Meso-photonics for energy applications

Opportunity

Meso-scales are exactly compatible with the natural length-scale of the light that is relevant for energy applications: visible and infra-red wavelengths.

Tailoring the meso-structure, one can tailor the laws of physics (as far as light is concerned) almost at will.

Exploring plasmonics, one can “shrink” length-scales of light to even smaller scales, closer to natural length-scales of electronics, thus bridging the gap in the scales between electronics and photonics.

Meso Challenge

To enable massive adoption in the energy sector, one needs to have the ability to control meso-structure in macro-scopic objects: novel cheap and reliable mass-fabrication methods are needed.

Novel gain materials are needed, compatible with meso-fabrication methods.

Plasmonic losses are large: novel plasmonic materials/approaches are needed.

We create the laws of physics ⇒ large opportunities to explore novel physics emerge: imagination is the limit.

Approach

Electro-magnetic phenomena can be modeled exactly, with no approximations apart for the discretization ⇒ “numerical experiments” are thus enabled, dramatically speeding-up the scientific progress.

Numerous large-scale, cheap meso-fabrication techniques have emerged recently, including: nano-imprint, interference lithography, self-assembly.

Impact

92% of all primary energy sources are converted into electrical and mechanical energy via thermal processes ⇒ ability to tailor thermal radiation and/or absorption has numerous applications in the energy sector.

Solar energy is perhaps the most promising clean-energy source: at the heart of its exploration lies the need to control the behavior of light ⇒ meso-photonics promises a wide range of applications: more efficient photo-voltaics, solar-pumped lasers, solar-thermal systems…

~25% of US electricity consumption is due to lighting: meso-photonics could enable dramaticaly more efficient lighting, in terms of: better LEDs, incadescent sources…

U.S. DEPARTMENT OF ENERGY | Office of Science

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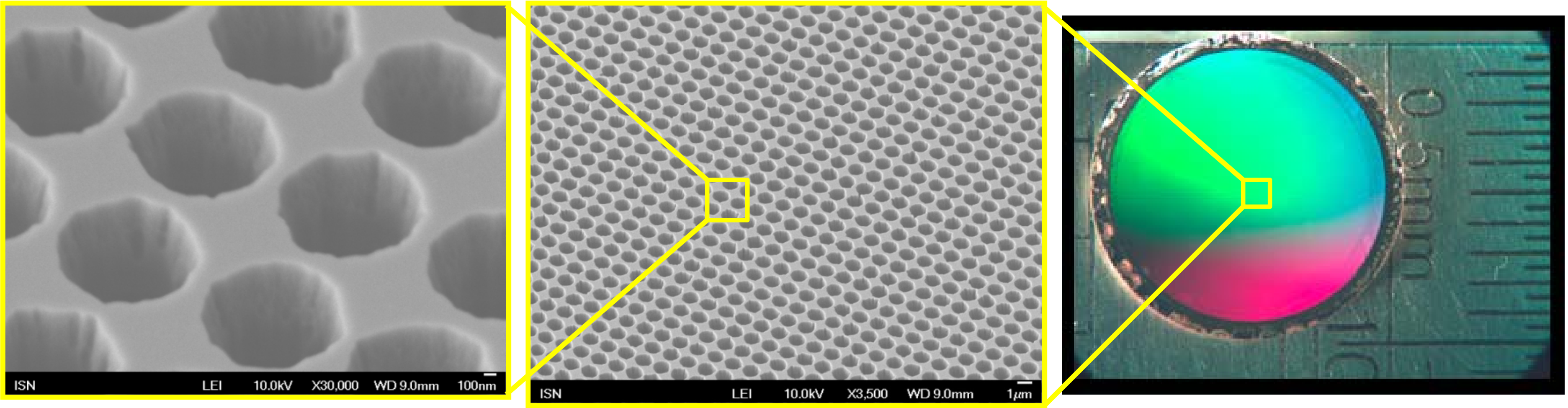
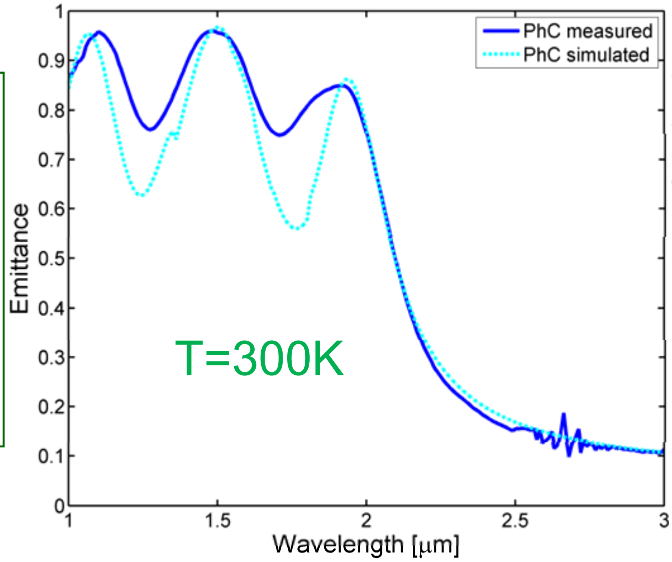
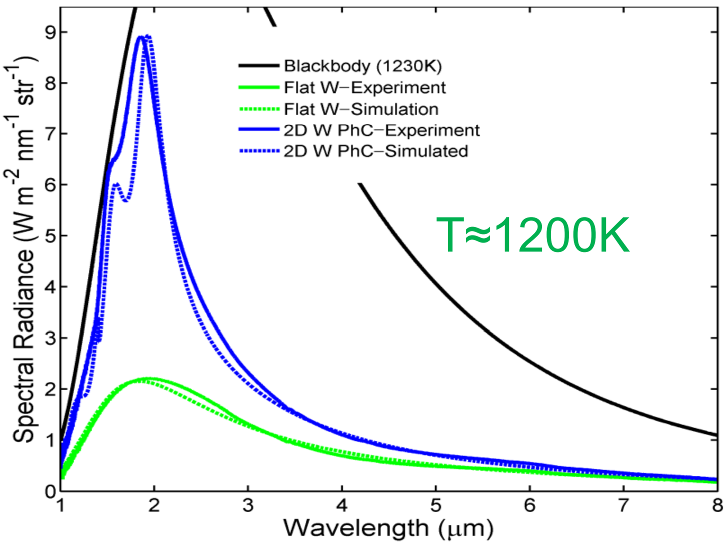
Meso-photonics for energy applications



2D photonic crystals (PhC) for selective emitters/absorbers in Tungsten: high absorptance/emittance for short wavelengths, low for long wavelengths





Y.X.Yeng et al. *Proceedings of the National Academy of Sciences*, (2012).

Meso-photonics for energy applications

Opportunity

In meso-photonics, we explore artificially created materials (meta-materials), in which the structure is tailored at length-scales smaller than the wavelength of light of interest. Because the sub-structure is smaller than the wavelength, light cannot really resolve the structure: it appears to the light as if it were propagating in a uniform medium, whose physical properties are substantially modified. By tailoring the meso-structure, we can tailor the laws of physics (as far as light is concerned) almost at will. This way, we can create artificial materials that display physical phenomena that do not exist in any naturally existing materials. For example, meta-materials have been used to demonstrate negative refraction, as well as to implement invisibility cloaks.

Photonic bandgap crystals (PhCs) are an example of this approach: they behave like "semiconductors for light": light of the frequencies within the badgap is prohibited from propagation, while the frequencies outside of the bandgap are allowed to propagate. This way, by tailoring the meso-structure, one can tailor the photonic density of states almost at will; e.g. within the photonic bandgap, the density of states is zero, while at some other frequencies, it can be dramatically enhanced. PhCs have been explored for example to implement some of the lowest power-threshold lasers. Moreover, since thermal emission of a hot body depends on the density of states, one can also tailor thermal emission (as well as absorption) of hot bodies almost at will.

In addition, one can explore plasmonic meta-materials: surface plasmons are hybrid creatures, lying on the interface between photonics and electronics. They comprise very rapid surface-current oscillations; since they exist close to the surface, they also generate electromagnetic fields close to the surface. The spatial length scale of a surface plasmon can be much smaller than the free-space wavelength of the same-frequency light. This way, one can generate much smaller wave-packets of light than one could do in free space, and thereby bridge the scale-gap between photonic devices (which are meso-scopic) and electronic devices (which can often be nano-scopic).

Finally, note that meso-science is exactly compatible with the natural length scale of the light that is of interest for energy applications: visible and infra-red wavelengths. In that sense, many if not most of the exciting opportunities for the entire field of photonics lie precisely in the domain of meso-science.

Meso challenge

To enable massive adoption in the energy sector, one needs to have the ability to mass-produce large objects and surfaces whose structure is meso-scopically tailored. Novel cheap and reliable mass-fabrication methods for meso-structures are needed.

For many applications of interest (e.g. lighting, solar-pumped lasers), one needs to explore gain and/or fluorescent materials, that need to be integrated in a close proximity (so meso-effects would be pronounced) with other meso-structured materials. This requirement is incompatible with many of the existing fabrication processes. For example, most approaches to meso-patterning well-performing gain materials lead to dramatic deterioration of their gain properties. Thereby, novel approaches to meso-structuring gain materials are needed, as well as exploration of novel gain media that are compatible with the most promising and scalable meso-fabrication methods.

The field of plasmonics offers many exciting opportunities. Unfortunately, it faces one large (so far insurmountable) obstacle: plasmonic losses are enormous: e.g. propagation loss of 6dB/micron is not unusual. Although there are applications (most notably in energy sector) where this is not an impairment, there are numerous other applications that could be enabled if losses were at least 2-3 orders of magnitude smaller.

Meso-photonics truly enables us to tailor the laws of physics (as far as light is concerned) almost at will. This creates a wide range of opportunities: not only is there a variety of novel physics to be explored, but one can purposely design materials whose laws of physics one suspects will support particularly interesting and novel physics. Once these materials are fabricated, one can in turn investigate novel physics enabled by these novel physics laws. For example, novel topological insulators, as well as novel topological states have recently been proposed in photonics, with properties unparalleled in electronic systems. Since the field of opportunities is so large, imagination is very often the biggest limiting factor to faster progress.

Approach

Electro-magnetic phenomena can be modeled exactly, with no approximation apart for the discretization. When doing such "numerical experiments" they most often reproduce real experiments point-by-point. This dramatically speeds-up the scientific discovery process because one can explore much wider experimental parameter spaces much faster. Moreover, one can develop analytical models, and intuitive understanding much faster, because numerical experiments can be much more easily controlled than real experiments, thus enabling faster (and "cleaner") result analysis.

Numerical experiments can easily be coupled with nonlinear optimization techniques which optimize in thousands of parameters simultaneously, to find optimal designs and structures. This way computer effectively performs a substantial part of the process of innovation.

In terms of fabrication, numerous promising large-scale, cheap meso-fabrication techniques have emerged recently, including: nano-imprint, interference lithography, and self-assembly.

Impact

92% of all primary energy sources are converted into electrical and mechanical energy via thermal processes, so the ability to tailor thermal radiation emission and/or absorption has numerous applications in the energy sector.

Solar energy is perhaps the most promising clean-energy source: at the heart of its exploration lies the need to control the behavior of light. Thereby, meso-photonics promises a wide range of applications: more efficient photo-voltaics, solar-thermal systems, solar-pumped lasers…

In solar-thermal systems, selective absorbers are of crucial importance: ideally, they have high absorptance for short wavelengths (where most of solar energy is), and low absorptance (and hence, according to Kirchoff's law also low thermal emittance) for the long wavelengths (where most of thermal energy re-emission is). Meso-photonics enables some of the most powerful approaches for designing selective absorbers/emitters.

Conversion of light into electricity has been studied broadly in a wide variety of systems. In contrast, solar-pumped lasers have been much less studied. Meso-photonic advances of the last decade enabled novel lasers of unique properties: e.g. some of the lowest power-threshold lasers have been recently implemented using photonic crystals. Low threshold lasing is particularly important for solar applications, because it reduces the solar concentration factors needed to achieve lasing. Hence, there is a substantial unexplored opportunity for scientific studies of meso-photonic solar-pumped lasers. In solar-pumped lasers, broad-bandwidth incoherent sun light is converted into coherent monochromatic light. Such light can subsequently either be wirelessly transferred in free space or routed to designated locations through optical fibers. The ability to transport the harvested solar energy to wherever it is needed at the speed of light without consuming much extra power could greatly enhance the prospect of solar energy utilization at a massive scale. Laser light could alternatively be used to produce solar fuels via photo-catalysis. Needless to say, numerous laser applications can benefit from powering their light-sources with green energy.

~25% of US electricity consumption is due to lighting; therefore, meso-photonics could enable dramatically more efficient lighting, in terms of better LEDs, incandescent sources, etc.