Electronic Supplementary Information

Unidirectional light scattering with high efficiency at optical frequencies based on low-loss dielectric nanoantennas

Toshihiko Shibanuma [a, b], *Pablo Albella* [a, *] & *Stefan A. Maier* [a]

[a]The Blackett Laboratory, Department of Physics, Imperial College London, London SW7 2AZ, UK.

[*]E-mail: p.albella@imperial.ac.uk

[b]Central Technical Research Laboratory, JX Nippon Oil & Energy Corporation, 8, Chidori-cho, Naka-ku, Yokohama 231-0815, Japan.

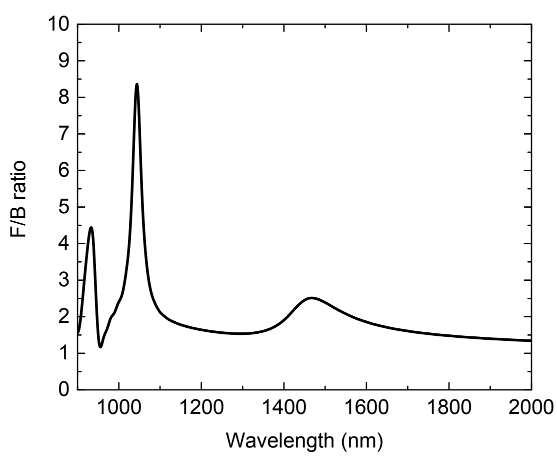

Figure S1 | F/B ratio of the optimized single disk. Spectrum of F/B ratio of the nanodisk with diameter of 620 nm and thickness of 220 nm as reported in the previous work. The calculation was conducted with the same conditions as the one used in the main manuscript, that is using light illumination by plane wave and light collection by the top and bottom scattering hemispheres.

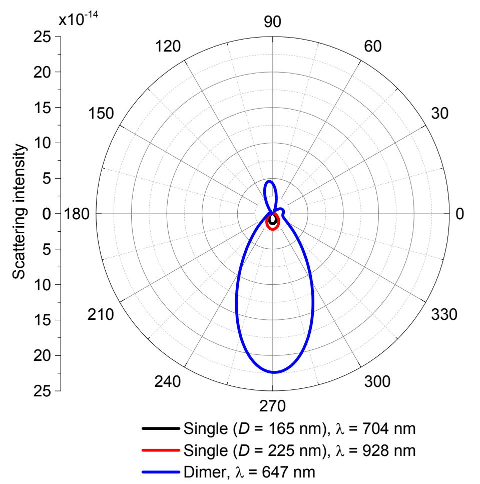

Figure S2 | Scattering radiation pattern in far field from the single spheres and dimer configuration projected in y-z plane.

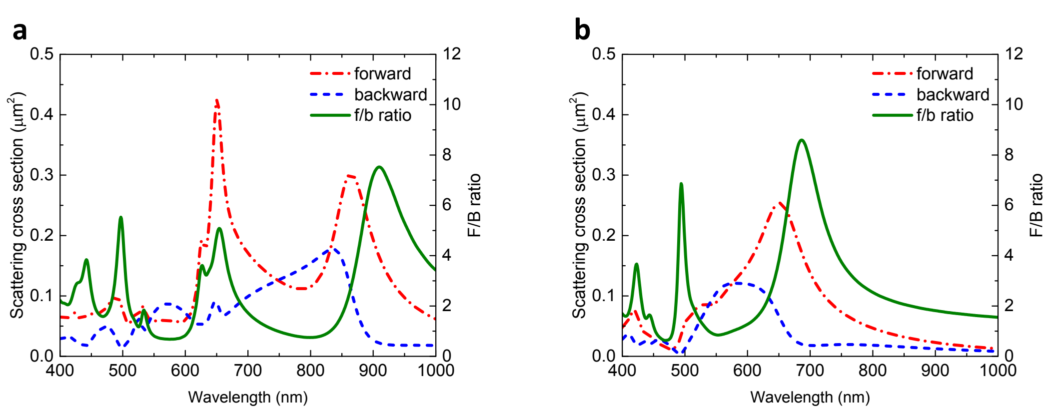

Figure S3 | Comparison between the asymmetric and symmetric dimer with 30 nm gap. Spectra of scattering cross section to the forward and backward direction and F/B ratio of the asymmetric dimer (a) and symmetric dimer (b) with the gap separation of 30 nm.

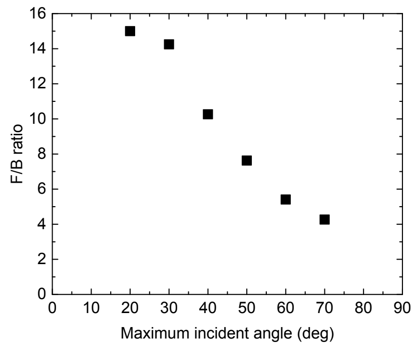

Figure S4 | Incident angle and F/B ratio. Maximum F/B ratio of scattered field from the dimer of silicon nanodisks on a sapphire substrate as a function of the incident angle.

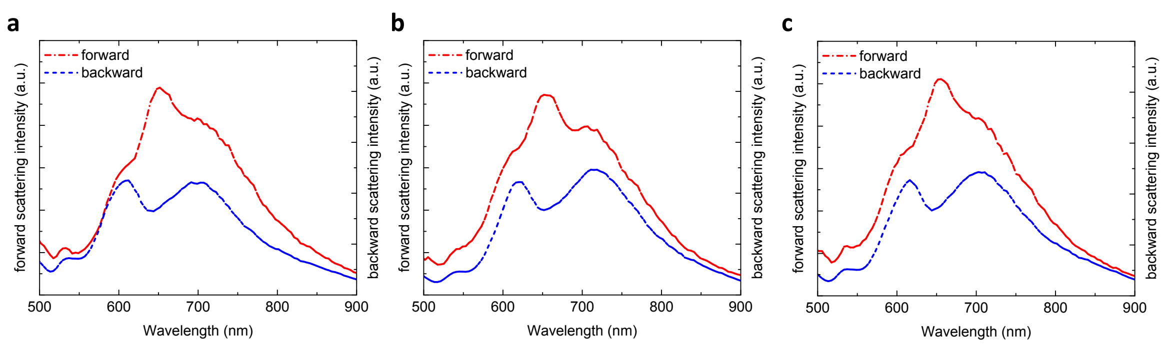

Figure S5 | Scattering spectra of dimers obtained in experiments. (a-c) Spectra of the scattered field from the dimer measured with the single particle dark field spectroscopy measurements.

Supplementary notes

Supplementary note 1

F/B ratio of the optimized single disk. The single disk optimized for directional forward scattering in ref [31] was investigated using the FDTD method with plane wave illumination and hemisphere collection. The shape of the F/B ratio spectrum was very similar to the result in ref 31; however, the F/B value was around 8. Therefore, the quantitative difference between our results and was not because of the optical properties of the nanoantenna but because of the different method used to calculate the F/B ratio.

Supplementary note 2

Scattering radiation patterns. The far field distribution of the scattered field from the single spheres and dimer were compared on y-z plane. As well as the cross section on x-z plane, the dimer showed forward scattering intensity more than 10 times higher than that of single spheres. A small tilt of 2 ° to +y direction was observed in the forward scattering. Asymmetric silicon dimer was reported in ref [39] to show the switchable directional scattering after optimization. Other structures such as single stair-like nanoantenna can steer light due to unparallel magnetic dipole excited in the nanoparticle[1]. However, this is not the case of the asymmetric dimer. Although the electric dipole excited in the large particle was tilted as shown in Figure 3b, the far field pattern of the scattering light from the asymmetric dimer was mainly determined by the coupling between the electric and magnetic dipolar resonances. This may make the tilted angle small in the dimer case.

Supplementary note 3

Comparison between the asymmetric and symmetric dimer with 30 nm gap. The asymmetric and symmetric dimer configurations were compared in the case of 30 nm gap separation. While the asymmetric dimer showed an overlapping of the maximum of forward scattering cross section and F/B ratio, the symmetric one exhibited the spectral separation between the two plots. As a consequence, the asymmetric dimer presented 17 % and 25 % higher in forward scattering efficiency and F/B ratio than the symmetric one at the maximum of forward scattering. 30 nm gap would be reliably available by using common lithography technique.

Supplementary note 4

Incident angle and F/B ratio. Scattering spectra of the dimer of silicon nanodisks on a sapphire substrate were calculated with changing the incident angle of the dark field source from 10 – 20 ° to 60 - 70 ° by 10 °, and plotted the F/B ratio as a function of the maximum incident angle. When the incident axis was small, the F/B ratio reached around 15 at 640 nm. However, the F/B ratio was decreased as the incident angle increased. This may be because the disk has a non-symmetric shape and the electric and magnetic resonances are excited in a tilted direction, which could cause inefficient constructive and destructive interferences.

Supplementary note 5

Scattering spectra of dimers obtained in experiments. The spectra of the scattered field to forward or backward direction from the dimers of silicon single nanodisks on a substrate were measured with the same measurement system in the main body. The unidirectional forward scattering with high scattering efficiency was observed in every samples. However, the obtained spectra were slightly different. This may be because the small defects which made the structure imperfect disk shape caused some perturbation in the spectra.

Supplementary references

1 J. Tian, Q. Li, Y. Yang and M. Qiu, *Nanoscale*, 2016, **8**, 4047–4053.