.; Ye, X.; Li, C. Optimal design of a 4×4 MMI thermal optical switch with trapezoidal air trenches. *Appl. Opt.* **2023**, *62*, 1521. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Wang, W.; Zhao, Z.; Han, X.; Wang, Y.; An, J.; Liu, J. Low Loss 16-Channel Photodetector Array Receiving Module with Fine Tuning Ability. *IEEE Photonics J.* **2022**, *14*, 6656406. [\[CrossRef\]](#)
19. Liu, Q.-H.; Pan, P.; You, J.; Zhang, J.-S.; Wang, Y.; Wang, Y.-T.; Wang, L.-L.; An, J.-M.; Cui, D.-J.; Zhou, L.; et al. Four-stage cascaded variable optical attenuator with large attenuation range for quantum key distribution. *Chin. Phys. B* **2023**, *32*, 054207. [\[CrossRef\]](#)
20. Li, F.; Bai, Y.; Hu, H.; Li, L.; Li, L.; Zhang, F.; Luo, X.; Zhang, X. Elastoplastic contact model of pitch-based rough surface and its polishing characteristics. *Opt. Express* **2023**, *31*, 42150–42164. [\[CrossRef\]](#)
21. Noh, Y.-O.; Lee, C.-H.; Kim, J.-M.; Hwang, W.-Y.; Won, Y.-H.; Lee, H.-J.; Han, S.-G.; Oh, M.-C. Polymer waveguide variable optical attenuator and its reliability. *Opt. Commun.* **2004**, *242*, 533–540. [\[CrossRef\]](#)
22. Yuan, P.; Wu, Y.; Wang, Y.; An, J.; Hu, X. Monolithic integration of a 16-channel VMUX on SOI platform. *J. Semicond.* **2015**, *36*, 084005. [\[CrossRef\]](#)
23. Itoh, M.; Watanabe, K.; Nasu, Y.; Yamazaki, H.; Kamei, S.; Ogawa, I.; Kaneko, A.; Inoue, Y. 1-square-inch 100 GHz 40 ch VMUX/DEMUX based on single-chip PLC integration with 2.5%- silica-based waveguides. In Proceedings of the 33rd European Conference and Exhibition on Optical Communication—ECOC 2007, Berlin, Germany, 6–20 September 2007; IEE: Berlin, Germany, 2007; Volume 2007, p. 251.
24. Ma, J.; Wang, L.; Zhang, J.; Wang, Y.; Chen, J.; Sun, B.; Zhou, T.; Cui, P.; Wu, Y.; An, J. Compactly integrated polarization insensitive 24-channel variable optical attenuator arrays using silica-based. *Opt. Commun.* **2023**, *549*, 129932. [\[CrossRef\]](#)
25. Han, Y.-T.; Shin, J.-U.; Park, S.-H.; Han, S.-P.; Lee, C.-H.; Noh, Y.-O.; Lee, H.-J.; Baek, Y. 10 channel polymer variable optical attenuator array for power monitoring and equalization in integrated PLC ROADM module. In Proceedings of the 2008 International Conference on Photonics in Switching, Sapporo, Japan, 4–7 August 2008; IEEE: Sapporo, Japan, 2008; pp. 1–2.
26. Shin, J.-U.; Han, Y.-T.; Han, S.-P.; Park, S.-H.; Baek, Y.; Noh, Y.-O.; Park, K.-H. Reconfigurable Optical Add-Drop Multiplexer Using a Polymer Integrated Photonic Lightwave Circuit. *ETRI J.* **2009**, *31*, 770–777. [\[CrossRef\]](#)
27. Li, S.; Zhang, J.; Wang, L.; You, J.; Wang, Y.; Yin, X.; Chen, J.; Sun, B.; An, J.; Wu, Y. The O-band 20-channel 800 GHz Arrayed Waveguide Grating based on silica platform for 1 Tb/s or higher-speed communication system. *Opt. Laser Technol.* **2022**, *156*, 108475. [\[CrossRef\]](#)
28. Yue, J.; Wang, C.; Lin, H.; Ding, S.; Shi, Z.; Cui, Z.; Chen, C.; Zhang, D. Interlayer directional coupling thermo-optic waveguide switches based on functionalized epoxy-crosslinking polymers. *Opt. Express* **2022**, *30*, 13931. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Lee, E.-S.; Chun, K.-W.; Jin, J.; Lee, S.-S.; Oh, M.-C. Monolithic integration of polymer waveguide phase modulators with silicon nitride waveguides using adiabatic transition tapers. *Opt. Express* **2023**, *31*, 4760. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Deng, Z.; Ding, Z.; Chen, T.; Zhang, Z. Thermal Gradient Driven Variable Optical Attenuator with On-Chip CNT Absorber. *IEEE Photonics Technol. Lett.* **2024**, *36*, 243–246. [\[CrossRef\]](#)
31. Gao, F.; Xie, W.; Tan, J.Y.S.; Leong, C.; Li, C.; Luo, X.; Lo, G.-Q. Comprehensive Investigation of Thermo-Optic Phase Shifters on a Multi-Layered SiN-on-SOI Platform. *J. Light. Technol.* **2023**, *41*, 3108–3114. [\[CrossRef\]](#)

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