Plasmonic enhancement of stability and brightness in organic light-emitting devices

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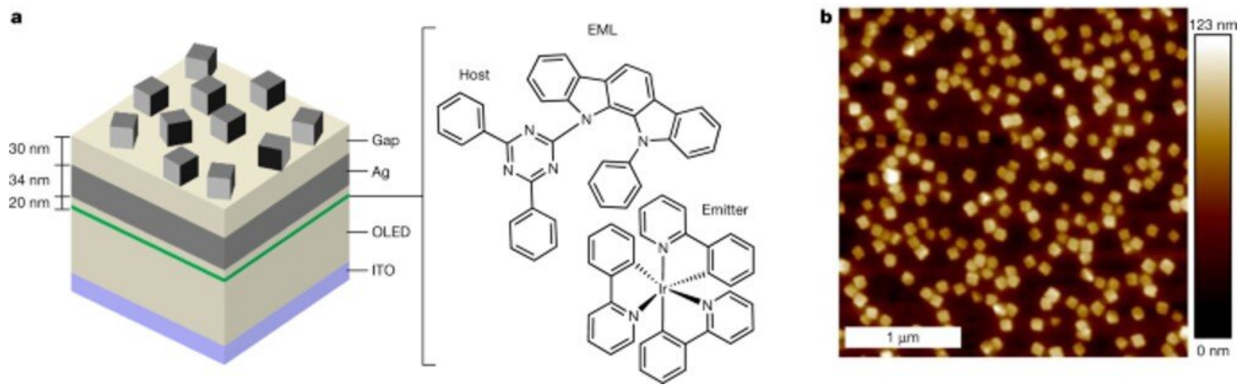


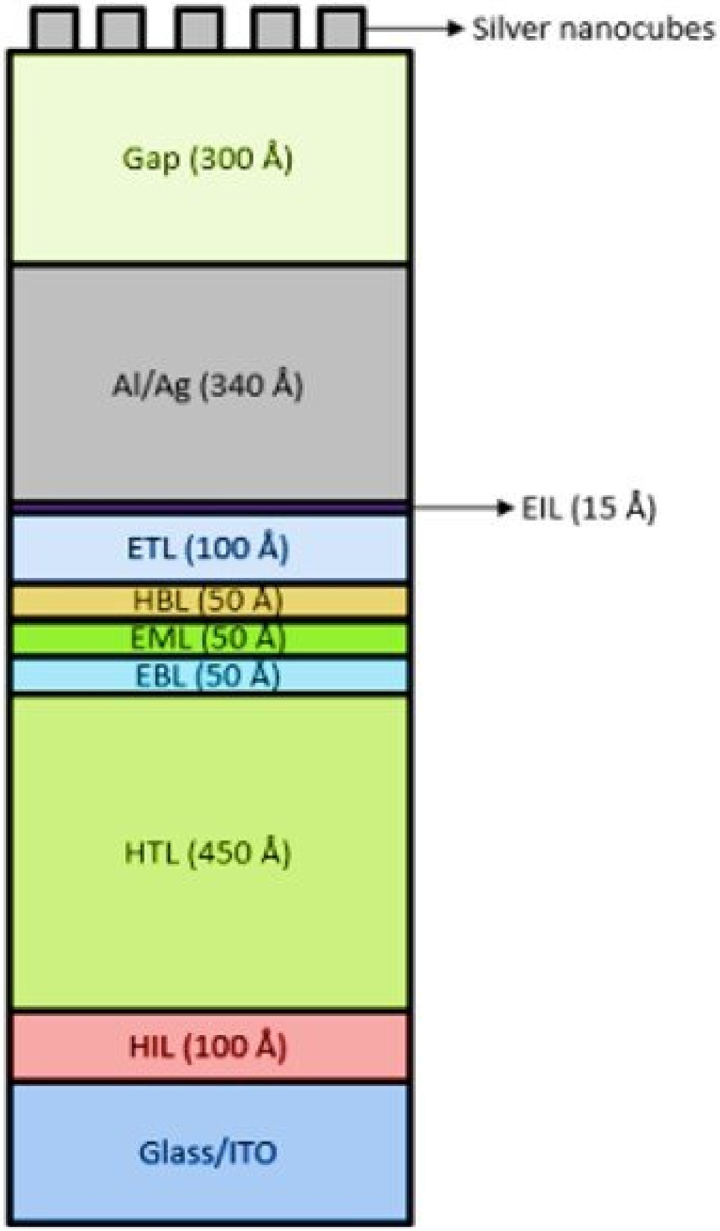
Plasmonic device diagram and nanocube morphology. (a) Schematic of the plasmon NPA, with relevant layer thicknesses annotated. The EML position and width within the OLED are denoted by the green line. The chemical structures of the EML components, host (DIC-TRZ) and emitter (Ir(ppy)3), are also presented. (b) Atomic-force micrograph of Ag nanocubes spun on top of the OLED. The fill fraction of Ag cubes is 15%, with a centre-to-centre spacing of ~200 nm. ITO, indium tin oxide. Credit: Nature, doi: 10.1038/s41586-020-2684-z

Scientists investigate free electrons and the resonant interactions of electromagnetic waves in the field of plasmonics. However, the discipline still remains to be extended to large-scale commercial applications due to the loss-associated with plasmonic materials. While organic light-emitting devices (OLEDs) are incorporated into mass-scale commercial products due to properties such as good color saturation, versatile form factor and low-power consumption, their efficacy and stability remain to be optimized. During its function, OLEDs accumulate localized build-up of slow-decaying, triplet excitons and charges, which gradually reduce the brightness of the device in an "aging" process, which can then cause a burn-in effect on the display. As a result, it is important to improve the performance of the OLED technology.

In a new report now published on *Nature*, Michael A. Fusella and a research team at the Universal Display Corporation U.S. developed an OLED (organic light emitting device) with plasmonic decay rate enhancement to increase device stability, they maintained the efficiency by including a nanoparticle-based out-coupling scheme to extract energy from the plasmon mode. The team used an archetypal phosphorescent emitter to achieve a two-fold increase in functional stability at the same brightness as a reference conventional device and extracted 16 percent of the energy from the plasmon mode as light. The new approach will improve the stability of OLED while avoiding material-specific design limitations. Possible applications include lighting panels, and television and mobile displays.

Surface plasmons and plasmon nanopatch antenna (NPA)

Surface plasmons are collective oscillations of electrons that reside at the interface of a metal and the surrounding dielectric environment. The phenomenon can contribute to large electric fields and improve the decay rate in orders-of-magnitude across the visible and near infrared regions for ideal use with organic light-emitting devices (OLEDs). Much work on ongoing OLED development focus on minimizing the quenched exciton energy loss that is dissipated as heat. Here, Fusella et al. optimized the device by coupling the energy to the surface plasmon mode of the OLED cathode. To accomplish this, they used a phosphorescent emitter hosted by a material abbreviated as DIC-TRZ, short for 2,4-diphenyl-6-bis(12-phenylindolo)[2,3-a]carbazole-11-yl)-1,3,5-triazine.

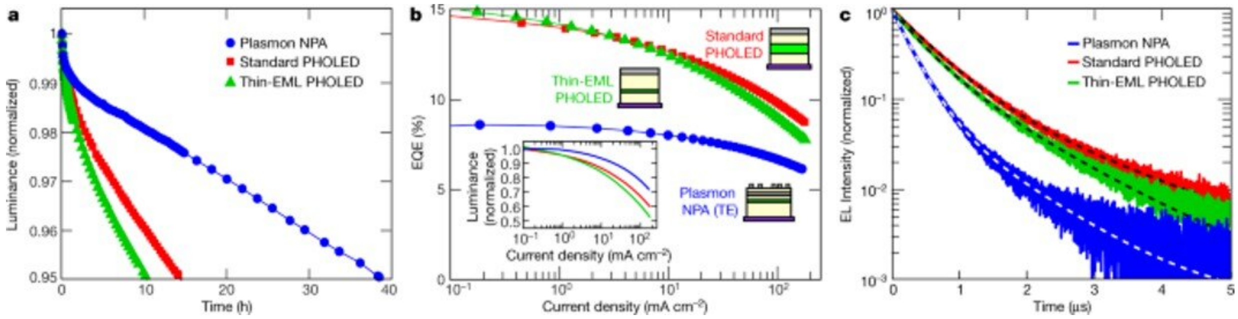


Annotated device stack of the plasmon NPA structure. Note that the glass/ITO layers and silver nanocubes are not drawn to scale while the remaining layers are scaled relative to each other to provide a representation of the device structure. Where ETL: electron transport layer, HBL: hole blocking layer, EML: emissive layer, EBL: electron blocking layer, HTL: hole transport layer, HIL: hole-injection layer, EIL: electron injection layer. GAP: space between the cathode and silver nanocubes. Credit: Nature, doi: 10.1038/s41586-020-2684-z

The team out-coupled light by randomly arranging silver nanocubes separated from the silver (Ag) cathode by a dielectric layer and named the device the plasmon nanopatch antenna (NPA), although the design paradigms varied from the NPA architecture used in previous work. The plasmon NPA developed here achieved a nearly three-fold stability increase compared to a reference device. The thinner device architecture of the plasmon NPA did not cause shorting during the life test and achieved dramatic enhancement of device stability without loss of efficiency.

Plasmon-enhanced lifetime and efficiency

In the experimental setup, the plasmon nanopatch antenna (NPA) had a transparent anode to convert energy coupled to the surface plasmon mode of the silver cathode to photons via randomly arranged silver nanocubes in its architecture to facilitate light emission from the top of the device. They noted the external quantum efficiency for the light emitted from the top of the plasmon nanopatch antenna to be eight percent (8%), while the same device without nanocubes had a top emission external quantum efficiency (TE EQE) of only negative one percent (-1%); highlighting the importance of nanocubes in out-coupling. Fusella et al. intentionally designed an architecture with simultaneous top and bottom emission to help the plasmon nanopatch antenna distinguish the energy coupled in and scattered out from energy that does not couple into the plasmon mode (bottom emission). When translating this experimental concept to a commercial device, scientists will need to eliminate any bottom emission light by coupling all excitons to the plasmon mode or by employing an opaque metal anode to reflect the bottom emission light back to the top of the device.



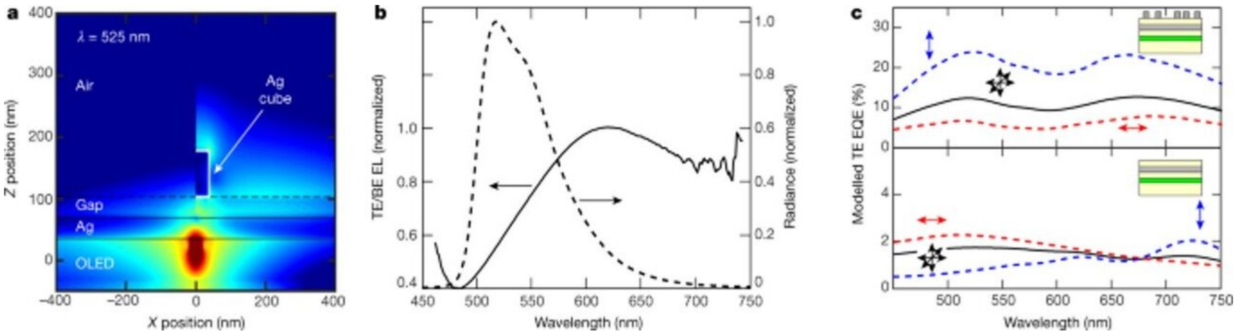
Plasmon-enhanced lifetime and efficiency. (a) Accelerated ageing stability measurement at a fixed current density of 80 mA cm−2 for the plasmon NPA (TE), standard PHOLED (BE) and thin-EML PHOLED (BE). (b) EQE curves of the plasmon NPA (TE), standard PHOLED (BE) and thin-EML PHOLED (BE). The inset shows the EQE curves normalized at 0.1 mA cm−2, demonstrating reduced efficiency roll-off for the plasmon NPA. Schematic depictions of the device stacks are displayed near each EQE curve and indicate variations in the EML thickness and position relative to the cathode. (c) Transient EL for the plasmon NPA (TE), standard PHOLED (BE) and thin-EML PHOLED (BE), showing reduced excited-state lifetime for the plasmon NPA. The dashed lines mark the bi-exponential fit for each curve. The plasmon non-NPA transient (omitted for clarity) is nearly identical to that of the plasmon NPA. Credit: Nature, doi: 10.1038/s41586-020-2684-z

Optical properties of the plasmon nanopatch antenna (NPA)

The scientists next investigated the exciton dynamics inside the emissive layers of the three devices investigated in the study, including:

1. plasmon nanopatch antenna (NPA)
2. standard organic light emitting device incorporating organic phosphors (PHOLED)
3. a thin-emissive layer PHOLED

Of these, the plasmon NPA maintained its external quantum efficiency (EQE) at high current densities comparatively better than the reference devices, alongside shorter decay time and therefore greater stability. The device architecture of the plasmon NPA with 75-nm silver nanocubes separated from the planar silver cathode contributed to its high external quantum efficiency. This architecture deviated from the typical patch-antenna-based approach, allowing surface plasmon coupling to the planar silver cathode, while the silver nanocubes performed out-coupling. The mechanism resulted in broadband rate enhancement without compromising the device architecture.



Measured and modelled optical properties of plasmon NPA. (a) Simulated electric-field intensity maps for a vertical dipole within the OLED without (left) and with (right) a silver (Ag) nanocube. Maps are overlaid at 0 nm in the X direction. When the Ag cube is present, there is considerable increase in electric-field intensity between the Ag cube and the Ag film, as well as at the corner of the Ag cube, which is the source of radiation to free space. (b) Plot of the TE/BE

EL spectrum (solid line) for the plasmon NPA, showing the spectral shape of the NPA out-coupling. The TE/BE ratio is offset to accentuate that the intrinsic emission spectrum of Ir(ppy)3 (dashed line) is not well aligned with the NPA out-coupling. (c) Modelled TE EQE versus wavelength for a dipole 20 nm from the Ag cathode with (top) and without (bottom) Ag nanocubes. The dipole orientation—vertical (blue arrows), horizontal (red arrows) or isotropic (black arrows)—is denoted next to each EQE curve. The modelled EQE curves with Ag nanocubes are averages of multiple simulations. Credit: Nature, doi: 10.1038/s41586-020-2684-z

Fusella et al. then used finite-difference time-domain modeling to calculate the external quantum efficiency of the device to estimate its ultimate efficiency and noted a considerable increase in the predicted values after including the silver nanocube architecture to the simulation. The results were in close agreement with the experimental outcomes. Although the results modeled for external quantum efficiency were promising, they were still considerably lower than those observed in previous work. The team therefore aim to redesign the nanocube architecture to enhance the out-coupling efficiency of the device in future studies.

In this way, Michael A. Fusella and colleagues showed enhanced organic light-emitting device (OLED) stability by improving the decay rate through surface plasmon coupling. Typically, this strategy is detrimental to the overall performance of the device, but in this instance, the setup improved the stability of the device architecture to establish parallel paths of OLED development. The fully optimized device geometries will allow external quantum efficiencies greater than 40 percent with greater stability. The work presents a new paradigm for OLED design, paving the way for low-cost lighting panel applications and ultrafast and high luminance applications.

More information: Michael A. Fusella et al. Plasmonic enhancement of stability and brightness in organic light-emitting devices, *Nature* (2020). DOI: 10.1038/s41586-020-2684-z

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