The emission of light through thin metal films via surface plasmon-polaritons

Armando Giannattasio, Stephen Wedge, Lucy H. Smith and William L. Barnes
School of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL, United Kingdom, E.U.

ABSTRACT

When the emission of light by molecules, excitons etc. takes place close to a thin metallic film, coupling of power to surface plasmon-polariton (SPP) modes supported by the metal film often dominates. We explore the nature of the SPP modes and examine how the energy lost to them can be recovered through the use of periodic, wavelength scale microstructure. We show that the photoluminescence emission from a structure containing is much stronger than that from a similar planar structure. We look at the importance of the exact details of the microstructure on the emission process.

1. INTRODUCTION

Top-emitting organic light-emitting diodes (OLEDs) continue to attract attention for applications such as displays. These device are of particular interest since they may be fabricated directly on top of an opaque substrate, such as silicon, thereby allowing display elements and control electronics to be integrated. In top-emitting OLEDs emission usually takes place through the metallic cathode, typically 50 – 100 nm thick [1]. As with all displays efficiency is a key issue, and optical out-coupling remains the least developed aspect of device efficiency. Excitons are generated within an OLED by the injection of charge carriers and it is the subsequent radiative decay of these excitons that produces light. However, the probability that exciton decay will lead to an emitted photon is reduced by coupling of the exciton to bound optical modes, specifically waveguide [2] and surface plasmon-polariton (SPP) modes [3] supported by the structure. As we have previously shown [4], power lost to SPPs can account for up to 40% of the power that would otherwise have been radiated. In this paper we examine the photoluminescence (PL) emission of light through various micro-structured thin metal films in order to determine whether some of the power lost to SPP modes can be recovered, and thus lead to improved device efficiency in top emitting OLEDs.

SPPs are trapped electromagnetic surface modes that occur at the interface between metal and dielectric media and are a combined oscillation of the electromagnetic field and the surface charge density of the metal. SPPs have electromagnetic fields that decay exponentially into both the metal and dielectric media that bound the interface. On a planar surface their combined electromagnetic field/surface charge nature means that they are non-radiative in nature. This non-radiative nature is illustrated in figure 1(a) which shows a schematic dispersion diagram, angular frequency, ω, vs. in-plane wavevector, $k_{//}$, for a thin planar metal film bounded on one side by an organic layer and on the other by air (here in-plane refers to the plane defined by the interfaces of the structure and, where it refers to emission, $k_{//}$ is also in the plane containing the emission direction). The shaded area in Fig. 1(a) is the air light-cone representing those combinations of frequency and in-plane wavevector associated with photons propagating in the air half-space. From Fig. 1(a) it may be seen that for a given frequency the wavevector of the SPP mode always lies outside this light cone, and is thus non-radiative nature.

One method of recovering the energy lost to SPP modes is to introduce some means by which the SPP may Bragg scatter so as to reduce its momentum (wavevector) and thus couple to light. Figure 1(b) shows how the introduction of a periodic microstructure (pitch λ_g) into the metal allows the momentum (wavevector) of the SPP mode to be reduced/augmented by a integer number of grating vectors k_g (= $2\pi/\lambda_g$) to lie within the air light-cone and thus couple to light. In the work presented a number of such a periodically micro-structured metal films have been used to demonstrate that SPP mediated emission of light through a thin metal film may be achieved.

From figure 1 it may be seen that a metal film bounded on one side by an organic emissive material and on the other by air will support two SPP modes, one associated with each metal/dielectric interface. Excitons within the organic emissive material may then couple to each of these modes via the near-field of the emitting exciton.

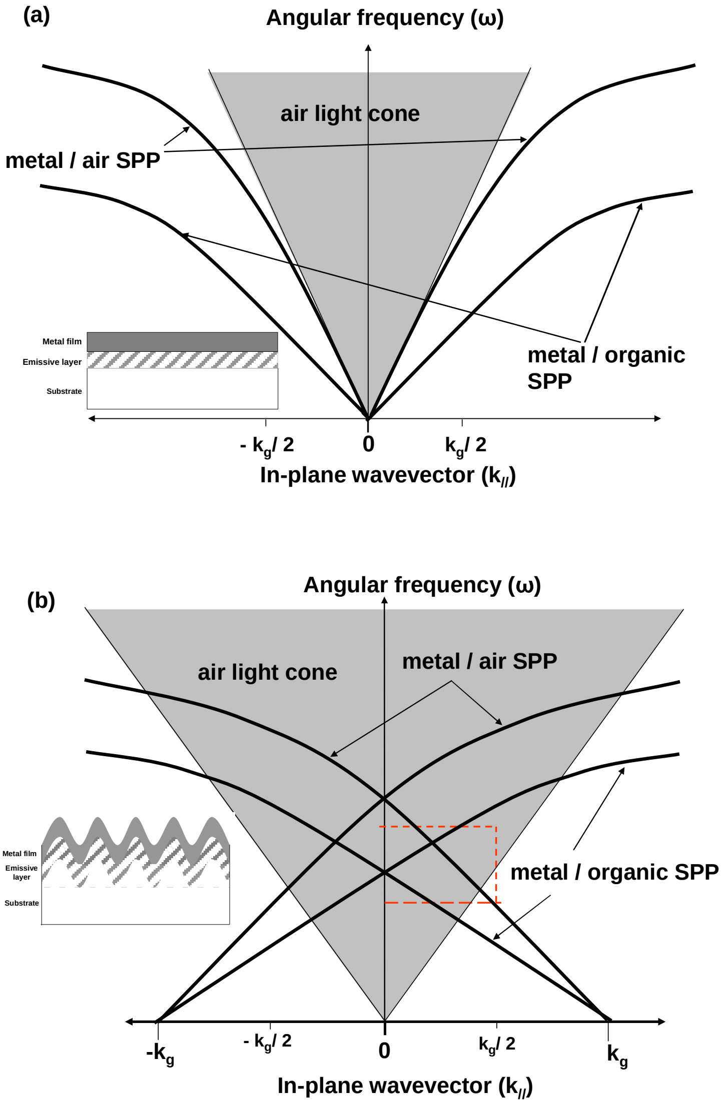

Fig. 1 (a). Schematic representation of a dispersion map for a thin metal film bordered on one side by an organic light-emitting material and on the other side by air. The shaded region labeled “air light-cone” represents the frequencies and wavevectors accessible to light propagating in air. Note, the in-plane wavevector range from -k_g/ 2 to k_g/ 2 corresponds to the first Brillouin zone. (b). A schematic representation of a dispersion map for a corrugated thin metal film bordered on one side by an organic light-emitting material and on the other side by air. The area enclosed within the dashed lines represents the range of frequencies and wavevectors presented in Figure 3. (Note that for clarity the horizontal scale used in Fig. 1b is not the same as 1a.)

Numerical calculations in which the emitter is modelled as an electric dipole (Fig. 2) show that this process is dominated by losses to the SPP mode associated with the metal/organic interface, with the coupling to this mode being approximately 2 orders of magnitude greater than that to the metal/air SPP. These data (Fig. 2) indicate that any scheme to recover energy lost to SPP mode should focus on the recovery of the metal/organic SPP in order to maximize emission.

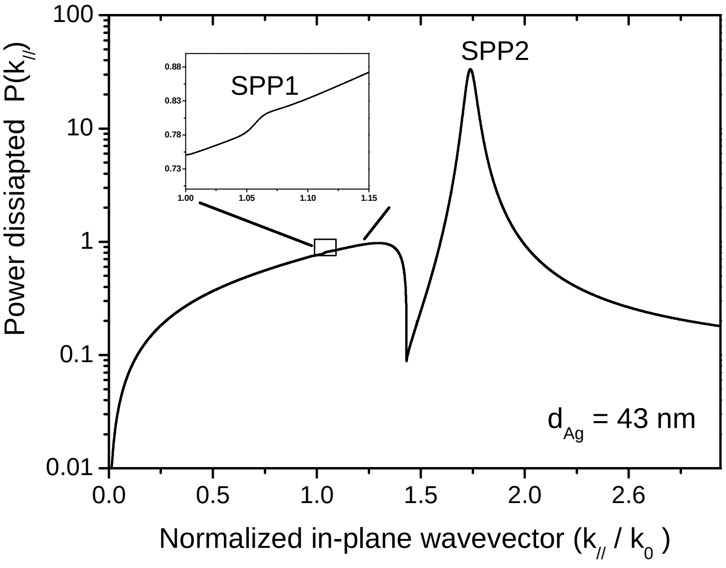

Fig. 2. Calculated power dissipation spectrum on a logarithmic scale for an emitter located in the light-emitting layer at a distance of 20 nm from the metal surface. The large peak at a normalized in-plane wavevector of ~ 1.7 represents power being lost to the metal/organic SPP (SPP2), the inset is an expanded plot (linear scale) of the feature associated with the metal/air SPP (SPP1).

2. RESULTS

A natural approach from the fabrication perspective to introducing the microstructure is to impose this microstructure in the substrate on which the OLED is fabricated. We did this by using interference lithography, followed by deposition of a dielectric layer doped with Alq_3, capped with a thin layer of silver. The PL data shown in figure 3 from this structure reveal something very interesting; the SPP associated with the Ag/air interface is the strongest feature present in these data, whereas the calculations showed (figure 2) that the SPP mode associated with the Ag/organic interface takes much more energy from the emitters.

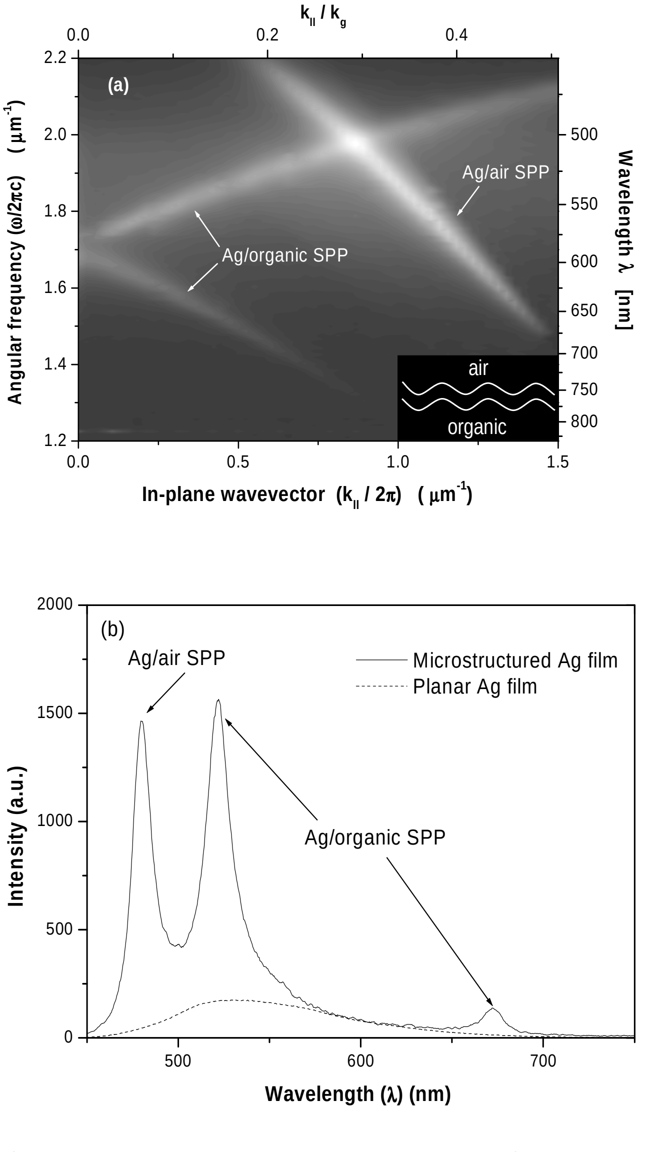

Fig. 3. (a) Dispersion maps of the TM polarized photoluminescence emission obtained from a sample containing a 43 nm thick micro-structured Ag film, λ_g = 338 nm (shown inset). (b) TM polarised PL emission through both micro-structured and planar 43 nm thick Ag films, both spectra were obtained at an emission angle θ of 20˚.

A natural approach from the fabrication perspective to introducing the microstructure is to impose this microstructure in the substrate on which the OLED is fabricated. The PL data shown in figure 3 from just such a structure reveal something very interesting; the SPP associated with the Ag/air interface is the strongest feature present in these data, whereas the calculations showed (figure 2) that the SPP mode associated with the Ag/organic interface takes much more energy from the emitters.

The reason for the SPP associated with the Ag/air interface appearing stronger in the PL even though the Ag/organic interface SPP carries much more power turns out to arise from a subtle interplay between two different routes by which the Ag/organic SPP may be scattered to radiation. These two pathways are, first, the mode may scatter off the corrugation at the Ag/organic interface and then be attenuated as it propagates through the metal into the air half space, second, the field associated with this SPP mode that exists (attenuated by the metal film) at the Ag/air interface may be scattered by the corrugation at that interface. These two routes by which emission may take place are of similar amplitude (both suffer the same attenuation) but are almost exactly out of phase so that there is nearly complete cancellation [5]. There are a variety of ways in which this cancellation may be overcome. One way is to provide a corrugation on just one of the metal surfaces. In figure 4 we show PL data from just such a structure, here a planar system was fabricated and the grating was milled into the metal film using a Focussed Ion-Beam milling system (FEI Nova 600).

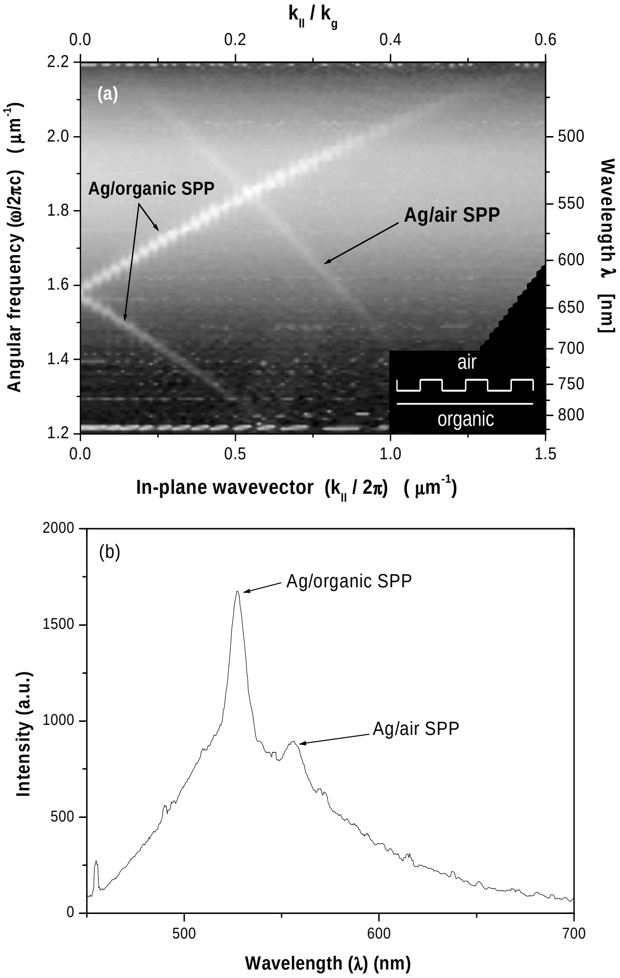

Fig. 4. (a) Dispersion map of the TM polarized photoluminescence emission obtained from a sample containing a 50 nm thick Ag with the metal/air interface containing a 400 nm pitch microstructure (shown inset). (b) TM polarised PL emission through both micro-structured obtained at an emission angle θ of 20˚.

3. SUMMARY

The data shown in figures 3 and 4 show that the details of the profile of the microstructure used to scatter SPP modes to light when such scattering takes place through a metal film have an important bearing on the effectiveness of the generation of useful light. As the interest in top-emitting OLEDs gathers pace these results are expected to become of relevance in the design of optimised top-emitters where recovery of power to SPP modes becomes an important issue.

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