Design of photonic crystal directional couplers for electro-optical wavelength switching

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Abstract:
Photonic crystal directional couplers are designed for the realization of compact electro-optical wavelength switches in SOI technology. Influence of group velocity dispersion properties of slow Bloch modes involved in the device operation is studied and switching devices' performances are evaluated as a function of refractive index variations induced by carrier plasma effect in a wide range.

Introduction

Silicon nanophotonics has received a growing interest from several years. Integration of optics within the mainstream silicon technology is expected to enable the realization of dense and complex photonic integrated circuits and the design of new on-chip applications. In this context, implementation of optical wavelength division multiplexing (WDM) communications is viewed as an important step to enable high bandpass aggregate data transfers [1]. Elements to be considered in WDM communications are optical multiplexers/demultiplexers, selective filters, and wavelength switches.

This work is focused on the design of electro-optical wavelength switches in silicon on insulator (SOI) technology. Resonators have been mainly considered for channel dropping devices. Although ring resonators between two optical waveguides provide an ideal basic structure for removal of a wavelength channel from an input bus, it was shown that surface roughness in this kind of devices adversely affects performances by the coupling between counterpropagating optical waves. For this reason, the use of other optical resonators was proposed. It was theoretically shown that 100% efficiency selective dropping is possible provided that very well defined conditions are fulfilled to achieve the desired transfer characteristics [2,3]. The used resonator should have two degenerate modes that possess appropriate symmetries with respect to resonator symmetry planes and coupling rates between these modes and the two device ports should be properly balanced. The possible combination of this approach in photonic crystal (PC) compact structures was theoretically shown. In spite of excellent predicted performances, this approach raises very challenging issues from the technological point of view as mode forced degeneracy is obtained using very fine tuning of device parameters such as individual hole diameters and positions.

On the other hand, simpler approaches based on traditional integrated optics have been proposed in planar PC configurations [4]. These approaches basically rely on a directional coupler configuration without any kind of mediating structure between coupled waveguides. Strongly corrugated PC waveguides are then essential to allow high phase mismatch between coupled supermodes, so that overall structures can be designed with only few-wavelength sizes.

Starting from a directional coupler configuration, active switching can be obtained. In ref [4], an electro-optical switch implemented in coupled PC waveguides was proposed. Short coupling lengths (< 10λ) were demonstrated but it was shown that electrical conductivity induced by carrier plasma effect as high as 10 Ω^{-1} cm^{-1} was necessary in planar silicon air-hole PC waveguides corresponding to carrier concentrations in excess than 10^{20} cm^{-3}. Structural modifications of the directional coupler geometry have been proposed in ref [5] to allow small switching length and wide bandwidth, but no study was made on device performances as a function of refractive index variations practically reachable in the silicon technology, as well as on the possible influence of group velocity dispersion (GVD) effects of the slow Bloch supermodes sustaining the device principle of operation.

Photonic crystal directional couplers

In this work, simple design PC directional couplers allowing a continuous tuning of GVD effects is studied for the realization of wavelength electro-optical switches. Refractive index in silicon induced by carrier plasma effect is considered. Active coupling lengths are evaluated as a function of carrier injection level in selected configurations, and electro-optical switch device design is proposed for working wavelengths around λ=1.55µm.

The investigated structure is based on a 2D PC formed by a triangular lattice with lattice parameter a=400nm, and hole diameter 2r =240nm (r/a = 0.3), respectively. Refractive index of slab regions is 2.872, while hole refractive index is 1.45. These values correspond to the effective index of a 240 nm thick SOI slab waveguide at λ=1.55µm and to silicon oxide, respectively. PC band diagram has been calculated with the MIT plane wave software [6] in TE polarization and a frequency bandgap was found extending from band 1 at $\omega_r = a/\lambda = 0.2463$ to band 2 at ω_r=0.2802. From this starting point, symmetric photonic crystal directional couplers can be obtained by removing two rows of holes. Two W1 PC waveguides can be coupled through three rows of holes. The two coupled PC waveguides then give rise to the appearance of two guided supermode bands, with even and odd symetries with respect to the directional coupler mirror plane.

An even supermode is then carefully prepared to present a flat band in the wide normalized wavevector range [5]. Due to this particular feature, even low refractive variations that only slightly shifts photonic bands can induce a strong varation between the even and odd wavectors at a given frequency. Contrary to previous approaches based on both hole size tuning and shift of multiple holes, design strategy was simplified to the variation of only one parameter.

Figure 1 shows the studied directional coupler configuration, as well as the obtained even and odd supermode photonic bands as a function of normalized wavevector along the propagation direction. Hole radius of the central row was varied from r/a=0.39 to r/a=0.43 to allow some tuning of the even supermode properties. It can be seen in figure 1 that a continuous change of the even-mode frequency slope can be obtained by this simple design strategy. Either positive or negative light group velocities can be obtained in a limited range of wavector values around k_R=0.37 and perfectly flat even supermode band can be ideally designed for r/a~0.42.

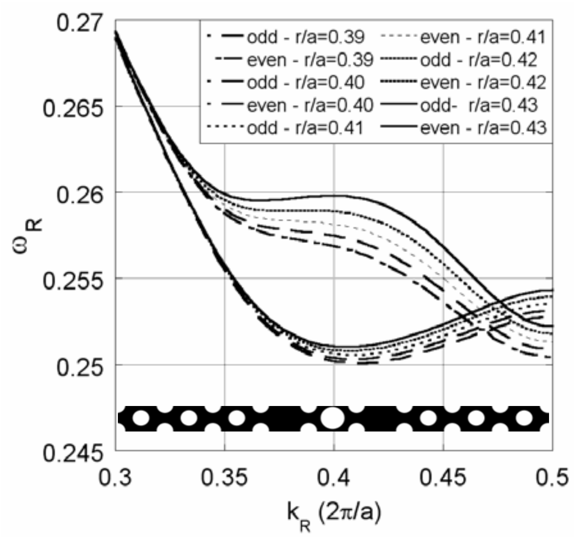

Fig. 1: Dispersion characteristics of the two even and odd supermode photonic bands of the studied photonic crystal directional coupler configuration

Influence of group velocity dispersion (GVD) on device properties

Although design of ideally flat even supermode band is desirable for the realization of compact PC directional coupler swiching devices, it is to be verified that compactness and sensitivity to refractive index variations is not allowed at the expense of a huge level of group velocity dispersion (GVD) that can be responsible for strong temporal deformations of optical pulse propagating in the device.

Group velocity v_{GR} and GVD coefficient D_λ of even supermodes obtained for r/a ranging from 0.39 to 0.43 have been calculated. D_λ was estimated as:

$$D_\lambda = -\frac{2\pi c}{\lambda^2}\frac{d^2k}{d\omega^2} = \frac{a}{c\lambda^2}\frac{1}{{v_{GR}}^3}\frac{dv_{GR}}{dk_R} \qquad (1)$$

, with a the lattice parameter and $c=3.10^8$ ms^{-1}.

To ensure negligeable temporal distorsions of τ=100ps width optical pulses after a propagating length L_{Device} of 300μm, a practical limit of $D_\lambda \approx 10^5$ ps/(nm.cm) is found according to:

$$D_\lambda << \frac{2\pi c}{\lambda^2}\frac{\tau^2}{L_{Device}} \qquad (2)$$

Figure 2 and figure 3 show the evolutions of the even supermode v_{GR} and D_λ parameters as a function of normalized wavevector k_R, respectively.

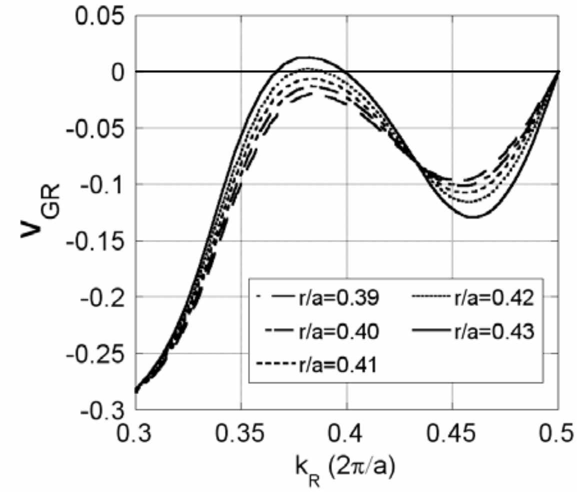

Fig. 2: Influence of the hole radius of the central row holes on the even supermode group velocity

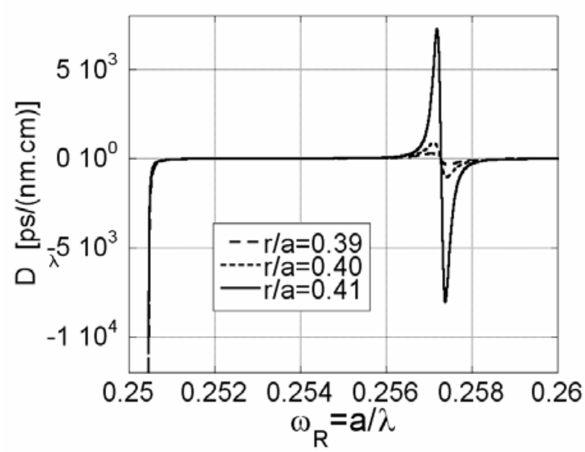

Fig. 3: Group velocity dispersion coefficient of the even supermode for several values of the hole radius in the central row of the symmetric directional coupler

It can be seen that two zero group velocity points are obtained for r/a values above 0.41, while non-zero v_{GR} slopes are found at this particular points. According to relationship (1), it turns that infinite values of D_λ are then reached, which is not desirable from a practical point of view. For this reason, values of r/a leading to the flattest even band (r/a~0.42) have to be removed due to GVD-induced pulse distorsions. At the same time, Figure 3 shows that r/a values around 0.41 lead to a good compromise, with peak D_λ values near the frequency operating point ($\omega_R \approx 0.257$) around 8.10^3 ps/(nm.cm).

Design of electro-optical wavelength switch

Electro-optical wavelength switch has been further designed with a hole radius in directional coupler central row r/a of 0.41.

Figure 4 shows a schematic of the complete device.

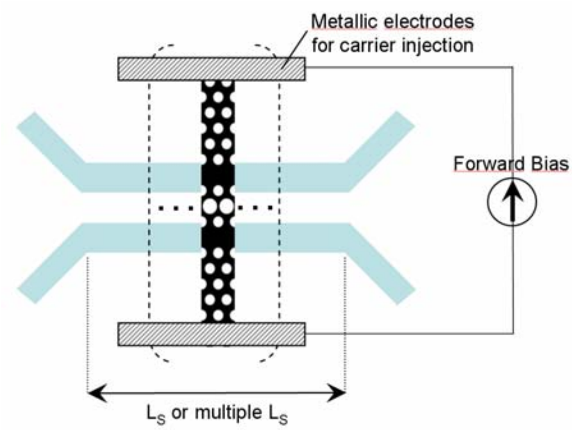

Fig. 4: Schematics of the studied device configuration

Static coupling length L_S is define as the required size to ensure a π phase shift between the even and odd supermode in absence of free carrier injection:

$$L_S(\omega_r) = \frac{\pi}{k_e(n,\omega_r) - k_o(n,\omega_r)} \quad (3)$$

Active coupling length L_A from one output port to the other then results from from refractive index variation -Δn and was estimated as:

$$L_A(\omega_r) = \frac{\pi}{\left[k_e(n-\Delta n,\omega_r) - k_e(n,\omega_r)\right] - \left[k_o(n-\Delta n,\omega_r) - k_o(n,\omega_r)\right]} \quad (4)$$

, with $k_e=k_e(n,\omega_r)$ and $k_o=k_o(n,\omega_r)$ the even and odd dispersion relationships.

L_A can be viewed as the required length to ensure an additional π phase shift between both supermodes for a given level of refractive index decrease -Δn at a given normalized frequency.

Figure 5 shows the obtained static and active coupling lengths L_S and L_A as a function of refractive index variation Δn ranging from -10^{-4} to -2.10^{-3}. This value range corresponds to layer refractive index variations pratically reachable using plasma dispersion effect in silicon.

It can be observed that low active coupling length values are obtained for frequency around $\omega_r=0.258$. This corresponds to the condition of flat even supermode photonic band. The higher Δn the lower L_A. It is also visible that the region with lowest values of static coupling length ($\omega_r<0.2577$) is not the best operating configuration. This is due to the fact that extremely low L_S values (~3µm) are obtained in this condition due to to strong mismatch between ke and ko, but sensitivity of (ke-ko) to index variation is then relatively poor. For this reason, the optimization procedure is first made on the criterium of low active coupling length. This allows the choice of operating normalized frequency. Static length is then deduced from the knowledge of ω_r.

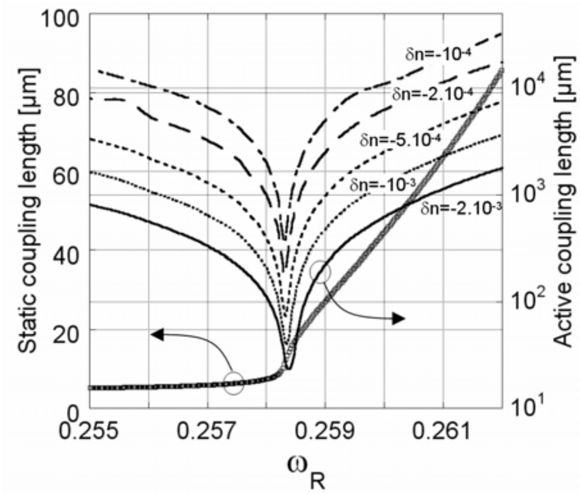

Fig. 5: Static coupling length and active coupling length obtained for several values of refractive index variation

Table 1 shows the minimum values of L_A as a function of Δn obtained around $\omega_r=0.258$ ($\lambda \approx 1550$nm for lattice parameter a equal to 400nm as previsouly stated).

-Δn	L_A (µm)	L_S (µm)
10^{-4}	139.5	4.5
2×10^{-4}	70.5	4.55
5×10^{-4}	29.7	5.0
10^{-3}	16.0	5.2
2×10^{-3}	9.5	5.8

Table 1: Minimum active coupling lengths and associated static coupling lengths

It is shown that reasonable active coupling length are obtained (< 140µm) even for low refractive index variation ($\Delta n = -10^{-4}$).

Extremely low active coupling length (~16µm) is obtained for a refractive index variation of 10^{-3}. According to the plasma dispersion relationship in silicon given by:

$$\Delta n = -8{,}8.10^{-22}\Delta N - 8{,}5.10^{-18}\Delta P^{0{,}8} \text{ at } \lambda=1.55\mu m$$

, this correspond to a carrier injection level ΔN (electrons) or ΔP (holes) around 5.10^{17} cm^{-3}.

A possible implementation to realize an electro-optic wavelength switch at λ=1550nm is shown in figure 6. A static coupling length of 20.8µm ($L_S=4\times5.2$ µm) is chosen so that even and odd supermodes are phase-matched ($\Delta\varphi=4\pi$) after propagating through the whole device in absence of free carrier injection. Light injected in input port n°1 is thus to be collected at output port n°1 ('bar' state). A limited area of 16µm length is chosen for carrier injection with electrode and silicon doping level engineered to ensure $\delta n=-10^{-3}$ in the 'cross' state (light collection at output port n°2 in case of injection into input port n°1). Bandpass of the device was also estimated to around 1 nm in the studied conditions.

Considering a possible chirp of lattice parameter a, it is envisioned that similar electro-optic wavelength switch could be designed in a wavelength wide range around 1.55 µm.

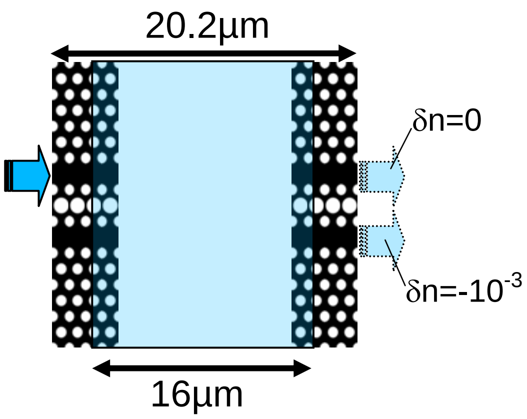

Fig. 6: Design of a 16µm long PC wavelength directional coupler for wavelength switching around λ=1.55µm

Conclusions

This work reports the study of a wavelength-sensitive switch based on a optimized PC SOI directional coupler configuration. Previous approaches have been simplified to limit the number of tuned technological parameters to only one to obtain the required Bloch mode slow light properties.

Influence of GVD in the studied configuration is studied for the first time. It is shown that the most desirable configuration with respect to flat bland condition and device compactness are not desirable due to temporal pulse deformations induced by GVD.

Cross-bar active coupling length is estimated as a function of refractive index variations pratically reachable in silicon with plasma dispersion effect.

It is shown that device length only around 10λ can be obtained provided that index variation around 10^{-3} is induced which corresponds to free carrier injection concentration about 5.10^{17} cm^{-3} in silicon.

Studied optoelectronic devices exhibit bandpass around 1 nm at λ=1.55µm and can be designed for operation in a wide wavelength range around this central wavelength.

Acknowledgments

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