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Non-polarization and high-coupling-efficiency coupler using multilevel grating structure*

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A multilevel grating coupler based on silicon-on-insulator (SOI) material structure is proposed to realize the coupling between waveguide and waveguide or waveguide and fiber. This coupler is compatible with the current fabrication facilities for complementary metal oxide semiconductor (CMOS) technology with vertical coupling. This structure can realize coupling when the beams with transverse electric (TE) polarization and transverse magnetic (TM) polarization are incident at the same time. The influences of the grating coupler parameters including wavelength, the thickness of waveguide layer, the thickness of SiO_2 layer and the number of steps on the TE mode and TM mode coupling efficiencies are discussed. Theory researches and simulation results indicate that the wavelength range is from 1533 nm to 1580 nm when the TE mode and TM mode coupling efficiencies are both more than 40% as the grating period is 0.99 μm. The coupling efficiencies of the incident TE and TM modes are 49.9% and 49.5% at the wavelength of 1565 nm, respectively, and the difference between them is only 0.4%.

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Many types of high-efficiency grating couplers have been put forward[1-6]. Feng et al[7] demonstrated a polarization beam splitter with two layers using a binary blazed grating coupler. Shao et al[8] showed a compact polarization-independent grating coupler. Yang et al[9] presented a binary blazed grating beam splitter via vertical coupling.

In this paper, we show a multilevel polarization-independent grating coupler. The multilevel grating has high diffraction efficiency, and vertical coupling structure is compatible with the current fabrication facilities for complementary metal oxide semiconductor (CMOS) technology. The diffractive characteristics of the coupler are analyzed using coupling wave theory, and simulated in the method of finite-difference time-domain (FDTD). The simulation results indicate that the coupler can realize the coupling when the light beams with transverse electric (TE) polarization and transverse magnetic (TM) polarization are incident at the same time. The wavelength range is from 1533 nm to 1580 nm when the TE mode and TM mode coupling efficiencies are both more than 40% as the grating period is 0.99 μm. The coupling efficiencies of incident TE mode and TM mode are 49.9% and 49.5% at the wavelength of 1565 nm, respectively, and the difference between them is only 0.4%.

It is well known that grating is a periodic device, and the basic coupling theory is Bragg condition[10]:

$$K_{\text{in}} + m\cdot K_T = \beta, \quad (m=0,\ \pm1,\ \pm2...), \qquad (1)$$

where $K_T = k_0 / T = 2\pi / \lambda T$ is the reciprocal lattice vector of the grating along the direction of grating length, $K_{\text{in}} = |\boldsymbol{K}_{\text{in}}| \times \sin\theta = 2\pi / \lambda \cdot n_c \cdot \sin\theta$ is the incident wave vector (n_c is the refractive index of incident plane), and $\beta = K_0 \cdot N_{\text{eff}} = 2\pi/\lambda \cdot N_{\text{eff}}$ is the propagation constant of the guided mode in the grating waveguide, where N_{eff} is the effective refractive index of the waveguide for the propagating mode, and m is the diffraction order which is set to +1 in this paper. Fig.1 shows the wave-vector diagram for the grating in Bragg theory.

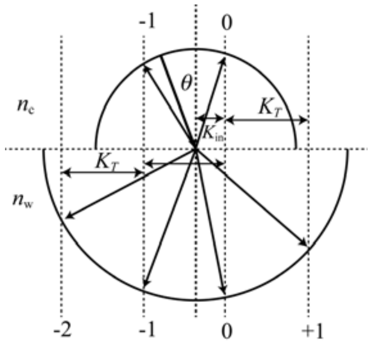

Fig.1 Wave-vector diagram for the grating in Bragg theory

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A grating period must satisfy the Bragg conditions between the gratings and the waveguide mode, and the incident light is designed as absolutely vertical incidence, so θ=0°. According to Eq.(1), the grating period can be given by

$$T=|\lambda/N_{\text{eff}}| . \tag{2}$$

From the slab waveguide theory[11], N_{eff} can be obtained from the mode dispersion equations of slab waveguide

$$(n_{\text{w}}^2-N_{\text{eff}}^2)^{1/2}\cdot\frac{2\pi}{\lambda}a=m\pi+\tan^{-1}[C_1\cdot(\frac{N_{\text{eff}}^2-n_{\text{c}}^2}{n_{\text{w}}^2-N_{\text{eff}}^2})^{1/2}]+\tan^{-1}[C_2\cdot(\frac{N_{\text{eff}}^2-n_{\text{s}}^2}{n_{\text{w}}^2-N_{\text{eff}}^2})^{1/2}] . \tag{3}$$

To TE and TM modes:

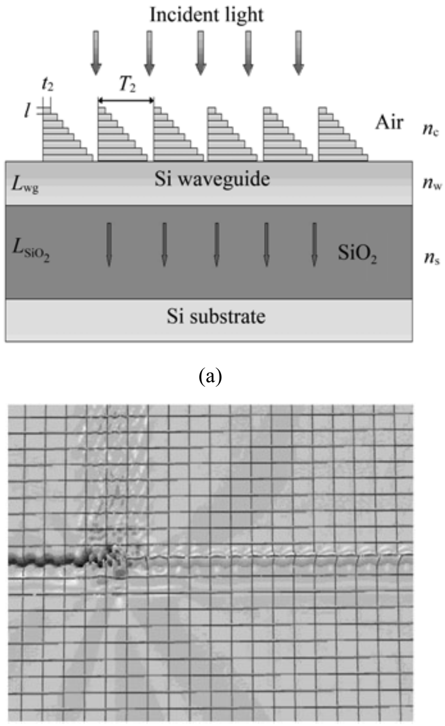
$$\begin{cases} C_1=C_2=1 & \text{(TE mode)} \\ C_1=(n_{\text{w}}/n_{\text{c}})^2;\quad C_2=(n_{\text{w}}/n_{\text{s}})^2 & \text{(TM mode)}, \end{cases} \tag{4}$$

where n_{c}, n_{w}, n_{s} are the refractive indices of air, Si and SiO_2, which are set to be 1, 3.48 and 1.48 respectively in the simulation. a is the thickness of waveguide layer, which should be less than 270 nm[8], so here we choose it as 220 nm in our simulation. By choosing advisable wavelength and m=+1, we can compute the grating period using Eqs.(2) and (3) under the condition of vertical incidence ($\theta=0°$). From the theory analyses[10], we know that grating period should vary in the range of 0.455−1.079 μm. In order to obtain more ideal result and facilitate subsequent simulation, in general we firstly make simulation around the computed grating period to get the optimum grating period. Then the parameters including wavelength, the thickness of waveguide layer, the thickness of SiO_2 layer and the number of steps are also simulated to obtain the optimum results.

In this paper, we want to analyze and design the structure of the non-polarization grating coupler. A grating structure which is sensitive to TE mode and another grating structure which is sensitive to TM mode are simulated, respectively. Then we combine the two gating structures by turns.

The coupling structure which is sensitive to TE mode is illustrated in Fig.2(a), where T_2 is the grating period, t_2 is the width of every step, and l is the thickness of every step. Zhou et al[12] have done some similar researches. After the simulation with the parameters of L_{wg}=0.22 μm and $L_{\text{SiO}_2}=0.7$ μm in this paper, we see that the coupling efficiency of incident TE mode can reach about 50% around the wavelength of 1550 nm, and it can reach about 50.7% at the wavelength of 1540 nm. Fig.2(b) shows the optical field distribution of the TE mode coupling case at the wavelength of 1540 nm.

The coupling structure which is sensitive to TM mode is illustrated in Fig.3(a), where T_1 is the grating period, t_1 and l are the width and thickness of every step, respectively. The simulation indicates that the coupling efficiency of TM mode incidence can reach about 68% at the wavelength of 1565 nm. Fig.3(b) shows the optical field distribution of the TM mode coupling case at the wavelength of 1565 nm.



(a)

(b)

Fig.2 (a) Grating structure which is sensitive to TE mode incidence with T_2=0.45 μm, t_2=0.05 μm, l=0.05 μm; (b) Optical field distribution of TE mode at the incident wavelength of 1540 nm

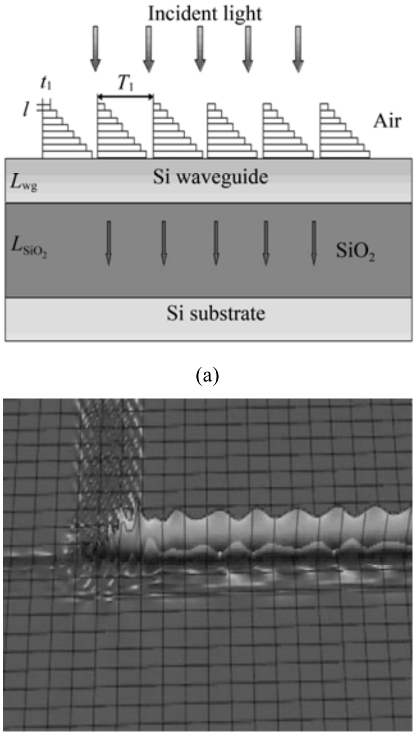
The grating coupler structure of non-polarization designed in this paper is shown in Fig.4.

The coupler is based on silicon-on-insulator (SOI) structure, which is composed of the top silicon waveguide (refractive index n_{w}), SiO_2 layer (refractive index n_{s}) and substrate layer (refractive index n_{w}). The multilevel grating is the core of the coupler, which is etched on the top silicon waveguide of an SOI wafer. The multilevel grating combines two kinds of grating structures by turns, which are sensitive to TE mode and TM mode, respectively. The multilevel grating structure with step width of t_2 and grating period of T_2 has high coupling efficiency to TE mode. The multilevel grating structure with step width of t_1 and grating period of T_1 has high coupling efficiency to TM mode. Then the whole grating structure can realize the coupling with TE polarization and TM polarization at the same time, so it is a non-polarization coupler.

In this paper, the grating period is T=0.99 μm (T=T_1+T_2), the number of periods is 3, the grating length is about 3 μm, the grating distance is d=(t_1+t_2)/2=0.055 μm, the thickness of every step is l=0.05 μm and the total thickness of 8 steps is 0.4 μm. N is the number of steps.

The influences of wavelength on the TE mode and TM mode coupling efficiencies with other parameters of

T=0.99 μm, t_1=0.06 μm, t_2=0.05 μm, l=0.05 μm, $L_{\mathrm{SiO_2}}$ = 0.7 μm, L_{wg}=0.22 μm, N=8 are shown in Fig.5.



(a)

(b)

Fig.3 (a) Grating structure which is sensitive to TM mode incidence with *T*$_1$=0.45 μm, *t*$_1$=0.05 μm, *l*=0.05 μm; (b) Optical field distribution of TM mode at the incident wavelength of 1565 nm

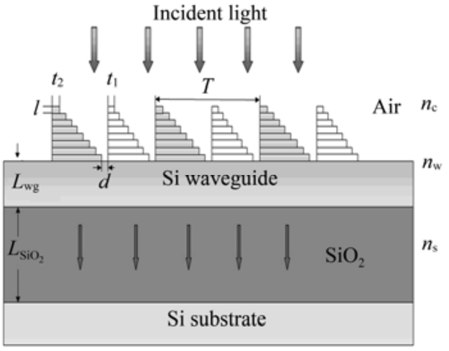


Fig.4 Schematic diagram of the proposed grating coupler structure

We know that the incident wavelength is a core parameter of Bragg conditions, and the change of wavelength has large influence on the coupling efficiency. The incident light can't couple to waveguide very well if the incident wavelength is far from the optimum wavelength. From Fig.5, we see that the coupling efficiencies of TE mode and TM mode both gradually increase first and then drop with the increase of wavelength. The wavelength range is from 1533 nm to 1580 nm when the coupling efficiencies of TE mode and TM mode are both more than 40% as the grating period is 0.99 μm. The coupling efficiencies of incident TE mode and TM mode can reach 49.9% and 49.5% at the wavelength of 1565 nm respectively, and the difference between them is only 0.4%. Fig.6 shows the optical field distributions of TE mode and TM mode. The light propagates along the right direction as shown in Fig.1.

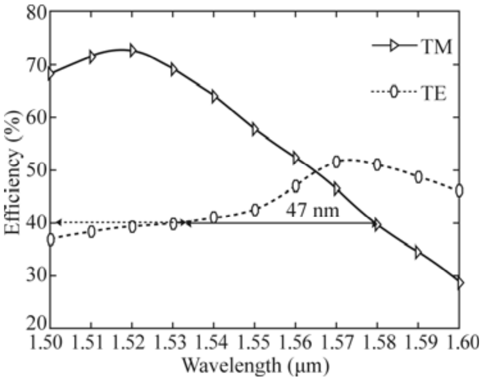
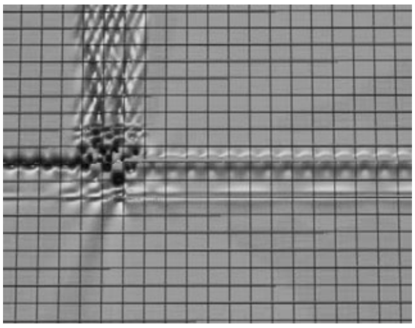
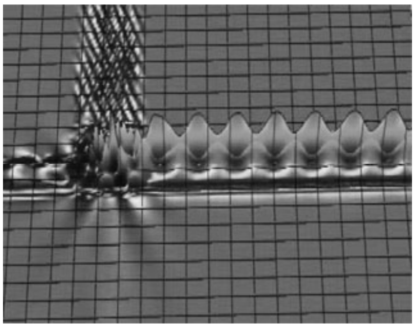


Fig.5 Influences of wavelength on the coupling efficiencies of TE mode and TM mode



(a) TE mode



(b) TM mode

Fig.6 Optical field distributions of TE mode and TM mode at the incident wavelength of 1565 nm

The influences of thickness of waveguide layer (L_{wg}) on the TE mode and TM mode coupling efficiencies with other parameters of T=0.99 μm, t_1=0.06 μm, t_2=0.05 μm, l=0.05 μm, $L_{\mathrm{SiO_2}} = 0.7$ μm, N=8, λ=1.565 μm are shown in Fig.7.

From the theory mentioned above, we know that the thickness of waveguide layer of grating coupler should be less than 270 nm[8]. Fig.7 shows that the coupling efficiencies of TE mode and TM mode are also different when the thicknesses of waveguide layer are different, and the difference of coupling efficiency between TE mode and TM mode is little when the thickness of waveguide layer is in the range of 210−240 nm. So we can choose 220 nm as the thickness of waveguide layer in this paper.

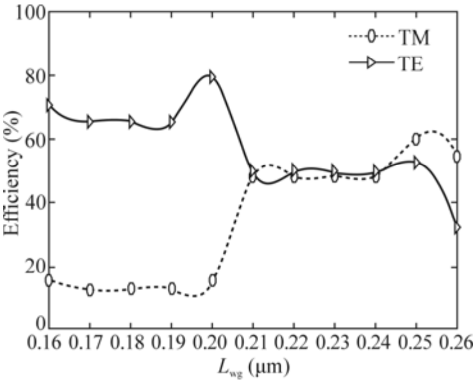


Fig.7 Influences of thickness of waveguide layer on the coupling efficiencies of TE mode and TM mode

The influences of thickness of SiO_2 layer (L_{SiO_2}) on the TE mode and TM mode coupling efficiencies with other parameters of T=0.99 μm, t_1=0.06 μm, t_2=0.05 μm, l=0.05 μm, L_{wg}=0.22 μm, N=8, λ=1.565 μm are simulated and discussed as shown in Fig.8.

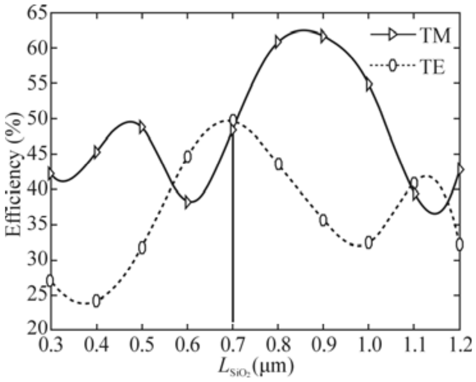


Fig.8 Influences of thickness of SiO_2 layer on the coupling efficiencies of TE mode and TM mode

The thickness of SiO_2 layer has large influence on the grating coupling efficiency of SOI waveguide[13]. As the SiO_2/Si substrate can be treated as a reflector, the coherence stack happens between the incident light and the reflected light. Consequently, the grating coupling efficiency varies periodically as a function of the SiO_2 layer thickness. Fig.8 shows that the coupling efficiencies of TE mode and TM mode approximately vary periodically as a function of the SiO_2 layer thickness. But the coupling efficiencies of TE mode and TM mode are also mostly different at the same thickness of the SiO_2 layer, and they are nearly the same and higher at the thickness of 0.7 μm. So we choose 0.7 μm as the thickness of SiO_2 layer in this paper.

The grating structures with 8, 4 and 2 steps are simulated with other parameters of t_1=0.06 μm, t_2=0.05 μm, l=0.05 μm, L_{SiO_2}=0.7 μm, L_{wg}=0.22 μm, λ=1.565 μm. Tab.1 shows the contrast of coupling efficiency between TE mode and TM mode with different numbers of steps.

Tab.1 Contrast of coupling efficiency between TE mode and TM mode with different numbers of steps

Number of steps	Efficiency of TE mode (%)	Efficiency of TM mode (%)
8	49.1	47.0
4	7.0	13.0
2	13.0	9.6

We can see that the coupling efficiencies of TE mode and TM mode with 8 steps are the highest as shown in Tab.1. It accords with the theory.

Although it needs multitasks for etching processing due to multilevel pattern, it can be compatible with the mature fabrication techniques for CMOS technology.

A multilevel grating coupler based on SOI material structure is proposed to realize the coupling between waveguide and waveguide, or between waveguide and fiber, which has the characteristic of non-polarization and extremely compact dimension (with the grating length of 3 μm). This coupler can realize the coupling under the condition of incident TE polarization and TM polarization at the same time. This coupler can be applied to optical computations and optical interconnects.

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