Nanoparticle meta-grid for enhanced light extraction from light-emitting devices

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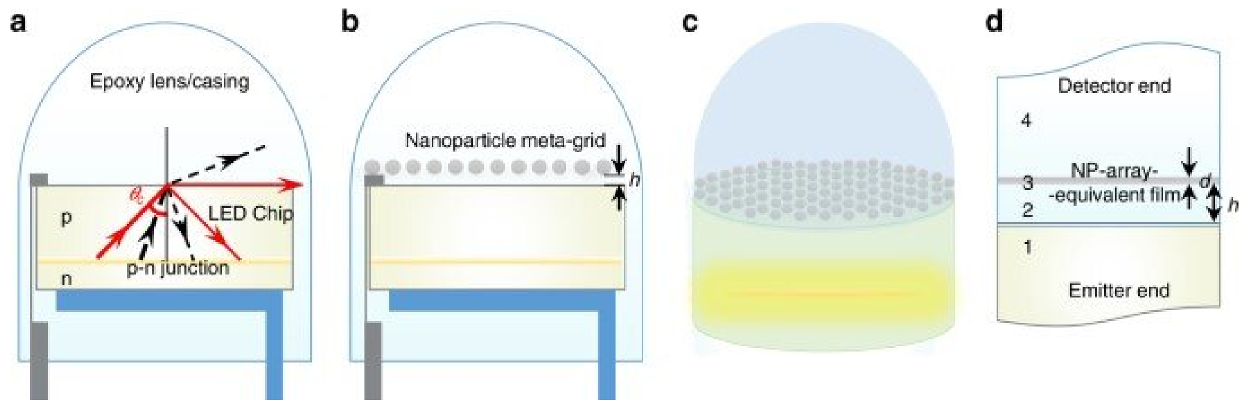
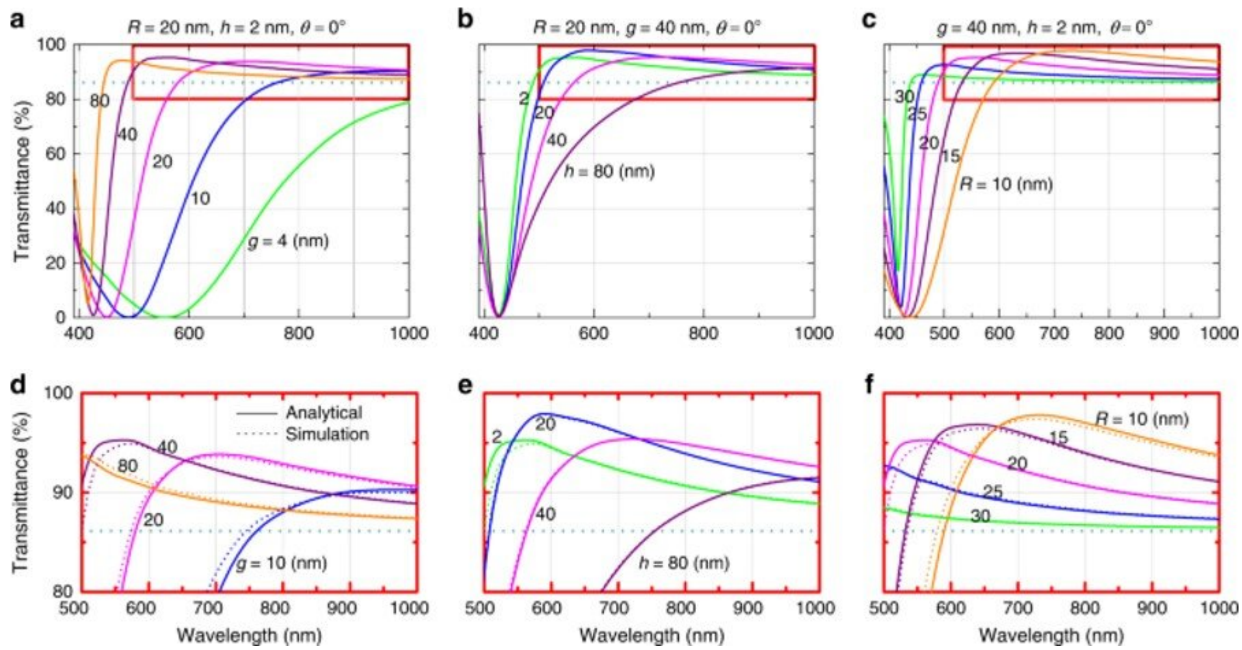


Schematics of the classical and modified light-emitting diode (LED) device (not to scale). a Cross-sectional cartoon of a standard LED (including its electrical contacts), where an epoxy lens/casing encapsulates the semiconductor LED chip. Light emitted from the p–n junction escapes into the epoxy lens as long as the incident angle is less than the critical angle θc. b Side-view and c 3D view of the proposed new design for enhanced light extraction with a 2D array (“meta-grid”) of nanoparticles (NPs) embedded in the epoxy material at a height h from the LED-chip surface. d Four-layer-stack theoretical model for analysing the optical transmission through the proposed system, where the NP array is represented by an effective film of thickness d, whose properties are derived from the effective medium theory. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-00357-w

A tailored layer of plasmonic nanoparticles can be introduced into the epoxy casing of a light-emitting diode (LED) to improve the device's light output, to benefit energy savings and boost the LED lifetime. In a new report on *Nature Light: Science & Applications*, Debrata Sikdar and a team of scientists in chemistry, electronics and physics at the Imperial College London and the Indian Institute of Technology, showed the benefits of including a two-dimensional (2-D) array of silver nanoparticles known as a 'meta-grid' to the lens shaped epoxy packaging. They tested their theory using computer simulations and demonstrated the ability to improve light extraction from the nanoparticle meta-grid based LED. The alternative approach can be customized to suit a specific color of emission, the authors proposed a few additional schemes to implement the strategy into the existing LED manufacturing technology.

Conventional light extraction from LEDs

Light-emitting diodes (LEDs) are ubiquitous in the modern-world, from traffic lights to electronic displays and in applications of water purification and decontamination. Since typical semiconductor LEDs are encapsulated by a transparent insulator that limits the efficiency of light extraction, researchers have attempted to enhance the light extraction efficiency of LEDs for improved light output. The chip-encapsulating material itself can be a limiting factor alongside Fresnel loss; i.e. when a significant amount of the incident light is reflected back from the interface into the chip. To mitigate such limits, researchers had introduced materials with higher refractive indices than epoxy or plastic, although the amends are yet difficult and economically unfavorable for mass production adaptation. Additional schemes have included nanoparticle-epoxy nanocomposites or engineered epoxy resins to ensure higher refractive indices without compromising transparency. However, a larger refractive index can again lead to a larger portion of the light being reflected back from the encapsulant/air interface to contribute to Fresnel loss.

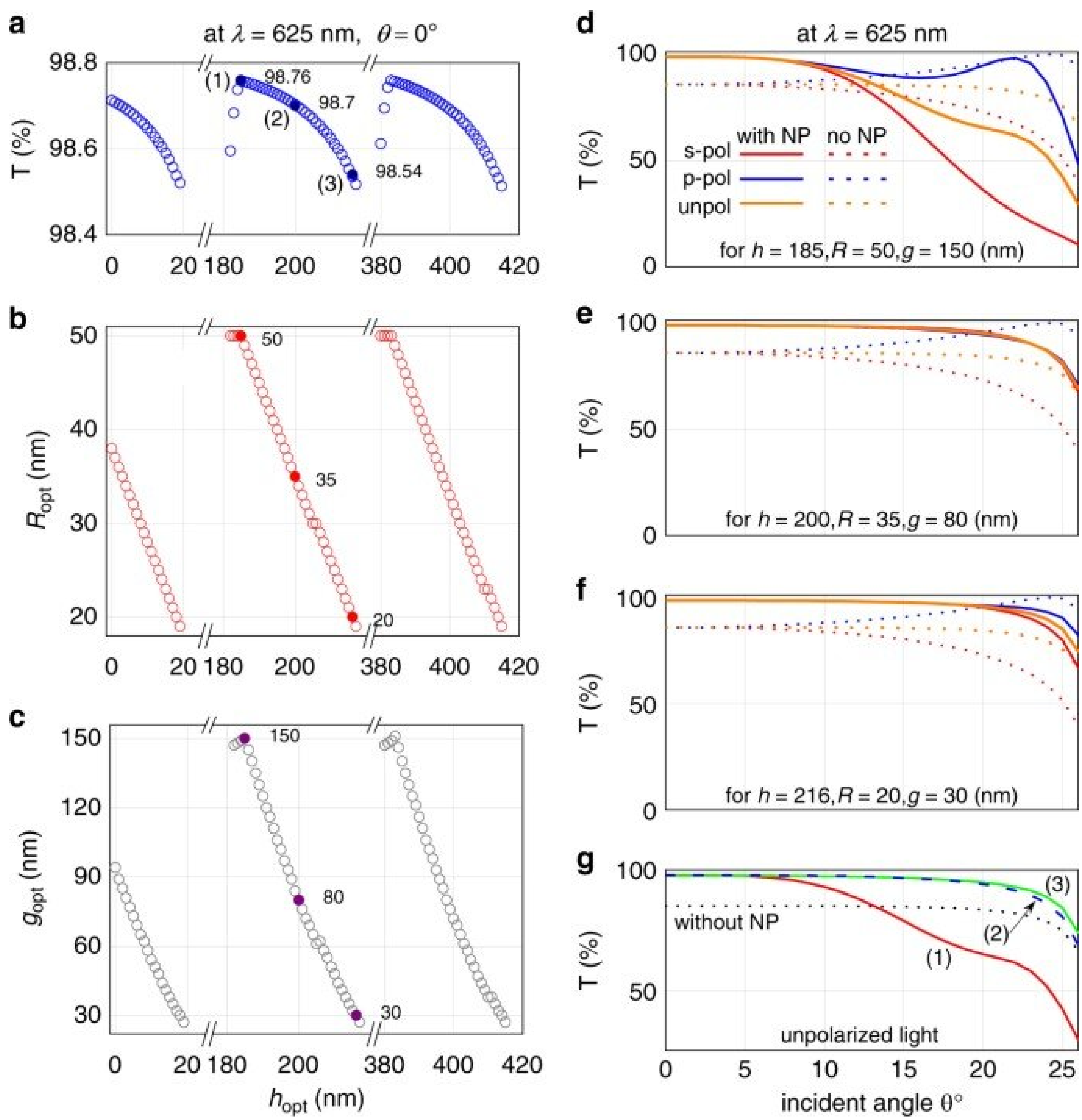


Transmission spectra depicting effects of different physical paramaters of NP meta-grid. Transmittance spectra, calculated from the theoretical model, depicting the effects of different physical parameters of the hexagonal array of silver nanospheres, such as the radius R, interparticle gap g, and "height" h from the interface between typical semiconductor (n1=3.5) and encapsulating (n2=1.6) materials: a variation with g for fixed radius (R=20nm) and height (h=2nm), b variation with h for fixed radius (R=20nm) and gap (g=40nm), and c variation with R for fixed gap (g=40nm) and height (h=2nm). d–f Zoomed-in view of the theory-based ("analytical") spectra, in the domains highlighted by the red boxes in (a–c) compared with data (colored dotted curves) obtained from full-wave simulations. For all cases, only normally incident light is considered. The dotted horizontal lines indicate transmittance without the nanoparticle layer. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-00357-w

An alternative route to improve light-extraction from LEDs

In this work, Sikdar et al. proposed minimal changes to the manufacturing process to reduce Fresnel loss at the chip/encapsulant interface by using a fixed photon escape cone to increase light transmission across the setup. To accomplish this, they placed a monolayer of sub-wavelength metallic nanoparticles (NPs) as a 'meta-grid' on top of a conventional LED chip within the chip's usual encapsulating packaging. The resulting enhancement of LED light transmission occurred as a result of destructive interference between light reflected from the chip/epoxy interface and light reflected by the NP meta-grid. By reducing reflection from the chip/epoxy interface they increased the lifetime of the LED chip and minimized waste heat.

To demonstrate nanoparticle-assisted enhanced transmission, they used silver nanospheres as strong plasmonic resonators, with minimal absorption loss. The team studied the roles of the NP radius, interparticle gaps formed by the nanospheres during bottom-up assembly in to a two-dimensional (2-D) hexagonal array and the influence of nanoparticle (NP) height. To calculate the light transmittance, Sikdar et al. used a light emitter and detector placed inside the chip and the encapsulating medium, respectively. Diverse sets of NP arrays provided maximum enhancement in light transmission across different spectral windows and therefore the 'meta-grid' could be optimized for each LED relative to its emission spectral range.



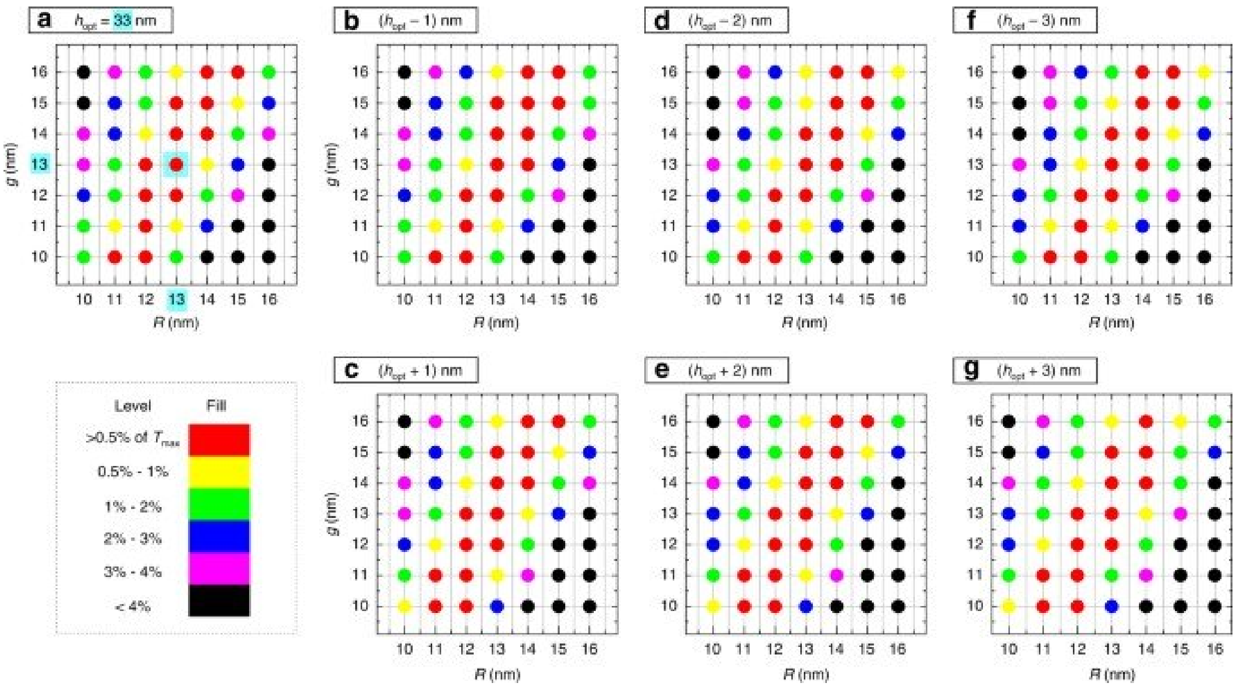
Obtaining parameters for optimal transmission and its dependence on incident angle. a–c Optimization of the optical transmittance (T) at 625nm for normal incidence via tuning of the NP array parameters. a Maximum transmittance obtained at each height h (where T≥98.5%), and corresponding optimal (b) radius Ropt, and (c) interparticle gap gopt. d–f Transmittance at different permissible incident angles for s-polarized (red), p-polarized (blue), and unpolarized (green) light for cases (1)–(3) [marked in (a)]; for each polarization, the dotted curves show the light transmission without the NP array. g

Comparison among the transmittance for unpolarized light in those three cases. The dotted line, obtained without the NP array, serves as a reference. Here, AlGaInP ($n1=3.49$) is the semiconductor material and epoxy ($n2=1.58$) is the encapsulating material. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-00357-w

Optimizing the nanoparticle meta-grid

The team then maximized transmittance across a specific spectral range using an optimized structure of the meta-grid. The scientists observed enhanced light transmission with the setup, and credited the outcome to the Fabry-Perot effect between the chip/encapsulant interface and NP meta-grid. The transmission dip, also known as the extinction peak, depended on the height, gap, and other parameters of meta-grid NPs, and illustrated the underlying physics of the device. As a result, by varying the gap and height of the nanoparticle meta-grid and radius of the constituent silver nanoparticles, the scientists influenced the transmission dip or extinction peak during LED emission.

Furthermore, light reflected from the chip/encapsulant interface distinctly interfered with light reflected from the NP array, to effectively reduce reflection from the setup and increase transmission due to Fabry-Perot effect based transmission enhancement. The chip/encapsulant interface and NP meta-grid acted as two reflective surfaces to form the cavity in between them. The team placed the meta-grid at the closest possible height to the chip/encapsulant interface to optimize its position and restrict any leakage of radiation. They also showed how the small NPs exhibited better angle-averaged transmittance for unpolarized light.



Optimization of the transmittance (over a spectral window of 580–700 nm averaged over all permitted incident angles (below the critical angle) and its sensitivity to the NP meta-grid parameters. a Dots with different fill colors depicting the deviation from the maximum transmittance (Tmax) for a fixed height of hopt = 33 nm but various radius R and gap g, where both these parameters are assumed to be larger/smaller than their optimal values by up to 3 nm. Tmax (of 96.2%) is achieved at the optimal height hopt = 33 nm, for the optimal radius of 13 nm and gap of 13 nm [highlighted in cyan]. b–g Same as in (a), but for different heights of (hopt − 1), (hopt + 1), (hopt − 2), (hopt + 2), (hopt − 3), (hopt + 3), respectively. Note that, for the calculations the spectral window between 580 and 700 nm was considered at a step of 1 nm and angles between 0° and 26° were taken at a step of 1°. Here, AlGaInP (n = 3.49) is the semiconductor material and epoxy (n = 1.58) is the encapsulating material. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-00357-w

Light transmission in the NP meta-grid

The scientists obtained enhanced transmission in the presence of the optimized meta-grid, which was significantly greater than that obtained without NPs across the same range of wavelengths. The maximum transmittance of the system was sensitive to any imperfections in the fabrication process. They precisely tuned and adjusted the meta-grid of nanoparticles on the LED chip for optimal performance. The resulting NP meta-grid allowed a 96 percent increase in light transmission (which is otherwise 84 percent) from the emissive layer to the encapsulant layer.

In this way, Debrata Sikdar and colleagues proposed a scheme to significantly enhance light extraction from LEDs by boosting the transmission across the chip/encapsulant interface. They accomplished this by introducing a monolayer of plasmonic nanoparticles (NPs) on top of the LED chip to reduce Fresnel loss and enhancing light transmission originating from the Fabry-Perot effect. The team propose implementing the scheme either by itself or in combination with other available strategies to enhance the LED efficiency.

More information: 1. Sikdar D. et al. Nanoparticle meta-grid for enhanced light extraction from light-emitting devices, *Light: Science & Applications*, doi.org/10.1038/s41377-020-00357-w

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3. Sikdar D. & Kornyshev A. A., An electro-tunable Fabry–Perot interferometer based on dual mirror-on-mirror nanoplasmonic metamaterials. *Nanophotonics*, doi.org/10.1515/nanoph-2019-0317

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