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Design of Silicon Photonic Crystal Waveguides for High Gain Raman Amplification Using Two Symmetric TE-Like Slow-Light Modes

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1. Introduction

Recent years have seen increased attention on silicon photonics as a key technology for future photonics-electronics integrated circuits. Various approaches have been investigated to realize efficient silicon-based light sources, which are missing parts in silicon photonics. One of them is to utilize stimulated Raman scattering (SRS) in silicon waveguide [1]. Pulsed and continuous-wave silicon Raman lasers [2-3] and Raman amplifiers [4] have been demonstrated. However, strong pump beam intensity required for their operations is the biggest obstacle for practical applications. To reduce the power requirement, it is important to increase the effective Raman gain by optimizing the device structures.

Photonic crystal (PhC) waveguide (WG) has been examined as a promising structure for this purpose. Small mode cross section and low group velocity v_g in PhC WGs can enhance the Raman gain dramatically. Several designs and experimental observations in PhC WGs have been reported [5-8]. In previous reports, the group velocity is low enough at the Stokes wavelength, but relatively high at the pump wavelength. This limited the enhancement of Raman scattering efficiency. However, the advantages of PhC WGs have not been fully utilized. It has been proposed to use a slow light mode with anti-symmetric field distribution [5]. However, this mode is hardly excited from outside.

Here, we propose new designs of silicon PhC WGs for efficient Raman amplifiers or lasers. The structures support two WG modes with symmetric electric field distributions, which can be coupled from outside efficiently. These modes enable us to use pump and Stokes wavelengths both in ultraslow-light regions. Compared with previous reports, 200 times improvement of effective gain is predicted in an optimized design.

2. Design Criteria and Gain Factor

The basic structure in our study is air-bridge-type PhC WGs as shown in Fig. 1 (a). The thickness of the slab and radius of holes are $0.467a$ and $0.28a$, respectively. Here a is the lattice constant of PhC. We investigated so-called TE-TE configurations, where TE-like pump photons produce TE-like Stokes photons inside WGs. Thanks to photonic bandgap (PBG) effect for TE-like mode, it is easier to realize TE-like slow light mode than TM-like one. This configuration has been investigated using a narrow waveguide (x=0.66) [7], in which both pump and Stokes modes could set on the same TE-like band. However, v_g of pump beam was not as slow as at Brillouin-zone edge. Moreover, only frequencies close to the light line could be used for pump beam. This limits the flexibility in operations. Therefore, we seek two TE-like modes in PBG so that frequencies at the Brillouin-zone edge can be used both for pump and Stokes beam. The other conditions are the mode symmetry and frequency separation. For practical devices, both modes must be coupled from outside efficiently. Thus, electric field distribution of the modes must be symmetric as discussed later. The frequency difference should match the Raman shift of silicon $\Delta\omega_R = 2\pi\times 15.6$ THz.

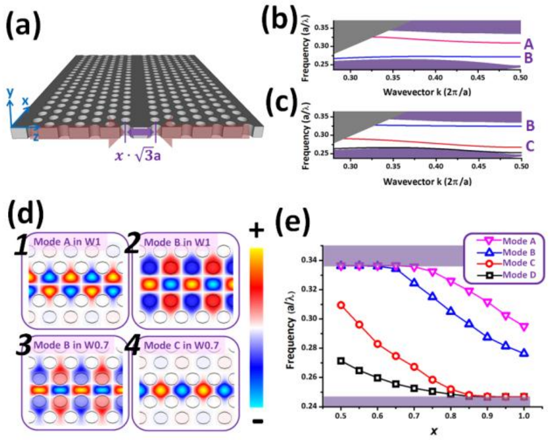

Fig. 1 (a) Illustration of Wx WG, where x defines the WG width as $x\cdot\sqrt{3}a$. Band structures of W1 (b) and W0.7 (c) calculated by plane wave expansion method. (d) H_y field profiles. (e) Shift of WG Modes with x.

The advantage of individual design is estimated by calculating a gain factor $G.F. \equiv S_s S_p / A_R$, where S_s and S_p are slow down factors (S, defined as $n_g/n_{si} = c/n_{si}v_g$, c is light velocity in vacuum, n_g is group index, and n_{si} is refractive index of silicon) of Stokes and pump signal, respectively [8]. A_R is Raman cross section effective area defined by

$$A_R = \frac{\left[\int_{V_{tot}} n_s{}^2(\mathbf{r})|E_s(\mathbf{r})|^2 dV\right]\left[\int_{V_{tot}} n_p{}^2(\mathbf{r})|E_p(\mathbf{r})|^2 dV\right]}{a n_{s,Si}^2 n_{p,Si}^2 \int_{V_{Si}} E_s^*(\mathbf{r}) \xi_R E_p(\mathbf{r}) E_p^*(\mathbf{r}) E_s(\mathbf{r}) dV},$$

where ξ_R is a normalized version of the Raman susceptibility tensor χ_R, V_{tot} is the volume of one PhC unit cell, and V_{Si} is the silicon volume in the unit cell. A_R reflects not only the overlap between pump and Stokes modes but also the selection rules of Raman scattering in silicon. Thus, A_R varies with the waveguide orientation.

3. Tuning Structures and Comparisons

Considering the design criteria discussed in Sec. 2, a widely used W1 WG, which is formed by omitting one row of air holes, cannot be used. As shown in Fig. 1 (b), two modes appear in PBG. However, one of them is anti-symmetric mode (see Fig. 1(d)). In order to find two symmetric TE-like modes, we first investigate the evolution of mode frequencies with the width *x*. Results are shown in Fig. 1 (e). There are four modes named A, B, C, and D in the PBG for the range: W0.5~W1. Mode B and C are symmetric modes. Therefore, we focus our attentions on these modes. Taking the frequency difference into account, we chose the W0.7 and W0.8 WGs as starting structures and tuned the structure finely in order to achieve a correct frequency difference (15.6 THz) between modes at the Brillouin edge. H_y field distributions for W0.7 are shown in Fig.1 (d).

The first idea (Type 1) of optimization is to decrease the frequency of mode B by changing the air hole radius of the second row beside to central waveguide region as shown in Fig.2 (a). In this design, the shrunk circle radius (r') is 0.6r. The band structure and mode profile (H_y field) are shown in Fig.2 (b) and (c). This simple method actually achieves the frequency difference between mode B and C match to Raman shift. But this method also made the mode distribution of mode B concentrate around the second row as Fig. 2 (c), which leads to A_R increasing. The other disadvantage is the existence of many high-order modes which are colored by green line in Fig. 2(b). The second idea (Type 2) is a design using a Mickey-mouse-like pattern as shown in Fig.2 (d). The position and radius of ear circles will influence mode C directly and increase its frequency. The final optimized pattern is a W0.8 structure with r/a of 0.28, h/a of 0.467, r_2 of 0.5r, θ of 35°, and D of 1.4r (the definition of parameters are shown in Fig2.(d)).

v_g, A_R, and *G.F.* of our designs are summarized in Table 1 along with them for WG structures reported so far. Here, we omit the design reported in the scheme 1 of ref.[5], because pump mode cannot be excited from outside efficiently. In ref.[5] ,only scheme 2 is listed in table I. For easier comparison, all structures in references are with their parameters but calculated by our method again in the same conditions. We kept the Stokes mode just at the Brillouin-zone edge. The lattice constants were determined so that the pump wavelength is 1550 nm. Both our designs show superior performance in *G.F.* Particularly, the *G.F.* of type 2 along crystal direction [110] is 200 times as large as past works. This large enhancement is attributed to the smaller A_R and ultra-low v_g's for pump and Stokes modes. Again, note that both modes can be coupled from outside.

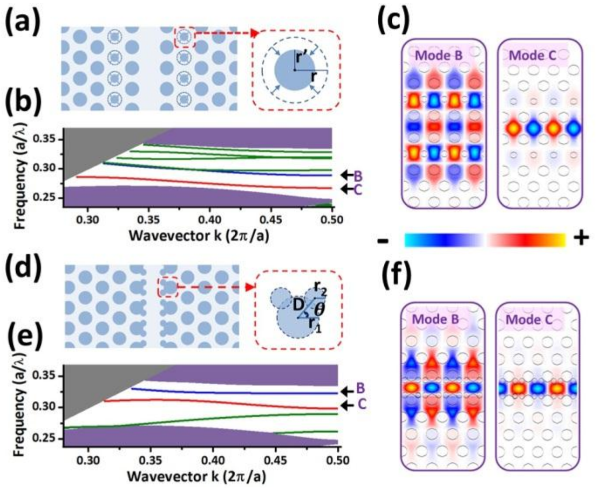

Fig. 2: Type 1 WG structure (a) and its band structure (b). Here r'=0.6r. (c) $\underline{H_y}$ field profile of mode B and C. Type 2 WG (d) and its band structure (e) with r/a of 0.28, h/a of 0.467, r_2 of 0.5r, θ of 35°. H_y field profile of mode B and C (f).

Table I Performance comparison in different scheme

Type	$v_{g,p}$	$v_{g,s}$	Along	A_R(μm^2)	*G.F.* (μm^{-2})
Ref[5]	$2.39\times10^{-1}c$	$0.84\times10^{-3}c$	[100]	0.6141	7.02×10^{2}
			[110]	0.4281	1.01×10^{3}
Ref[7]	$2.28\times10^{-1}c$	$0.17\times10^{-3}c$	[100]	0.3773	5.92×10^{3}
			[110]	0.3640	6.13×10^{3}
Ref[8]	$1.24\times10^{-1}c$	$2.55\times10^{-3}c$	[100]	0.7229	3.78×10^{2}
			[110]	0.0833	3.28×10^{3}
1	$1.71\times10^{-3}c$	$1.68\times10^{-3}c$	[100]	0.6991	4.31×10^{4}
			[110]	0.8925	3.36×10^{4}
2	$1.23\times10^{-4}c$	$2.37\times10^{-3}c$	[100]	0.4379	6.78×10^{5}
			[110]	0.2033	1.46×10^{6}

4. Conclusions

Silicon slow-light PhC WGs ultra-slow light modes both in pump and Stokes wavelengths are designed for high efficient Raman amplifiers and lasers. The highest Raman gain enhancement factor *G.F.*, which is 200 times larger than past works, is demonstrated in a W0.8 WG with a modified hole structure. Importantly, in our design, slow pump mode is accessible from, for instance, optical fibers because only symmetric modes are used. Therefore, our designs are directly applicable to PhC WG Silicon Raman amplifiers and lasers.

Acknowledgements

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