Research Topic

VISION

The primary research of Thermal Radiation (TRAD) Laboratory at KAIST 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 TRAD Lab 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***.

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.*

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]. Currently, we are performing optimal design of a volumetric solar collector using plasmonic nanofluids for low-temperature heating applications [4, 5], and will extend the application of plasmonic nanofluids to the high-temperature power generation in the future. As a first step towards the concentrated solar power system, we recently developed an analytical method of determining the absorption coefficient of nanofluids with unknown refractive index by measuring both reflection and transmission spectra [6], which can be readily applied to any Therminol-based nanofluid for high-temperature applications.

Broadband Solar Absorber using Optical Metamaterials

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 [7]. 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 [8, 9]. After gaining strong theoretical backgrounds in the near-field interactions of light with complicated nanostructures, we successfully designed and fabricated the solar thermal absorber based on optical metamaterials [10]. 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 [11].

Another important aspect of the broadband absorber (or emitter) is that if we are able to change the structrue 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. 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.

Near-Field Thermal Radiation

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 [12]. 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 [13]. 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 [14], and also demonstrated that near-field TPV system can produce more electric power with the use of monolayer graphene [15]. 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 [16].

Recently, 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 [17,18]. 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. 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. We strongly believe that our effeor will pave a way to develop the near-field thermophotovoltaic (TPV) energy conversion device in the future.

Non-Contact Temperature Measurement at Nanometer Scale

Thermoreflectance is a technique to determine the temperature of a specimen by measuring its temperature-dependent reflectance. Due to its cost-effectiveness and simplicity compared with other non-contact techniques, such as Raman and infrared thermometries, the thermoreflectance has been widely used. If the probing laser is tightly focused, the thermoreflectance technique can be used to measure the local temperature of microstructures. We employed thermoreflectance microscopy to measure the local temperature distribution in heated microcantilevers at both steady and dynamic operations [19]. In 2014, we also demonstrated that two-wavelength thermoreflectance technique can simultaneously determine the local temperature and thickness of a heated cantilever [20]. In fact, the two-wavelength thermoreflectance was able to distinguish the thermal characteristics of different heated cantilevers. Recently, we have extended the two-wavelength thermoreflectance microscopy to achieve sub-beam size temperature measurement [21]. We showed that it is possible to determine the absolute temperature of a local region of the heater from the measured reflectance during the linear scanning by taking into account the size of the focused laser beam and the width of the line heater, even though the width of the heater is only 39% of the size of focused laser beam (i.e., sub-beam size).

In addition to the thermoreflectance microscopy, we also proposed one of the simplest form of a AFM-based thermometry capable of temperature sensing with a sub-100 nm spatial resolution. In fact, we have demonstrated that local temperature profile at resolution down to 30 nm can be obtained by exploiting the thermoreflectance characteristic of the conventional AFM Si probe. The laser diode and the quadrant photo detector in the AFM, originally used for topography imaging, can also be directly used to detect the change of the laser intensity reflected from the Si probe, whose temperature is determined by the heat transfer from the sample that is in contact with the probe tip. Thus, the change in the reflected laser signal depending on the temperature of the cantilever (i.e., thermoreflectance) can be used to estimate the change in the temperature of the sample. The temperature measured with the present technique (i.e., AFM-Thermoreflectance) showed excellent agreements with the temperature measured with a commercially available scanning thermal microscopy (SThM) probe such that maximum error between the results obtained with both methods was found to be only 1.1%. This is quite compelling result because the proposed technique does not require a specially fabricated probe and an additional complex signal processing system as the SThM technique does. Without using fragile and expensive probes and complex accessories, the AFM-thermoreflectance provides a unique opportunity to measure the local temperature only with the conventional AFM setup.We strongly believe that our efforts toward nanoscale thermal analysis will further advance our understanding of the phonon transport in nanostructures, which is critically important for designing and optimizing high-speed electronic and photonic devices, such as transistors and light-emitting diodes.

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