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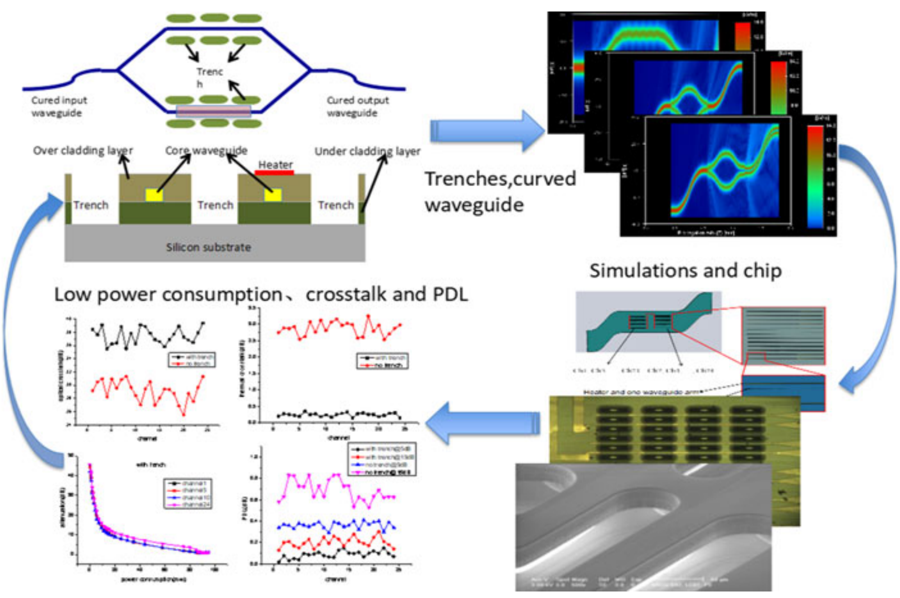

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Low Power Consumption VOA Array With Air Trenches and Curved Waveguide

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Abstract: The paper introduces a 24-channel air-trench isolated Silica-based VOA array. The air trenches thermally insulate the VOAs with etched-free waveguide technologies. Reactive ion etching and wet etching were used at different channel locations to suppress thermal crosstalk and reduce power consumption. When thermal crosstalk is declined by 3 dB for the straight waveguide, the power consumption was decreased from 195 to 95 mW because the lightwave radiation can be scattered by the air trench in the dark state. This crosstalk is improved by 9 dB for the curved waveguide. The polarization dependent loss falls down to 0.28 dB at 15 dB attenuation since the air trench and etched-free waveguide also releases the stress.

Index Terms: Variable optical attenuator, Planar lightwave circuit, Mach-Zehnder interferometer, Waveguide, Trench.

1. Introduction

In the dense wavelength division multiplexing (DWDM) system, the optical power of each wavelength is different. When the optical signals are amplified by erbium-doped fiber amplifier (EDFA), the difference of optical power between different channels will become much greater, since the optical signals are not uniform, the optical signal-to-noise ratio (OSNR) and bit error rate (BER) will be deteriorated as well [1]. The variable optical attenuator (VOA) is urgently needed to keep each wavelength the same optical power, especially VOA arrays. Until now, there are several kinds of VOA, such as micro-electromechanical systems (MEMS) VOA, liquid crystal VOA, polymer VOA, silicon VOA and silicon nitride VOA etc. MEMS VOA is easily damaged by vibration and mechanical shock, moreover the cost is higher [2], [3]; for the liquid crystal VOA, its response time and temperature dependent loss (TDL) are considerable [4], it's hard to integrated them into one chip; for the polymer VOA, its dynamic range is limited by high temperature than silica material [5]–[7]; the VOA based on silicon waveguide, its power consumption is higher; the VOA based on silicon nitride waveguide, and its polarization dependent loss (PDL) is hard to control because of high birefringence characteristics [8]. The planar light wave circuit (PLC) VOA based on silica is

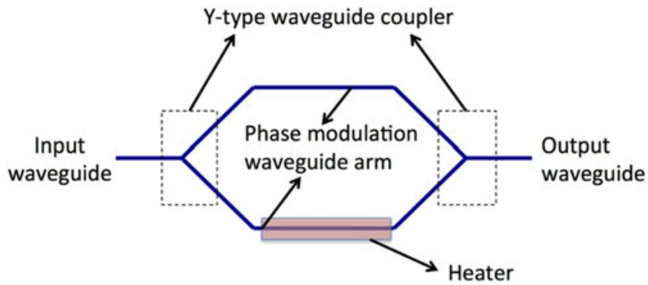


Fig. 1. The schematic diagram of PLC-VOA traditional design.

easily to integrated into one chip, and the cost is also low, but the crosstalk and power consumption are both higher because of the thermo-optic effect [9], [10].

In this paper, we designed a novel low crosstalk, low power consumption and low polarization dependent loss VOA array based on silica with thermally-insulating trench and etched-free technologies in different channel waveguide, it demonstrated a highly integrated 24-channel VOA. When the optical crosstalk is reduced to 39 dB at 15 dB attenuation, and the power consumption is reduced by 50% from 195 mw to 95 mw, while the insertion loss (IL) is about 0.8 dB, and the PDL is very low 0.25 dB at 15 dB attenuation. Furthermore, the dark function can reduce the overshoot effect of DWDM.

2. Principles of VOA With Air Trench

The VOA array discussed in this paper has 24 channels. Each channel of the VOA array adopts the Mach-Zehnder interferometer (MZI) that consisted of two 3 dB Y-type waveguide couplers, two waveguide arms and a heater on one of the waveguide arms, as shown in Fig. 1. The two waveguide arms are phase modulation arms, where a phase difference is generated between the beams passing through. The input light signal is split into two identical light signals in the first Y-branch region. Then the two beams pass through the two arms separately and interfere with each other in the second Y-branch region. The heater changes the phase of the beam passing through the MZI arms because of the thermo-optic effect. If the phase difference between the two beams past the two arms is 0, the constructive interference will appear at the Y combiner, in which case the intensity of the output light is maximal. If the phase difference is π, the interference is destructive and the intensity of the output light is minimal. When the phase difference changes from 0 to π, the intensity of the output light varies from the maximum to the minimum.

The heater which assembled by a thin metal film is designed on one top of phase modulation arms. When the voltage is applied to the heater, its temperature will rise and the heat will be transferred to the core through the over cladding layer. Then the temperature of the core changes and the refractive index of this arm is altered as a result. The light passing through this arm takes on a corresponding phase shift as below [11]:

$$\Delta\phi_{\text{heater}} = \frac{2\pi}{\lambda} \cdot \frac{\partial n}{\partial T} \cdot \Delta T \cdot L_{\text{heater}} \tag{1}$$

where λ is the wavelength, n is the refractive index of the core, $\frac{\partial n}{\partial T}$ is the thermo-optic coefficient of the waveguide material, ΔT is the change in temperature of the core after heating, and L_{heater} is the length of the heated waveguide.

The phase difference $\Delta\phi_{\text{original}}$ caused by the original length difference between the two arms without applying power to heater can be described as:

$$\Delta\phi_{\text{original}} = \frac{2\pi \cdot \Delta L}{\lambda} \tag{2}$$

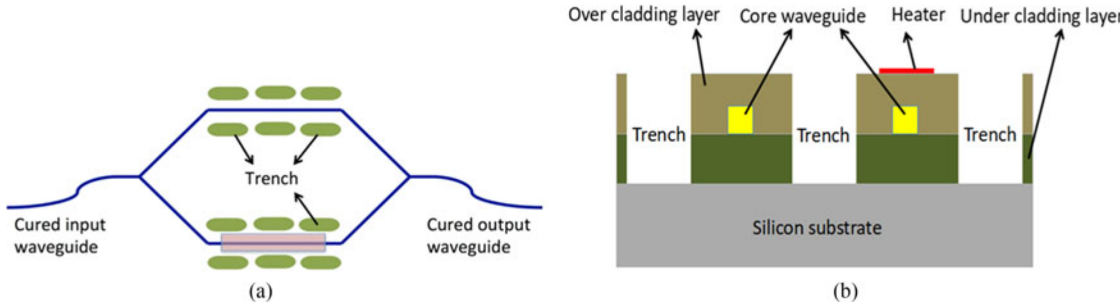


Fig. 2. The schematic diagram of PLC-VOA new design: (a) with air trench and curved input/output waveguide (b) cross-section diagram.

where ΔL is the original length difference between the two waveguide arms. Therefore, the total phase difference between the lights after passing the waveguide arms is $\Delta\phi_{\text{original}} + \Delta\phi_{\text{heater}}$. For an ideal MZI, the relation between the transmission and the phase difference is derived from [12]:

$$T = \frac{I_{\text{out}}}{I_{\text{in}}} = \frac{1}{2}\left[1 + \cos(\Delta\phi_{\text{original}} + \Delta\phi_{\text{heater}})\right] \quad (3)$$

where I_{out}, I_{in}, are the intensity of the output light and the input light respectively.

In the traditional structure, the two waveguide arms are cladded by silica without air trench. The silica cladding layer has higher thermal conductivity than air trench. It transfers heat from the heated arm to other VOA arms, thus leading to higher heat crosstalk and power consumption. In addition, the silica cladding layer has a different thermal expansion efficient from the silica core layer and silicon substrate, so the temperature changes will lead to the stress. High PDL is then generated in the waveguide when subjected to stresses from different directions. The optical power which attenuated and scattered will be transmitted into other VOA arms through silica cladding layer, Since there is a high relative refractive-index difference and coarse interface between the silica cladding layer and air, the scattered reflection will occur, so the optical crosstalk in VOA with an air trench can be suppressed greatly.

In order to reduce the power consumption,the optical and thermal crosstalk between the two MZI arms, the thermally-insulating air trenches are etched freely, using reactive ion etching and wet etching method to isolate heat, and to release the waveguide and heater stresses. Fig. 2(a) shows the schematic configuration of the PLC VOA with the trench structure and curved input/output waveguides, and Fig. 2(b) presents the cross-section views of the VOA. On the one hand, using thermal isolation trenches in channel intervals can stop useless optical transmission and reduce optical crosstalk. On the other hand, these trenches also function as heat insulators, and reduce the power consumption and thermal crosstalk.

In traditional structure, input and output waveguides are designed straightly [12]. When couple the LD and input waveguide, the leak light will enter into output waveguide to arise optical crosstalk. In order to avoid this kind of optical crosstalk, curve input and output waveguide are proposed, as shown in Fig. 2(a). The input and output waveguides have an offset position. Thus the leak light at the input waveguide can't enter into the output waveguide. So the optical crosstalk is improved further.

3. Simulation and Experiments

3.1 Simulations With Finite Difference Beam Propagation Method

The simulations were carried out to study the performance of the proposed air trenches and curved input/output waveguides. Three-dimensional (3-D) finite difference beam propagation method (FD-BPM) was used together with the OlympIOs [13] which integrated optical software to simulate the proposed structure. The propagation step size (Δz) is 0.1 μm. The silica waveguide is 4 μm $\times$ 4 μm

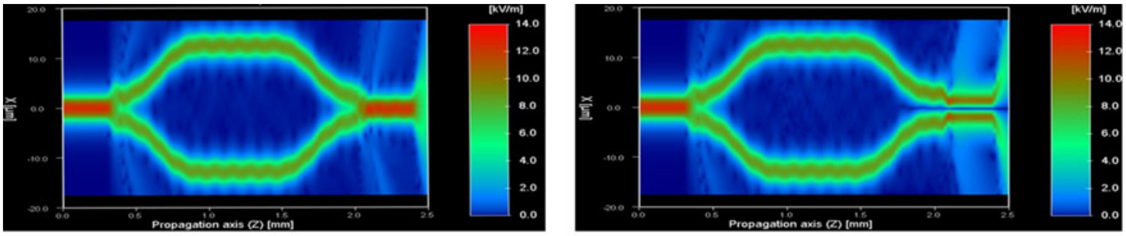


Fig. 3. BPM simulated propagating optical field for traditional structure: (a) constructive interference (b) destructive interference.

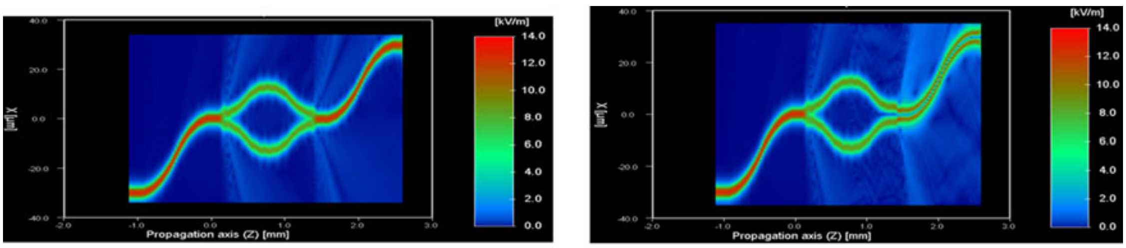


Fig. 4. BPM simulated propagating optical field for the newly proposed structure: (a) constructive interference, (b) destructive interference.

and has an index contrast defined by the relative refractive index difference between the waveguide ($n_{\max}$) and cladding (n_s):

$$\Delta = \frac{n_{\max}^2 - n_s^2}{2n_{\max}^2} * 100\% \tag{4}$$

where Δ is commonly expressed as a percentage. In fact, the refractive index values of $n_{\max}$ and n_s are close to each other, so (4) can be approximated as:

$$\Delta \approx \frac{n_{\max} - n_s}{n_{\max}} * 100\% \tag{5}$$

In simulation, $n_{\max} = 1.46923$, $n_s = 1.447$, and $\Delta = 2.0\%$ can be calculated. Figs. 3 and 4 present the simulation results in constructive and destructive interference states with beam propagation method (BPM). Silicon substrate and silica cladding layers have high thermal conductivity. The heat generated by the heater could diffuse laterally and vertically and affect the other arms, so in the traditional design, higher power consumption and thermal crosstalk are inevitable. In order to reduce power consumption, the cladding silica and silicon around the waveguide are etched, shaping the waveguide into a cantilever. The air among waveguides blocks the thermal transfer between both MZI arms, so the power consumption and thermal crosstalk between channels can be improved greatly. From Figs. 3(b) and 4(b), it can be seen that there is much radiation light between waveguides in dark or destructive states, which results in optical crosstalk. The thermally insulating trench scatters the radiation light and thus suppressing optical crosstalk. In addition, these trenches can release waveguide stress and heater stress, so the PDL should be low. Fig. 4 shows that when the thermal phase shift is changed, the output power is changed too, so the function of VOA can be realized.

3.2 Simulations With Thermal Analysis

In order to prove that the air trench can reduce the heat crosstalk, the simulation using Flotherm was performed to compare the difference between the VOAs with and without the air trenches. Fig. 5 gives the structures of these VOAs. All the parameters of the two types of VOAs (geometrical size

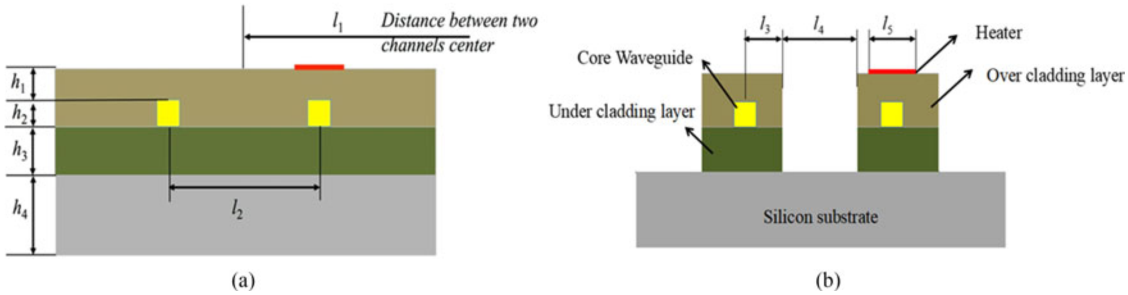


Fig. 5. The structures of the VOAs (a) without trench and (b) with trench.

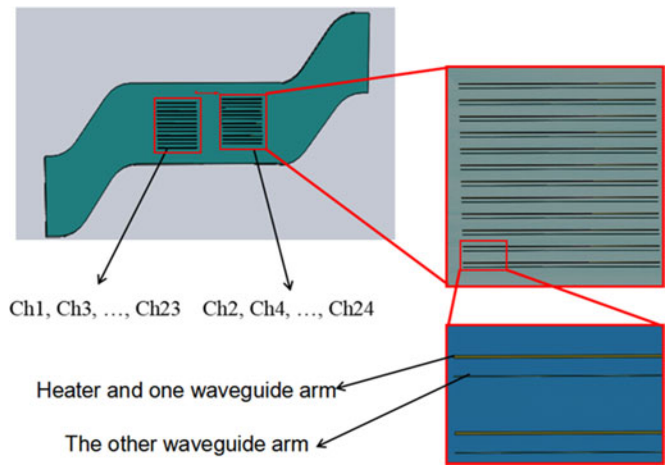


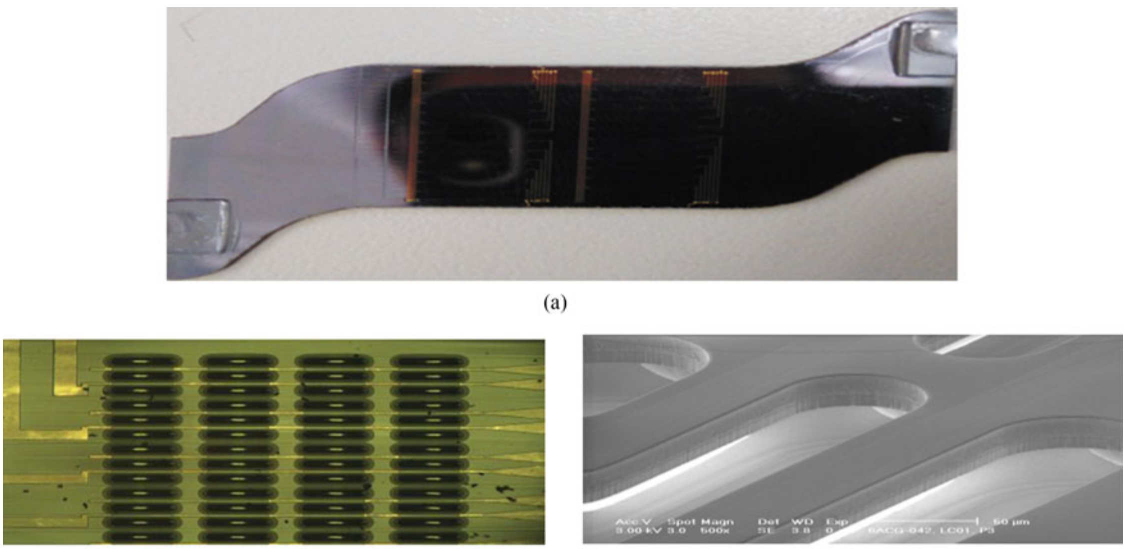
Fig. 6. The structures of the 24 channel VOA array.

and refractive index of each material) are the same except the air trench, as shown in Fig. 5. The values of the parameters in Fig. 5 are given as: $h_1 = 12\ \mu$m, $h_2 = 6\ \mu$m, $h_3 = 20\ \mu$m, $h_4 = 625\ \mu$m, $l_1 = 380\ \mu$m, $l_2 = 125\ \mu$m, $l_3 = 30\ \mu$m, $l_4 = 65\ \mu$m, $l_5 = 20\ \mu$m. The depth of air trench is the sum of the depths of over cladding layer and under cladding layer, and the width is $l_4 = 65\ \mu$m. The heater is 6 mm long, 20 μm wide and 500 nm thick. The material of the substrate is silicon, the material of the over and under cladding player is SiO_2, and the material of the package shell is Al. The shell bottom supporting the VOA chip is kept at a constant temperature of 60 °C. If power is applied to the heater, the temperature of the corresponding waveguide arm will rise, and the heat will be transmitted into other VOA arms through silica cladding layer. The trench can isolate the thermal transmitting.

The designed VOA array has 24 channels, and the channels distribute as shown in Fig. 6. The 10th channel was chosen to study the thermal crosstalk, and the heater is placed over the waveguide arm of Ch10-2 channel. The temperature of the arm with heater is set to be 80 °C. In the two conditions of with and without trench, the power consumptions of the heaters are 100 and 50 mW. Table I presents the simulation results for the VOAs with and without air trench. From Table I, it can be seen that using the same power supply, the temperatures of Ch10-2 (without and with air trench) are 80.7597 °C and 80.8593 °C, and the temperatures of the corresponding Ch10-1 (the other arm of the same channel) are 62.0869 °C and 60.4039 °C. It means that the air trench can isolate the heat transmitting to the adjacent waveguide arms and reduce the heat crosstalk with half power consumption.

TABLE 1
Simulation of the Effect of Air Trench on Heat Crosstalk

Channel	Temperature of the channels without trench (°C)	Temperature of the channels with trench (°C)
Ch8-1	60.0093	60.0092
Ch8-2	60.0128	60.0128
Ch10-1	62.0869	60. 4039
Ch10-2	80.7597	80.8593
Ch12-1	60.0183	60.0184
Ch12-2	60.0128	60.0127



(a) (b) (c)

Fig. 7. Diagram of PLC-VOA production (a) 24-channel VOA array (b) optical microscope image of the middle part of chip (c) the SEM of air trenches.

3.3 Experimental Results

Fig. 1 shows the schematic configuration of a PLC-VOA with heat-insulating air trench and curved input and output waveguides. It consists of an MZI with two 3-dB Y-branch couplers, and a thin film metal heater which integrated on the surface of one of the waveguide arms. Heat-insulating trenches beside the waveguide arms are designed to suppress horizontal heat diffusion between both arms, and trenches below waveguide arms are designed to suppress the flow of heat into the silicon substrate. First of all, standard PLC with heaters and electrodes is fabricated. Both ends of the heater are connected to the power supply via the metal lead. The generated heat,which is proportional to the square of the current flowing, is conducted to the core waveguide, The heater is made of titanium with a high resistivity of $4.2 \times 10^{-7}\Omega\cdot$m. The thickness of the titanium heater is 0.4 μm, the width 18 μm and the length 5.5 mm. The width of the lead is 120 μm. The electric power is mainly converted into the heat of the heater. Secondly, some short shallow trenches are etched in the over-clad layer to form the braces. Then etching is performed over the top of these

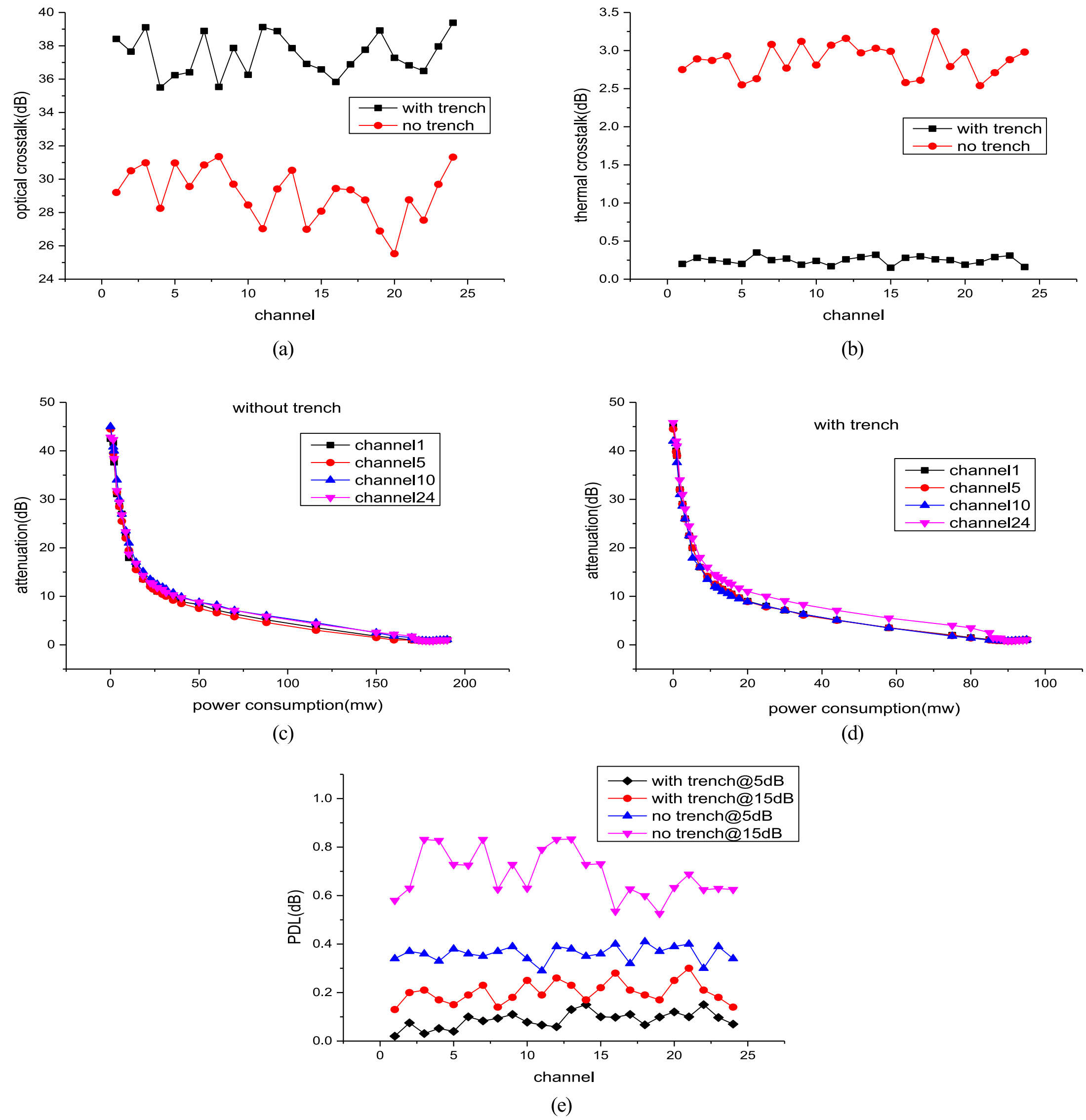


Fig. 8. The test data of PLC-VOA (a) the optical crosstalk at 15 dB attenuation (b) the thermal crosstalk at 15 dB attenuation (c) the power consumption from dark to bright without trench (d) the power consumption from dark to bright with trench (e) the PDL data at 5 dB and 15 dB attenuation.

trenches to form deep trenches with several short shallow trenches at the bottom. The etching is stopped when the surfaces of the silicon substrate appear at the bottom of the trenches. The spaces between the trenches serve as braces. Finally, the silicon substrate beneath the waveguide is removed partly by isotropic dry etching. For further improvement to optical crosstalk, the curved input and output waveguides are adopted.

Two kinds of different VOA arrays are fabricated. One is traditional structure without trench, and its input and output waveguides are both straight The other is our new structure with trench and curved input and output waveguides. Fig. 7 shows the diagram of the 24-channel voa chip, the optical microscope image of the middle part of the chip, and the SEM picture of the air trenches in the waveguide. Then tests are carried out in terms of optical crosstalk, thermal crosstalk, power consumption and PDL for the two kinds of VOA array chip with and without trenches respectively. Fig. 8(a) shows that optical crosstalk at 15 dB attenuation is 30 dB for traditional VOA, while the optical crosstalk is 39 dB for our proposed novel structure. The optical crosstalk is 9 dB lower. The obvious improvement of optical crosstalk is attributed to the curved input and output waveguides and heat-insulating trenches. The experimental result shows that our novel structure can improve optical crosstalk obviously. Fig. 8(b) shows that for VOA without trench, the thermal crosstalk at 15 dB attenuation is 3 dB, but for VOA with trench the thermal crosstalk is 0.25 dB only. Fig. 8(c) and (d) show the power consumption of our new structure is 95mw, while the traditional VOA based on MZI is 195 mw of each channel at 0 dB, and the insertion loss is 0.8 dB for both structures. The effect is very easily understood. Heat-insulating prevents heat diffusion, thus suppressing heat crosstalk and improving the utilization efficiency of heat energy. Fig. 8(e) shows that the PDL is also a very low 0.15 dB at 5 dB attenuation and 0.28 dB at 15 dB attenuation with trench, 0.41dB at 5dB attenuation and 0.83 dB at 15 dB attenuation without trench. These heat-insulating trenches can insulate heat flow, and release waveguide stress and heat stress at the same time. Thus the waveguide has low stress and low birefringence. These test data are consistent with the quantitative analysis above. Results of the simulation and device attenuation properties illustrated the fact that the designed VOA has good performance.

4. Conclusion

In conclusion, this paper introduces a low crosstalk, low power consumption and low PDL 24-channel dark VOA array based on Silica-on-Silicon PLC technologies. We use thermally insulating trenches between different channels with etched-free waveguide technologies, while curved input and output waveguides are used to improve optical crosstalk further; when the crosstalk is reduced to 39 dB, the power consumption decreased half from 195 mw to 95 mw. At the same time, the IL is about 0.8 dB, and PDL falls down to 0.28 dB at 15 dB attenuation.

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