Subwavelength-diameter silica wire for light in-coupling to silicon-based waveguide

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Coupling between subwavelength-diameter silica wires and silicon-based waveguides is studied using the parallel three-dimensional (3D) finite-different time-domain method. Conventional butt-coupling to a silica-substrated silicon wire waveguide gives above 40% transmission at the wavelength range from 1300 to 1750 nm with good robustness against axial misalignments. Slow light can be generated by counter-directional coupling between a silica wire and a two-dimensional (2D) silicon photonic crystal slab waveguide. Through dispersion-band engineering, 82% transmission is achieved over a coupling distance of 50 lattice constants. The group velocity is estimated as 1/35 of the light speed in vacuum.

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Silicon-based waveguides are widely used for modern photonic integrated circuits (PICs). However, it is challenging to couple light into PICs directly from a single-mode fiber (SMF). The butt-coupled light-injecting method usually causes large insertion loss due to small overlap of the mode profiles and large index mismatch. Some solutions include using polymer inverse taper to increase the mode overlap[1] or adding in-plane gratings to couple light out-of-plane from fiber to silicon wire[2]. Both methods involve additional and precise fabrication steps.

In this work, we compute the power transmission from a SMF to a silicon wire waveguide (Si-Wg) on a silica-substrate using direct butt-coupling. It shows that the efficiency can be improved by reducing the fiber diameter, forming a subwavelength-diameter silica wire (SiO_2-Wr). A convenient way to draw such SiO_2-Wrs can be found in Ref. [3]. Directional coupling between SiO_2-Wr and air-suspended Si-Wg is then studied. In the end, we investigate evanescent counter-directional coupling between SiO_2-Wr and two-dimensional (2D) photonic crystal silicon-slab waveguide (PCSW) for slow light generation.

The parallel three-dimensional (3D) finite-difference time-domain method (P3D FDTD) is used in our studies. The code, MBfrida, is part of the GEMS suite from E-field AB[4] and is fully parallelized using message passing interface. The simulations are run on Lucidor cluster located at Center for Parallel Computers, Royal Institute of Technology (KTH).

The direct butt-coupling between SMF and Si-Wg is believed to be rather inefficient, however, to our knowledge there still lacks a fully 3D study in the time domain. The structure schematic is shown in Fig. 1(a). The fiber is chosen as Corning SMF-28. The silicon waveguide is 450 nm wide along the x direction and 250 nm thick along the z direction. The refractive index of silicon is 3.6. The fiber axis and the Si-Wg center axis are aligned along the y direction. In our simulations only 2% of light power is measured in Si-Wg at 1550 nm. Most light is either scattered above in the air or leaking into the substrate.

With reducing fiber diameter, the fiber mode and Si-Wg mode share a larger overlap and the coupling efficiency should increase. We first set the SiO_2-Wr diameter to 1 μm and lump the refractive index to 1.5. The axial spacing parameter H_s and the axial misalignment parameters O_s, V_s are all set to zero. The power transmission result is shown in Fig. 1(b). More than 40% of light is transferred from SiO_2-Wr to Si-Wg at the wavelength range from 1300 to 1750 nm. The E_x field distribution at central y-z plane is shown in Fig. 1(c).

We vary H_s, O_s and V_s, respectively. The three parameters are changed one at a time while keeping the other two at zero. It is seen from Fig. 2(a) that coupling efficiency is critical on H_s. When SiO_2-Wr and Si-Wg detach 200 nm, the power transmission drops around 15% for all wavelengths. However, this coupler is insensitive to

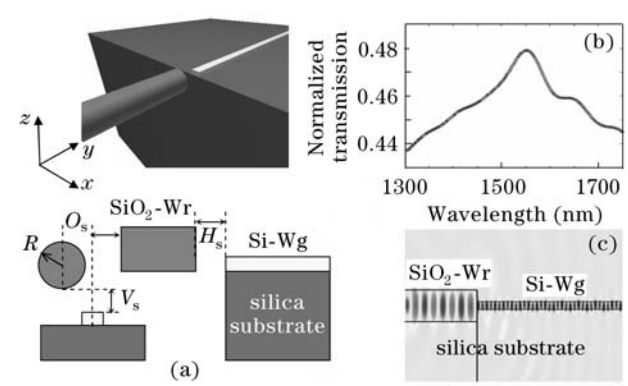

Fig. 1. (a) Schematic of SiO_2-Wr and Si-Wg butt-coupler; (b) power transmission when silica wire diameter is reduced to 1 μm; (c) E_x field distribution at central y-z plane for 1550-nm wavelength.

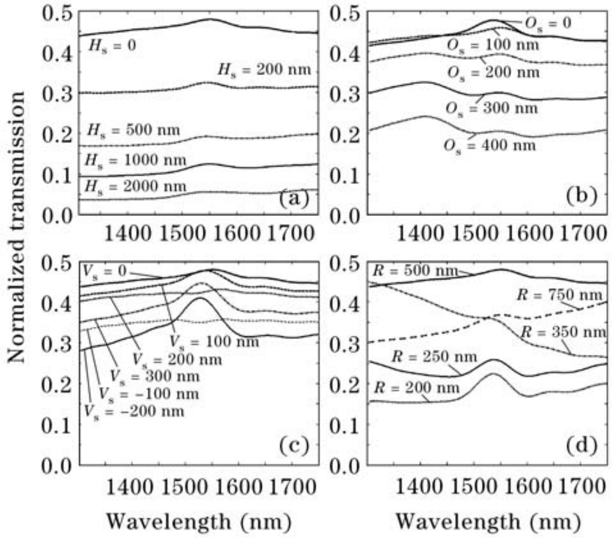

Fig. 2. Power transmission with respect to (a) H_s, (b) O_s, (c) V_s, and (d) SiO_2-Wr radius R.

axial misalignments. From Figs. 2(b) and (c), the power transmission only drops a few percentage when the Si-Wg center moves 100 nm away from SiO_2-Wr axis either in the y or z direction.

In the last step we vary the radius of SiO_2-Wrs. The chosen wires all remain single-mode at 1550-nm region. As seen from Fig. 2(d), the 1-μm-diameter wire still gives the highest coupling efficiency. When the radius goes up, the mode mismatch between SiO_2-Wr and Si-Wg increases, leading to more scattering and less coupling. However, when the wire radius goes down, larger portion of the mode moves to the air-cladding. This also brings down the coupling efficiency. The optimal SiO_2-Wr diameter is around 1 μm.

The directional coupling between suspended silica and silicon wire has been studied using scalar analysis[5,6]. In this work we provide a fully vectorial 3D analysis of the coupling system in the time domain. The structure is shown in Fig. 3(a). To prevent light leaking into the substrate, Si-Wg is suspended in air.

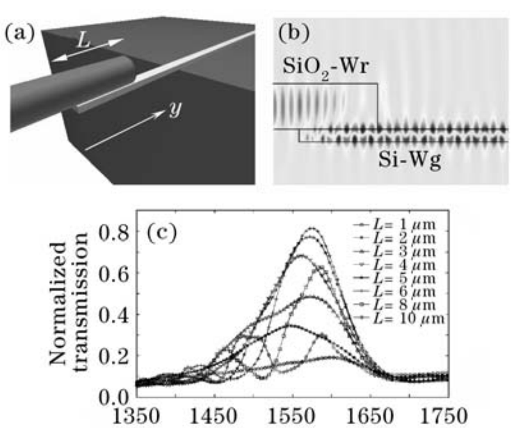

Fig. 3. (a) Schematic of SiO_2-Wr and Si-Wg directional coupler; (b) E_x field distribution at central y-z plane for 1575-nm wavelength; (c) power transmission at different overlapping distances L.

We first assume weak coupling scheme and according to coupled mode theory, the SiO_2-Wr waveguide mode A and air-suspended Si-Wg mode B are related by[7]

$$\frac{\mathrm{d}A}{\mathrm{d}y} = -i\kappa B\mathrm{e}^{-2i\delta y},$$
$$\frac{\mathrm{d}B}{\mathrm{d}y} = -i\kappa A\mathrm{e}^{2i\delta y}, \tag{1}$$

where $\delta = \beta_b - \beta_a$ is the difference between the modified propagation constants of modes A and B in the coupled system, κ is the coupling coefficient. Under initial condition $A(0) = A_0$ and $B(0) = 0$, the power relation in the couple system becomes

$$\begin{aligned} P_b(y) &= P_0\tfrac{\kappa^2}{\kappa^2+\delta^2}\sin^2[(\kappa^2+\delta^2)^{1/2}y], \\ P_a(y) &= P_0 - P_b(y), \end{aligned} \qquad 0 \le y \le L. \tag{2}$$

In this system δ is not zero and light cannot be completely transferred from SiO_2-Wr to Si-Wg or *vice versa*. Nevertheless, if the coupling between the two modes is strong enough so that $\kappa \gg \delta$, the power transfer can still be high. However, the weak-coupling equations above are not justified and the system must be solved numerically. We bring the two waveguides into contact to strengthen their mode coupling. Figure 3(b) gives the E_x field distribution and Fig. 3(c) shows the variation of power transmission with respect to coupling length L. For L = 6 μm, 81% peak transmission occurs at 1575 nm with 3-dB bandwidth around 100 nm.

Unlike in the butt-coupling case, the waveguide mode in Si-Wg, as shown in Fig. 3(b), is not simply TE-like. In fact air-suspended Si-Wg with cross-section of 450×250 (nm) supports four eigenmodes while the same wire on silica substrate only supports two, i.e., the fundamental TE and TM modes. Further studies reveal that this strong interaction from SiO_2-Wr excites mostly higher-order mode. The junction loss between air-suspended and silica-substrated Si-Wg is rather high and only 1% of light is measured transmitting from SiO_2-Wr to silica-substrated Si-Wg. This strong directional coupling is only favorable in generating higher-order modes in air-suspended Si-Wg and is inefficient to couple light to silica-substrated Si-Wg.

There have been studies of slow light in 2D PCSW[8]. To couple slow light efficiently, a fast-to-slow mode converter is usually needed[9]. Alternatively we investigate evanescent counter-directional coupling between SiO_2-Wr and PCSW for slow light generation. There has been some work on this type of directional coupler[10,11]. However the coupling at slow light region has not been investigated.

The schematic is shown in Fig. 4(a). The silicon photonic crystal slab has index of 3.6 and thickness of 0.6a, where a is the lattice constant. A simple waveguide is formed by removing one row of air holes along ΓK. The index of SiO_2-Wr is 1.5 and the diameter is 1 μm. We choose to place it 500 nm above the slab. Because of the opposite slope signs of the dispersion curves, the evanescent coupling between these two waveguides is counter-directional. From coupling mode theory, this type of coupling is an accumulating process. For lossless waveguides, when the coupling length L goes to infinity, light can be

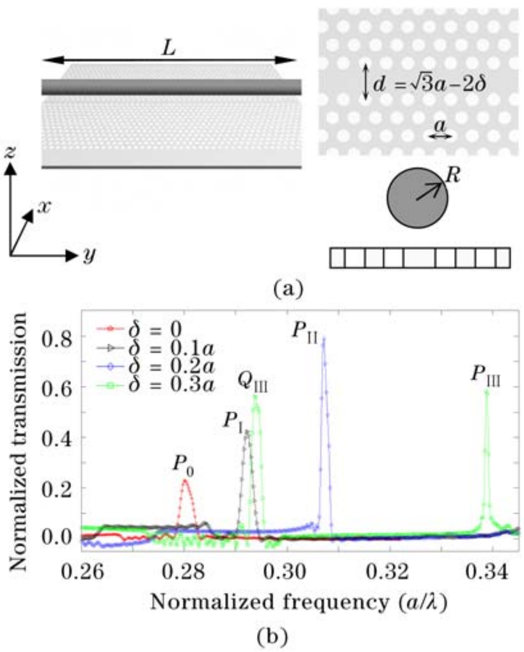

Fig. 4. (a) Schematic of SiO_2-Wr and PCSW directional coupler; (b) transmission comparison for PCSWs with different widths.

completely transferred from one waveguide to the other. We set L to $50a$ for all cases and try to improve the coupling coefficient by modifying PCSW waveguide dispersion band. Note that owing to modal and structural symmetry, SiO_2-Wr mode will only couple with the symmetric (even) mode(s) of PSCW.

For original PSCW ($\delta = 0$), the peak coupling efficiency is 25% and the group index of PSCW mode is 5.6. We seek to modify the PCSW dispersion band by shrinking the waveguide width d. As shown in Fig. 4(a), $d = \sqrt{3}a - 2\delta$, and we set δ to $0.1a$, $0.2a$, and $0.3a$. By doing so, we have actually flattened the band at the coupling point. The group indices for these waveguides become 12.1, 35.0, and 40.2, respectively.

Figure 4(b) shows the normalized transmission for the modified waveguides in comparison with $PCSW_0$. When $\delta = 0.2a$, the peak coupling efficiency reaches 82%, indicating a large increase of the coupling coefficient in the slow light region. Note that for $\delta = 0.3a$, coupling with higher-order even mode comes into the frequency window (Q_{III}). At work point P_{III} the power transmission drops to 58%, despite an increase of group index compared with P_{II}. We believe this is caused by the fact that P_{III} is located closer to the photonic band edge and therefore undergoes higher waveguide loss.

In summary, we have studied various coupling methods from SiO_2-Wr to silicon-based waveguides. To inject light to Si-Wg on silica substrate, butt-coupling is suitable with 40% power transmission from 1300 to 1750 nm. For air-suspended Si-Wg, directional coupling gives over 80% transmission at 1575 nm. However, this coupling generates mostly higher-order modes. SiO_2-Wr can also generate slow light efficiently in PCSW by counter-directional coupling. The PCSW dispersion band can be flattened at the coupling point, which increases the power transmission to 82% over 50 lattice constants and drops the group velocity to 1/35 of light speed in vacuum. SiO_2-Wrs offer an alternative way to couple light efficiently into PICs.

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