Photothermal Cellulose-Patch with Gold-Spiked Silica Microrods Based on *Escherichia coli*

Soomin Han, Kyoungho Han, Jaehwan Hong, Do-Young Yoon, Chulhwan Park, and Younghun Kim*

Department of Chemical Engineering, Kwangwoon University, Wolgye-dong, Nowon-gu, Seoul 139-701, Republic of Korea

**ABSTRACT:** Plasmonic-mediated photothermal heating under near-infrared (NIR) irradiation is an emerging key technology in the field of photothermal therapy and chemical reactions. However, there are few reports of photothermal films (dry-type patch), and thus, in this work, we developed the plasmonic-induced photothermal cellulose-patch operating in the NIR region. Hollow and spikelike gold nanostructures, gold-spikes, as plasmonic nanoparticles were prepared and decorated on silica microrods, which were prepared based on a unicellular organism, *Escherichia coli*, as a framework. In addition, freestanding cellulose-patch was prepared by mixing filter-paper pulp and armored golden *E. coli* (AGE) microrods. The major absorbing peak of AGE solution was revealed to be 873 nm, and the surface temperature of patch was increased to 264 °C within a very short time (1 min). When NIR laser was irradiated on the patch dipped in the water, the formation of water vapor and air bubbles was observed. The heating efficiency of indirect heat transfer via conduction from patch-to-water was 35.0%, while that of direct heat transfer via radiation from patch in water was 86.1%. Therefore, the cellulose-patch containing AGE microrods has possible applicability to desalination and sterilization because of its fast heating rate and high light-to-heat conversion under the irradiation of low-powered IR laser.

1. **INTRODUCTION**

The elevation of reaction temperature in a reactor is enhanced by the overall reaction rate, and a higher temperature in thermotherapy of cancer cells shows the effective inhibition of cancer cell growth. Because the conventional approach in the chemical reaction and thermotherapy could not localize heat in the target region, the heat dissipation into the surrounding system in the chemical reaction and in thermotherapy induced low energy efficiency and damage to surrounding tissues and cellular components, respectively. In contrast, localized heating at the nanoscale region in solution or inner cell achieved using localized surface plasmon resonance (LSPR) of metallic nanoparticles (NPs), such as Au, Ag, and Cu, could enhance the energy efficiency in the chemical reaction and minimize the unintended damage to nearby cells. Therefore, LSPR-mediated photothermal heating under near-infrared (NIR) irradiation is used as an emerging key technology in the field of photothermal therapy (PTT), and chemical reactions.

It is well-known that the fundamental requirements of ideal photothermal heating agents are that they should exhibit strong absorbance in the NIR region and efficiently transfer the absorbed NIR optical energy to heat. Among the photothermal agents, NIR organic dyes also show strong potential in noninvasive tumor therapy, and indocyanine green as an NIR-heptamethine cyanine dye has been used in clinical diagnosis. This dye preferentially accumulates in tumor cells, yielding a good signal-to-background ratio. As reported by Jain et al., AuNPs of 40 nm size show an absorption cross section that is 5 orders higher than conventional absorbing dyes, making plasmonic NPs ideal photothermal agents, with much higher efficiency than the more commonly used organic dyes. Therefore, metallic NPs offer enhanced absorption and scattering in the NIR region, facile synthesis, and good biocompatibility, as compared to organic dyes. In addition, the thermoplasmonic feature of metallic NPs could be easily and readily controlled by adjusting their size and shape.

To expand the absorption band to the NIR region and enhance the light-to-heat conversion, new nanomaterials were recently suggested by altering their shape: Au nanospheres to Au nanospikes or Au nanorods. Au nanospikes showed an obvious strong absorption band in the NIR region in the range (700–1000) nm, with a strong peak at 800 nm, providing a local electromagnetic (EM) field. Au nanorods possess large extinction cross sections and have synthetically tunable longitudinal plasmon wavelengths that cover the entire solar spectrum.

Other than PTT or photothermal reactions, the photothermal feature of metallic NPs is being applied to a wide range of applications, such as solar steam generation, desalination, and sterilization. Zhou et al. found that the thermoplasmonic absorber-based solar steam generation showed over 90% efficiency under solar irradiation of 4 kW/
shell22 structures show the red shift of the LSPR band within
regions. While spherical AuNPs have a plasmonic band at ca.
adjustable by varying the size, shape, and shell across the NIR
groups to AuNS. Therefore, photothermal application of metallic NPs is required to have fast heating rate, repeatability, thermal stability, and high conversion of light-to-heat under low-powered laser (<4 W/cm²) in the NIR region.

In this work, we developed the plasmonic-induced photothermal cellulose-patch operating in the NIR region. Herein, gold-spikes (AuNS) with hollow and spikelike nanostructures as plasmonic NPs were prepared and decorated on silica microrods, which were prepared based on a unicellular organism, *Escherichia coli* (*E. coli*), as a framework. The resulting materials are herein referred to as armored golden *E. coli* (AGE) microrods. Although silica microrods decorated with AuNS showed good performance with higher conversion efficiency and stable activity during multiple reactions under NIR irradiation, they should be dispersed in solution phase, before use as the photothermal agent. To extend the application area, freestanding cellulose-patch was prepared by mixing and drying of mixture of filter-paper pulp distributed in water, with AGE microrods. Paper-based preparation has some advantages, such as cost-effectiveness, easy and simple synthesis, and mass repetitive production.18 Temperature monitoring of the surface of the photothermal patch and in water was analyzed in real time with an IR-camera, and its energy efficiency was calculated with the heat transfer rate in the region of the cooling curve.

2. RESULTS AND DISCUSSION

Silica microrods decorated with AuNS were prepared using a three-step procedure: *E. coli* with the shape of microrods was first coated with a silica layer by a modified Stöber method19 to prepare the silica microrods, and then, polyvinylpyrrolidone (PVP)-stabilized AuS was prepared via the galvanic replacement reaction (GRR) between AgNPs and HAuCl₄ and subsequently allowed to adsorb onto the amine-terminated silica microrods (Figure 1a). The silica microrods were fully covered with AuNS because of the strong affinity of amine groups to AuNS.

The optical properties of metallic plasmonic NPs are readily adjustable by varying the size, shape, and shell across the NIR regions. While spherical AuNPs have a plasmonic band at ca. 520 nm in the visible region, AuNPs with rod,20 star,21 or shell22 structures show the red shift of the LSPR band within the visible and NIR regions. It is known that hot electrons induced via high EM field enhancements are produced at the junctions between adjacent metal NPs and at sharp edges in anisotropic nanostructure.23 Namely, spikes on AuNPs act as efficient nanoantennae, so that high EM fields are generated, giving rise to multiple intrinsic hot spots within a single NP. Therefore, among these AuNPs with different shapes, gold-spikes with the shell structure were selected here as the photothermal agent, working under NIR irradiation.

Figure 2 shows representative transmission electron microscopy (TEM) images of AuNS and AGE particles dispersed in aqueous phase. First, *E. coli* of rod-type was covered with the silica layer (ca. 80 nm of thickness), and then, silica microrods were used as a vehicle to load the AuNS NPs. The sizes in the axial/longitudinal direction for silica-coated *E. coli* and AGE particles were (3076.0/699.6) and (4156.4/951.5) nm, respectively. Richardson et al. reported that when AuNPs dispersed in solution were illuminated, the temperature profile might no longer be localized around each NP because of some thermal collective effect.24 Although the temperature can become uniform throughout the NP assembly, it is usually not favorable for nanoscale applications where localized heating is desired.25 In addition, for the applications of an efficient and broadband plasmonic absorber, it is desirable to assemble random-sized, widely anisotropic-shaped AuNPs in close-packed but not aggregated form.13 When AuNPs are close-packed in random distribution, the plasmonic band of each AuNP will overlap and hybridize, leading to multiple overlapping plasmonic modes that give rise to broadband absorption.26 Whereas, NPs dispersed in the aqueous phase could easily be aggregated and/or agglomerated by changing the environmental conditions: pH, temperature, and salts.27 Therefore, to effectively absorb light in a wide wavelength range of the NIR region, AuNS with a rough surface and shell structure was randomly decorated on the microrod vehicle, to provide a high density of hybridized LSPR feature.

Because AuNS particles were prepared by the GRR based on AgNPs,28 it showed a hollow-shell structure with a rough surface,29 which looks like a hollow roseberry. The particle size of AuNS measured by TEM and dynamic light scattering (DLS) spectroscopy is ca. (115.9 ± 22.7) and (100.0 ± 22.9) nm (Figure S1). The surface roughness and spiky morphology of AuNS gives rise to an enhanced surface plasmon resonance (SPR) band corresponding to tip plasmon modes.28 Ma et al. reported that Au nanospikes synthesized by the GRR showed a hollow structure and a representative SPR peak at 670 nm, while Au nanostar prepared via a seed-mediated growth method by Serrano-Montes et al. had a solid structure and showed an LSPR peak of 785 nm.23 The AuNS particles prepared in this work have an LSPR peak of 823 nm, as shown in Figure 2d. After decorating AuNS on silica microrods, a similar optical response was found for AGE composite, with some differences, such as LSPR red-shift to 873 nm and broadening. This effect

![Figure 1. Scheme of (a) gold-spikes decorated silica microrods prepared using the *E. coli* template and (b) assembly of cellulose-patch of AGE microrods and cellulose-paper pulp.](image-url)
might be due to the presence of silica vehicle, increased refractive index, and plasmon coupling effects induced from the close proximity between neighboring AuNS on the silica surface. This trend was also found for the Au nanostar-coated polystyrene (PS) beads. With increasing density of Au nanostars on PS, the LSPR band represented increasing intensity and broadening band. Therefore, the AGE microrods prepared herein could be utilized as a high-efficiency photothermal agent, when AGE microrods were composited on cellulose-paper.

In the literature, there are a few reports of photothermal film or patch of dry-type, but there are few reports of the paper-based patch, notwithstanding the advantages of lightweight, cheapness, and ease of preparation. The CuNP hydrogel16 and
Au nanohole–graphene oxide patch were prepared to evaluate their antibacterial properties and subcutaneous wound infections, respectively, via photothermal irradiation. Howard et al. prepared a AuNPs–PVP thin film to use as heat sink via thermoplasmonic dissipation. Liu et al. tested NIR-responsive elastomer film containing photothermal conjugated polymer and then confirmed the potential utility for NIR-responsive shape-memory materials. Therefore, to evaluate the feasibility of AGE particles as dry-type photothermal agents, AGE microrods were mixed with pulp of cellulose filter-paper dispersed in water, followed by centrifugation and drying under ambient conditions, to obtain the cellulose-patch containing AGE (Figure 1b). Figure 3 shows scanning electron microscopy (SEM) images, which reveal the E. coli template treated with 80 v/v % ethanol and sequentially 100 mg/L of AuNS has maintained its intrinsic rod-structure. AuNS particles were randomly immobilized on the silica microrods (Figure 3b), and some of the AuNS particles that were not fixed on the microrods after centrifugation formed agglomerates. When the stirring time of mixture between paper-pulp and AGE particles was prolonged, AuNS attached on the silica microrods could be readily removed by cellulose fibers, like a broom sweeps dust. Therefore, the agitation time in Figure 1b should be set within 10 min. The color of filter-paper was changed from white to gray after the addition of AuNS and AGE particles in cellulose-patch, and its color was gradually darkened with the added concentration of AGE in patch (Figure 3e). Because the cellulose-patch has gray or black color, it is suitable to absorb light-energy in the visible and NIR regions.

The photothermal heating of cellulose-patch containing AGE microrods is due to the LSPR phenomena of metallic NPs. As described by the two-temperature model of photothermal heating, plasmons can be launched via the EM coupling between incident light and free electrons in metallic NPs. The absorbed photon energy decays via both radiative and nonradiative damping, and then, LSPR excitations significantly increase the yield of hot electrons in the nonradiative process. The lattice temperature increases through the coupling between the hot electrons and phonons of the metal lattice. Finally, the thermal energy of lattice transfers to the local environment. Because the thermal equilibrium between plasmonic NPs and the surrounding medium can be reached within several nanoseconds, this light-to-heat conversion is highly efficient via swift relaxation dynamics.

To confirm the photothermal conversion efficiency by the cellulose-patch containing AGE microrods, the change of elevation temperature on the surface of the patch and in water was measured by an IR-camera. The cellulose-patch was cut into a small piece (1 cm × 1 cm) and attached to the outside surface of a cuvette cell with thermal grease, and then the cuvette was filled with 1 mL of water. The surface of patch was then irradiated by 808 nm of NIR laser with an energy density of 1–4 W/cm². The cellulose-patch containing different concentrations of AGE microrods (50–300 mg/L) was prepared to find the optimum concentration of AGE on the patch. Figures S2a and S3a show that the surface temperature of patch (Tpatch) was rapidly increased within 1 min and reached equilibrium in very short time. The patch containing a concentration of 50, 100, and 300 mg/L of AGE showed temperature increases of approximately 67, 104, and 115 °C for the initial 1 min, respectively, and the maximum Tpatch was reached at 105, 148, and 154 °C. When the patch generates heat by the photothermal effect, the water in the cuvette cell is heated by heat transfer through its wall. Unlike Tpatch, the water temperature (Twater) was gradually increased (Figures S2b and S3b) and reached 55, 74, and 75 °C for 50, 100, and 300 mg/L of AGE, respectively. While the fast temperature increase of Tpatch was due to the direct irradiation of NIR laser, the gradual elevation of Twater was induced by both the indirect transfer of photothermal heat via conduction and the large heat capacity of water. Although Tpatch and Twater were increased with the concentration of AGE, the Twater of 100 mg/L AGE was almost the same as that of 300 mg/L AGE. Thus, the AGE in the cellulose-patch was fixed as 100 mg/L for the following test.

The numerical and experimental investigation by Baffou et al. showed that the elevation temperature through plasmonic NPs under illumination was inversely proportional to the square of the interparticle distance between neighboring NPs. The interparticle distance between AuNS particles loaded on silica microrods was closer, compared to AuNS dispersed in solution, and thus, the heating efficiency by plasmonic-mediated photothermal effect might be enhanced. Herein, the elevation effect of Tpatch and Twater by AuNS fixed on the silica microrods, in comparison with that by individually separated AuNS on the patch, was also tested. While Tpatch and Twater by patch containing AGE showed efficient photothermal heating (Figure 4), that by the bare filter-paper was less changed, and that by the patch with AuNS particles reached about two-thirds of the maximum temperature for patch with AGE. The elevation rate of Twater by patch with AuNS and AGE was 7.2 and 4.9 °C/min, respectively, during the initial 5 min. It is noted that the photothermal heating by individual AuNS particles is good, but the heating effect and rate was larger and faster when the
interparticle distance between neighboring AuNS particles, which were fixed on the silica microcruds, was closer.

With increase of the intensity of the light source, the elevation temperature of patch surface and water naturally increased because of the increasing generation of hot electron contributing to photothermal heating. For 4 W/cm² of NIR laser, \( T_{\text{patch}} \) was increased to 264 °C with 200 °C/min rate during the initial 1 min (Figure S4). The dependence of \( T_{\text{patch}} \) and \( T_{\text{water}} \) per watt of NIR laser was 58.8 and 8.5 °C/W, respectively. As shown in Figure S5, the thermal decomposition temperature of patches under \( T_f \) and area condition is about 347 and 340 °C, respectively. When the high-powered laser was irradiated on the patch, the surface of patch was slightly smudged, resulting in damage to the photothermal agents. Whereas when 4 W/cm² powered NIR was irradiated on the patch surface dipped in the water in the cuvette cell, the photothermal energy generated from the surface of patch was dissipated to the water, and thus, damage to the patch structure was not caused. Using this feature, the experiment for generation of water vapor by the cellulose-patch was carried out.

It is reported that strong nonradiative plasmon decay concentrates light on a nanometer-sized volume, leading to the localized heating of water, which is favorable for effective steam generation.\(^{30,36}\) However, the generated plasmonic heat was easily and rapidly dissipated to the environment, and this decay of heat energy is inefficient in water vapor generation. Therefore, to prevent heat dissipation via heat transfer from inside water to the outside of the cuvette cell, the cuvette cell was wrapped with styrene foam as an insulator (Figure 5). The evaporation rate was slightly decreased to 12.9 kg/m²·h at 1 W/cm² irradiation power of NIR laser was adjusted from 2 to 4 W/cm², and 340 °C with a cooling rate of 50 °C per 20 min. These results demonstrate that the cellulose-patch has excellent photothermal stability and fast cooling—heating performance.

A continuum energy balance on the heating—cooling procedure can be established as the following equation,\(^{26}\) and the photothermal heating efficiency by light-to-heat could be calculated in the cooling curve.

\[
\sum m_i C_{pi} \frac{dT}{dt} = Q_{in} - Q_{out} = 0 - hA(T - T_o)
\]  

(1)

where \( m_i \) and \( C_{pi} \) are the mass and heat capacity of water, cuvette, and patch, respectively, \( Q_{in} \) and \( Q_{out} \) are the heat transfer rate from patch-to-water and water-to-air, respectively, \( h \) is the total heat transfer coefficient, \( A \) is the surface area of the system, and \( T_o \) is the ambient temperature. In the cooling period for 20 min, \( Q_{in} \) was eliminated because of laser-off. Equation 1 was simplified with dimensionless constant, \( \theta \), as eq 2, integrating as eq 3.

\[
\frac{d\theta}{dt} = \frac{hA}{mC_p} \left( \frac{T - T_o}{T_e - T_o} \right) = \frac{1}{\tau_e} \theta
\]

(2)

\[
t = \tau_e \ln \theta
\]

(3)

where \( \tau_e \) is the time constant, which means the ratio between the heat loss \( (mC_p)_w \) of water and the total heat transfer \( (hA) \) to outside per \( \Delta T \). The photothermal efficiency \( (\eta) \) can be determined by eq 4:

\[
\eta = \frac{hA(T_e - T_o)}{I}
\]

(4)

where \( I \) is the applied power of light on the patch. When the photothermal NPs was dispersed in water during NIR irradiation, \( I \) should be changed in the form of \( I (1 - 10^{-\delta}) \), by considering the absorbance \( (A) \) of NPs in water.\(^{37}\) In this experimental configuration, light was directly illuminated on the patch surface in air as incident power \( (I) \), and thus, the denominator of eq 4 was only considered as a form of \( I \), that is, it was assumed that all the energy of the light source was transmitted to the patch.\(^{38}\) The time constant for heat transfer from the system was determined by applying the linear time data from the cooling period (20 min), versus the negative natural logarithm of \( \theta \). The specific heat capacity of the patch was calculated as ca. 1.33 J/g·K. The total heat transfer of the patch was obtained from the cooling curve, and the numerator term in eq 4 represents the thermal energy by photothermal heating of the patch alone. Thus, the photothermal conversion efficiency of light-to-heat could be calculated and that of the
patch containing 100 mg/L of AGE under 2 W/cm² of NIR irradiation showed 25.3%.

Table S1 summarizes the conversion efficiency according to variables, such as the concentration of AGE, type of patch, and power density of laser. On increasing the amount of AGE on the patch, the heating efficiency was increased from 20.6 to 35.8%. The patch containing individually separated AuNS particles showed a low efficiency of 24.9%. Note that as shown in the experiment of photothermal heating, the photothermal efficiency of patch was high when silica microrods were decorated with AuNS particles. In contrast, when the power of incident light was increased, the efficiency decreased due to the energy loss during heat transfer from patch to cell and water, although $T_{\text{water}}$ rose to a high temperature. Namely, the excess supply of energy appears to be partially used for the photothermal heating and the rest to be lost. Evaluation of the photothermal heating by AGE particles dispersed in water showed a high heating efficiency of 44.0%. Namely, the heating efficiency of water was decreased, because the thermal energy of patch induced by the photothermal effect was transferred to the cuvette and water via conduction. Actually, in test of steam generation, $T_{\text{water}}$ was increased to 100 °C when NIR was illuminated directly to the patch dipped in the water. As summarized in Table S2, the heating efficiency under adiabatic conditions was higher, compared to that under nonadiabatic conditions. Therefore, the heating efficiency of indirect heat transfer via conduction from patch-to-water was 35.0%, while that of direct heat transfer via radiation from patch in water was 75.2 and 86.1% for nonadiabatic and -adiabatic conditions, respectively. The results show that the plasmonic-mediated photothermal patch displayed a fast heating rate, good stability, high light-to-heat conversion, and good heating efficiency of water, and thus, it is expected to be used in the field of desalination or steam generation.

3. CONCLUSIONS

The gold-spikes decorated silica microrods (AGE) based on the unicellular cell, E. coli template, were synthesized for photothermal agents, and the cellulose-patch containing AGE microrods was also successfully prepared. The patch not only demonstrated a strong SPR band in the NIR region and high photothermal conversion characteristics, but also exhibited fast heating rate in steam generation. The as-made cellulose-patch was stable under the irradiation of NIR laser after four times recycling experiments, and no tendencies to decrease temperature were observed. For 4 W/cm² of NIR laser, the surface temperature of the cellulose-patch with 100 mg/L of AGE particles was increased to 264 °C with 200 °C/min rate during the initial 1 min. The fast heating rate and high photothermal conversion efficiency of the as-made materials are suitable to apply to steam generation. The experiment for generation of water vapor was performed and showed fast elevation rate (13.5 °C/min) of $T_{\text{water}}$ and a large amount of air bubbles and water vapor in the water in 5 min. In addition, as shown in the experiment of photothermal heating, the photothermal efficiency of the patch was high when the silica microrods were decorated by AuNS particles, compared to the patch containing individually separated AuNS particles. Namely, the interparticle distance between AuNS particles loaded on silica microrods was closer, compared to the AuS dispersed in solution, and thus, the heating efficiency by plasmonic-mediated photothermal effect might be enhanced. Therefore, it is believed that the paper-type cellulose-patch containing AGE particles provides good potential in various fields, such as steam generation, desalination, and sterilization, via photothermal heating.

4. METHODS

4.1. AuNS Synthesis. Hollow and spikelike gold NPs (gold-spikes) were synthesized by the GRR method between AgNPs and HAuCl₄. First, AgNPs as sacrificial materials were prepared as follows: first, 10 mL of 0.025 M AgNO₃ was added to 80 mL of boiling water, followed by adding 1 wt % trisodium citrate dehydrate. The mixture was boiled for 20 min and cooled to room temperature. Then, AuNS was prepared with the as-made AgNP solution, as follows: 5 mL of AgNPs was dispersed in 25 mL of 3 mM HAuCl₄ and 5 mL of 10 mM ascorbic acid was injected into the resulting solution. To enhance the dispersion stability in the aqueous phase during storage, 0.1 g/mL of PVP was added into the final solution at 50 °C for 6 h.

4.2. AGE Synthesis. To form a rod-shaped nanostructure, unicellular cell, especially E. coli was selected, which was easily cultivated and reproduced. Thus, using them as frameworks was an adequate strategy for easy modification. The cell culturing of E. coli followed the reported protocol, and the silica layer was coated on the E. coli by a modified Stöber method. Then, 10 mL of culturing solution containing E. coli was dispersed in 50 mL of 80 v/v % ethanol solution, followed by sequentially adding 1 mL of NH₄OH and tetraethyl orthosilicate solution dropwise. The mixture was stirred for 6 h, and the resulting particles were collected by centrifugation and washed three times with ethanol. To decorate the AuNS particles on the silica microrods, amine-functional group was introduced, using (3-...
aminopropyl)triethoxysilane (APTES). First, 1 mL of APTES was slowly added to 40 mL of ethanol solution of 0.01 g silica microrods, and the mixture was stirred at 50 °C for 12 h. The precipitated particles were separated by centrifugation and washed three times with ethanol. Then, 20 mL of amine-functionalized silica microrod solution was added to PVP-coated AuNS solution (700 mL). After stirring for 12 h, the resulting particles, AGE, were collected by centrifugation, washed three times with water, and re-dispersed in water.

4.3. Cellulose-Patch Synthesis. A piece of filter-paper (Advantec, cellulose) was placed in water and stirred for 24 h, and then, the paper became loosened, like pulp. The appropriate concentration (50–300 mg/L) of AGE particles was added to the pulp solution during just 10 min. The water in the mixture of paper and AGE was squeezed with centrifugation, and the wet-pulp composite was spread thinly on a Petri dish, and dried for 2 days, making the white paper with pulp.

4.4. Photothermal Performance. The photothermal performance was investigated using 808 nm NIR laser with a power density of 1–4 W/cm². The cellulose-patch (1 cm × 1 cm) was attached on the outer surface of the cuvette cell containing 1 mL of water using thermal grease (Momentive SU8010). The particle size distribution dispersed in water was measured by DLS (Photal, ELS-Z). Their UV-Vis absorption spectra were obtained by spectrophotometry (Shimazdu, UV-28494). The particle size distribution curve, heating efficiency, temperature profiles, IR-camera images, and evaporation rate curve (PDF)

4.5. Characterization. The morphology of AuNS and AGE was analyzed by TEM (JEOL, JEM-2010) and SEM (Hitachi, SU8010). The particle size distribution dispersed in water was measured by DLS (Photal, ELS-Z). Their UV–Vis absorption spectra were obtained by spectrophotometry (Shimadzu, UV-1800). The temperature profiles of patch and water were recorded in real time by an IR-camera (FLIR System, FLIR ONE).

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsomega.8b00639.

DLS distribution curve, heating efficiency, temperature profiles, IR-camera images, and evaporation rate curve (PDF)

Formation of water vapor and air bubble generation with the irradiation power of NIR laser adjusted from 2 to 4 W/cm² under adiabatic and nonadiabatic conditions (ZIP)

AUTHOR INFORMATION

Corresponding Author
*E-mail: korea1@kw.ac.kr (Y.K.).

ORCID

Younghun Kim: 0000-0003-4860-8632

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF-2017R1A2B4001829).

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