Plasmonic Wood for High-Efficiency Solar Steam Generation

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Plasmonic metal nanoparticles are a category of plasmonic materials that can efficiently convert light into heat under illumination, which can be applied in the field of solar steam generation. Here, this study designs a novel type of plasmonic material, which is made by uniformly decorating fine metal nanoparticles into the 3D mesoporous matrix of natural wood (plasmonic wood). The plasmonic wood exhibits high light absorption ability (=99%) over a broad wavelength range from 200 to 2500 nm due to the plasmonic effect of metal nanoparticles and the waveguide effect of microchannels in the wood matrix. The 3D mesoporous wood with numerous low-tortuosity microchannels and nanochannels can transport water up from the bottom of the device effectively due to the capillary effect. As a result, the 3D aligned porous architecture can achieve a high solar conversion efficiency of 85% under ten-sun illumination (10 kW m$^{-2}$). The plasmonic wood also exhibits superior stability for solar steam generation, without any degradation after being evaluated for 144 h. Its high conversion efficiency and excellent cycling stability demonstrate the potential of newly developed plasmonic wood to solar energy-based water desalination.

Nowadays, water shortage is one of the most severe global issues that urgently needs to be solved.[1] Numerous efforts have been dedicated to finding technological solutions to address water scarcity.[2–10] Metal-nanoparticle-based plasmonics have generated tremendous interest in the field of solar steam generation, which can be used for water purification and alleviate hardship faced in areas affected by water shortage.[11–13] For most of solar-steam-generation devices based on plasmonics, metal nanoparticles are ubiquitously deposited on various substrates to form freestanding structures. For example, Zhu et al. demonstrated high-performance plasmonics for water desalination using an anodic aluminum oxide (AAO) membrane as the metal nanoparticle substrate.[2,14] The open and straight nanochannels in AAO play an important role in improving the solar steam generation due to the low tortuosity for water transport as well as the excellent optical absorption. However, the AAO membrane is a brittle ceramic with potential challenges in cost and scalability. Therefore, finding an alternative low-cost 3D host for decorating metal nanoparticles is still greatly needed. Recently, cellulose-based structures have attracted much attention. For example, Singamaneni’s group pioneered plasmonic cellulose paper by decorating metal nanoparticles into its mesoporous matrix.[15] They demonstrated a biofoam based on bacterial nanocellulose to realize high-efficiency solar steam generation.[9] But the bottom-up fabrication approach is not cost effective, and the mechanical performance needs further improvement.

Wood with its mesoporous, low-tortuosity, and hierarchical structure has attracted much research interest recently.[16–18] Cellulose nanofibers and cellulose nanocrystals extracted from wood have found a range of applications, including transparent and haze paper for optoelectronics, biodegradable electronics, and solar cells.[19–25] These advanced applications using wood-based materials are promising toward a sustainable future. However, these bottom-up approaches are time- and energy-intensive. In this work, for the first time, we proposed a plasmonic wood by decorating a range of plasmonic metal nanoparticles directly in a natural wood matrix for solar steam generation. Similar to recent works about the wood-based evaporators,[17,18] the plasmonic wood possesses the following advantages: (1) naturally hydrophilic; (2) numerous aligned microchannels for fast water transport; (3) low thermal conductivity along the channel axis direction; (4) high light absorption within a wide wavelength range; (5) excellent mechanical properties (vs brittle AAO template); (6) superior stability in water and nontoxic; and (7) top-down fabrication that is potential low cost. As a result, the obtained plasmonic wood with a high solar absorption of ~99% can reach an impressive solar conversion efficiency of 85% under ten-sun illumination. It also displays superior reusability and stability for solar steam generation, without any performance degradation after cycling 144 h. The
plasmonic wood shows favorable overall performance compared with other reported solar steam generators.[2–8,17,18]

The plasmonic wood for solar steam application is derived from the natural wood in trees (Figure 1a), which can pump water up to over a record 100 m in height owing to its transpiration ability.[26] To mimic the water pumping process in our plasmonic wood, a basswood slice is obtained by cutting perpendicular to the growth direction of tree. The plasmonic metal nanoparticles were then deposited on the wall of the wood microchannels based on the solution method, forming the plasmonic wood (Figure 1b). The black plasmonic wood can float on water without the help of additional auxiliaries. The plasmonic Pd nanoparticles on the surface of the microchannels convert the incident light into heat based on the plasmonic effect (Figure 1c,d). As a result, the high light absorption can be achieved within a broadband wavelength range from 400 to 2500 nm, which can effectively harvest most of the solar energy. Since the decoration layer of metal nanoparticles is thin, it will not block the pathways of water in the microchannels, ensuring continuous water transport. Owing to the low thermal conductivity along the microchannel direction of the plasmonic wood, the heat is localized on the evaporation surface when exposed under solar illumination, leading to an effective solar steam generation. The hydrophilic nature of the plasmonic wood can effectively transport water up, maintaining a continuous water supply for the vapor generation (Figure 1e).

To fabricate a plasmonic wood, a wood block with a thickness of about 2 cm was cut perpendicular to the tree growth direction (Figure 2a). Note that when the wood is too thick, the water uptake to the evaporation layer is not sufficient for solar steam generation, which decreases the evaporation rate. When the wood is too thin, the heat converted by sunlight cannot be confined to the top of the plasmonic wood (heat dissipates into bulk water and decreases the energy at the surface). After decoration with palladium (Pd), gold (Au), and silver (Ag) metal nanoparticles, the wood matrices totally turn black (Figure 2b–d; Figure S1, Supporting Information). Note that the open and aligned microchannels in wood matrix with a diameter from 5 to 50 µm act as ideal hosts for 3D uniform deposition of plasmonic nanoparticles (Figure 2c; Figures S2 and S3, Supporting Information). Our plasmonic wood has an all-in-one structure, which is different with the separated bilayer structure of the wood-GO evaporator.[18] The separated structure of the wood-GO evaporator cannot ensure the perfect contact between the GO layer and wood surface, which can potentially reduce the water uptake to the evaporation layer and lower the evaporation rate. The microchannels in wood matrix are made of numerous aligned nanofibers, which is revealed in Figure 2f. As shown in Figure 2g, the deposited Pd nanoparticles are about 5 nm in diameter (Figure 2g). Even decorated with metal nanoparticles, the plasmonic wood still maintains hydrophilic properties (Figure 2h). The density of the plasmonic wood with Pd nanoparticles was measured, 0.52 g cm$^{-3}$, allowing the wood to float on water for potentially easy deployment in large-scale solar steam generators (Figure 2i). The specific weight of wet plasmonic wood is double that of dry plasmonic wood, demonstrating the highly porous structure (Figure 2j).

The plasmonic wood has excellent optical and thermal properties for high-efficiency solar steam generation. Unlike the AAO membrane, the diameter of the aligned microchannels along the growth direction of wood is much larger than light wavelengths (from 5 to 50 µm), which can allow the light with different wavelengths goes into the 3D plasmonic wood, enhancing the light absorption within a broadband range (Figure 3a). Finite difference time-domain (FDTD) modeling was carried out for Pd, Au, and Ag plasmonic woods at different wavelength (Figure 3b and Optical Modeling in the Supporting Information). The plasmonic nanoparticles can absorb light due to the dipole resonance coupling with incident
light. Extremely high absorption over 99% is achieved for all plasmonic woods. Experimental results of the light absorption confirm the optical simulation results (Figure 3c; Figure S4, Supporting Information). The plasmonic wood shows a high light absorption from the wavelength of 250 to 2500 nm, which is much higher than that of the natural wood. The absorption of the natural wood is attributed to the colored lignin, which limits the light wavelengths that can be absorbed. More importantly, the absorption of plasmonic wood exhibits less sensitivity to light incident angle (Figure 3d; Figure S5, Supporting Information). High absorption over 98% is maintained at all of the measured incident angles from 0° to 60°, which is attributed to the repeated light reflection or scattering and absorption inside the plasmonic wood’s unique microstructures with numerous aligned microchannels.

The broadband and angle-independent light absorption is beneficial for the practical solar light absorption. As shown in Figure 3e and Figure S6 (Supporting Information), the wet-state plasmonic wood also has low thermal conductivity along the microchannel direction. The thermal conductivity of plasmonic wood does not largely increase compared with the natural wood.[27] The low thermal conductivity of the wet-state plasmonic wood can help to localize the heat on the evaporation surface for effective steam generation. An IR camera was used to study the temperature distribution in plasmonic wood under different solar intensities (Figure 3f; Figure S7, Supporting Information). For one-sun illumination, the temperature of water on the wood surface is 30.6 °C; when the illumination increases to five suns, the water surface temperature increases to 55.0 °C. The high temperature is localized near the top of the
evaporation surface at all light intensities, which is beneficial for the high-efficiency solar steam generation.[8,14,28]

We have systematically investigated the solar-steam-generation performance of the plasmonic wood. As a demonstration, we mainly focus on the Pd nanoparticles-decorated plasmonic wood, which acts as an example to study the process of solar steam generation. As shown in Figure 4a, the formed vapor column out from the plasmonic wood can be clearly observed even under three-sun illumination. When the light reaches up to ten-sun intensity, the vapor column became bigger, indicating faster evaporation rate. The evaporation rate was calculated based on the weight loss of water, which was accurately monitored by using an electronic balance. The evaporation rates for the pure water, natural and plasmonic wood on water are plotted in Figure 4b and Figure S8 (Supporting Information). Note that the evaporation rates under illumination measured in our work subtracted the evaporation rates under dark field. The vapor generation rate of the plasmonic wood increases almost linearly as the sun intensity increases up to ten suns. A maximum vapor evaporation rate of 11.8 kg m$^{-2}$ h$^{-1}$ at ten-sun illumination is achieved, which is much larger than those of the natural wood and pure water. The enhancement factor, defined as the vapor rate of water with plasmonic wood versus bare water, was plotted in Figure 4c. A large enhancement factor up to 3.9 was achieved, higher than values reported in literature using metal nanoparticles for solar steam generation (Figure 4d). The following equation is used for calculating the solar energy conversion efficiency

$$\eta = \frac{m \cdot \nu_{LV}}{q \cdot C_{opt}} \tag{1}$$

where $\eta$ is the conversion efficiency, $m$ denotes the evaporation rate under dark field. $\nu_{LV}$ is the liquid-vapor phase change enthalpy, including sensible heat and phase change enthalpy, $q_i$ is the nominal solar illumination of 1 kW m$^{-2}$, and $C_{opt}$ is the optical concentration.[29]

The efficiency increases gradually with the increase of the sunlight intensity. A high efficiency of about 85% under ten-sun illumination is achieved, which is comparable with many of other solar steam generators (Table S1, Supporting Information). Furthermore, the plasmonic wood exhibits excellent mechanical performance (Figure 4e). The plasmonic wood shows almost the same high performance mechanical properties as the natural wood, which is much stronger than commonly used materials like graphene aerogel, alumina foil, etc. The plasmonic wood also shows excellent stability in pure, acid, and alkaline water (Figure S9, Supporting Information). There are a little of weight losses of the natural wood matrixes under each condition. Additionally, we have tested the stability of the plasmonic wood through ultrasonication for 30 min in neutral, acidic, and alkaline aqueous solutions. As shown in Figure S10 (Supporting Information), the plasmonic woods after ultrasonication are intact, and there are no metal particles falling off from the wood matrices. It can be concluded that the metal
nanoparticles strongly anchor on the surface of the microchannels, which can ensure the long-term stability in water.

Importantly, the open microstructures in wood enable the plasmonic wood unique ability of salt selfcleaning (Figure 4f). The phenomenon of salt formation on the surface of the plasmonic wood is not obvious under one-sun illumination. In order to highlight the advantage of the strong selfcleaning ability of our plasmonic wood, we conducted the experiment under five-sun illumination to demonstrate the conception of selfcleaning ability. When the light is on, saline water continuously evaporates on the top surface of the plasmonic wood under illumination. The concentration of saline water on the top surface of the plasmonic wood increases, and then salt crystals gradually form on the surface. When the solar lamp is shut off (to mimic evening conditions), the evaporation of water stops. The formed salts gradually dissolve back into the saline water which is accommodated in the aligned microchannels and diffuse into the bulk water. Due to the large diameter of the microchannels, the microchannels in plasmonic wood remain partially open to allow rapid water transport even when salt accumulates over the 8 h day. In contrast, the small nanochannels in the commercial AAO membrane can be blocked after a few hours under sunlight illumination. The results from our investigation on the cycling performance of the plasmonic wood under five-sun illumination are shown in Figure S11 in the Supporting Information. The plasmonic wood shows excellent cycling performance for solar steam generation, without any degradation after being evaluated for 144 h.

For the first time, we designed novel plasmonic woods for high-efficiency solar steam generation. The plasmonic wood is prepared by homogenously decorating metal nanoparticles on the 3D open elongated microchannels in the porous wood matrix. Owing to the plasmonic effect of the fine metal nanoparticles and the waveguide effect of microchannels in the wood matrix, the plasmonic wood has a high solar absorption (≈99%) within a wide wavelength range from 200 to 2500 nm. The porous wood matrix with numerous aligned microchannels and nanochannels can effectively absorb water from bottom to the evaporation surface due to the capillary effect. Additionally, the low thermal conductivity along the microchannels contributes to the heat localization, which can effectively suppress the heat dissipation to the bulk water. Therefore, the plasmonic wood with a unique 3D porous aligned microstructure can reach a high solar energy conversion efficiency of 85% under ten-sun illumination. The obtained plasmonic wood also exhibits great cycling stability and selfcleaning, which cycles for 144 h without any performance degradation. Benefiting from the above merits, the plasmonic wood may open up a range of applications relevant to water sterilization and desalination.

**Experimental Section**

*Materials and Chemicals:* Basswood used was from Walnut Hollow Company. Palladium (II) chloride (PdCl₂), silver nitrate (AgNO₃), chloroauroic (IV) acid (HAuCl₄·3H₂O), and hydrochloric acid (HCl, 37%) were purchased from Sigma-Aldrich.
Preparation of Pd NPs, Au NPs, or Ag NPs on Wood Membrane: PdCl₂ (0.01 M) aqueous solution was prepared by mixing PdCl₂ (88.5 mg) with HCl solution (20 × 10⁻³ M, 50 mL), followed by heating at 60 °C for 1 h until the PdCl₂ powder was completely dissolved. The natural wood slices were cut perpendicular to the growth direction and immersed in the solution of PdCl₂ and heated at 80 °C to obtain the Pd-based plasmonic woods. Ag or Au nanoparticles were deposited on the wood surface using Sn²⁺Pd-based plasmonic woods. Ag or Au nanoparticles were deposited on the surface of the wood.

Optical Characterization: The reflection spectrum was measured by a UV–vis Spectrometer Lambda 35 from 250 to 2500 nm (PerkinElmer, USA). An integrating sphere was used to collect the reflected light.

Infrared Images: IR images were recorded by FLIR Merlin MIDs. IR camera to observe the temperature distribution of wood illuminated by light with different intensity. The IR camera detected IR radiation at wavelengths from 1 to 5.4 µm, had a sensor resolution of 320 × 256 pixels, and was connected to a computer via Thermacam Researcher software.

Thermal Conductivity: The thermal conductivities of wood samples were measured by the thermal transport option in a physical property measurement system (PPMS, Quantum Design, Inc.) at 300 K. These samples were cut into cuboids with sizes of ~10 × 1 × 1 mm and mounted on a sample puck using silver-filled epoxy. A standard four-terminal geometry was applied to minimize the thermal resistances of the gold-plated copper leads. Each measurement was performed in a high vacuum (10⁻⁴ Pa) to reduce the effect from thermal convection.

Optical Modeling of Plasmonic Wood: A commercial FDTD solver was used to obtain the absorption curve of wood fiber structure. In the simulation, a periodic wood channel (lumen) model was constructed by introducing disordered irregularities on the standard cylindrical sidewall. Then, the surface of the wood channel was coated with a metal-absorbing layer having a thickness of 500 nm. High absorption rate was achieved from the accumulation and the absorption peak broadening of a large number of different diameter of the metal particle. The diameter of the metal nanoparticle was generally less than 60 nm. In order to simplify the simulation, an equivalent absorption layer was introduced. Researchers of this study first measured the transmittance and calculated the absorption properties of the metal nanoparticle. In order to simplify the simulation, an equivalent absorption layer having a thickness of 500 nm. High absorption rate was achieved from the accumulation and the absorption peak broadening of a large number of different diameter of the metal particle. Then, the equivalent refractive index and absorption properties of the equivalent absorption medium were calculated.

Experiment for Water Desalination: All of the solar desalination experiments were conducted using a custom optical measurement system, which included a multifunctional solar simulator (Newport Oriel 69907) as well as optical components (Newport Oriel 67005). The illuminated light intensity was adjusted by controlling the power of the solar simulator and the distance of the optical lens. The Thorlabs PM100D integration sphere precisely recorded the optical intensity on the wood sample. The plasmonic wood blocks were placed in a glass chamber filled with seawater. An electronic balance (Citizen CX301) as well as optical components (Newport Oriel 67005). The illuminated light intensity was adjusted by controlling the power of the solar simulator and the distance of the optical lens. The Thorlabs PM100D integration sphere precisely recorded the optical intensity on the wood sample. The plasmonic wood blocks were placed in a glass chamber filled with seawater. An electronic balance (Citizen CX301, 1.0 g) was used to accurately measure the evaporation rates, where a dish containing the sea water and wood sample were put on it. The weight loss was recorded in real-time with a digital video camera. The irradiated area on the wood sample was approximately 3.24 cm². Simultaneously, the surface temperature of the plasmonic wood samples was measured with two thermometers (Omega HH74K).

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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