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Design of Thermo-Optic Variable Optical Attenuator Based on Quartz Substrate

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ABSTRACT

In this paper, we designed a thermo-optic variable optical attenuator (VOA) based on quartz substrate, which consists of a Mach-Zehnder interferometer (MZI) and a thin film heater above the phase-modulation arm. The transmission properties of the waveguide and attenuation characteristics of the device have been simulated by beam propagation method (BPM), and the simulated results illustrated that the designed VOA had good performance.

Keywords: VOA; MZI; Thermo-optic; Quartz Substrate

1. Introduction

Variable optical attenuator (VOA) is one of the most basic optical passive devices in modern optical network, with a wide range of applications in optical communication and its main function is to control and attenuate optical signal power. With the application of dense wavelength division multiplexing (DWDM) system, to realizing optical signal propagation in high speed correctly, we need to monitor and balance the multi-channel optical power, resulting in dynamic channel equalizer (DCE), variable optical attenuator integrated multiplexer/demultiplexer (VMUX), optical add-drop multiplexer and other optical devices. VOA is the core component of these devices and plays a very important role in the gain control of linear-repeaters for wavelength division multiplexed networks and channel power equalization in wavelength division multiplexing (WDM) cross-connect nodes. The study of PLC-VOA has just started in our country, but the demand for VOAs is larger and larger with the progress of optical communication. Only the new optical attenuators of low cost, easy integration, and good performance can meet the growing market demand [1,2].

SiO_2 material has a lot of advantages compared with other materials that are used in the manufacture of optical waveguide devices from early times. The coupling loss of optical waveguide devices produced between SiO_2 planar waveguide and single-mode fiber is quite low. The transmission loss of the optical signal in SiO_2 material is only 0.2dB/km. The SiO_2 material has certain thermo-optic coefficient and thus can be used for the modulation of refractive index. The devices based on SiO_2 materials can be directly grown on Si or quartz substrate, which can be integrated with other Si based waveguide devices. The SiO_2 material also has great environment stability. Internationally, most of the VOAs have been fabricated were based on the Si substrate and there was an undercladding layer between the core and the substrate. In this paper, we designed a Mach-Zehnder interferometer (MZI) thermo-optic variable optical attenuator based on quartz substrate. It eliminated the step of the fabrication of the undercladding layer, simplifying the manufacture process. The core and the substrate could match better because they were composed of the same material of SiO_2. Results of the simulation of the waveguide transmission properties and device attenuation properties illustrated that the designed VOA had good performance.

2. The Principles of VOAs

The structure of the MZI thermo-optic VOA based on quartz substrate is shown in **Figure 1**. It consists of input/output waveguide, two Y-branches, two symmetrical phase-modulation arms, and a metal film heater above one of the arms. The input light signal is split to two identical light signals in the first Y-branch region. Then the two beams of light will pass through the two arms separately and interfere in the second Y-branch region. If the two arms are completely symmetrical, the output light signal will emerge from the output waveguide, the same with the input light signal in the case of no modulation. In the device designed, one of the two phase-modulation arms will be modulated to develop phase difference between the two beams of light with same intensity. After the transmission through the two arms, the two beams of light will interfere. The intensity of the output light varies from the maximum to the minimum with the changes of the phase difference from 0 to π. When one of phase-modulation arms is heated by the thin film heater, its temperature rises and the refractive index of the arm will be changed. The light going through the arm will develop a corresponding phase shift

$$\Delta\phi_h = \frac{2\pi}{\lambda}\frac{\partial n}{\partial T}\Delta T L_h \quad (1)$$

where λ is the wavelength of the light; n is the refractive index of the core of the arm waveguide; ΔT is the temperature variation of the core after heating; $\partial n/\partial T$ is the thermo-optic coefficient of the waveguide material; L_h is the length of the heated waveguide. From (1) we can get that when the thermal phase shift is π, the temperature variation of the waveguide is that

$$\Delta T = \frac{\lambda}{2L_h}\left(\frac{\partial n}{\partial T}\right)^{-1} \quad (2)$$

In the one-dimensional linear assumption, if the phase shift is π, the power consumption P_π could be derived as [3]

$$P_\pi = \frac{\lambda k_w}{2}\frac{w_h}{t_c}\left(1+0.88\frac{t_w}{w_h}\right)\Big/\left(\frac{\partial n}{\partial T}\right) \quad (3)$$

where k_w is the thermal conductivity of the core and the cladding layer. It is assumed that the thermal conductivity of the core and the cladding layer are the same because they are all based on SiO_2 material and their refractive index are very close; w_h is the width of the heater above the phase-modulation arm; t_c is the location of the core; t_w is the total thickness of the core and the cladding layer. As seen from (2), the device power consumption and the core position t_c is inversely proportional. However, large t_c will affect the propagating velocity of heat from the heater to the core, resulting in low modulation

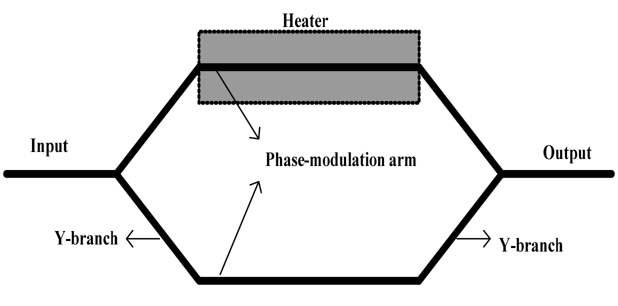

Figure 1. Basic configuration structure of the VOA.

rate. Furthermore, to lower the device power consumption, deep isolated grooves have been etched at the both sides of two phase-modulation arms of the VOA, as shown in **Figure 2**, better limiting the lateral diffusion of heat in the modulation area.

3. Design of the Device

The schematic of the VOA with isolated grooves is shown in **Figure 2**.

3.1. Design of the Waveguide

The material of the core and the overcladding layer is SiO_2. The cladding layer is directly grown on the core by plasma enhanced chemical vapor deposition (PECVD) technology based on the quartz substrate, as shown in **Figure 3**.

In our experiment, the refractive index of the cladding layer is 1.445 and its refractive index difference (Δ) between the core and the cladding is 0.75%. The thickness of the overcladding layer is 18μm and the cross-section dimension of the core is $6\times6\mu m^2$. The simulation results showed that under the condition of $\lambda = 1.5\mu m$,

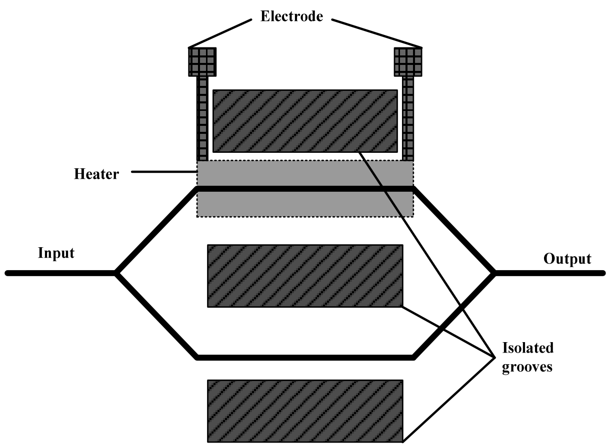

Figure 2. Schematic of the VOA with isolated grooves.

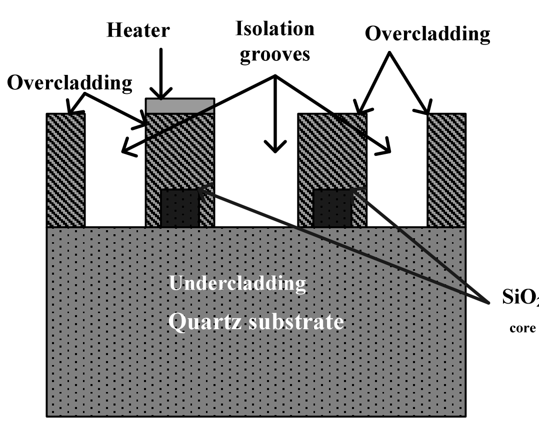

Figure 3. Cross-section diagram of the VOA.

$\Delta = 0.75\%$, the waveguide could achieve good single-mode propagation. We adopted the traditional Y-branch MZI structure, as shown in **Figure 4** [4,5]. It contains a single input waveguide of length L_1 and a reduced width (10%) waveguide of length L_2. The narrowed waveguide has been induced to filter out the high order mode, weaken the interference effect of the high order mode with the fundamental mode and improve the uniformity of the output light [6]. A waveguide with a 0.75% Δ has strong light confinement, allowing us to realize a curvature radius as small as 5000 μm. Other parameters in same situation, the radius of the bent waveguide is larger, the propagation loss is lower. Considering the device size, we adopted $r = 8000\mu m$, ensuring that the distance between two phase-modulation arms is 100 μm. A segment junction occurs between the two bent waveguides with positive radius and negative radius respectively. Through the simulation, we got that the optimal value of the offset is 0.1 μm, as shown in **Figure 5**. Where I_0 is the input light intensity; I is the output light intensity.

3.2. Design of the Heaters and Grooves

Both ends of the heater are connected to the power supply via the metal leads. The heat generated, which is proportional to the square of the current flowing, is conducted to the core, achieving the purpose of thermo-optic modulation.

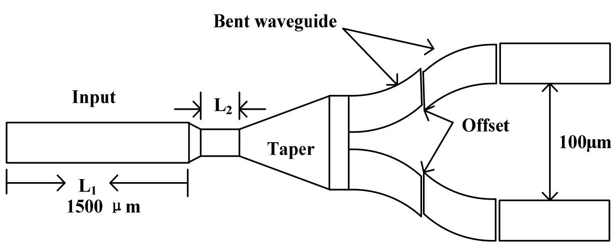

Figure 4. Schematic of the Y-branch (input section).

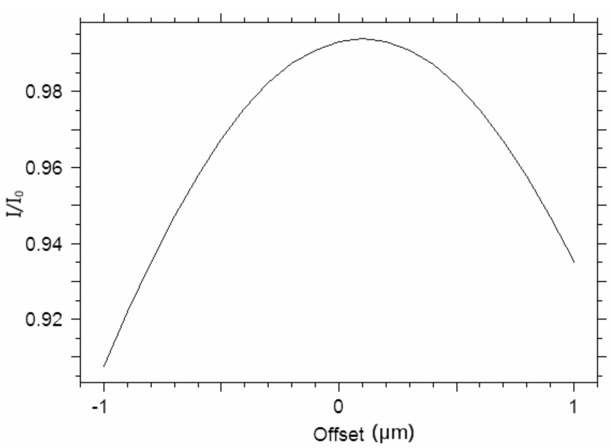

Figure 5. Results used to find optimal value of Offset.

The heater and leads are composed of titanium (Ti) of high resistivity and aluminium (Al) of low resistivity respectively to reduce the power consumption. The thickness of the Ti is $t_h = 0.3\mu m$, the length is $L_h = 5000\mu m$, the width is $w_h = 20\mu m$ and the resistivity is $\rho_h = 4.2\times10^{-7}\Omega\cdot m$. The thickness of the Al is $t_w = 1\mu m$, the length is $L_w = 10000\mu m$, the width is $w_w = 10\mu m$ and the resistivity is $\rho_w = 2.65\times10^{-8}\Omega\cdot m$. Using the fundamental formula of resistance

$$R = \rho\frac{L}{S} = \rho\frac{L}{wt} \tag{4}$$

The resistance of the heater can be calculated as $R_h = 350\Omega$ and the resistance of the leads as $R_w = 26.5\Omega$, so that the electric power is mainly converted into the heat of the heater rather than the leads.

SiO_2 has a certain thermal conductivity and the heat generated by the heater could diffuse laterally and affect the other arm, increasing the power consumption. In order to reduce the power consumption, a groove has been etched at the center of the two phase-modulation arms. The other groove etched along the heated arm was to prevent the heat from being lost. The third groove was etched along the side of the unheated phase-modulation arm for the high dynamic modulation range. The depth of the grooves etched is 26 μm, slightly greater than the total thickness of the cladding layer and core. Because the air has a much lower thermal conductivity than the silica, the heat will be better confined and reduce the power consumption with the same attenuation.

4. Simulation of the Device Properties

4.1. Simulation of the Static Loss

Waveguide transmission loss associated with the waveguide structure and parameters is an important factor to affect the device insertion loss. **Figure 6** shows the results simulated of the device static loss. The length of the input/output waveguide is L_(in(ou)) = 1500 μm, the radius of the bent waveguide is r = 8000 μm. The amount of the optical power is defined as

$$A = -10\lg(I/I_0) \tag{5}$$

From the **Figure 6** and (5) we could calculate that the static loss is about 0.46 dB after the transmission in the MZI structure in the case of no modulation.

4.2. Simulation of Attenuation Characteristics

Connect the both ends of the heater with the power supply and the temperature of the waveguide will be changed by the heat generated. As a result, the refractive index of the waveguide will be changed and the phase difference will be induced, achieving the purpose of the

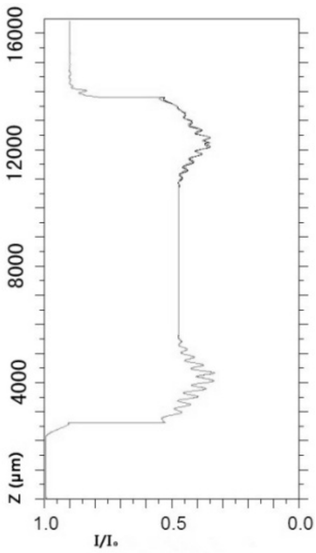

Figure 6. Simulation result of the device static loss.

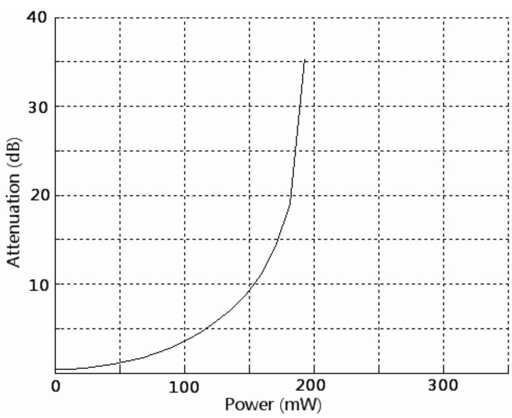

Figure 7. Relations between attenuation and power consumption.

attenuation of the optical power. Equation (1) could be written as another form

$$\Delta\phi = 2\pi\Delta n\frac{L_h}{\lambda} \quad (6)$$

It can be calculated that when the phase difference is π that the corresponding variation of the refractive index is $\Delta n = 1.55\times10^{-4}$. From (2), as the phase difference is π, we could calculate that the corresponding temperature variation is $\Delta T = 13K$. Finally, we could get the relation between attenuation and power consumption, as shown in **Figure 7**. When the attenuation is 30 dB, the power consumption is about 180 mW.

5. Conclusions

We designed a MZI thermo-optic VOA based on quartz substrate and simulated its properties using the BPM. We found that the static loss of the device is less than 0.5 dB and the power consumption is only 180 mW with the attenuation of 30 dB. Device fabrication and measurement experiments are being carried on presently and the results of the experiments will be published soon.

6. Acknowledgements

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