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A visual guide to light trapping limits and design principles

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Light trapping is an essential ingredient for high efficiency silicon solar cells. The fundamental ergodic (Yablonovitch) limit of $4n^2$ to broadband light trapping in dielectric structures has been derived from purely thermodynamic considerations [1]. Recently, many structures have been proposed that surpass this broadband limit, as they aim to enhance light trapping for only a narrow frequency range. In this contribution, we give a visual derivation of the broadband light trapping limit using iso-frequency curves that also explains in an intuitive way, why and how the limit can be broken for narrowband applications.

A ray of light can be defined by amplitude, position, frequency and wave-vector. The relation between frequency and wave-vector depends on the refractive index of the medium of propagation. For uniform media with negligible loss, the allowed wave-vectors sit on the surface of a sphere whose radius depends on the refractive index. Interfaces between different media allow for scattering between different wave-vectors. In wave-vector space the displacement through scattering with a structured surface can be expressed with simple geometrical operations, while the scattering amplitudes are determined through more complicated, often numerical, calculations. The framework of iso-frequency curves lends itself to a particularly easy visual calculation of the scattering directions (see Figure 1).

Iso-frequency curves are a widely used tool in metamaterials research that displays all the states in wave-vector space that a photon with a given frequency can occupy in a medium defined by its refractive index. In general, the frequency dependence of the refractive index is important to determine the possible wave-vectors. For the case of a planar slab of silicon near its band-edge, that is of particular importance to photovoltaics, iso-frequency curves can be represented in good approximation by spheres that lend itself to simple geometric operations. Using those iso-frequency spheres we analyse the different situations typically encountered in solar cell research.

For completely random surfaces, all displacements in wave-vector space are equally likely and the Yablonovitch limit arises purely from the consideration of the surface of the spheres in wave-vector space that determines the modal density, as well as the average path length of the rays. The Yablonovitch limit is also contingent on time-reversal symmetry of the optical paths. For surfaces with a periodic structure, the scattering angle depends on frequency. Therefore, it is possible to enhance the average path length beyond $4n^2$ in a narrow frequency range by scattering to oblique angles. The exact conditions for this can be read geometrically from the iso-frequency curves.

In summary, we introduce the tool of iso-frequency curves to photovoltaics. This allows us to visually derive the ergodic light trapping limit and design considerations for narrowband light trapping structures. We believe that iso-frequency curves can be a great tool to guide light trapping structure design as well as for photovoltaics education.

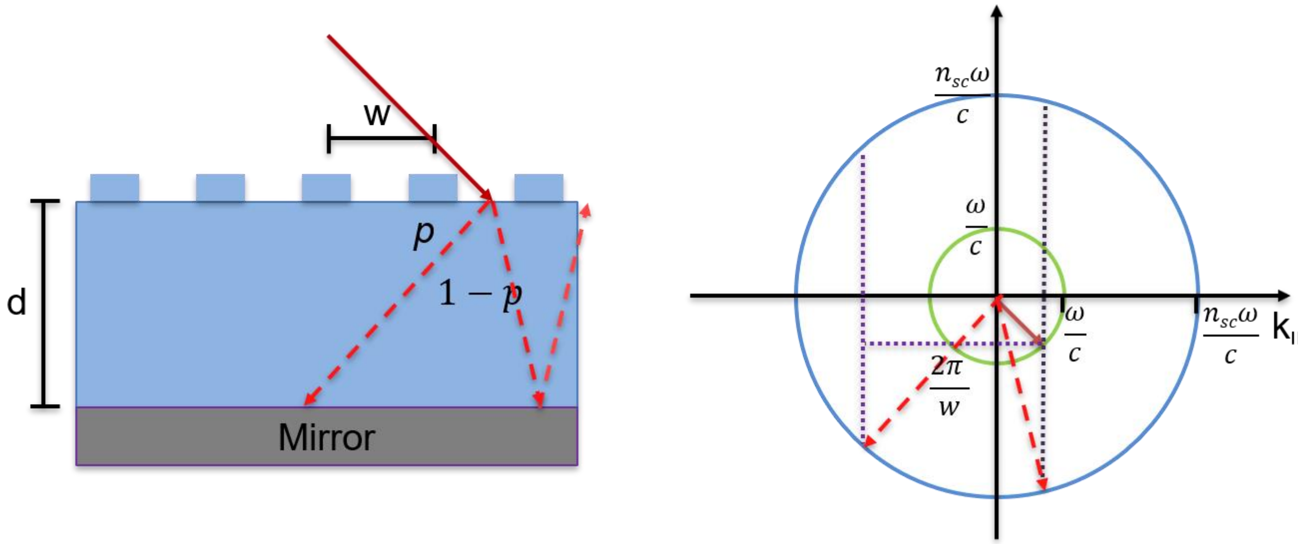

Figure 1. A dielectric with a periodic surface structure and the scattering at the surface described in iso-frequency curves for light inside the dielectric (blue) and in air (green). The width w of the device is mapped to a wave-vector displacement

References

Yablonovitch, E., 1982, 'Statistical Ray Optics', *J.Opt.Soc.Am.,* 72, p899