Research article

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Subwavelength grating slot (SWGS) waveguide at 2 μm for chip-scale data transmission

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Abstract: We propose, design, fabricate and characterize a subwavelength grating slot (SWGS) waveguide on silicon platform at short-wave infrared (SWIR) wavelength of 2 μm . The mode guiding mechanism, i.e. SWGS mode, is a combination of surface-enhanced supermode and Bloch mode. We also design and fabricate a low-loss strip-to-SWGS mode converter. We further demonstrate chip-scale direct modulation data transmission at 2 μm through the fabricated SWGS waveguides. Favorable operation performance is achieved in the experiment.

Keywords: integrated optics devices; subwavelength structures; waveguides.

1 Introduction

Silicon waveguides are promising candidates for building blocks of complicated photonic integrated circuits [1]. The typical silicon waveguide structures include strip/channel waveguide, ridge/rib waveguide, and photonic crystal waveguide. Very recently, subwavelength grating (SWG) waveguide, comprising of a periodic arrangement of high and low refractive index materials with a pitch less than one wavelength, has shown its unique advantages in propagation loss [2], broadband coupling character, and high coupling efficiency [3–6]. Meanwhile, a slot waveguide structure could enhance the light confinement in

the slot region [7]. By introducing the subwavelength slot structure in the SWG waveguide, subwavelength grating slot (SWGS) waveguides may further offer added flexibility in controlling the optical properties of the guided mode [8], which have not yet been widely studied. The effective index, mode profile, and dispersion can be simply engineered by modifying the waveguide parameters including silicon width, slot width, period, and duty cycle of the SWGS waveguides. Compared with conventional photonic wire waveguides, the optical mode of SWGS waveguides is further delocalized from the silicon core material, which offers a possible way to minimize the nonlinearity of the waveguide. Remarkably, such subwavelength structures (tens of nanometers) are somehow difficult to fabricate with high precision at near-infrared wavelengths. However, SWGS waveguides operating in the short-wave infrared (SWIR) (2–3 μm) wavelength range allow for relatively larger subwavelength dimensions, facilitating the fabrication process [9]. Meanwhile, 2- μm communication has emerged as a strong contender for the next generation of communication systems. Many recent works have been reported on silicon mid-infrared photonics, such as arrayed waveguide grating [10], microring resonator (MR) [11], and multimode interference (MMI) [12]. It could be interesting to demonstrate the SWGS structure in this attractive waveband. In this scenario, a valuable goal would be to design, fabricate, and characterize SWGS waveguides at 2 μm .

In this paper, we propose, design, fabricate, and characterize an SWGS waveguide on silicon-on-insulator (SOI) platform. We demonstrate 5-Gbit/s 2- μm data transmission in the fabricated SWGS waveguide via direct laser modulation, which may find potential applications in chip-scale data transmission for optical interconnects.

2 Concept and simulation

Figure 1A depicts the cross-section view of a typical SOI wafer to form various silicon waveguides (e.g. SWGS waveguides). The SOI wafer considered here has a 340-nm top silicon layer and a 2- μm Silica (SiO_2) buried oxide (BOX)

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Figure 1: Schematic illustration of silicon platform and SWGS waveguide.

(A) Illustration of an SOI wafer to form various silicon waveguides. (B) Top-view structure of the SWGS waveguide. (C) 3D structure of a SWGS waveguide.

layer. Figure 1B depicts the top view structure of the proposed SWGS waveguide. The corresponding 3D structure is illustrated in Figure 1C. SiO_2 with 1- μm thickness is used to fulfil and cover the silicon-based SWGS waveguide. The SWGS waveguide takes advantage of both slot waveguide and SWG waveguide. The mode guiding mechanism, i.e. SWGS mode, can be regarded as the combination of surface-enhanced supermode and Bloch mode. The high refractive index contrast and resultant electric field discontinuity at the slot boundaries (silicon- SiO_2) and the narrow slot region lead to the surface-enhanced supermode. The periodic structure of silicon- SiO_2 with subwavelength periodicity leads to the Bloch mode. The proposed SWGS waveguide features reduced nonlinearity due to tightly confined SWGS mode in the SiO_2 slot region and less residual light in the silicon region.

Remarkably, in order to couple light from the strip waveguide into SWGS mode of the SWGS waveguide, a strip-to-SWGS mode converter is designed, which is composed of a strip-to-slot mode converter [13] and two strip-to-SWG mode converters [4], as illustrated in Figure 2.

First, the strip-to-slot mode converter is based on a stable Y branch taper structure through mode-matching method. To obtain higher conversion efficiency, we choose the method of adiabatic coupling. Then, the slot mode is converted into the SWGS mode. Two triangle taper structures, each enabling the conversion from the strip mode to the SWG mode (Bloch mode), are employed to implement the evolution from the slot mode to the SWGS mode.

We choose the taper length of Y branch taper structure and triangle taper structure large enough to obtain conversion efficiency close to 100%. The SWGS waveguide geometric parameters are set as follows: silicon width: 375 nm, slot width: 100 nm, period: 200 nm, duty cycle: 50%. Figure 3A shows the top view of the simulated electric field distribution. The electromagnetic fields of strip waveguide, SWGS waveguide, and the mode conversion region between them are accurately calculated using the three-dimensional (3D) finite-difference time-domain (FDTD) method. In the simulations, the coupling efficiency is as high as 99.3%, which indicates the mode conversion loss to be only 0.0305 dB. We further monitor the

Figure 2: 3D structure of the strip-to-SWGS mode converter, consisting of one strip-to-slot mode converter and two strip-to-SWG mode converters.

Figure 3: Simulation results for strip-to-SWGS mode converter.

(A) Simulated top view of electric field distribution of the strip-to-SWGS mode converter and (B–E) cross-section view of mode evolution. (B) Strip waveguide region. (C) Middle of the strip-to-slot mode converter. (D) Slot waveguide region. (E) Middle of the slot-to-SWGS mode converter. (F) Si segment of SWGS waveguide. (G) SiO_2 segment of SWGS waveguide.

mode evolution process from strip mode to slot mode and to SWGS mode, as shown in Figure 3B–G.

The mode properties of conversion process are analyzed also using the 3D FDTD method. We further show in Figure 4A–F the mode normalized intensities along the x and y directions of the guided and propagated fundamental TE mode in six cross-sections corresponding to Figure 3B–G, respectively. It is shown in Figure 3B–G and Figure 4A–F that the slot mode and SWGS mode are confined outside the silicon region. In particular, SWGS mode is further delocalized from the silicon region. We calculate and compare the light concentration ratio of the slot waveguide and Si segment of SWGS waveguide, defined by the ratio of the light confined in the slot region to that of the total light. The light concentration ratio is $\sim 22\%$ for the slot waveguide while $\sim 24.8\%$ for the Si segment of SWGS waveguide. Moreover, for the SiO_2 segment of SWGS waveguide, almost all the light is within the low refractive index SiO_2 region. Hence, it is expected that the SWGS waveguide features reduced nonlinearity due to great light delocalization from the silicon region.

We calculate the effective refractive index (n_{eff}) of silicon-based SWGS waveguide with periodic structures along the propagation using the 3D FDTD method. To guarantee the calculation accuracy, we investigate the

effective refractive index of the SWGS waveguide as a function of the mesh resolution (mesh size) at 2100 nm. The results shown in Figure 5A depict that the n_{eff} gets stable when the mesh resolution is less than 30 nm. In the following simulations, we set the mesh resolution as 20 nm to achieve highly accurate results. As shown in Figure 5B, the effective refractive index slightly decreases (1.604–1.553) with the increase of the wavelength (1900–2100 nm).

The proposed SWGS waveguide effectively delocalizes the SWGS mode from the silicon region, holding the potential to greatly reduce nonlinearity. We study the nonlinearity of the SWGS waveguide. In the calculations, the nonlinear refractive indices n_2 used for silicon and SiO_2 are 4.5×10^{-18} and $2.6 \times 10^{-20} \text{ m}^2/\text{W}$ [14], respectively. A full-vector model that can weigh the contributions of different materials to the nonlinear coefficient is considered to achieve accurate results.

Using given materials and geometric parameters, one can calculate the effective nonlinear coefficient of the waveguide. The effective mode area is written as follows [15]:

$$A_{\text{eff}} = \frac{\left| \int (e_v \times h_v^*) \cdot \hat{z} dA \right|^2}{\int |e_v \times h_v^* \cdot \hat{z}|^2 dA}, \quad (1)$$

Figure 4: Simulated mode normalized intensities along the x and y directions of the guided and propagated fundamental TE mode in strip-to-SWGS mode converter.

(A) Strip waveguide region. (B) Middle of the strip-to-slot mode converter. (C) Slot waveguide region. (D) Middle of the slot-to-SWGS mode converter. (E) Si segment of SWGS waveguide. (F) SiO₂ segment of SWGS waveguide.

where e_v and h_v are field distributions. The nonlinear coefficient γ can be expressed as follows [16]:

$$\gamma = \frac{2\pi\bar{n}_2}{\lambda A_{\text{eff}}} \quad (2)$$

$$\bar{n}_2 = k \left(\frac{\varepsilon_0}{\mu_0} \right) \frac{\int n^2(x, y) n_2(x, y) \left[2|e_v|^4 + |e_v^2|^2 \right] dA}{3 \int |(e_v \times h_v^*) \cdot \hat{z}|^2 dA}, \quad (3)$$

where $\bar{n}_2$ is the nonlinear refractive index averaged over an inhomogeneous cross-section weighted with respect to field distribution, λ is the wavelength, k is the wavenumber, ε_0 is the permittivity of vacuum, and μ_0 is the permeability of vacuum. The effective nonlinear coefficient is finally given as:

$$\bar{\gamma} = \frac{\int \gamma(z) dz}{\int_L dz} \quad (4)$$

Figure 6 depicts the calculated effective nonlinear coefficients as a function of the wavelength for strip and SWGS waveguide. It is shown that nonlinearity slightly decreases with the increase of the wavelength. The nonlinearity of the SWGS waveguide at 2100 nm is 4.05/W/m. For comparison, the nonlinearity of the silicon strip waveguide at 2100 nm is 69.1/W/m. As expected, the SWGS waveguide with more light delocalized from the silicon region features much lower nonlinearity.

3 Fabrication and experimental setup

We then fabricate the designed silicon-based SWGS waveguide. As shown in Figure 7A, 100-μm and 500-μm SWGS waveguides are well fabricated. SiO₂ with 1-μm thickness is used to cover and fulfil SWGS waveguides. The device

Figure 5: Effective refractive index as functions of the mesh resolution and wavelength.

(A) Calculated effective refractive index of SWGS waveguide at 2100 nm vs. mesh resolution. (B) Calculated effective refractive index of SWGS waveguide vs. wavelength. The mesh resolution is set as 20 nm.

Figure 6: Calculated effective nonlinear coefficients of strip waveguide and SWGS waveguide vs. wavelength (silicon width: 375 nm, slot width: 100 nm, period: 300 nm, duty cycle: 50%).

with SiO_2 cladding is more stable than the one with air cladding because SiO_2 cladding could protect the delicate structure from vibration, dust, and touching of lensed fiber. Surface grating couplers optimized at 2 μm are used to efficiently couple light in and collect the light output of the waveguides, as shown in Figure 7B. Strip-to-SWGS mode converters, as shown in Figure 7C, are adopted to efficiently convert light from strip mode to single-side Bloch mode and convert light back to strip mode after 100- μm /500- μm chip-scale data transmission.

Using electron-beam lithography (EBL), the designed layout is transferred to ZEP520A light-sensitive lacquer. The type of the electron beam lithography system is Vistec EBPG 5000, which worked with a voltage of 100 Kv and a spot size of 30 nm. Then we etch the wafer to remove 340-nm silicon layer using induced coupled plasma (ICP) etching in a single-step way, which is more simple and reliable than the two-step etching process. Meanwhile, the residual ZEP520A electron-beam resist is also eliminated in the ICP system (Oxford Plasmalab system 100 ICP180) [17], which protects elaborate periodic SWGS waveguide blocks from ultrasonic cleaning. The Sulfur hexafluoride (SF_6) and Octafluorocyclobutane (C_4F_8) plasma chemistry is used in the ICP etching process. Finally, through the plasma-enhanced chemical vapor deposition technique, the wafer is covered by 1- μm -thick SiO_2 cladding.

We measured the strip waveguide loss, which contains vertical-coupling grating loss and 100- μm propagation loss. We also measured the SWGS waveguide loss, which contains vertical-coupling grating loss, mode conversion loss, and 100- μm propagation loss. By subtracting the strip waveguide loss (21.84 dB) from the SWGS waveguide loss (22.34 dB), the mode conversion loss is obtained. It shows that due to well-designed mode converter, stable electron-beam resist elimination process, and covered SiO_2 cladding, the mode conversion loss is controlled below 0.25 dB. The vertical-coupling grating loss is controlled at 10.97 dB.

In the experiment, as shown in Figure 8, at the transmitter, a 5-Gbit/s electrical OOK signal is generated by an arbitrary waveform generator (AWG) and amplified to directly modulate a 2- μm laser diode (Eblana EP2000), which emits 3 dBm of continuous wave light at 2 μm . Before launching the signal into the waveguides, the transmitter power is boosted to 24.5 dBm using a thulium-doped fiber amplifier (TDFA). At the receiver side, after transmission through the SWGS waveguide, the signal is filtered by a band-pass filter (with a 3-dB bandwidth of 1 nm) to remove the out-of-band amplified spontaneous emission (ASE) noise. The filtered signal is attenuated by a variable optical attenuator (VOA) and then amplified by another TDFA before being sent to a 2- μm photodetector (PD). The

Figure 7: Measured microscope image of the fabricated devices.

(A) Optical microscope image of the fabricated silicon-based 100- μm - and 500- μm -long SWGS waveguides. (B) Zoom-in view of 2- μm broadband grating. (C) Zoom-in view of strip-to-SWGS mode converter.

Figure 8: Experimental setup for chip-scale data transmission through the fabricated silicon-based SWGS waveguides.

AWG, arbitrary waveform generator; PC, polarization controller; TDFA, thulium-doped fiber amplifier.

type of 2- μm PD we used is ET-5000. The detected signal by PD is then sampled at 80 GS/s by a Keysight DSA-Z 204A real-time oscilloscope. After that, bit-error rate (BER) performance is measured, assisted by digital signal processing process.

4 Experimental results and discussion

Figure 9 depicts the measured experimental results for chip-scale data transmission in the fabricated SWGS

Figure 9: Experimental results.

(A) Measured spectrum after filter and VOA in Figure 8. (B) Measured BER vs. received OSNR and eye diagrams for chip-scale data transmission through 100- μm and 500- μm SWGS waveguides.

waveguides. As shown in Figure 9A, the achieved OSNR is ~ 40 dB. Figure 9B plots the measured BER as a function of the received OSNR for 100 μm and 500 μm SWGS waveguides. The inserts are measured eye diagrams. The measured OSNR penalties at a BER of 3.8×10^{-3} (enhanced forward error correction threshold) are less than 2.5 dB for all the waveguides. Although 100- μm and 500- μm SWGS waveguides are relatively short and their propagation losses are somehow negligible, the experimental results still show slightly added loss of 500- μm SWGS waveguide compared to the 100- μm one. The measured BER performance shows the slight performance degradation of 500- μm SWGS waveguide.

Our previous work proposed and theoretically analyzed the performance of the SWGS waveguide at 1550 nm. Here, we further design and fabricate the SWGS waveguide at 2 μm and demonstrate its interesting application in chip-scale data transmission. In the experiment, no significant extra loss is observed for the SWGS waveguide at 2 μm .

The obtained results indicate that the designed and fabricated SWGS waveguides have favorable operation performance for chip-scale data transmission at 2 μm . It is believed that further improvement of transmission performance could be achieved by reducing the additional noise introduced by TDFAs and optimizing the SWGS design and fabrication conditions.

5 Conclusion

In summary, we propose, design, fabricate, and characterize a silicon-based SWGS waveguide. We further demonstrate chip-scale data transmission through the fabricated SWGS waveguides at the extended 2- μm communication waveband. We anticipate that the SOI platform will play a key role in the newly emerging 2- μm communication for chip-scale data transmission applications. The presented SWGS structures may find more applications in chip-scale data processing and communication systems.

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