Supporting information

Evanescent wave interaction with nanoparticles on optical fiber modulate side emission of germicidal ultraviolet light

Zhe Zhao[1], Mariana Lanzarini-Lopes[1], Emma Westerhoff[3], Xiangxing Long[1,2], Hojung Rho[1,5], Yuqiang Bi[1], Li Ling[4], Paul Westerhoff[1*]

[1] NSF Nanosystems Engineering Research Center for Nanotechnology-Enabled Water Treatment, School of Sustainable Engineering and the Built Environment, Ira A. Fulton Schools of Engineering, Arizona State University, Tempe, AZ 85287-3005, USA

[2] Biodesign Swette Center for Environmental Biotechnology, Arizona State University, Tempe, AZ 85287-5701, USA

[3] Olin College, Needham, MA 02492, USA

[4] Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Hong Kong, China

[5] Department of Land, Water and Environment Research, Korea Institute of Civil Engineering and Building Technology, 283 Goyang-Daero, Ilsanseo-Gu, Goyang-Si, Gyeonggi-Do, 10223, Republic of Korea

*Corresponding author:

orcid ID: 0000-0002-9241-8759

Email: p.westerhoff@asu.edu

Phone: 480-965-2885

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Table SI.1 Calculated/linearly fitted scattering coefficient (α) along the side-emitting optical fiber treated with different concentration of Na_2SO_4.

Fiber length (cm) / Scattering coefficient (α)/ [Na_2SO_4] (mol/L)	0	0.02	0.05	0.10	0.15	0.20
2	0.139	0.191	0.217	0.268	0.374	0.356
4	0.109	0.193	0.188	0.248	0.364	0.392
6	0.122	0.149	0.198	0.210	0.370	0.378
Average	0.123	0.178	0.201	0.242	0.369	0.375
Standard deviation	0.015	0.025	0.015	0.029	0.005	0.018
Linearly fitted α	0.137	0.163	0.201	0.265	0.329	0.394

Because the scattering coefficient depends on fiber properties and coating layers, the value on each concentration remains a constant at any length of the fiber, and results were linearly fitted from 0 M to 0.2 M. Based on the irradiance results and Equation (3), the scattering coefficient (α) was calculated at a distance of Δx=2 cm (Figure 2f) because we measured the light intensity at every 2 cm. Table SI.1 shows the calculated and linearly fitted scattering coefficients at different SEOF positions (2, 4, and 6 cm) treated with different ionic strengths. Because a portion of light was reflected back at the distal end, the scattering coefficient at 8 cm was not considered. There is no significant difference between fitted data and experimental data ($p<0.05$). The α increased from 0.123 to 0.375 when the concentration of Na_2SO_4 increased from 0 to 0.2 M. Further increasing the ionic strength after the concentration of Na_2SO_4 reached 0.2 M did not keep increasing the scattering coefficient.

Table SI.2 Calculated UC of SEOF under different Na_2SO_4 concentrations.

[Na_2SO_4] (mol/L)	0	0.02	0.05	0.10	0.15	0.20	Modified SEOF
UC	0.523	0.417	0.363	0.309	0.166	0.134	0.805

Table SI.3 Calculated scattering coefficient (α) from the modelling data along the SEOF with the separation distance from 1 to 100 nm

Separation distance(α) / Scattering coefficient (α)/ Fiber length (cm)	2	4	6	8	Average	Standard deviation
1	0.671	0.463	0.387	0.427	0.487	0.127
5	0.550	0.417	0.316	0.325	0.402	0.109
10	0.428	0.344	0.259	0.344	0.344	0.069
15	0.335	0.285	0.229	0.280	0.283	0.044
20	0.262	0.230	0.177	0.255	0.231	0.039
25	0.205	0.169	0.153	0.191	0.179	0.023
30	0.152	0.130	0.102	0.179	0.141	0.033
35	0.131	0.102	0.086	0.131	0.113	0.022
40	0.116	0.065	0.092	0.096	0.092	0.021
45	0.089	0.065	0.053	0.094	0.075	0.020
50	0.076	0.043	0.034	0.091	0.061	0.027
55	0.066	0.036	0.042	0.051	0.049	0.013
60	0.067	0.026	0.027	0.063	0.046	0.023
65	0.054	0.023	0.011	0.060	0.037	0.024
70	0.034	0.035	-0.006	0.074	0.034	0.033
75	0.035	0.012	-0.001	0.063	0.027	0.028
80	0.060	-0.004	0.005	0.043	0.026	0.030
85	0.053	0.008	0.000	0.039	0.025	0.025
90	0.013	0.015	0.006	0.058	0.023	0.024
95	0.050	0.003	-0.016	0.057	0.023	0.036
100	0.023	0.016	-0.002	0.043	0.020	0.018

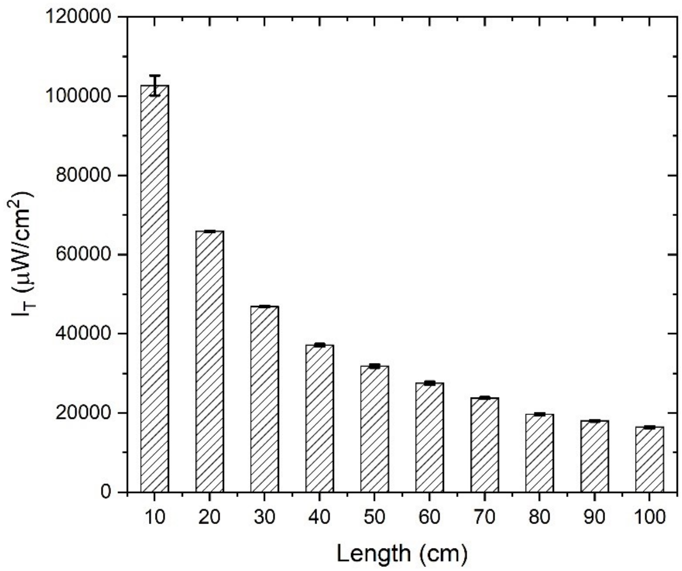

Figure SI.1 UV-C light attenuation inside the high-OH Thorlabs optical fiber. The distance between fiber cut end and LED is zero.

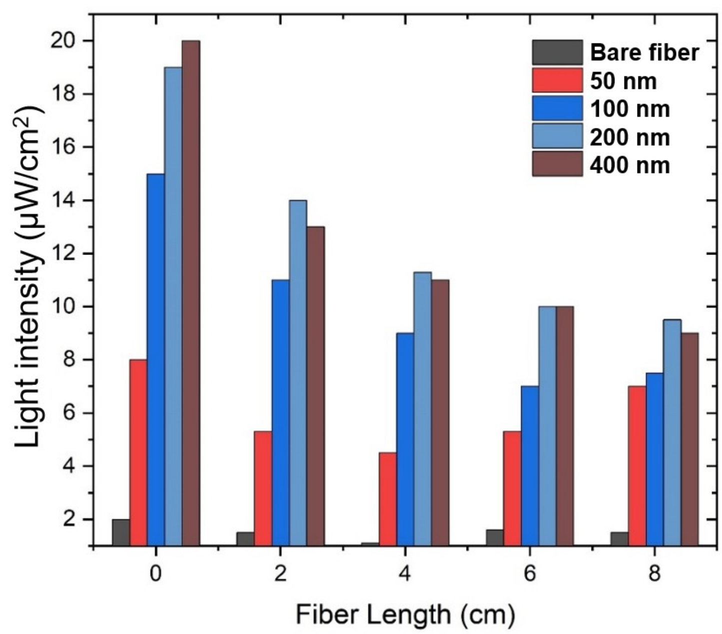

Figure SI.2 Effect of nanoparticle size on 265 nm UV-C LED launched optical fibers.

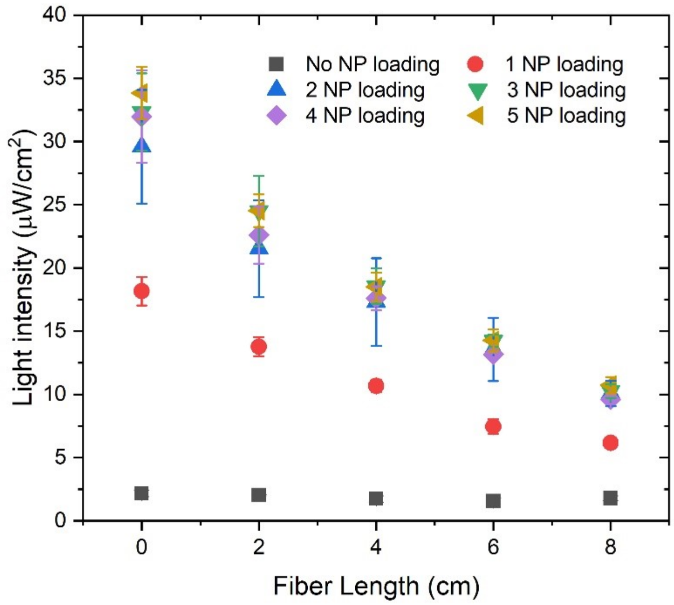

Figure SI.3 Effect of nanoparticle loading on 265 nm UV-C LED launched optical fibers. Particle loading was varied by the number of dip-coating cycles. Each dipping cycle resulted in (0.41 μg/ mm^2 ± 6%) additional loading for 200 nm silica NPs.

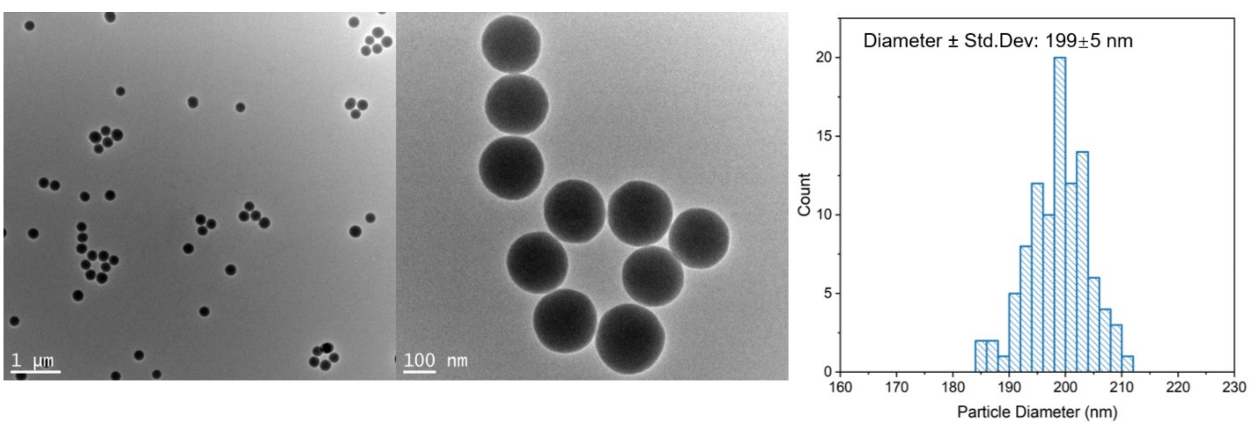

Figure SI.4 TEM images and the size distribution of silica sphere nanoparticles.

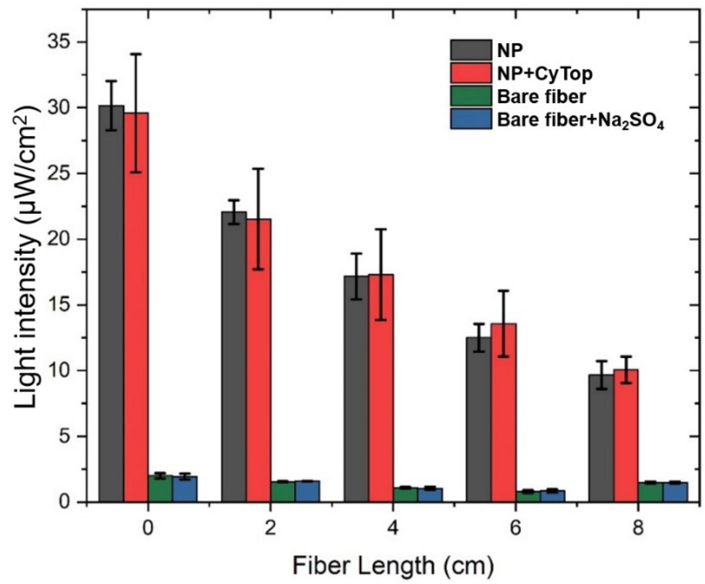

Figure SI.5 Light irradiance measured at different distances along the optical fiber with 200 nm nanoparticles, 200 nm nanoparticles with CyTop™ polymer, without NP (bare fiber), and bare fiber with Na_2SO_4.

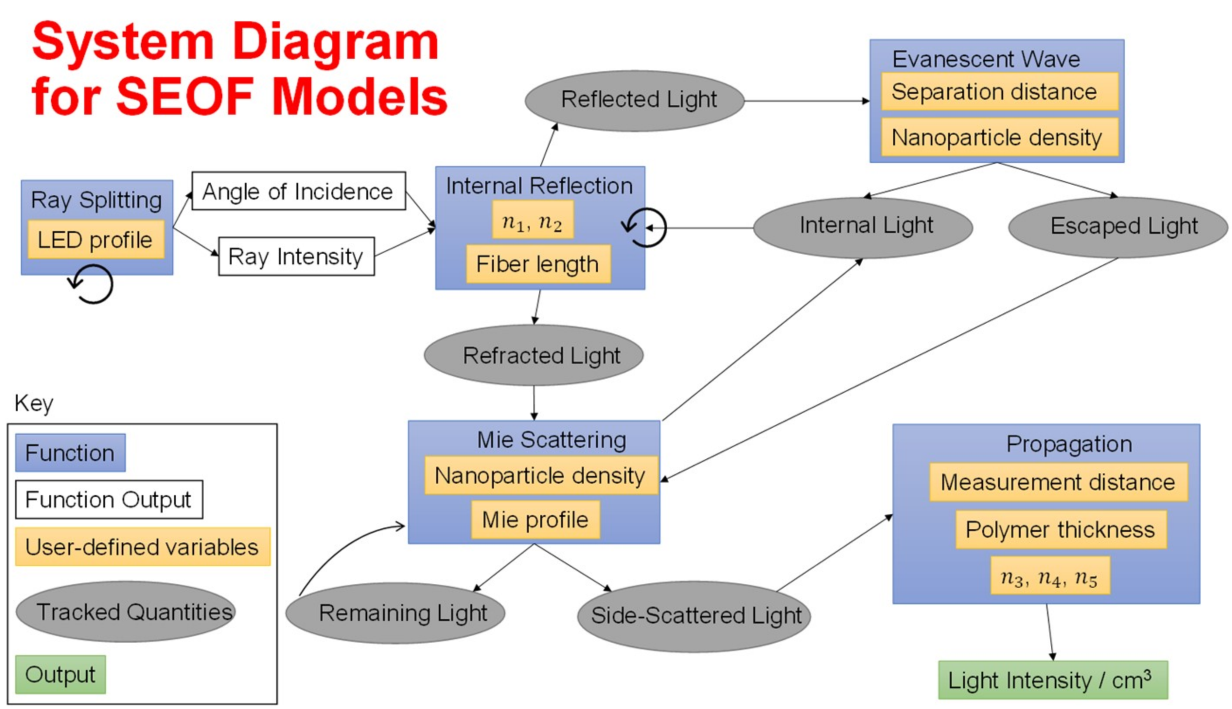

Figure SI.6 System diagram of SEOF scattering efficiency model.

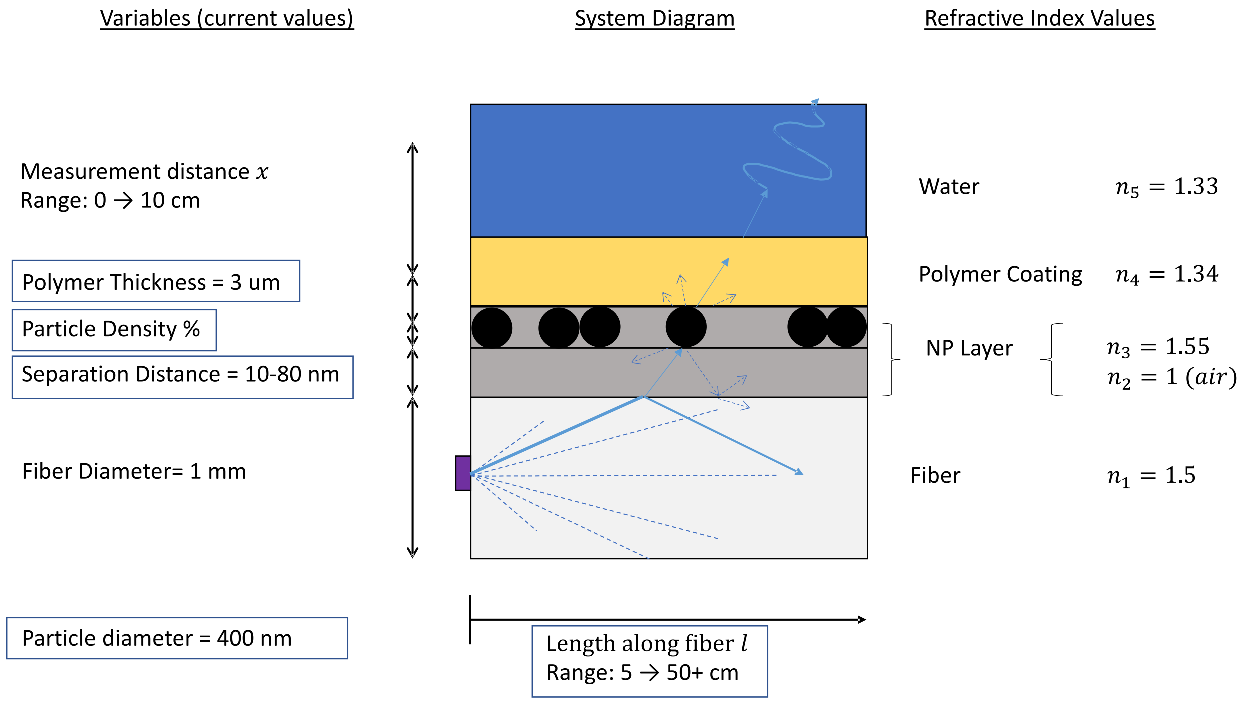

Figure SI.7 Scattering efficiency model variables and input parameters.

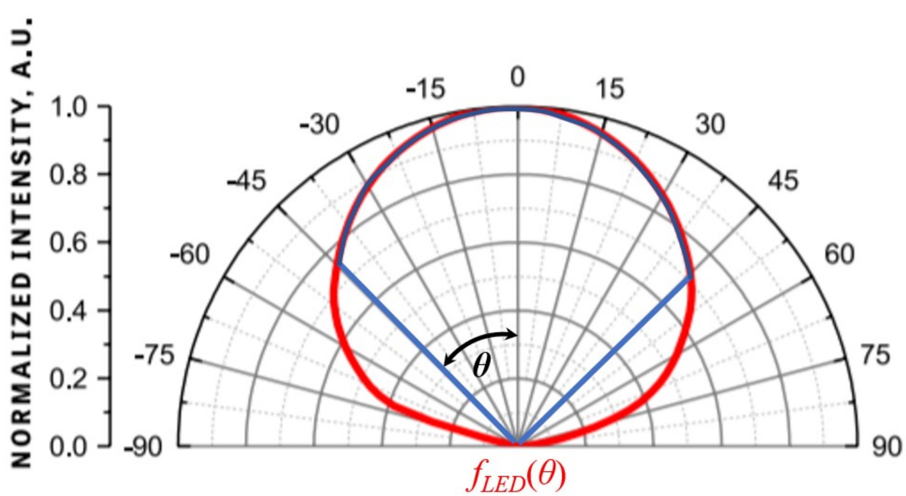

Figure SI.8 Radiation pattern of UV-C LED in the first principle model.

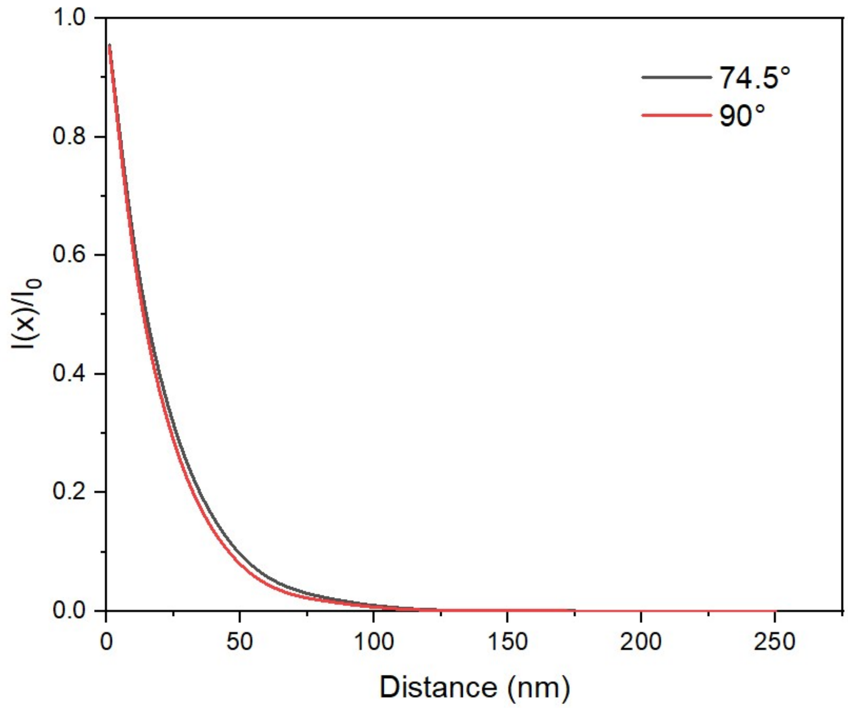

Figure SI.9 Evanescent wave intensity as a function of radial distance (nm) from the optical fiber surface for 265 nm light at an incident angle of 90° and 74.5° (minimum).

DLVO and Energy barrier calculation

Hamaker constant (A_{312})

$$A_{312} = (\sqrt{A_{33}} - \sqrt{A_{11}})(\sqrt{A_{22}} - \sqrt{A_{11}})$$

Where A_{11} for water = $4.35*10^{-20}$

A_{22} for glass fiber =$6*10^{-20}$

A_{33} for aminated silica = $6.5*10^{-20}$

A_{312}=$1.688*10^{-21}$

Use the following relationships:

$$\psi_{LVW} = \frac{-A_{312} a_1 a_2}{6(a_1 + a_2) H_0}$$

$$\psi_{DL} = \varepsilon_{EPS} \times \frac{a_1 a_2 (\psi_1^2 + \psi_2^2)}{4(a_1 + a_2)} [\frac{2\psi_1 \psi_2}{(\psi_1^2 + \psi_2^2)} \ln(\frac{1 + e^{-kH_0}}{1 - e^{-kH_0}}) + \ln(1 - e^{-2kH_0})]$$

$$\psi_{TOTAL} = \psi_{LVW} + \psi_{DL}$$

Where ψ_{LVW} is the potential for attraction by London van der waals forces

Ψ_{DL} is the potential for repulsion due to double layer repulsion

Radii of glass fiber $a_1 = 5*10^{-4}$ m

Radii of aminated silica particles $a_2 = 10^{-7}$ m

Surface potential for glass fiber $\psi_1 = -0.065$V

Surface potential for aminated silica $\psi_2 = +0.028$V

$\varepsilon_{EPS} = 7*10^{-10}$

Table SI.4 Thickness of electrical double layer versus ionic strength.

Ionic strength (M)	Thickness of electrical double layer *1/k* (nm)
0.06	1.143
0.15	0.723
0.30	0.511
0.45	0.417
0.60	0.361

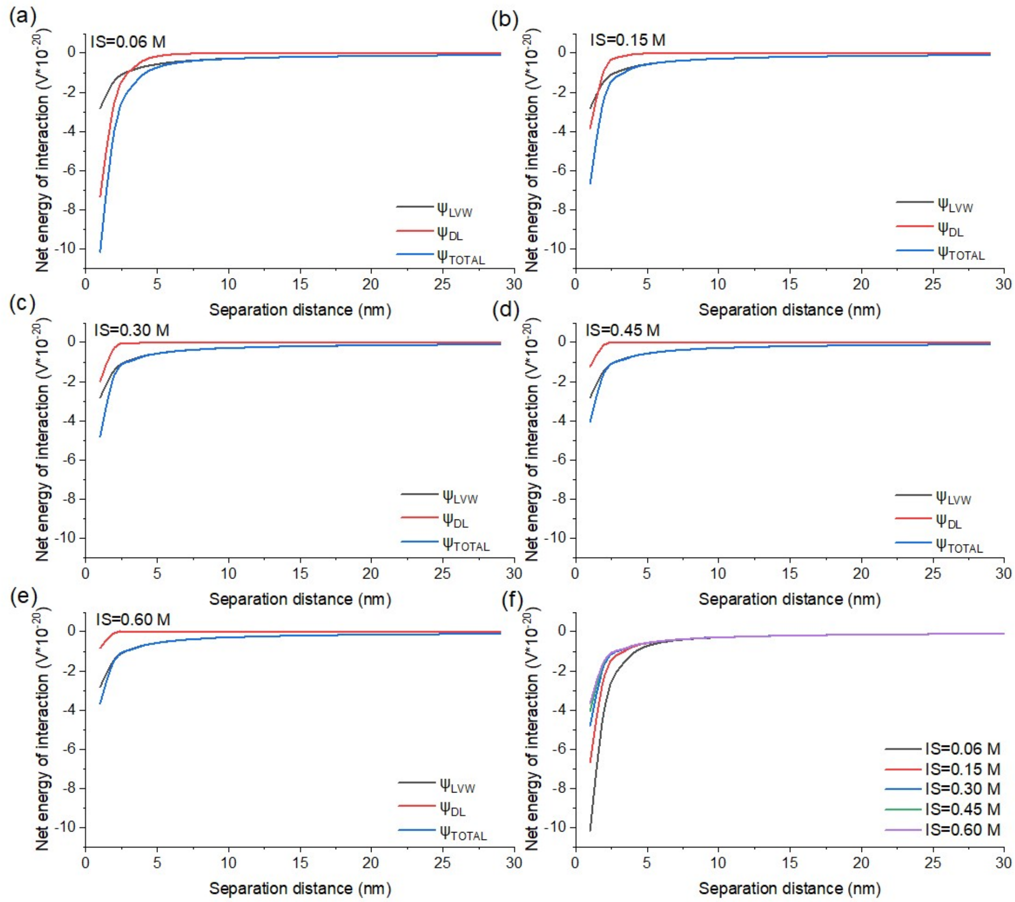

Figure SI.10 Energy of interaction between fiber interface and aminated silica nanoparticles with separation distance under ionic strength at (a) 0.06 M, (b) 0.15 M, (c) 0.30 M, (d) 0.45 M, and (e) 0.60 M. (f) shows the net energy of interaction under ionic strength from 0.06 M to 0.60 M. Ψ_{LVW}, Ψ_{DL} and Ψ_{TOTAL} represents the potential for attraction by London van der Waals forces, potential for repulsion due to double layer repulsion and total energy barrier, respectively.

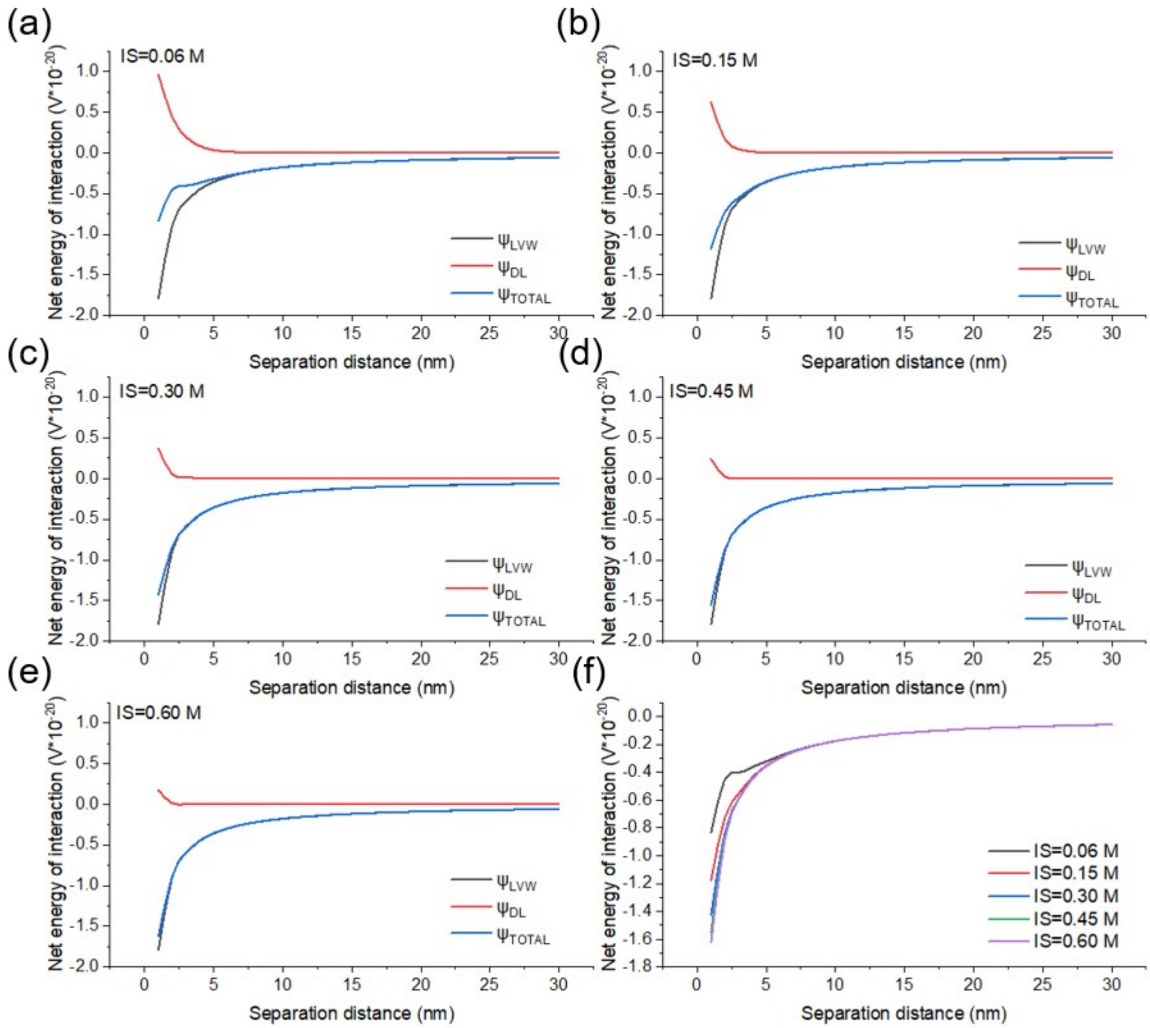

Figure SI.11 Energy of interaction between two aminated silica nanoparticles with separation distance under ionic strength at (a) 0.06 M, (b) 0.15 M, (c) 0.30 M, (d) 0.45 M, and (e) 0.60 M. (f) shows the net energy of interaction under ionic strength from 0.06 M to 0.60 M. Ψ_{LVW}, Ψ_{DL} and Ψ_{TOTAL} represents the potential for attraction by London van der Waals forces, potential for repulsion due to double layer repulsion and total energy barrier, respectively.

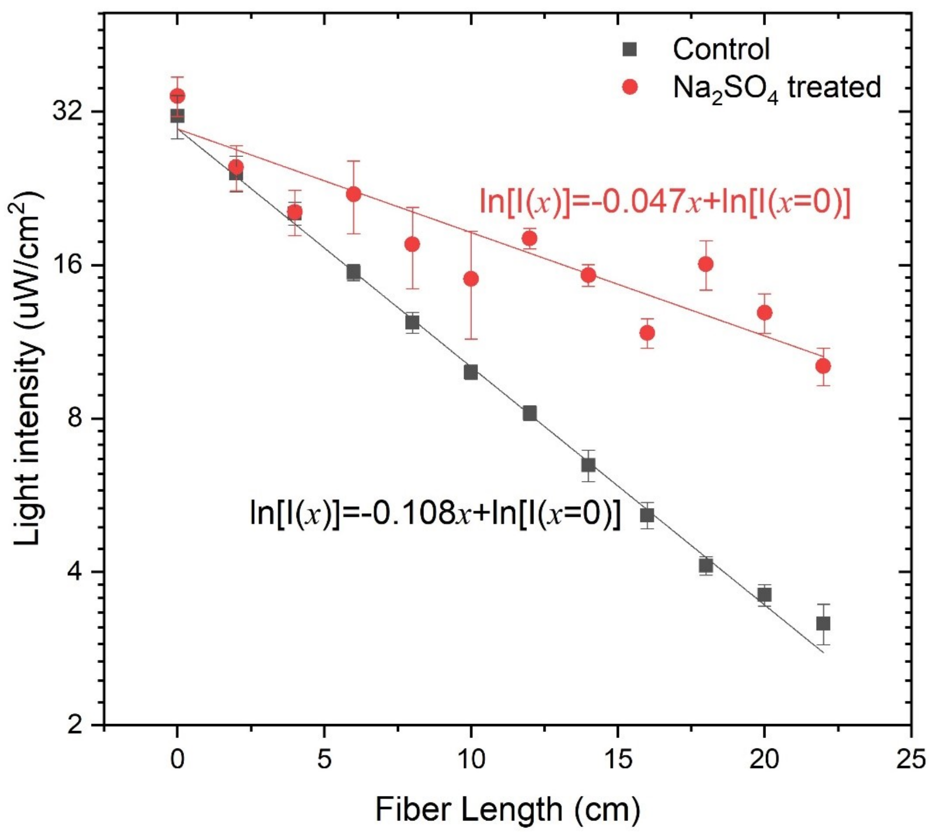

Figure SI.12 Natural logarithm fit of light intensity along optical fiber with and without different concentration of ionic strength treatment. Slope of fitted equation represents the scattering coefficient (α) at each condition.

Table SI.5 Comparation between proposed method with other methods reported in literature.

Application	Type of Nanoparticle	Fiber Length	UC value	Wavelength utilized in fiber	Reference
UV-C disinfection	SiO_2	>30 cm	0.52	265 nm	This work
	SiO_2	10 cm	0.15	265 nm	Lopez et al. 2020 [1]
Photo-catalysis	TiO_2	10 cm	0.04	365 nm	Wang et al. 2003 [2]
	TiO_2	6.5 cm	0.14	365 nm	Song et al. 2021 [3]
	TiO_2	48 cm	<0.1	365 nm	Hofstadler et al. 1994 [4]
	TiO_2	15 cm	0.05	375 nm	Peill et al. 1998 [5]

Reference:

[1] M. Lanzarini-Lopes, Z. Zhao, F. Perreault, S. Garcia-Segura and P. Westerhoff, Germicidal glowsticks: Side-emitting optical fibers inhibit Pseudomonas aeruginosa and Escherichia coli on surfaces, *Water Research*, 2020, **184**, 116191.

[2] W, Wen, and Young Ku, The light transmission and distribution in an optical fiber coated with TiO2 particles, *Chemosphere*, 2003, **50**, 999-1006.

[3] Y. Song, L. Ling, P. Westerhoff and C. Shang, Evanescent waves modulate energy efficiency of photocatalysis within TiO2 coated optical fibers illuminated using LEDs, *Nature Communications*, 2021, **12**, 4101.

[4] K. Hofstadler, R. Bauer, S. Novallc and G. Heisler, New reactor design for photocatalytic wastewater treatment with TiO2 immobilized on fused-silica glass fibers: photomineralization of 4-chlorophenol, *Environmental Science and Technology*, 1994, **28**, 670–674.

[5] N. Peill and M. Hoffmann, Mathematical Model of a Photocatalytic Fiber-Optic Cable Reactor for Heterogeneous Photocatalysis, *Environmental Science and Technology*, 1998, **32**, 398–404.