ARTICLE

Supplementary Information for "Low Loss Waveguiding and Slow Light Modes in Coupled Subwavelength Silicon Mie Resonators "

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Lu Ding,*[a] Ye Feng Yu,[a] Dmitry Morits,[a] Mingbin Yu,[b] Thomas Y. L. Ang,[c] Hong Son Chu,[c] Soon Thor Lim,[c] Ching Eng Png,[c] Ramon Paniagua-Dominguez,*[a] and Arseniy I. Kuznetsov,*[a]

S1. CMOS Compatible 193 nm Photolithography

The devices are fabricated on a commercial 200 mm silicon-on-insulator (SOI) wafer, which has a 220 nm top silicon layer and a 2 µm buried SiO_2 layer on the silicon substrate. The structures are patterned on the top silicon layer by the 193 nm ArF photolithography and etched by reactive ion etching (RIE) process. Thereafter, the structures are capped by a PECVD-grown SiO_2 cladding with a thickness of 2 µm. Deep trench is patterned and dry etched for wafer dicing. The final chip after dicing is ready for characterization through edge coupling.

S2. Numerical Simulation

Finite difference time domain (FDTD) was used to calculate the dispersion relation of an infinite chain of similar silicon nanoparticles using commercial software (Lumerical FDTD). A single unit cell of the nanoparticle chain with D = 340 nm and g = 170 nm is simulated. In the case of FDTD, the system is excited with a random dipole cloud and Bloch boundary conditions applied in the propagation (z) direction, while Perfectly Matched Layers (PML) are applied in the transverse (x, y) directions.

The mode profile in xz cross section of the guided modes are simulated using FDTD. The simulation domain consists of one input waveguide, one output waveguide, and 100 nanoparticles in a chain. The mode of the waveguide is injected on the input waveguide and recorded using the appropriate monitors. The whole system is surrounded with PMLs.

FDTD scattered field formulation was used to calculate the total scattering efficiency of a single nanoparticle. In addition, we used the total-field scattered-field (TFSF) source and 3D cuboidal index and field monitors to record the permittivity and the electric field inside the nanoparticle. These are then used to compute the scattering current density, which allows computing the electric and magnetic dipole contributions through the multipole decomposition technique.[1] The nanoparticle is illuminated by a plane wave propagating along the same direction that the modes propagate in the chain. The polarization is chosen so that it matches the main component of the corresponding modes.

S3. Design Guideline for Edge Coupling

The nanoparticle chain is patterned between two waveguides, leading to each side of the chip. For efficient edge coupling from a lensed fiber to the waveguide, spot-size converters based on inverted lateral taper geometry are fabricated on both ends of the waveguide. The width of the waveguide tip is 200 nm and the length of the taper is 200 µm. The input and output waveguides are displaced by 50 µm using an S-bend to avoid overlapping of the input and output light spots.

S4. Optical characterization

The device under test (DUT) is mounted on an XYZ translational and rotational stage. Light from a tunable continuous-wave NIR laser (Yenista TUNICS T100R, 1490-1650 nm) is coupled to a polarization maintaining (PM) fiber and TE polarization is selected by a polarization controller before being coupled to the DUT via a lensed PM fiber. The lensed fiber produces a spot with a beam waist of 2.5 µm with minimal mixing of TE and TM modes (rejection ratio is over 30 dB). After passing through the DUT, the light is collected by a lensed single mode (SM) fiber with a beam waist of 2.5 µm and the transmitted light is detected by an InGaAs photoreceiver (New Focus, Model 1811). Both lensed fibers are mounted on XYZ micrometer translation stages for precise alignment with respect to the DUT. The photovoltage is sent to a data acquisition card (NI, USB-6216) and recorded by a computer. Data recording is synchronized to the laser wavelength sweeping with a spectral resolution of 1 pm and a maximum sampling rate of 100 KHz. The DUT and the coupling fibers

[a] *Institute of Materials Research and Engineering, A*STAR (Agency for Science, Technology and Research), 138634, Singapore. Email: dingl@imre.a-star.edu.sg, ramon_paniagua@imre.a-star.edu.sg and Arseniy_Kuznetsov@imre.a-star.edu.sg*
[b] *Institute of Microelectronics, A*STAR (Agency for Science, Technology and Research), 138634, Singapore.*
[c] *Institute of High Performance Computing, A*STAR (Agency for Science, Technology and Research), 138632, Singapore.*
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are monitored by a top down visible light microscope with a 20× objective lens (Olympus, NA 0.40).

S5. Relative propagation loss

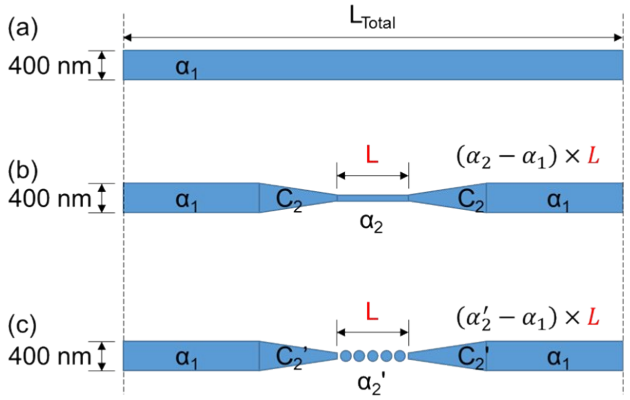

Fig. S1 Schematics of (a) a straight bus waveguide with the width of 400 nm, (b) a narrow stripe waveguide (width D) sandwiched between the bus waveguide via a pair of tapered couplers, and (c) a nanochain waveguide (w[illegible]ticle d[illegible] and inter-particle gap g) sandwiched between the bus waveguide via a pair of tapered couplers. Notations α_1, α_2, α_2' are the propagation losses of the bus waveguide, narrow stripe waveguide and nanochain waveguide respectively. Notations C_2 and C_2' are the transition losses of the tapered coupler for narrow stripe waveguide and nanochain waveguide respectively.

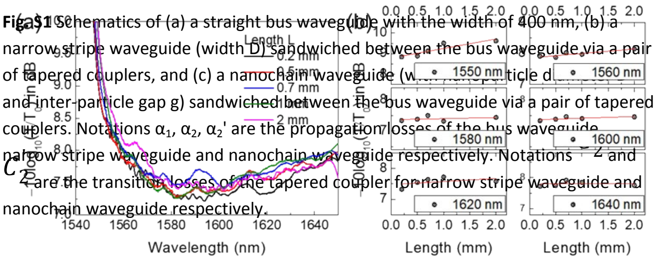

Fig. S2 (a) Log scale transmittance $-10log_{10}(T/T_0)$ of a series of nanochain waveguides (D = 340 nm and g = 170 nm) with L varying from 0.2 to 2 mm. (b) Linear fit of data at different propagation wavelengths taken from (a) as a function of L.

Fig. S1 shows a schematics of the waveguide designs for transmittance and propagation loss measurement. Fig. S1(a) shows the bus waveguide used for transmission normalization in Figs. 2, 3, and 5. Figs. S1(b) and S1(c) show that the narrow stripe waveguide (width D) and nanochain waveguide (uniform cylindrical nanoparticles with diameter D and gap g), respectively, are sandwiched between the input and output bus waveguides (width 400 nm) via a pair of tapered couplers reducing the width from 400 nm to the diameter of the nanocylinder over a distance of 100 µm. L is the variable to extract the relative propagation losses. This set of designs provides a direct comparison of the propagation losses between the bus and the nanochain waveguides and it minimizes the error introduced by the spatial dependent fabrication imperfections when the bus and the nanochain waveguides are fabricated separately.

The relative propagation loss (wavelength dependent) is deduced from the least squares linear-fit slope of the length dependent transmittance in log scale, as

$$-10log_{10}\left(\frac{T}{T_0}\right) \propto (\alpha_2 - \alpha_1)L$$

where $-10log_{10}(T/T_0)$ is the normalized transmittance in dB, $\alpha_2 - \alpha_1$ is the relative propagation loss of the nanochain waveguide compared to the bus waveguide. The error bar is given by the standard deviation. The transmission measurement of each waveguide was repeated a few times and the one with the highest transmission is used for fitting.

Fig. S2(a) is $-10log_{10}(T/T_0)$ taking transmittance spectra from Fig. 3(a). Fig. S2(b) plots the linear fit of the data at different propagation wavelengths taken from Fig. S2(a) as a function of L, showing how we deduce propagation loss shown in Fig. 3(b). The main error source in the propagation loss characterization is the control of coupling alignment from the lensed fiber to the waveguide. Tiny imperfection in alignment is reflected in the decrease of total transmission and counted to the propagation loss of the waveguide or chain. So the value we provided here is the upper limit of the propagation loss. In other word, we always overestimate the propagation loss as well as its error bar.

S6. Hybrid tapered coupler

Fig. S3 shows the schematics of the waveguide designs for characterization of the coupling loss of the hybrid tapered coupler. Fig. S3(a) shows the bus waveguide used for transmission normalization in Fig. 4. Figs. S3(b) and S3(c) show the nanochain waveguides (D = 340 nm, g = 150 nm, and 10 nanoparticles) sandwiched between the bus waveguides (width 340 nm) without and with a pair of hybrid tapered couplers. N represents the number nanoparticles in the coupler.

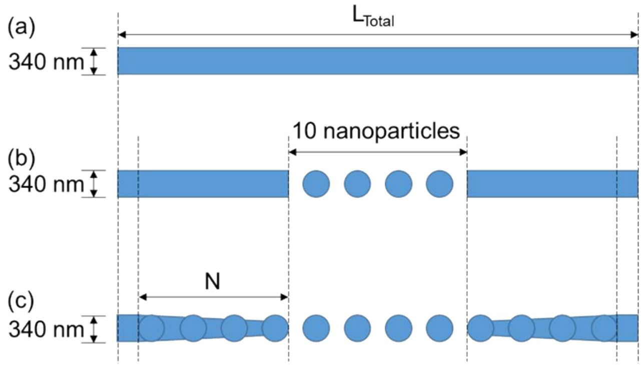

Fig. S3 Schematics of (a) a straight bus waveguide with width of 340 nm, (b) a nanochain waveguide (D = 340 nm, g = 150 nm, and 10 nanoparticles) sandwiched between the bus waveguides, and (c) the same nanochain waveguide sandwiched between the bus waveguides via a pair of hybrid tapered couplers with N number of nanoparticles.

Notes and references

1 P. Grahn, A. Shevchenko and M. Kaivola, *New J. Phys.*, 2012, **14**, 093033.