# Plasmonic enhancement in organic solar cells with metallic gratings

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*We propose an organic solar cell structure with combined silver gratings consisting of both a front and a back grating. It provides multiple, semi-independent enhancement mechanisms which act additively, so that a broadband absorption is obtained. Rigorous simulations show an optimized period of 490nm, with front grating elements of 60 by 10nm and back elements of 60 by 30nm. With these parameters an integrated absorption enhancement factor around 1.35 is observed, with absorption increasing from 48% to 65% under TM polarized light. Moreover, the proposed structure does not have large absorption suppression for TE polarized light.*

## Introduction

Organic solar cells (OSCs) are of great interest in recent years due to their low-cost processing and high-throughput potential. However, organic solar cells have very low efficiency, up to around 8% [1], much smaller than the commercial silicon-based solar cells. For organic materials the absorption length is usually in the order of 100nm. However this is still too thick to have efficient photocurrent generation because of the short exciton diffusion length which is in the order of 10nm. In order to overcome the thickness limitation, some light trapping techniques are required to achieve strong light harvesting together with good photocurrent generation and transport.

Surface plasmon polaritons (SPPs) are collective oscillations of free electrons at the boundary of a noble metal and a dielectric material. These modes can strongly concentrate light at the metal surface. We recently investigated OSCs with metallic gratings [2, 3]. Thanks to the SPPs excited by the gratings, the light can be concentrated in a thin active layer. Consequently light harvesting is increased, while the OSC still has very good free carrier generation and transport properties due to a thin active layer.

## Model setup

Here by means of the finite element method (FEM) we examine the combination of multiple gratings, both on the front and back surface of the absorbing layer, see the model in Fig 1. It is composed of a 50nm thick P3HT:PCBM with 1:1 weight ratio as the active layer, a periodic silver front grating on top of the active layer and a back grating on the silver reflector. The optical constant of P3HT:PCBM and Ag used in simulation can be found in [3]. In order to excite the SPP we only consider the TM polarized (H along x-axis) light shining on the structure (for TE results see [3]). Here we only report the optimized parameters, with period of 490nm, widths of 60nm for gratings, heights of 10nm

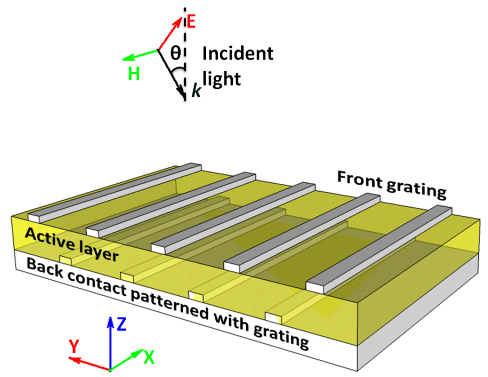


Figure 1: Schematic diagram of OSC with combined grating: front and back gratings.

and 30nm for front and back respectively, to show the enhancement mechanism and the angular light incidence response.

## Results

Figure 2(a) shows absorption spectra in the active layer for different OSCs with perpendicular incidence (along z-axis). The broadband enhancement is attributed to the enhanced field intensity in the vicinity of gratings due to the excitation of localized and propagating plasmon modes at different wavelengths.

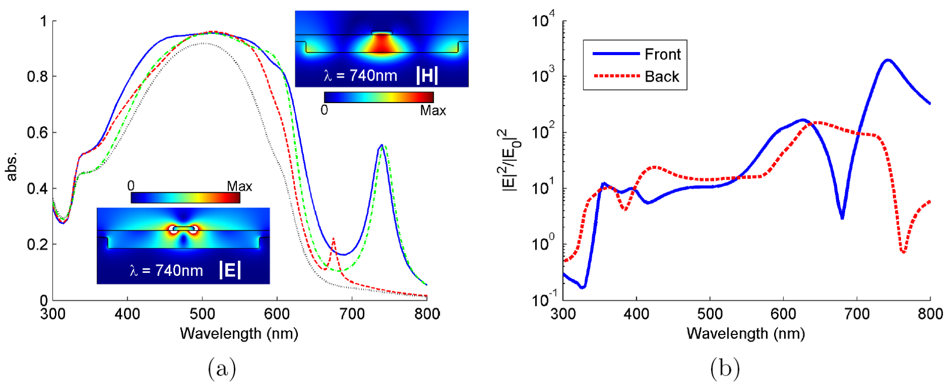


Figure 2: (a) The absorption spectra of the organic layer with combined grating (blue solid line), front grating only (green dash-dotted), back grating only (red dashed) and planar reference structure without grating (black dotted). The insets show the E and H magnitude profile at wavelength 740nm for the combined case. (b) Intensity enhancement spectrum at a point close to a lower corner of front grating (blue solid line) and at a point close to an upper corner of back grating (red dashed line) for combined grating, normalized by the incident field.

To verify this, Fig. 2(b) shows the intensity enhancement in the organic layer in the vicinity of the front and back teeth for combined grating structures. The intensity enhancement is the intensity ratio at a certain point between the cell with a combined grating and the incident field. We notice the strongly enhanced intensity at larger wavelengths ($\lambda >$ 600nm), but the point of largest ratio (near front or back grating) depends on the particular wavelength range. Thus, the back and the front gratings make fairly independent

contributions to different wavelength ranges and one arrives at a broadband enhancement from 350nm to 800nm in the combined grating structure.
The peak at 740nm is a Bloch state due to the periodicity in the structure. To better understand the property of the main peak at 740nm, electric E and magnetic H field magnitude distributions are shown in the inset of Fig. 2(a). A mixture between localized (LSP) and propagating (SPP) character is observed [4]. From the H magnitude we indeed see a strong coupling between the front grating element and the back silver interface. From the E magnitude on the other hand we see a strong contribution from the localized excitation of the front element.

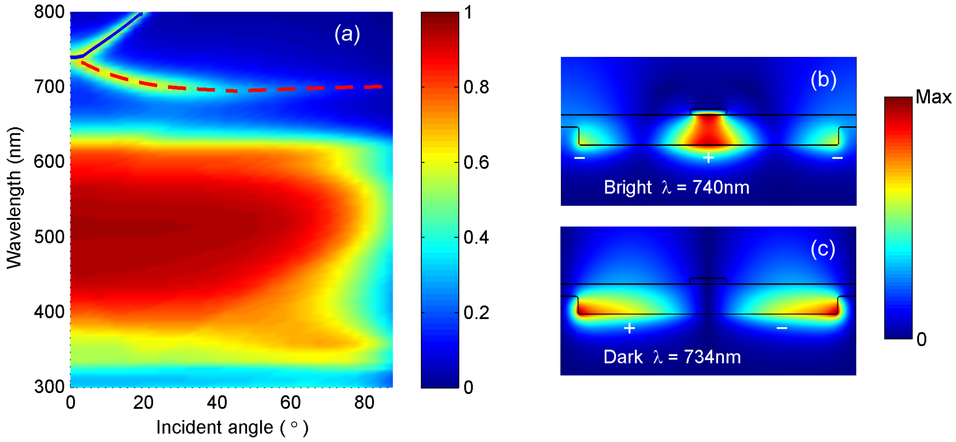


Figure 3: (a) Angular dependence of absorption with combined grating. Blue solid and red dashed lines are calculated Bloch mode dispersion curves. (b) and (c) H field magnitude distribution of Bloch modes, bright and dark. The '+' and '-' signs denote π phase differences in the field profiles.

Figure 3 shows the angular performance of cells with plasmonic gratings. To understand the phenomenon clearly in Fig. 3(d) we superimpose the band structure: a bright mode (solid blue line) and a dark mode (dashed red line). We observe very good fits between the Bloch modes and the peaks in the absorption map, verifying the importance of the Bloch modes for absorption enhancement.
Figure 3(b) and (c) show the profiles of two Bloch modes with different symmetry with respect to the plane in the middle of the structure. This leads to the bright and dark character of the modes, meaning that they can or cannot be excited by perpendicularly incident light, respectively. The symmetry of dark modes leads to a zero net dipole moment [5] and remains uncoupled to the incoming plane wave. The dark mode can only be excited when there is an asymmetry introduced into the system by means of tilting the light incidence or by breaking the symmetry of the geometry. As a consequence, we only observe the dark modes in Fig. 3(a) for non-perpendicular incidence.
Fig. 4 shows the angular dependence of the integrated absorption. Notice that the integrated absorption for TM reaches its maximum at 10° incidence for the combined grating case, because of the influence of the dark mode. At normal incidence the combined grating cell reaches around 65%, an enhancement factor of about 1.35 compared with the 48% of a planar cell. The dark mode effect at 10° leads to a further 67% absorption. Enhancement is quite angle insensitive and observed over a large angular range. Up to around 70°

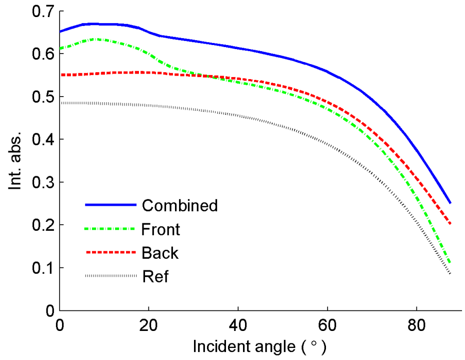


Figure 4: Angle dependence of integrated absorption in active layer for OSCs with combined, only front and only back gratings and the reference structure respectively.

the TM absorption is still larger than that of the reference at normal incidence. We can also see that the combined grating case dominates over the front and back single grating cases. Although our structures were mainly optimized for perpendicular incidence, we remark that the dark modes provide an important extra route towards large angular range enhancement.

## Conclusions

In conclusion, we investigated the influence of combined gratings on the absorption in the active layer of organic solar cells. We observed a broadband absorption enhancement over a large angular range because of excitation of different SPs, LSP and SPP. With an optimal period a factor 1.35 enhancement is reached for TM polarized perpendicular light. In the angular dependence investigation we found two modes, the bright and dark SPP modes, make absorption enhancement contribution. Over a large angular range a good absorption enhancement can be observed because of the dark mode.

## Acknowledgements

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