Numerical Studies on Silica Wire Directional Couplers

Ziyang Zhang, Min Yan and Min Qiu
Laboratory of Optics, Photonics and Quantum Electronics, Department of Microelectronics and Applied Physics, Royal Institute of Technology (KTH), Electrum 229, 164 40 Kista, Sweden

Abstract: Directional couplers based on silica and silicon wires are studied numerically using 3D FDTD *method. With 6µm overlapping length, 80% power transfer is achieved at 1.54µm. Silica wires can also be used to generate slow light in photonic crystal slab waveguide by counter-directional coupling.*

Introduction

Silicon wire waveguides with cross-section around 250nm by 400nm have been widely used for modern photonic integrated circuits (PICs). However, it is challenging to couple light directly from a conventional single-mode fiber with core diameter ~6µm. The butt-coupled light-injecting method causes large insertion loss due to the small overlap of the mode profile and index mismatch. One solution is to use polymer inverse taper to increase the mode overlap [1-2]. However, this requires precise fabrication control to bring down the tip of the silicon wire to below 100nm. Another solution is to use in-plane gratings to couple light out-of-plane from fiber to silicon wire [3]. This method also involves additional fabrication steps.

In this work, we propose a coupler design based on evanescent directional coupling between suspended silica and silicon wires. The schematic is shown in Fig. 1. The diameter of the silica (index 1.5) wire ***R*** is 1µm. The details involving fabrication of such wires are described in Ref. [4]. The silicon (index 3.6) wire has a cross-section of 250nm by 400nm. Both silica and silicon wires remain single-mode at 1550nm wavelength region. The two wires go parallel and axis-aligned with an overlapping distance ***l***. Their vertical spacing is ***s***. To prevent light leakage into the silica substrate the beginning section of the silicon wire is also suspended in air. This can be done by selective wet-etching during fabrication. The finite-difference time-domain (FDTD) cell size is 25nm in all three dimensions.

Silica and silicon wire coupling

From coupled mode theory, the silica waveguide mode ***A*** and silicon waveguide mode ***B*** along ***x*** direction are related by [5]

$$\frac{dA}{dx} = -i\kappa B e^{-2i\delta x}, \qquad \frac{dB}{dx} = -i\kappa A e^{2i\delta x} \tag{1}$$

where $\delta = \beta_b - \beta_a$ is the difference between the modified propagation constants of mode ***A*** and mode ***B*** in the coupled system. ***κ*** is the coupling coefficient. With initial condition $A(0)=A_0$ and $B(0)=0$, the

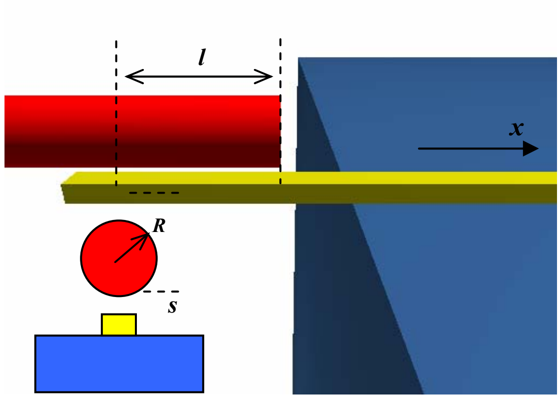

Fig. 1: schematic of silica and silicon wire coupler

power relation in the couple system becomes,

$$P_b(x) = P_0 \frac{\kappa^2}{\kappa^2+\delta^2} \sin^2[(\kappa^2+\delta^2)^{1/2} x] \tag{2}$$
$$P_a(x) = P_0 - P_b(x)$$

To reach maximum power transfer from A to B, the overlapping distance ***l*** must satisfy

$$\sin^2[(\kappa^2+\delta^2)^{1/2} l] = 1 . \tag{3}$$

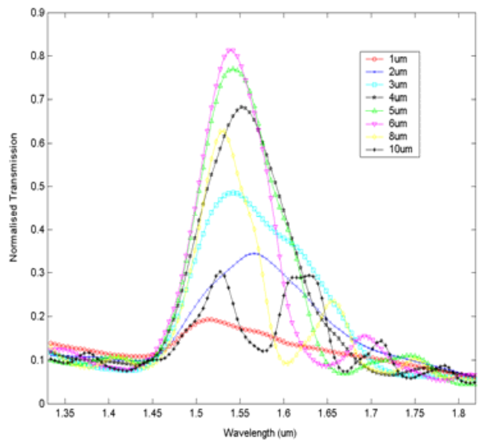

Fig. 2: Power transmission from silica to silicon wire at different overlapping distances.

In this system ***δ*** is not zero and from Eq. 2 light cannot be transferred completely from silica to silicon wire or vice versa. Nevertheless, if the coupling between the two modes is strong enough so that ***κ>>δ***, we can still have high power transfer.

In our FDTD simulations, we set ***s=0*** so that the two wires come into contact to improve their mode coupling. We vary the overlapping distance ***l*** in search for the maxmum power transfer. The results are shown in Fig. 2.

It is seen that as ***l*** goes from 1µm to 6µm, the power transferred from silica to silicon wire increases. At overlapping distance 6µm, 81% of light transferrs from silica wire to silicon waveguide at 1.54µm with 3dB bandwidth of around 100nm. When ***l*** further increases, the peak transfer power starts to drop.

Silica wire and photonic crystal waveguide coupling

There has been extensive study of slow light properties in two-dimensional photonic crystal slab (2D PCS) waveguide. To couple slow light efficiently, a mode converter is usually needed between 2D PCS and silicon wire [6]. As an alternative, we investigate the evanescent directional coupling between silica wire and one-missing-row waveguide (W1PC) in 2D PCS and try to find a way to improve this coupling. The schematic is shown in Fig. 3.

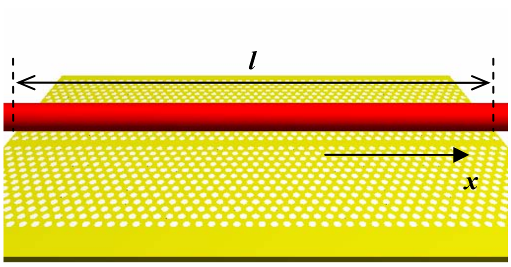

Fig. 3: Directional coupling of silica wire and 2D PCS waveguide (W1PC).

The silica wire diameter is 1µm and the W1PC waveguide goes parallel with their axis aligned. The silicon 2D PCS has index 3.6 and thickness 0.6***a***, where ***a*** is the lattice constant. The airhole diameter is 0.6***a***. As shown in Fig. 4, zero-order W1PC waveguide mode has a flat dispersion curve near the lower band edge and the group velocity is significantly reduced in this region. The silica waveguide mode on the other hand is approximately a straight line within a small frequency range. At cross point P, W1PC and silica waveguide mode share the same propagation constant. Considering the opposite slope sign of the two dispersion curves, the evanescent coupling between these two waveguides is counter-directional. The location of P can be varied by two methods, i.e., either changing the silica wire properties (refractive index or the diameter) to shift its propagation constant or modifying the geometry of W1PC to shift the dispersion curve of the zero-order guided modes. In this work, we choose to vary silica refractive index in our simulations. It is intented to demonstrate the feasibility of generating slow light when P moves to the flat band region. A more realistic way would be to modify W1PC structure and this will be done in our future work.

Assume the initial power in the silica wire is $P_A(0)$, the power variation of the system is,

$$P_A(x) = P_A(0)\frac{\cosh^2[\kappa(x-l)]}{\cosh^2(\kappa l)}$$
$$P_C(x) = P_A(0)\frac{\sinh^2[\kappa(x-l)]}{\cosh^2(\kappa l)} \quad (4)$$

The coupling coefficient $\boldsymbol{\kappa}$ is determined by wire and W1PC spacing as well as their individual mode profile. When $x = l \to \infty$,

$$P_A(\infty) \to 0$$
$$P_C(\infty) \to 0 \quad (5)$$
$$P_C(0) \to P_A(0)$$

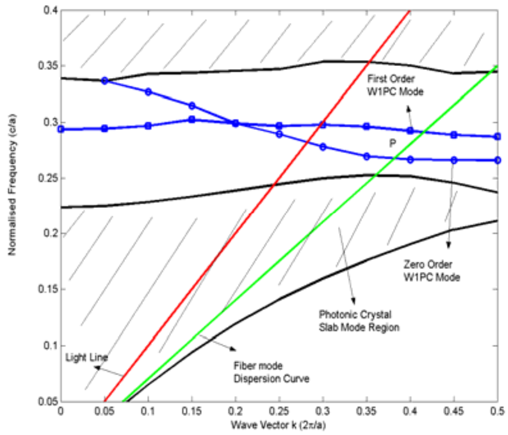

Fig. 4: Band diagram of 2D PCS and dispersion curve of W1PC waveguide modes.

From Eq. 5, complete power transfer from silica wire to W1PC waveguide is possible when their coupling distance ***l*** goes to infinity. In this case, their vertical spacing ***s*** can not be too small, as the close presence of silica wire modifies the 2D PCS band structure and seriously changes W1PC waveguide mode dispersion curve. ***s*** cannot be too large either, as it will-decrease coupling coefficient $\boldsymbol{\kappa}$. In our simulations, we set ***s=500nm***.

We take ***a=420nm*** and the results are shown in Fig. 5. By increasing silica index, the cross point P moves toward W1PC flat band region (longer central wavelength). This increases the coupling between silica wire and W1PC and the power transfer becomes more efficient. As the overlapping length ***l*** increases from ***23a*** to ***59a***, the maximum power transfer increases by 10% for n_f***=1.92***, which agrees well from Eq. 4. For the best case, 87% power transfer takes place at 1.55µm.

Conclusions

We have numerically studied the directional coupling between silica wire and other photonic waveguides such as silicon wire and W1PC in 2D PCS. With 6µm overlapping distance, more thn 80% light is transferred from silica to silicon wire. The strong coupling provides an alternative to inject light into photonic integrated circuits. The counter-directional coupling between silica wire and W1PC waveguide is a new method to generate slow light. This method involves careful W1PC band engineering so that the cross point of their dispersion curves stays in the slow light region. By changing the wire index, we have demonstrated the effectiveness of this coupling.

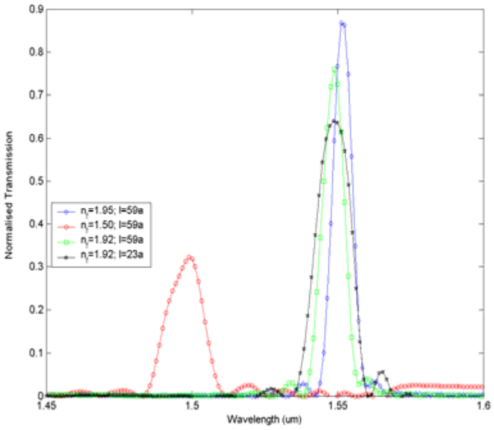

Fig. 5: Counter-directional power transfer from silica wire to W1PC waveguide at different index and overlapping lengths.

Acknowledgments
This work is supported by the Swedish Foundation for Strategic Research (SSF) through the INGVAR program, the SSF Strategic Research Center in Photonics, and the Swedish Research Council (VR).

References
1 T. Shoji et al, Electron. Lett. no. 38, p. 1669, 2002.
2 V.Almeida et al, J. Lightwave. Opt. Lett., no. 28, p. 1302, 2002.
3 D. Taillaert et al, Opt. Lett. No. 29, p. 2749, 2004.
4 L. M. Tong et al, Nature, no. 426, p. 816, 2003.
5 A. Yariv, “Optical Electronics in Modern Communications,” 5th ed. Oxford University Press, New York 1997, chpt 13.
6 M. Povinelli et al, Opt. Express, no. 13, p. 7145, 2005.