A New Class of Nonlinear Light Trapping for Photovoltaic Systems

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ABSTRACT

Light trapping is a useful way of enhancing photovoltaic (PV) conversion – particularly in thin-film PVs. To-date, fluorescence has been the only nonlinear process utilized. Herein, we introduce a new class of nonlinear light trapping which utilizes the saturation of the PV itself, within a mode-coupled architecture. Paradigm shifting to a new class of traps in which the light travels along – rather than through – a PN junction, we open the door to the possibility of importing energy collected elsewhere and mode coupling it directly into the PN junction. Coupling to the saturable absorber enables the nonlinear clamping of mode amplitudes so that the imported energy can be uniformly distributed over distances as long as we wish. Significantly this enables the design of utility scale, highly concentrated photovoltaic systems.

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Keywords: solar energy, photovoltaics, light trapping, nanoparticle scattering

1 OVERVIEW

Light trapping [1] is a useful way of enhancing photovoltaic conversion via any means by which light not converted to electricity in a photovoltaic (PV) in one pass through its PN junction, is given another opportunity to do so. Promising techniques include the use of: plasmonics (arrays of conductive nanoparticles) to generate surface waves to redirect light; photonic crystals (often as reflectors); and quantum dots (nanoscale encapsulated spherical semiconductors) to fluoresce and scatter light into different directions. To-date, fluorescence [2] has been the only nonlinear process utilized – which is also the defining element of an entire class of systems known as Luminescent Solar Concentrators [3]. Herein, we introduce a new class of nonlinear light trapping which utilizes the saturation of the PV itself, within a mode-coupled architecture as in Fig. 1. Stable critical points enable the nonlinear clamping of mode amplitudes so that the imported energy can be uniformly distributed over distances as long as we wish. This enables the design of utility scale, highly concentrated photovoltaic systems which can be roll-to-roll processed in flexible structures.

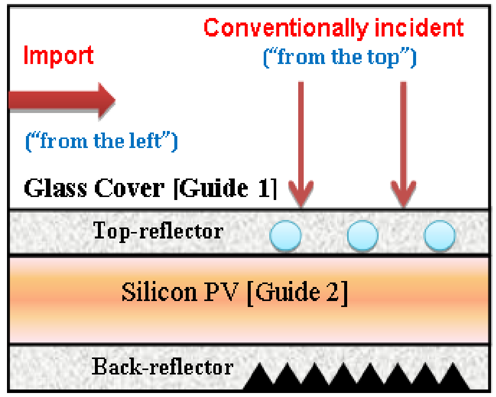

Figure 1: A mode trapping architecture.

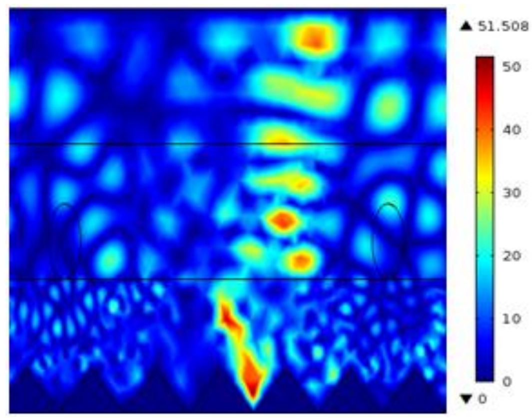

Figure 2: Electric field magnitude for elliptical nanoparticles interacting with a periodic back-reflector.

2 MODE TRAPPING

Rather than considering light as passing through a PN junction we paradigm shift to a new class of traps in which the light travels along a PN junction, as a guided mode. Significantly this opens the door to importing energy from elsewhere and mode coupling it directly into the PN junction. Simultaneously, the device could have conventionally incident light (from the top) which we also attempt to trap and we find, as exemplified in Fig. 2, that periodic structures can lead to highly localized resonances (here from elliptical silver nanoparticles interacting with a triangular perfectly conductive back-reflector). The top layer in Fig. 2 is air – demonstrating reflection at normal

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incidence from the entire device, the next layer is glass and the bottom layer is silicon. Surprisingly we find that for a given nanoparticle array: periodic back-reflectors can sometimes outperform pseudo-random structures. Periodicity induces a resonance which can surpass Lambertian (randomly rough – proved optimal for infinitely broadband signals in the ray-optics limit [1]) at a *single* frequency. Hence the surprise actually stems from the fact that we can provide a sufficiently large number of resonances over bandwidths as large as the responsivity of silicon (roughly 700nm).

Once trapped, the energy is "recycled" between the evanescently coupled glass and silicon waveguides, as depicted in Fig. 3 in which PABS is the power absorbed in the silicon (modeled here as a linear, non-saturable absorber); the distance z is normalized to the (1/e) absorption length; and P1 and P2 are the power in the glass and silicon (respectively). This linear trap works well for conventionally incident light; but for applications of importing energy (from elsewhere) the rapid absorption of P2 would not permit high intensity operation. Fortunately however, when include the nonlinear effects of loss saturation in the silicon, as in Fig. 4, the nonlinear trap can exhibit clamping of mode amplitudes so that the imported energy can be uniformly distributed over long distances.

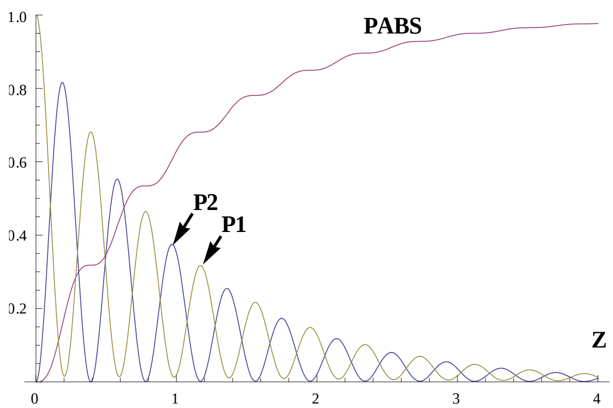

Figure 3: Rapid absorption in a linear light-trap.

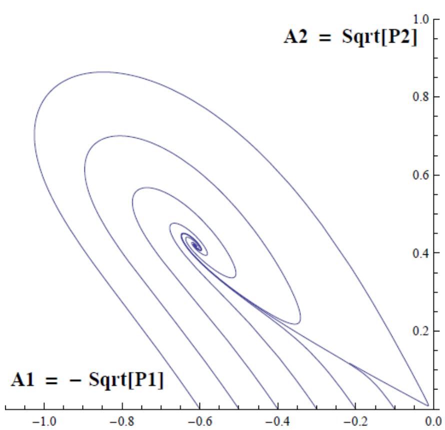

Figure 4: Clamping in a mode-trap with nonlinear loss.

3 NONLINEAR MODE TRAPPING

For example, the dimensions of realizable thin-film devices are such that the coupling constant can be increased to compensate for detuning (arising from the different speeds of propagation in the glass and silicon waveguides) [4]. Thus, nearly 100% power transfer can be rapidly achieved, as depicted in Fig. 3, for dimensions on the order of microns or less. For import applications however, linear mode trapping works almost too well in the sense that the energy transfer can be essentially too rapid. Therein a high intensity of imported energy would at some point simply melt the edge of the PV due to such rapid power transfer. This also would diminish the utility of larger PV dimensions (typically on the order of centimeters in thin-film cells; or even on the order of meters for flexible PV sheets). We would prefer that P2 not diminish at all – thereby producing a uniform distribution of power across the surface of the PV. Fortunately, when we incorporate the nonlinearity of loss saturation we find that is exactly what we can achieve.

Critical point analysis [5], [6] shows that such a coupled-mode saturably-absorbing structure can exhibit stable spiral points (as in Fig. 4) or stable nodes when the square of the coupling constant, k^2, lies in a range that has an upper bound of G_0 L_0 (where G_0 is the gain induced by the pumping action of the conventionally-incident light, and L_0 is the unperturbed, linear, loss of the silicon). The power to which P2 clamps (normalized to P_S – the saturation power of the silicon) can be shown to be $(G_0\, L_0)/\, k^2 - 1$. Thus, when k^2 approaches its upper bound for stability, the actual (non-normalized) power level to which we clamp can be small compared to the saturation power, P_S. Physically, this can happen because even at low intensities the multi-pass nature of the coupled-mode structure provides for the accumulation of small nonlinear perturbations. Clamping at modest intensities permits the design of standard scale PV cells. At higher intensities: the clamping converges even faster to a uniform power distribution and this permits the design of utility scale, highly concentrated systems.

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