Design of three-dimensional silica on a silicon single-mode single-polarization waveguide

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Abstract: We present a design of three-dimensional (3D) silica on a silicon single-mode single-polarization waveguide (SMSPW) by taking into consideration the induced birefringence effect of the silica. This can cut off the TM mode and transmit the TE mode. The characteristics of the light propagating across the polarization maintaining waveguide were simulated by 3D beam propagation methods (3D-BPM). The result showed that the SMSPW has a high extinction ratio over 50 dB for the TM mode. Without increasing the complexity of the waveguide fabricating process, this structure can be used as a polarizer directly, and can also be integrated easily into other waveguide devices.

Key words: SMSPW; birefringence; 3D-BPM; silica waveguide
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1. Introduction

Birefringence remains a key issue in integrated optical systems, particularly in silica-on-silicon planar waveguide technology. SMSP fiber applied broadly, but in waveguide system. Birefringence is present in any waveguide that is not perfectly symmetric in cross-section, for get single-mode single-polarization waveguide (SMSPW). A lot of effort has been made to tackle the birefringence problem, for example, the use of stress relief grooves[1−3], adding an Si film on the waveguide[4,5] and mid-infrared laser processing of integrated optical components[6], tuning the thermal expansion coefficient of the upper cladding layer[7], or ultraviolet[8] irradiating the waveguides, have been made to reduce or eliminate the waveguide birefringence. Generally, these methods demand additional complex and time-consuming processes to minimize the waveguide birefringence, and their fabrication process is complex and difficult to implement. In this paper, we have designed a novel SMSPW without increasing the complexity of the waveguide fabricating process, based on the Si-based silica waveguide birefringence effect using an effective-index method, which cuts off the TM mode and transmits the TE mode. Also, the characteristics of the light propagating across the polarization maintaining waveguide were simulated by three-dimensional beam propagation methods (3D-BPM).

2. Theory analysis

Birefringence is present in any waveguide that is not perfectly symmetrical in cross-section. A planar waveguide has three layers with indexes n_1, n_2, n_3. n_1 is the index of the core layer which has a width of w and a thickness of t; n_2 is the index of the buffer layer; and n_3 is the index of the cladding layer. In the effective-index method approximation, the channel waveguide is equivalent to two slab waveguides, as shown in Fig. 1, and the boundary conditions lead to the eigenvalue equations (1) and (2).

$$k(n_1^2 - N_1^2)^{1/2} w = m\pi + 2\tan^{-1}\left[\left(\frac{N_1^2 - n_3^2}{n_1^2 - N_1^2}\right)^{1/2} \eta_{13}\right], \tag{1}$$

where

$$\eta_{13} = \begin{cases} 1, & \text{TE mode,} \\ \left(\dfrac{n_1}{n_3}\right)^2, & \text{TM mode.} \end{cases}$$

k is the free space wave number, N_1 is the effective mode index of the first slab waveguide and m is mode number.

$$k(N_1^2 - N_{mn}^2)^{1/2} t = n\pi + \tan^{-1}\left[\left(\frac{N_{mn}^2 - n_3^2}{N_1^2 - N_{mn}^2}\right)^{1/2} \eta_{m3}\right] + \tan^{-1}\left[\left(\frac{N_{mn}^2 - n_2^2}{N_1^2 - N_{mn}^2}\right)^{1/2} \eta_{m2}\right], \tag{2}$$

where

$$\eta_{mj} = \begin{cases} 1, & \text{TE mode,} \\ \left(\dfrac{N_1}{n_j}\right)^2, & \text{TM mode.} \end{cases}$$

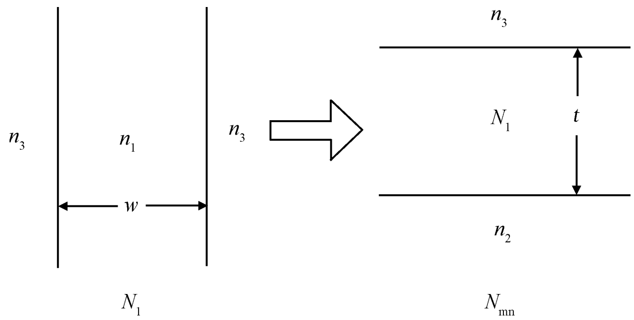

Fig. 1. Analytical model for the effective index method.

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Table 1. Material properties of the SMSPW.

Material	$\alpha(K)$	E (GPa)	υ	p_{11}	p_{12}	ΔT (K)
Cladding layer	Adjustable	65	–0.2	0.121	0.27	1000
Core layer	Adjustable	70	–0.2	0.121	0.27	1000
Buffer layer	Adjustable	72.5	–0.17	0.121	0.27	1000
Silicon substrate	3.6×10^{-6}	130	–0.279	0.121	0.27	1000

N_{mn} is the effective mode index of the channel waveguide and n is the mode number.

Equation (3) is obtained by substituting the guided-mode cut-off condition, $N_{mn} = n_2$, into Eq. (2).

$$k(N_1^2 - n_2^2)^{1/2} t = n\pi + \tan^{-1}\left[\left(\frac{n_2^2 - n_3^2}{N_1^2 - n_2^2}\right)^{1/2} \eta_{m3}\right]. \quad (3)$$

Then the single mode conditions are, for TE mode,

$$t_0(n = 0) < t < t_1(n = 1). \quad (4)$$

For TM mode,

$$t_2(n = 0) < t < t_3(n = 1). \quad (5)$$

The TM mode cuts off and TE transmits,

$$t_0(n = 0) < t < t_2(n = 0) < t_1(n = 1). \quad (6)$$

Likewise, the TE mode cuts off and the TM mode transmits,

$$t_2(n = 0) < t < t_0(n = 0) < t_3(n = 1). \quad (7)$$

It is well known that stresses are virtually always present in thin films, particularly in SiO_2 films grown by the thermal oxidation of silicon. According to the general theory of photo elastic effects in an anisotropic medium, an optical anisotropy can be caused by strains, and induce the birefringence $\Delta n = n_{TE} - n_{TM}$. The refractive index of n_{TE} and n_{TM} can be expressed as[9]

$$n_{TE} = n_0\left[1 - \frac{1}{2}(C_1 + C_2)\sigma n_0^2\right], \quad (8)$$

$$n_{TM} = n_0\left[1 - C_2\sigma n_0^2\right], \quad (9)$$

where

$$C_1 = E_r^{-1}\left[p_1 - 2\upsilon_r p_2\right], \quad (10)$$

$$C_2 = E_r^{-1}\left[(1 - \upsilon_r)p_1 - \upsilon_r p_2\right], \quad (11)$$

where C_1 and C_2 are the photo-elastic constants. n_0 is the isotropic refractive index in the strain and stress-free medium, p_1 and p_2 are the strain optic coefficients, E_r is Young's modulus, υ_r is Poisson's ratio of the film and σ is the stress that is parallel to the film surface.

Consider different thermal expansion coefficients of the substrate with each layer of film material. The stress calculation formula is

$$\sigma = \frac{(\alpha_s - \alpha_r)\Delta T E_r}{1 - \upsilon_r}, \quad (12)$$

Table 2. Parameters used for calculation.

Material	α_r	n_0	n_{TE}	n_{TM}
Buffer layer	0.5×10^{-6}	1.4475	1.4453	1.4463
Core layer	3.0×10^{-6}	1.4494	1.4490	1.4492
Cladding layer	2.8×10^{-6}	1.4451	1.4452	1.4479

where α_s and α_r are the thermal expansion coefficient in the substrate and film material, respectively, and ΔT is the temperature change during the cooling process.

Therefore, the SMSPW in which the TE mode transmits and the TM mode cuts off can be implemented by promptly adjusting the stresses σ of the film medium. The SMSPW structure contains a SiO_2 buffer layer, a Ge-doped SiO_2 core layer and a SiO_2 cladding layer, and the whole structure can be grown on a silicon substrate. We simulated the channel waveguide based on Table 1[10].

The refractive-index n_{TE} and n_{TM} of three layers considered thermal stress after annealing by Eqs. (8)–(12) are summarized in Table 2.

By substitution of the data in Table 2 into Eqs. (1)–(6) can be calculated to maintain the single-mode single-polarization conditions for cutting off the TM mode and transmitting the TE mode:

If $w = 4$ μm, then 3.0795 μm < t < 9.3761 μm;
If $w = 5.4$ μm, then 2.1088 μm < t < 4.4322 μm;
If $w = 6$ μm, then 1.9073 μm < t < 3.7921 μm.

3. Numerical simulation and results of SMSPW

In order to verify the accuracy of the calculation in the effective-index method, we simulated the light propagating in these configuration with 3D BPM based on the finite-difference method[11]. The starting field is Gaussian, which takes into account the loss of fiber and waveguide. In addition, in order to prevent spurious reflection from the computational window edges, the transparent boundary condition (TBC)[12] was used. Normalized output optical power versus the distance at different waveguide structures was calculated and shown in Figs. 2–5 at 1550 nm wavelength.

From Figs. 2–5, the optical power of the TM mode reduced quickly and was smaller than 0.01 when the transmission distance was larger than 2200 μm. The optical power of the TE mode decreased first and the changing rate was very slow when the transmission distance was larger than 3000 μm. So only the TE mode exists in this structure.

Why do the inserted beams of both polarizations decay rapidly in the first millimeter, and the TE polarized beam stays almost constant after that? The reason is a mismatch between the Gaussian beam with the guided modes, so some power is lost at conversion from Gaussian to guided mode. Also, we calculated the case when the initial field is a mode field by taking

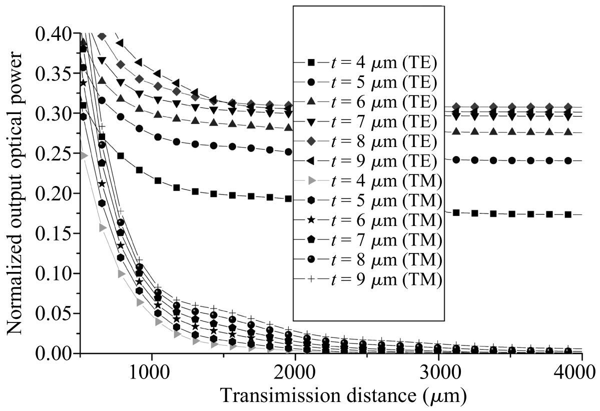

Fig. 2. Normalized output optical power versus transmission distance (the structure of w = 4 μm, 3.0795 μm < t < 9.3761 μm).

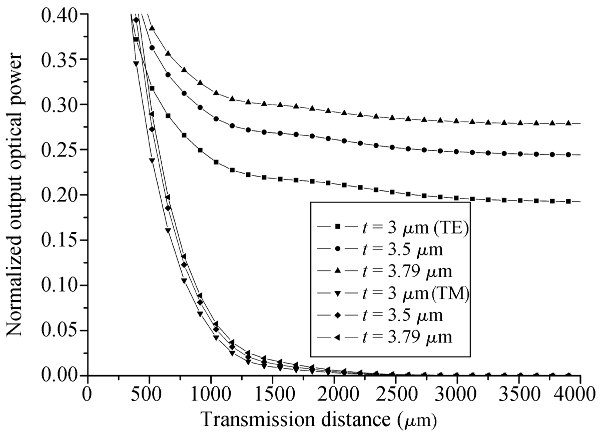

Fig. 3. Normalized output optical power versus transmission distance (the structure of w = 5.4 μm, then 2.1088 μm < t < 4.4322 μm).

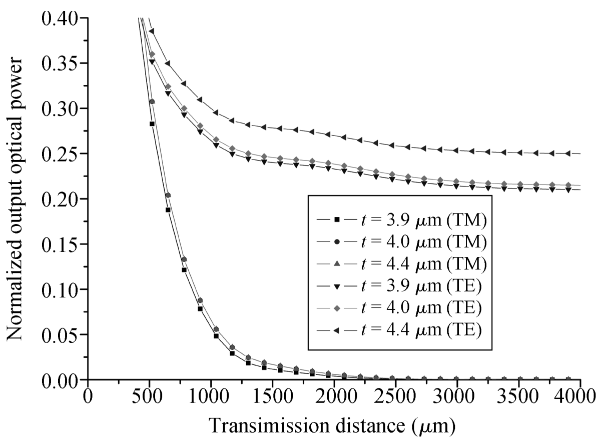

Fig. 4. Normalized output optical power versus transmission distance (the structure of w = 6 μm, 1.9073 μm < t < 3.7921 μm).

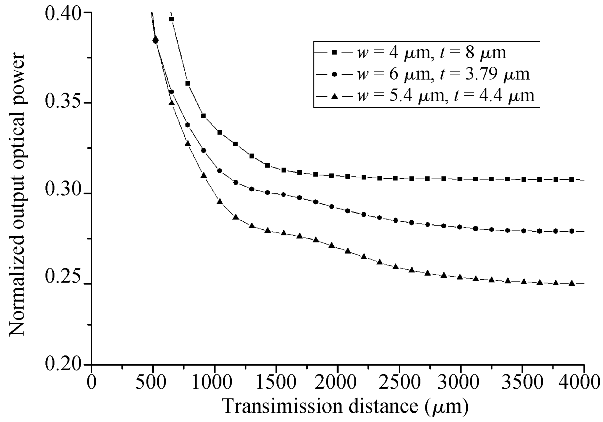

Fig. 5. Normalized output optical power versus transmission distance for three different structures.

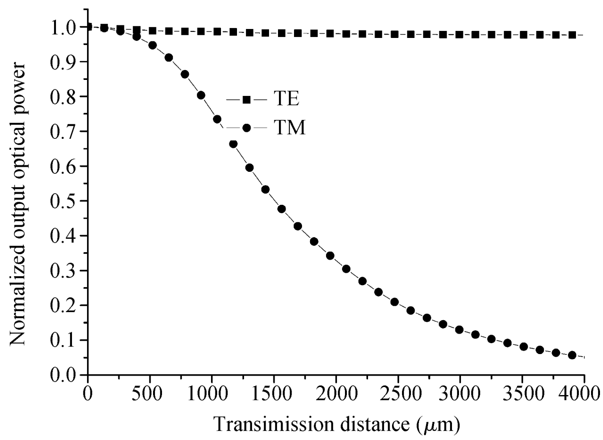

Fig. 6. Normalized output optical power versus transmission distance (the structure of w = 4 μm, t = 8 μm, considering the stress and starting field, is mode field).

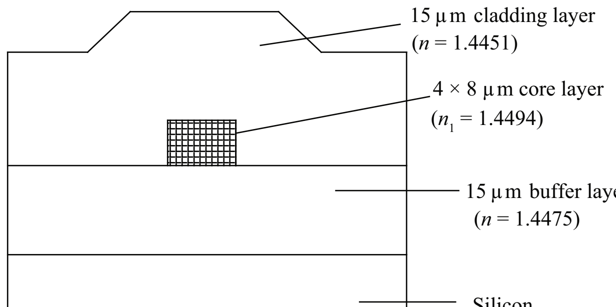

Fig. 7. Section profile of the design of the single polarization waveguide.

into consideration the stress birefringence effect. The results, as shown in Fig. 6, show that that our structure cuts off the TM mode and transmits the TE mode.

For different widths and thicknesses of waveguide, the loss varies. With the configuration of $w = 4$ μm, $t = 8$ μm, the propagation loss for the TE mode is lower than the other structures. The extinction ratio is defined as the power ratio of the wanted and the unwanted signals at the output. Thus, if the input is the TE mode, the P_{wanted} will be the power of the TE mode at the output port and P_{unwanted} will be the power of the TM mode at the same output port. We can obtain the extinction ratio as 50.8 dB. And ensured the size of SMSPW is 4×8 μm^2. Details of the channel guide geometry are given in Fig. 7.

4. Conclusion

In this paper, a silica on silicon single-mode single-polarization waveguide is proposed. The SMSPW structure that contains a Ge-doped silica core layer, a silica buffer layer and silica cladding layers cut off the TM mode and transmit the TE mode. We designed and simulated this using an effective-index method and a 3D FD-BPM method respectively. Numerical simulation results showed that the SMSPW had an ideal extinction ratio characteristic. Without increasing the complexity of the waveguide fabricating process, this structure can be used as a polarizer directly, and can also be integrated easily with other waveguide devices.

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