Design and analysis of integrated optical waveguide in optical interconnection on chips

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***Abstract*—With the reduction of integrated circuit feature size, increase of signal frequency and density of layout and wiring, problems caused by electrical interconnection, such as limited bandwidth, clock skew, signal distortion and increased interference, have become bottlenecks in the realization of ultra-high speed circuits. Because light travels at the speed of light and is an electromagnetic wave of high frequency, it does not depend on the movement of particles and can travel at very high speeds. It does not depend on the motion of particles, thus avoiding the influence of parasitic parameters. So optical transmission is a good alternative to electrical transmission. Optical interconnection based on optical transmission is composed of light source, interconnection channel and optical receiver by transmitting optical signals. With the rapid development of photoelectric integration, more and more people are devoted to the research of optical waveguide in optical interconnection on chips. Integrated silicon-based optical waveguide is a very important part in silicon-based optical integrated circuit. Because silicon based optical waveguide is an important part of photoelectric integrated circuit, it is necessary to study its material, structure and the way of constructing related components, so as to obtain low-loss optical waveguide components. In this paper, two materials, SOI and SiO2, are selected to analyze the ridge and rectangular waveguides in detail, and the Y-branch power splitter and 1×4 power splitter are designed with them, and the related properties are compared and discussed. The basic characteristics of these waveguides are analyzed theoretically and by simulation. Some instructive results are given for photoelectric integration in optical interconnection on chips.**

Keywords—Optical interconnection, Chips, Integrated circuits, Integrated optical waveguide, Photoelectric integration

I. INTRODUCTION

With the reduction of integrated circuit feature size, increase of signal frequency and density of layout and wiring, problems caused by electrical interconnection, such as limited bandwidth, clock skew, signal distortion and increased interference, have become bottlenecks in the realization of ultra-high speed circuits. Because light travels at the speed of light and is an electromagnetic wave of high frequency, it does not depend on the movement of particles and can travel at very high speeds. It does not depend on the motion of particles, thus avoiding the influence of parasitic parameters. In addition, photons are electrically neutral particles, so the light signal is not disturbed by electromagnetic waves. So optical transmission is a good alternative to electrical transmission[1].

Optical interconnection based on optical transmission is composed of light source, interconnection channel and optical receiver by transmitting optical signals. The parts are joined together. According to the level of interconnection, optical interconnection can be divided into computer interconnection, PCB interconnection, chip-to-chip interconnection and in-chip interconnection[2].According to the transmission medium, it can be divided into free space optical interconnection, optical fiber interconnection, and waveguide interconnection. Waveguide-based interconnection can be used between chips and within chips, where problems such as optical loss of waveguide interconnection and material stability exist[3]. However, with the rapid development of photoelectric integration, more and more people are devoted to the research of waveguide optical interconnection.

So monolithic integration is a worthy research direction, and silicon based optical interconnection is an important problem in the research of monolithic integration. Silicon based optical interconnection is to replace electrical signals on the chip with optical signals to realize the interconnection between modules. The silicon based optical interconnection integrated circuit is composed of an optical transmitting device and its driving circuit, an optical receiving device and its subsequent amplifying circuit and an optical transmission device[4].

Integrated silicon - based optical waveguide is a very important part in silicon - based optical integrated circuit. Integrated photoelectric circuit requires high optical transmission efficiency, which requires optical waveguides with very low loss, and also needs to achieve efficient coupling between optical waveguides and optical transmitters and receivers. It should be noted that whether the fabrication process is compatible with the microelectronic process is the key basis for the feasibility of monolithic silicon-based photoelectric circuit. CMOS technology is the standard technology in the current microelectronics technology[5]. The integrated optical waveguide structure made by the standard technology can improve the integration and coupling performance of microelectronics and optoelectronic integrated loop, and is conducive to reducing the cost. So it is very important to study various silicon based optical waveguides compatible with standard technology[6].

Because silicon based optical waveguide is an important part of photoelectric integrated circuit, it is necessary to study its material, structure and the way of constructing related components, so as to obtain low-loss optical waveguide components. In this paper, two materials, SOI and SiO2, are selected to analyze the ridge and rectangular waveguides in detail, and the Y-branch power splitter and 1×4 power splitter are designed with them, and the related properties are compared and discussed.

II. INTEGRATED OPTICAL WAVEGUIDE THEORY AND BEAM TRANSMISSION METHOD

A. Theory of linear optics

Firstly, a beam of light (Ei) transmitted in a medium with refractive index n1 is considered, incident at an incident Angle θ1 at the interface of the two media, as shown in Fig. 1 and Figure 2.

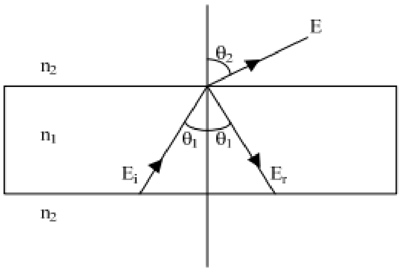


Fig. 1. Reflection and refraction of light rays at the interface of a medium

So we can define the reflection coefficient r to be : r = exp($j\phi$)

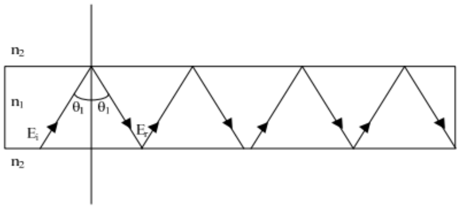


Fig. 2. Plate optical waveguide

B. Theory of Electromagnetic Fields

Linear optical theory is the approximation and simplification of electromagnetic wave theory, which can be used in dealing with simple optical problems, and wave optical theory is used for the accurate analysis involving optical waveguides and other components. The basis of wave optics is Maxwell's equations, whose differential equation is expressed as

$$\nabla \bullet D = \rho$$

$$\nabla \bullet B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{1}$$

C. Fundamental equation of electromagnetic field

In a linear, uniform, non-magnetically unrelated medium, Maxwell's equations can be written as

$$\begin{cases} \nabla \times E = -j\omega\mu_0 H \\ \nabla \times H = j\omega\varepsilon E \\ \nabla \times B = 0 \\ \nabla \times D = 0 \end{cases} \tag{2}$$

D. Basic principles of 3D FDBPM

1) Basic format of 3D scalar FDBPM

$$\frac{\partial^2 \phi}{\partial z^2} - 2j\beta\frac{\partial \phi}{\partial z} + \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \left(k_0^2 n^2 - \beta^2\right)\phi = 0 \tag{3}$$

2) The basic format of three - dimensional semi-vector FDBPM

The expression of semi-vector wave equation of quasi-TE module is

$$\frac{\partial^2 \psi}{\partial z^2} + P\psi = 0 \tag{4}$$

The semi-vector wave equation of quasi-TM module can also be expressed by equation.

3) The basic format of three-dimensional vector FDBPM

$$E_x\left(x, y, z\right) = E_{0x}\left(x, y, z\right)\exp\left(-j\beta z\right)$$

$$E_y\left(x, y, z\right) = E_{0y}\left(x, y, z\right)\exp\left(-j\beta z\right) \tag{5}$$

III. OPTICAL WAVEGUIDE MATERIAL AND STRUCTURE AND OPTICAL WAVEGUIDE COUPLER

A. Typical optical waveguide materials and structures

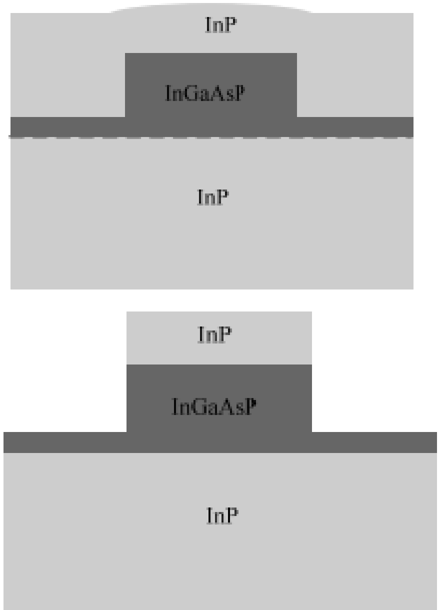


Fig. 3. Polymer optical waveguide

By comparing SiO2 with SOI and other materials, it can be seen that it is very suitable for the realization of optical waveguide, and the optical waveguide loss is very small, and the refractive index of the material can also be adjusted by doping SiO2. And for SOI, it can be used to make silicon nano optical waveguides, thus greatly improving the integration degree. Because of their compatibility with microelectronic technology, they are a good choice for optical waveguide materials in photoelectric integration, as shown in Figure 3.

B. Optical waveguide coupler

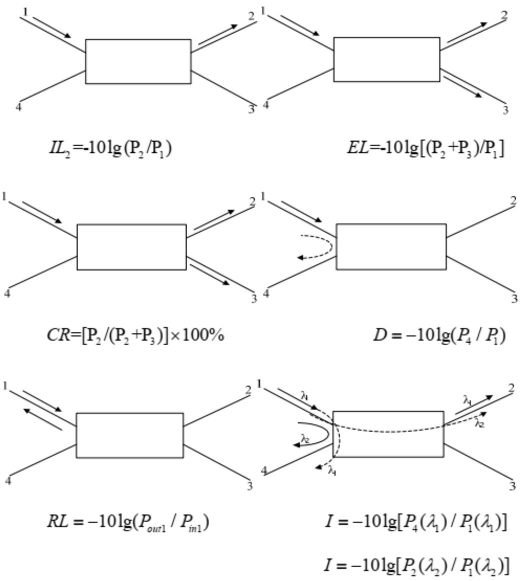


Fig. 4. Optical waveguide coupler

Here, a 1 × 2 power evenly divided Y branch power divider as an example to illustrate the specific design of Y branch A surname. The first step is to select the material and structure of the waveguide, which needs to take into account the single mode condition of the waveguide. The buried SiO2 waveguide of 6μm×6μm is used, as shown in Figure 4.

The second step is to determine the specific structural parameters of the Y branch. The minimum bending radius of the waveguide should be taken into account when choosing the structure of the bending part of the Y branch. Then need to determine the branch spacing according to the process conditions. S-shaped bending is adopted here.

In addition, the case where the branch spacing S is zero (i.e. the ideal case) is simulated. At the central wavelength of 1550nm, the additional loss of the Y-branch power splitter is less than 0.1dB. However, when the branch spacing is 2um conforming to the actual process conditions, the additional loss of Y branch power splitter is 0.34dB. This indicates that the branch spacing of the Y branch is indeed the main source of its additional loss. Many ways have been put forward to solve this problem.

IV. Design and Simulation of Ridge Y Branch Optical Waveguide

A. Theoretical analysis of ridge optical waveguides

In order to propagate light waves in a single mode in the waveguide, the refractive index of the core layer must be higher than that of the cladding layer. On this basis, combined with the single mode condition, the internal and external ridge height and ridge width of the ridge waveguide are designed comprehensively, and the iterative simulation is carried out to obtain the ridge waveguide carrying only the fundamental mode, as shown in Figure 5 and Figure 6.

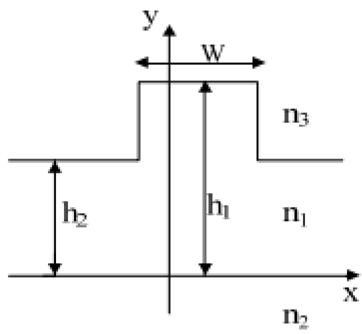


Fig. 5. The cross section of a ridge optical waveguide

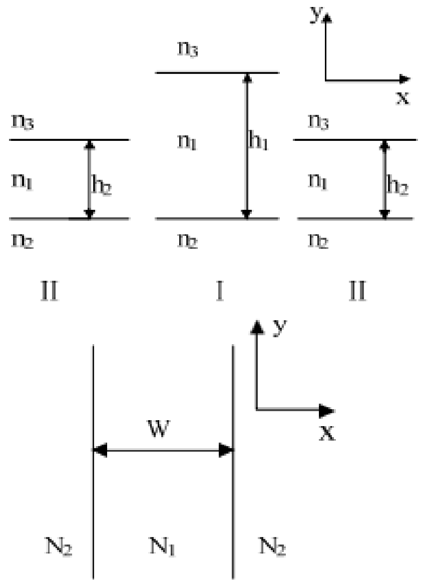


Fig. 6. Equivalent flat waveguide

B. Design of SOI ridge optical waveguides

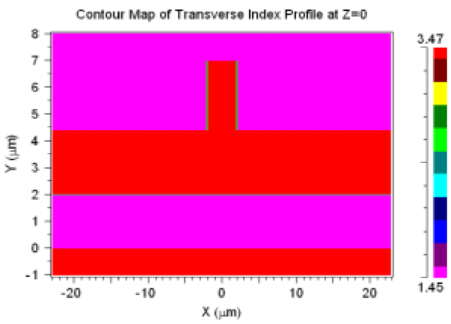


Fig. 7. Contour map of transverse index profile

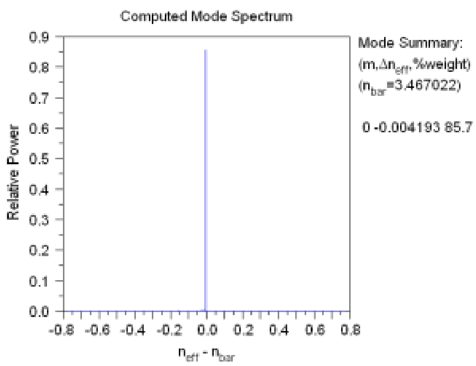


Fig. 8. Computed Mode Spectrum

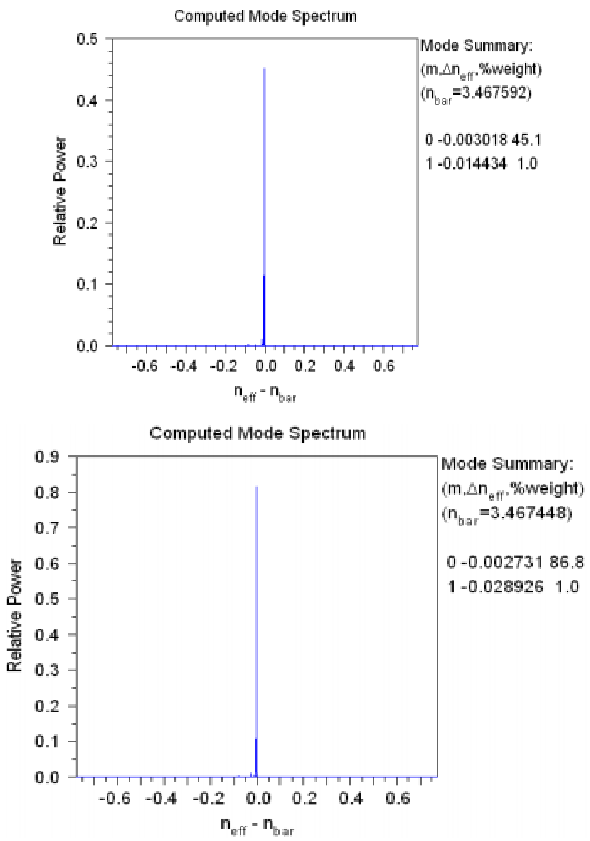


Fig. 9. Waveguide mode spectrum after changing dimension

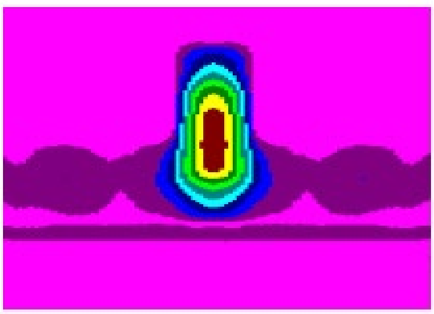


Fig. 10. Light wave leakage in the lower cladding in SOI *ridge optical waveguide*

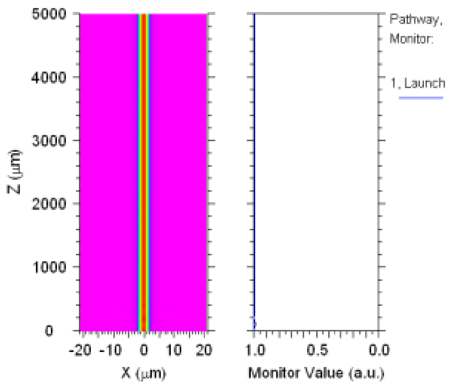


Fig. 11. Power transmission in ridge waveguide

As shown in Figure 7,8,9,10,11, these are the design and simulation results of SOI ridge optical waveguides.

C. Design of SiO2 ridged optical waveguides

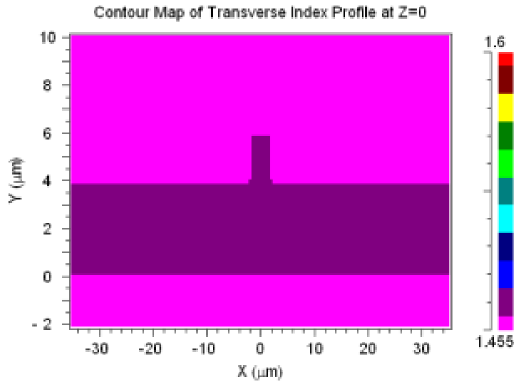


Fig. 12. Transverse refractive index distribution of SiO2 ridged optical waveguides

As shown above in Figure 12, this is the design and simulation result of SiO2 ridge optical waveguides.

It can be seen that the loss changes caused by different angles at the connection of the branch arm to the branch. In addition, the output power of the branches is not completely equal due to the coupling between the output branches. The additional output loss of this SiO2 ridged straight arm 1×4 power divider is 1.7dB, which is larger than that of the aforementioned SOI ridged S-arm 1×4 power divider with the same transverse separation distance.

Due to the large refractive index difference between silicon and silicon oxide, SOI can be used to make smaller devices, and due to its strong binding ability to light waves, it is suitable for making ridge optical waveguides. In addition, since the refraction index of cladding is much smaller than that of the core layer, there is a large margin from the core layer even if the refraction index of the outer cladding rises a lot due to the inclination of the refraction index distribution curve. In this way, when the refractive index of the cladding somewhere away from the core layer reaches the refractive index of the core layer, the electromagnetic field penetrating into the cladding has been fully attenuated, and the influence of the refractive index distribution tilt can be reduced to a small extent. Therefore, the SOI ridge curved waveguide can have a small radiation loss and is suitable for constructing S-arm Y branch, so that the Y branch can realize a large transverse separation distance at a short longitudinal length, and is suitable for integration.

Compared with SOI, the core refractive index of SiO2 optical waveguide is very close to the cladding refractive index. According to the above analysis of SOI optical waveguide, the bending loss of SiO2 optical waveguide will be large, which is also proved by the previous simulation results. Therefore, it is not suitable to construct the curved arm Y branch with silicon oxide ridge optical waveguide. However, the transmission loss of SiO2 ridge waveguide is 0.013dB, less than that of SOI ridge waveguide (0.026dB), so the power transmission efficiency of straight-arm Y branch constructed by sio2 ridge waveguide is better than that of SOI ridge Y branch. However, due to its weak constraint on light waves, it is very sensitive to the size of the branch Angle. It can be seen from the simulation that in order to obtain a small loss, the branch Angle can only change within a small range of less than 1°. Therefore, the traditional straight arm Y branch can only realize the small-angle branch, which will consume a large area. In addition, due to the difference of refractive index between the two materials, the size requirements for the realization of single-mode propagation are also different, so it is necessary to apply the corresponding single-mode conditions according to the specific materials and combine with software for accurate simulation to determine.

V. Design and Simulation of Rectangular Y Branch Optical Waveguide

A. Theoretical analysis of rectangular optical waveguides

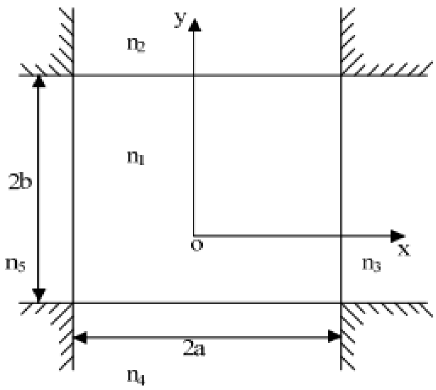


Fig. 13. Rectangular optical waveguide

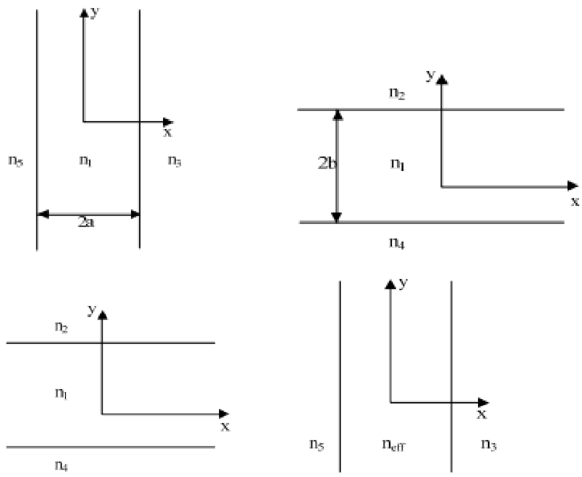


Fig. 14. Macatieri approximation of Rectangular optical waveguide

We can use the theory of Macatieri approximation to analyze rectangular optical waveguide as shown in Fig.13 and Fig.14.

B. Design of SOI rectangular optical waveguide

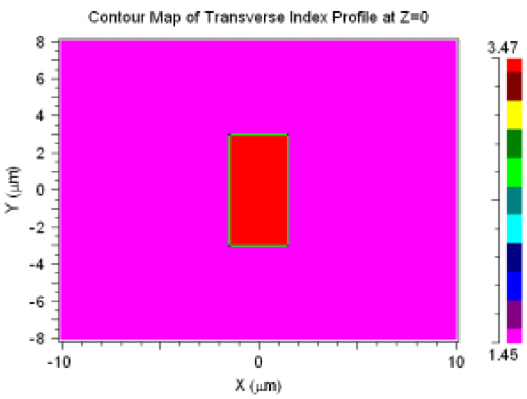


Fig. 15. Contour map of transverse index profile

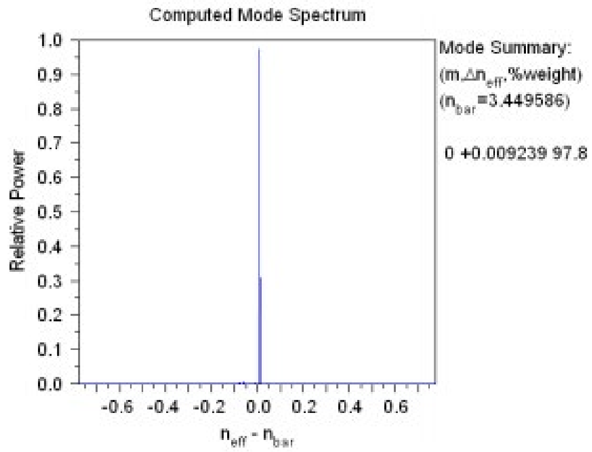


Fig. 16. Computed Mode spectrum

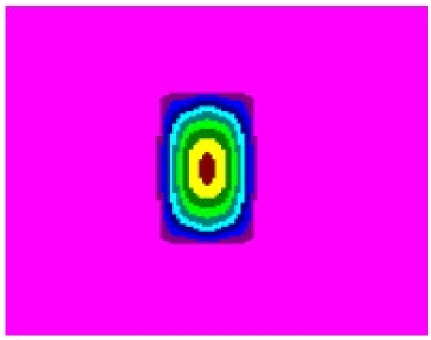


Fig. 17. Light wave leakage in the lower cladding in SOI rectangular optical waveguide

As shown above, these are the design and simulation results of SOI rectangular optical waveguides.

C. Design of SiO2 rectangular optical waveguide

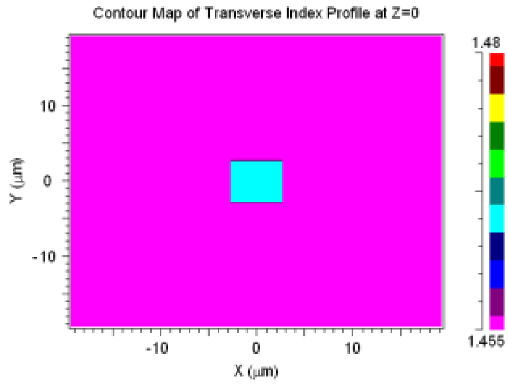
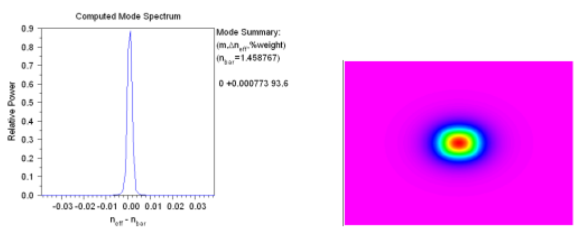


Fig. 18. Contour map of transverse index profile



(a) (b)

Fig. 19. Computed Mode Spectrum and Light wave leakage in the lower cladding in SiO2 rectangular optical waveguide

As shown above Figure 15,16,17,18,19, these are the design and simulation results of SiO2 rectangular optical waveguides.

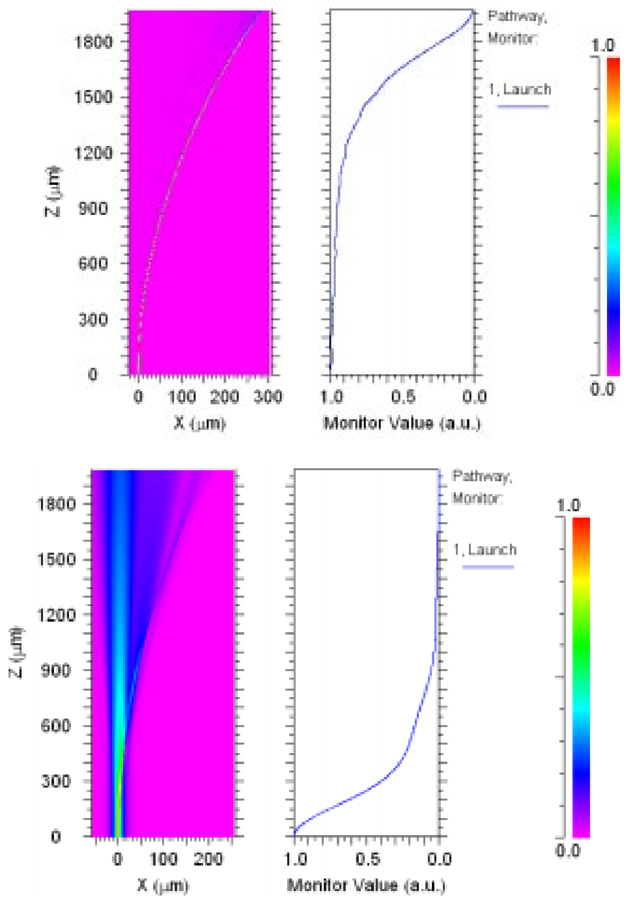
Both SOI rectangular optical waveguides and SiO2 rectangular optical waveguides can achieve single-mode propagation and have very small transmission loss by properly designing their sizes. The fundamental modes can be well confined in the rectangular optical waveguide.

However, due to the large coupling of the rectangular optical waveguide constituted by SOI, the branch spacing of the power splitter realized by SOI should be large to remove the coupling effect, which requires a large area and is not conducive to the integration implementation. In addition, its binding force on light waves is weak. In the Y branch structure, the light field energy radiated from the bifurcation is large, so the final loss is large. Therefore, it is not suitable for Y power splitter with large Angle branch.

The rectangular optical waveguides with SiO2 show good performance both in terms of bending loss and coupling. Both the S-arm and the straight-arm Y branch realized by this method have small output loss, and can still get large output power under the large-angle branch, so only a small longitudinal length is needed, so it is suitable for integration.

D. Comparison of designed optical waveguides

The bending loss simulation results of four waveguides are shown in the figure 20 below.



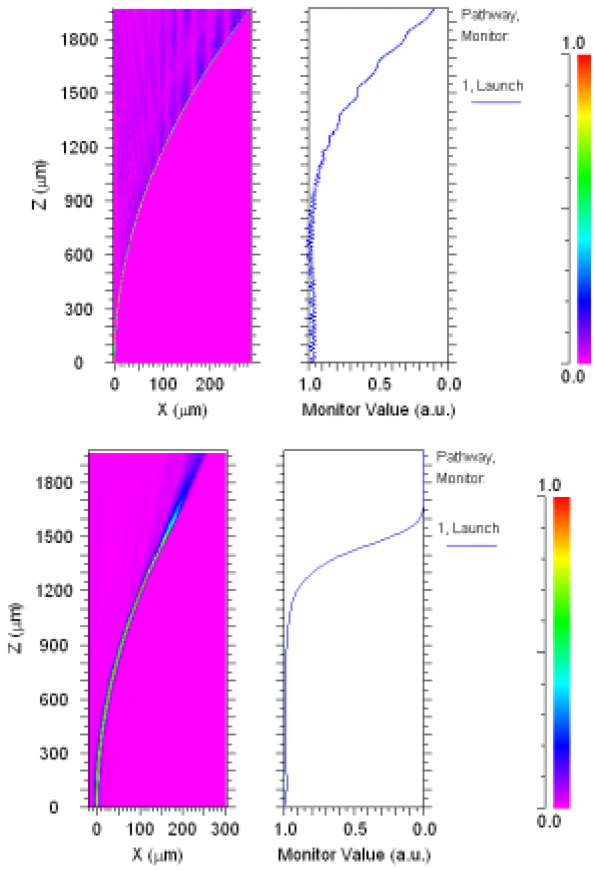


Fig. 20. Bending loss characteristics of four waveguides

Except the radius of SiO2 ridge waveguide is 10000um, the rest are 7000um. By comparison, it is found that the bending loss of SiO2 ridge waveguide is the largest, which is mainly because the difference of refractive index between the core layer and the cladding layer is small, and the ridge waveguide can not limit the optical field well. The other three have a propagation length, once exceeds the propagation length, the loss will increase sharply, so the general use should be controlled within the propagation length. Compared with the two rectangular waveguides, the loss of SOI ridge waveguides increases slowly with the propagation length before reaching the propagation length where the loss increases sharply, while the rectangular waveguides hardly change with the propagation length. Therefore, the bending loss characteristics of rectangular waveguides are better than those of ridge waveguides before a sharp increase, which can be seen from the S-bend formed by them, as shown in Figure 21.

Therefore, it can be known from the above comparison that the SOI ridge optical waveguides and SiO2 rectangular optical waveguides have strong binding on the optical field, small coupling and low loss. Generally, the ridged structure is suitable for the use of SOI materials, while the rectangular structure is suitable for the use of SiO2 materials. The SOI ridge and SiO2 rectangular optical waveguides can be used when constructing the S-arm Y branch, while the SiO2 rectangular optical waveguides should be used when constructing the straight-arm Y branch. In general, SiO2 rectangular optical waveguides have small coupling, strong optical field binding force and low loss, and have good performance whether forming straight arm Y branch or S-arm Y branch, and are compatible with silicon standard technology, so they are a good choice for photoelectric integration. Although the performance of SOI ridge optical waveguide is not as good as that of SiO2 rectangular optical waveguide, it does not require high technological accuracy, and it is easy to interface with optical fiber. Therefore, SOI ridge optical waveguide can be selected in some applications. In addition, although the loss of the straight-arm Y branch is similar to that of the S-arm Y branch, it consumes a large longitudinal length, that is, requires a large area, which is not conductive to intensive integration.

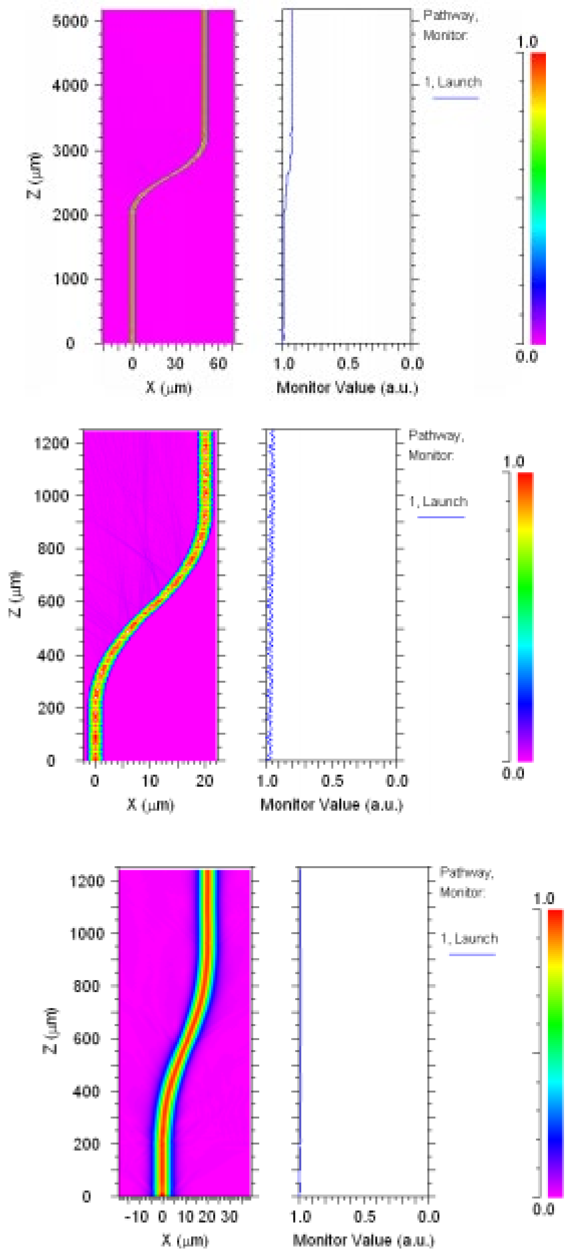


Fig. 21. Bending loss characteristics of S-bend waveguides

VI. Conclusion

In this paper, the performance of SOI optical waveguides and SiO2 optical waveguides related to standard silicon technology is studied mainly for process compatibility. The advantages and disadvantages of using ridged and rectangular optical waveguides for these two materials are explored, and the structure of Y branch suitable for different materials and different optical waveguides is also discussed. The results show that SiO2 rectangular optical waveguides have the best performance and are suitable for integration. However, considering the influence of process accuracy on rectangular optical waveguides, the dependence on process accuracy can be reduced by using SOI ridge optical waveguides with appropriate performance sacrifice. The specific work is described as follows:

(1) The linear optical theory and electromagnetic wave theory of optical waveguide are studied. Due to the complexity of strict analytical calculation of optical waveguide, numerical calculation method is introduced in practice for research. The finite-difference beam transmission method is simple, fast and can guarantee sufficient calculation accuracy. It is suitable to be used as a numerical method for analyzing optical waveguides. The research shows that the semi-vector scheme can obtain higher calculation accuracy under reasonable calculation amount for general three-dimensional waveguides.

(2) Some common optical waveguide materials and structures are discussed. It is shown that the performance of silicon based materials can also reach or surpass that of non-silicon based materials for optical waveguide applications. The performance indexes of optical waveguide couplers are given and the theoretical analysis and description of various optical waveguide couplers are carried out. Based on optical waveguide, different shape structures are constructed to obtain the required functional characteristics.

(3) The equivalent refractive index method is used to analyze the ridge optical waveguide. The design process and optimization method of Y branch and 1×4 power divider are described in detail. The bending loss of the waveguide is analyzed and it is shown that the bending loss of the waveguide with small refractive index difference is larger. The SOI ridge optical waveguide and SiO2 ridge optical waveguide, their Y branches and 1×4 power splitter are designed. The simulation results are given and analyzed in detail. The additional loss of the SOI ridge S-arm 1×4 power splitter is 1.4dB. The additional loss of SOI ridge type and SiO2 ridge type straight arm 1×4 power divider is 2.3dB and 1.7dB respectively.

(4) The rectangular optical waveguides are analyzed by Macatili method and equivalent refractive index method.The SOI rectangular optical waveguide and SiO2 rectangular optical waveguide, their Y branch and 1×4 power splitter are designed. The simulation results are given and analyzed. The additional loss of the designed SiO2 rectangular S-arm 1×4 power splitter is 0.232dB. The additional loss of SiO2 rectangular straight arm 1×4 power divider is 0.123dB, respectively. Finally, the four optical waveguides, their Y branches and 1×4 power dividers are compared and discussed. It is concluded that SiO2 rectangular optical waveguides are suitable for photoelectric integration.

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