SUMMARY OF RESEARCH

My primary research interests include: (i) investigating fundamental physics of the near-field thermal radiation; (ii) tailoring far-field radiative properties by exploiting electromagnetic resonances in nanostructures; and (iii) applying nanostructures with engineered radiative properties to novel energy conversion devices. With a clear aim of contributing to future development of the energy conversion & generation technology, the ultimate goal of Thermal Radiation (TRAD) Laboratory at KAIST is to conduct the **'Application-Driven Fundamental Research'** on the *thermal energy transport at the nanometer scale and make significant impact on future applications of nanoscale thermal radiation for energy conversion and utilization*.

1. Plasmonic Nanofluids for Direct-Absorption Solar Collector

After we have been intensively working on various application of the plasmonic nanostructures, we came up with an idea of using plasmonic structures for solar thermal absorption. We were specifically interested in nanofluid-based direct-absorption solar collector (DASC) because the poor light-absorption characteristics of typical working fluids, such as pure water, in the visible spectrum inherently limits the performance of the black-liquid collector. In this work, we reported a novel concept of a DASC that harnesses the localized surface plasmon of core-shell nanoparticles suspended in water [1]. Since the surface plasmon induces strong absorption with a sharp peak due to its resonant nature, we proposed to use four types of gold-nanoshell particles blended in the aquatic solution in order to achieve the broadband absorption in the solar spectrum. We have shown that the use of blended plasmonic nanofluids can significantly enhance the solar collector efficiency with an extremely low particle concentration of nanoparticles (e.g., approximately 70% for a 0.05% particle volume fraction). *The term of **"plasmonic nanofluid"** was first introduced by our group to the solar thermal community in 2012 [1] and is well adopted now by other researchers.*

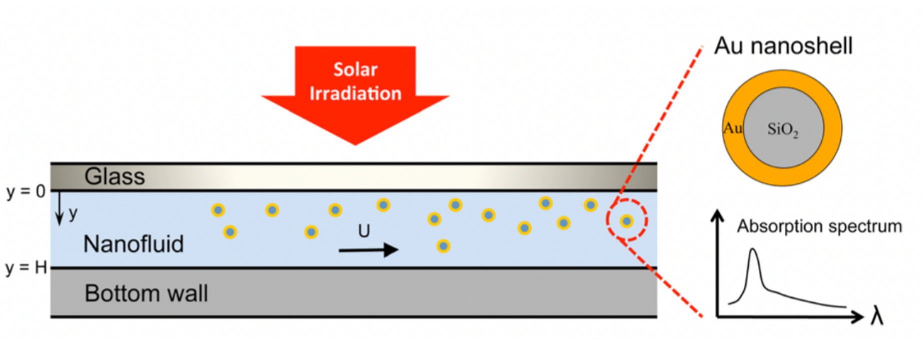


Figure 1: Concept of a direct-absorption solar collector using plasmonic nanofluids

In reality, there are few challenges in using the plasmonic nanofluids. Major challenge lies in the fabrication of core-shell nanoparticle in which the shell thickness is only few nanometers. In order to overcome this challenge, we employed metallic nanorod instead of core-shell nanoparticle because the diameter-to-length aspect ratio of nanorods can be used as a tuning parameter of plasmonic resonance. In 2014, we successfully demonstrated control of optical absorption of plasmonic nanofluids based on gold nanorods in the visible and near-infrared spectral region [2,3]. Because of our pioneering work in the field of plasmonic nanofluids, we received a funding from National Research Foundation of Korea (total of about 850K USD for three years). In this project, we systemically performed optimal design of a volumetric solar collector using plasmonic nanofluids for low-temperature heating applications [4,5], and also explored new types of nanoparticles capable of exhibiting multiple absorption peaks at different wavelengths, such as nanoparticles with sharp edges [6] and metal-insulator-metal nanodisk [6]. Recently, we also proposed a machine-learning-based design methodology of finding the optimal combination of plasmonic nanoparticles to achieve the desired spectral absorption coefficient of a nanofluid [7].

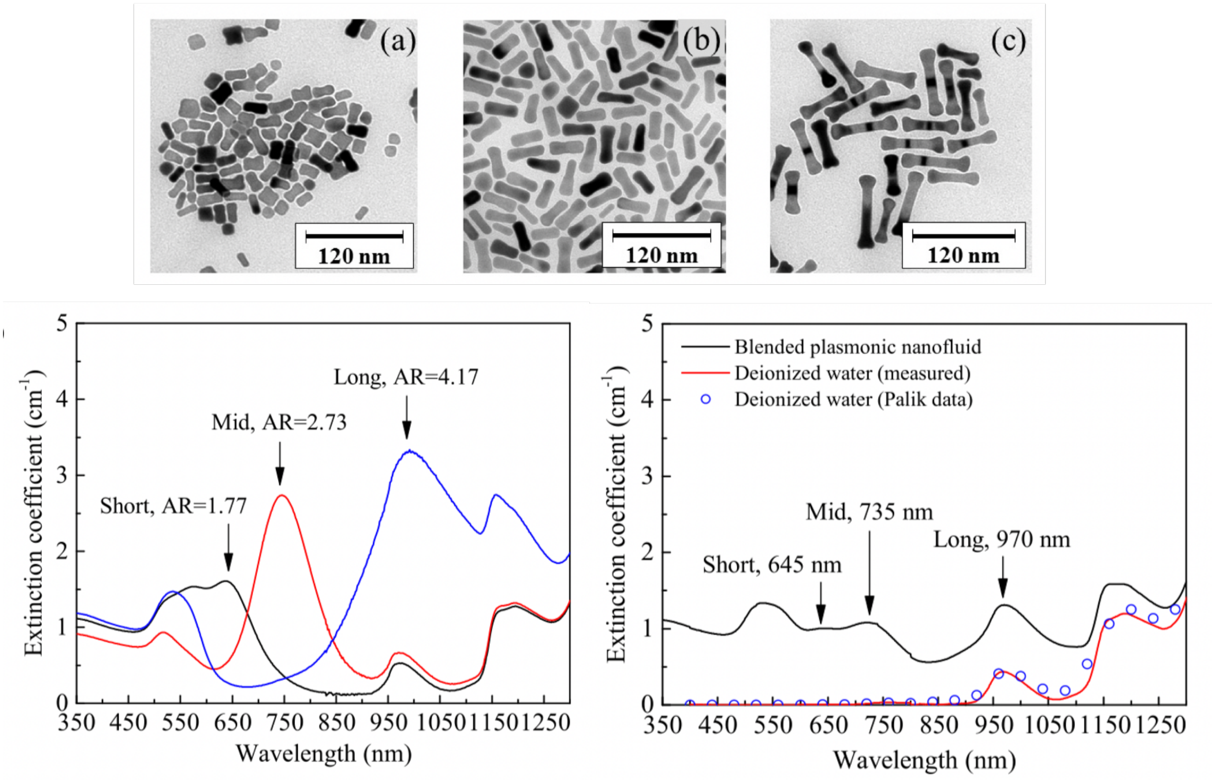


Figure 2: Blended plamsonic nanofluid made of AuNRs.

As a first step towards the concentrated solar power system, we successfully synthesized stable plasmonic nanofluids based on surface-modified metal@SiO_2 core/shell nanoparticles in Therminol VP-1 and demonstrated that the proposed plasmonic nanofluids sustained their stability even at a high temperature of 150°C [8]. To further enhance the collector thermal efficiency, we also proposed new types of direct-absorption parabolic-trough solar collector employing a highly reflective metal coating on the upper half of the inner tube outer surface [9–11].

2. Tailoring the Far-Field Radiative Properties of Nanomaterials for Solar Thermal Absorption or Radiative Cooling: Ability to tailor the far-field radiative properties is a direct result of the interaction between electromagnetic waves and surface nano/micro structures in the near-field regime (i.e., at the length scale comparable to the characteristic wavelength). Regarding solar thermal absorption, we are also interested in employing a solid-based hybrid nanostructure, which can support multiple electromagnetic resonance modes, to achieve so called '*perfect solar absorber*'. Design objectives include a broadband absorption peak in the solar spectrum (i.e., 300 nm ~ 2500 nm) and a quasi-isotropic angular absorption at both polarizations. For these purposes, we proposed to employ a 2-D Ni grating coated on a thin SiO_2 film atop a Ni substrate [12]. We showed that the solar absorptance of the proposed structure is enhanced more than 250% as compared to that of the flat Ni surface. Although the spectral absorptance exhibits the angular dependency to some extent, the proposed Ni-grating structure showed nearly constant absorptance value (> 0.85) at $\lambda = 500$ nm and 1000 nm up to incidence angle of $\theta = 45°$, suggesting that the designed solar collector could be operated without any sun-tracking system.

In order to further increase the solar absortance of nanostructures, we also theoretically investigated fundamentals of electromagnetic resonance phenomena on 2-D complex gratings [13,14]. After gaining strong theoretical backgrounds in the near-field interactions of light with complicated nanostructures, we successfully fabricated the solar thermal absorber based on optical metamaterials [15]. Our fabricated sample exhibited the solar absorptance of 90% as well as the infrared emittance of 23% at 800 K. It should be noted that precise fabrication of subwavelength-sized nanostructures is not a trivial task because in reality unavoidable errors always exist in the dimension of fabricated nanostructures, causing an undesirable deviation of the performance between the designed structure and the actually fabricated one. To overcome this issue, we recently proposed the robust optimization technique for designing an effective solar thermal absorber exhibiting a low-level of performance degradation due to the fabrication uncertainty of design variables [16].

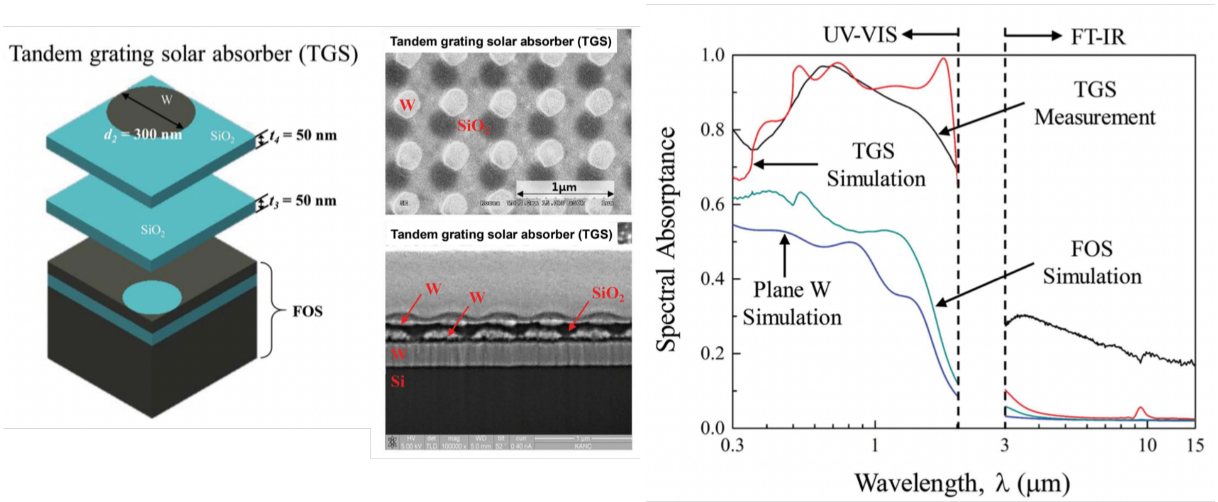


Figure 3: Broadband solar absorber made of tandem grating.

Another important aspect of the broadband absorber (or emitter) is that if we are able to change the structure design for spectrally controlling the emissivity in the mid-infrared region (e.g., 8 μm ~ 14 μm), the modified structure can be used to achieve the passive radiation cooling. In fact, the machine-learning-based design methodology that we have developed has been successfully employed to novel nanostructures for day-time radiative cooling [17–19]. We believe that our work on tailoring far-field radiative properties using nanostructures will greatly contribute to the future development of energy harvesting as well as thermal management technology.

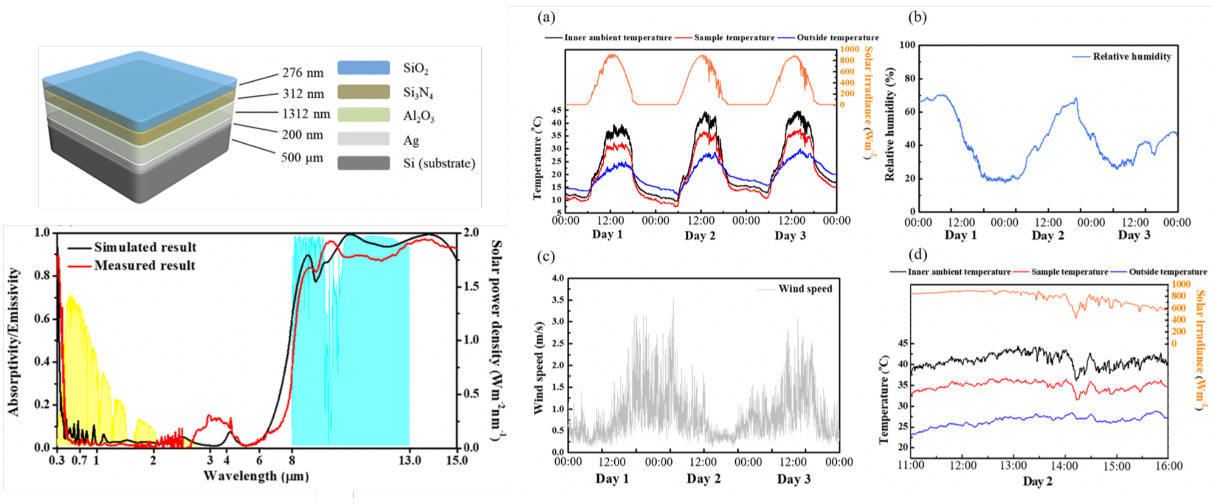
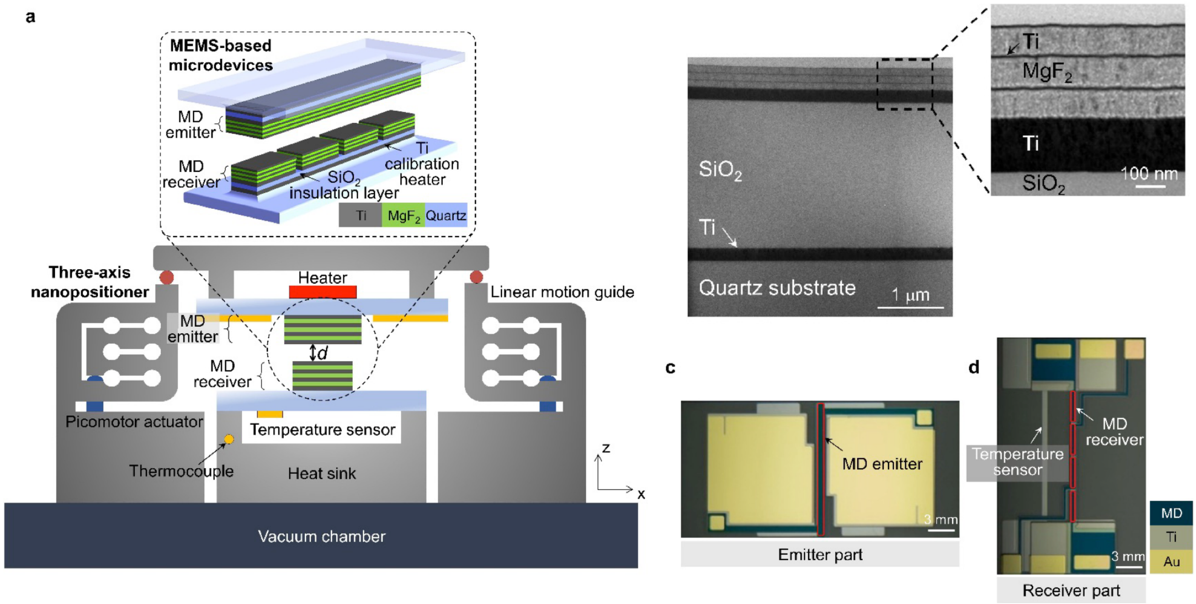


Figure 4: Daytime radiative cooling.

3. Near-Field Thermal Radiation & Its Application in Thermophotovoltaic Energy Conversion: Near-field thermal radiation dominates radiative energy transfer between two objects that are located closer than the characteristic wavelength of thermal radiation determined by Wien's displacement law. In fact, when two objects are held at a separation distance less than the characteristic wavelength, the radiative heat transfer rate can exceed that between two blackbodies (i.e., Stefan-Boltzmann law) by several orders of magnitude [20]. Due to difficulties in maintaining the nanoscale gap distance between the emitter and the receiver, experimental investigations of near-field radiative heat transfer are rather limited to relatively simple geometries, such as spherical or point-like emitters. In this work, we aimed to experimentally demonstrate the near-field thermal radiation between two parallel plates separated by a gap of few hundreds of nanometers. In order to overcome the challenges in maintaining the nanoscale gap, we employed conventional MEMS fabrication techniques and successfully fabricated a novel design of two parallel Si plates (width= 480 μm and length= 1.34 cm). In 2015, we reported for the first time quantitative measurements of the near-field radiation between parallel plates at sub-micrometer gaps [21]. A novel MEMS-based platform enables us to maintain doped-silicon plates at nanoscale gaps in a manner unachievable by other methods. The radiative heat transfer coefficient measured at 400-nm vacuum gap is approximately 2.77 times higher than the blackbody limit. Such an enhancement is unprecedented for the near-field radiation between parallel plates especially for near room temperature.

At the same time, we have also investigated the fundamental physics of near-field thermal radiation. With fundamental research in the near-field thermal radiation, our ultimate goal is to develop the near-field thermophotovoltaic energy conversion devices for recovering wasted heat. Especially we are seeking a novel way to further enhance the near-field thermal radiation at experimentally achievable vacuum gaps (about 100-nm ranges) by modifying surface conditions. We have employed monolayer of graphene to seek a feasibility of enhancing the radiative heat flux between doped Si plates [22], and also demonstrated that near-field TPV system can produce more electric power with the use of monolayer graphene [23]. However, we found that the favorable effect of graphene abruptly diminishes if the vacuum gap is greater than 50 nm. In order to overcome this limitation, we employed a hyperbolic metamaterial (HMM) because the dispersion relation of waves existing inside the HMM is hyperbolic rather than elliptical; thus, waves that are evanescent in isotropic media become propagating in the HMM. This characteristic of HMMs opens a novel way to spectrally control the near-field thermal radiation in which evanescent waves in the vacuum gap play a critical role [24].

In 2018, we found that the aforementioned novel feature of the HMM fundamentally originates from the coupled surface plasmon polaritons (SPPs) existing at the multiple metal-dielectric interfaces in the HMM. Due to the coupling of SPPs across thin metallic layers in the HMM, the dispersion curves of the resulting SPP modes shift to other regions in the domain of the wavelength and the parallel wavevector. In other words, HMMs provide a unique means by which to tune the resonance condition of the SPP, which in turn changes the nature of the photon tunneling of evanescent waves associated with the SPP [25, 26]. Motivated by the theoretical works, we also conducted experiments to demonstrate the novel concept of controlling the near-field thermal radiation by exploiting coupled SPPs between HMMs consisting of a metallo-dielectric multilayer [27]. In this work, we achieved a significant near-field enhancement (by a factor of 100 over the far-field radiation) with a 170-nm vacuum gap and with a heat transfer area of **7.56 mm**^{2}. Further, the measured value is 428 times greater than the far-field radiation between homogeneous materials. More importantly, we showed that the HMMs with the 170-nm vacuum gap allow the heat transfer rate identical to that between homogeneous materials separated by only 75 nm. This is quite compelling because existing experiments on near-field thermal radiation between planar geometries separated by tens of nanometers only involved extremely small heat transfer areas (approximately 0.0025 mm^2). Therefore, the difficulties in maintaining a sub-100-nm vacuum gap required for the considerable near-field enhancement can be avoided by employing HMMs, which will broaden the applications of near-field thermal radiation. Recently, we have moved one step further and demonstrated a substantially increased near-field radiative heat transfer between asymmetric structures (i.e., doped Si and SiO_2) by using a thin Ti film as a plasmonic coupler [28]. The measured near-field enhancement at vacuum gap of 380 nm is found to be 3.5 times greater than that for the case without the coupler.



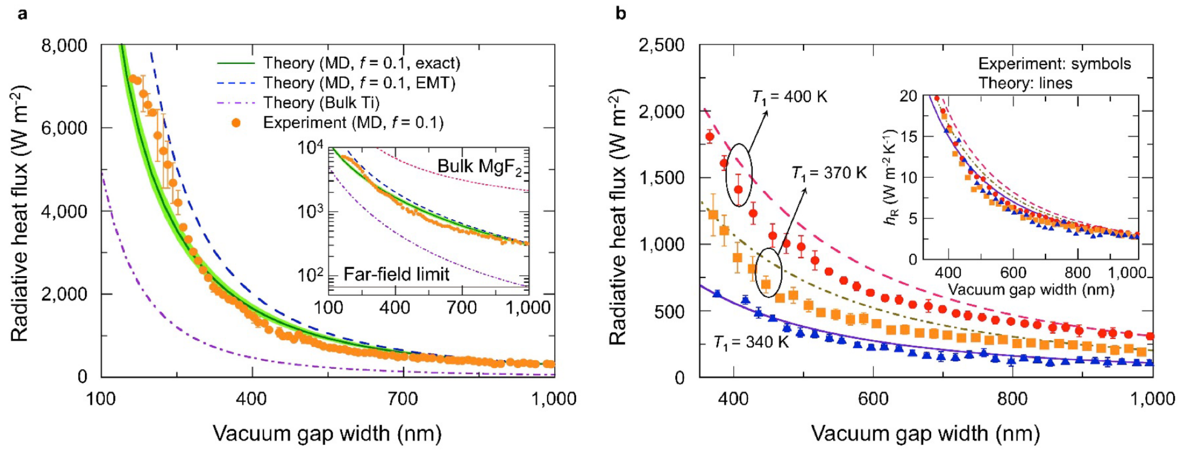


Figure 5: Measurement of near-field thermal radiation between metallo-dielectric structures.

In parallel to experimental works, we also proposed a precise performance analysis model for Schottky-junction based near-field TPV system [29], as well as for electroluminescent refrigeration system [30]. We strongly believe that our effort will pave a way to develop the near-field thermophotovoltaic (TPV) energy conversion device in the future.

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