Nanophotonic approaches for selective emission and absorption enhancement

Peumans Group

Chu-En Chang*, Nicholas P. Sergeant, Olivier Pincon, Mukul Agrawal and Peter Peumans

*cechang@stanford.edu

Main idea

We study efficient high-temperature solar absorbers and light emitters. The term “efficient” here means both

- highly radiative/absorptive in visible light
- highly inhibitive in IR

In order to achieve the above, our current activities include

- rigorous simulations on stack and surface structures
- measurements on optical properties at high temperatures

Design flow

Application-specific constraints ⇨ **Optical property measurements** ⇨ **Design and simulation** ⇨ **Manufacturing and testing**

- Thermophotovoltaics
- Concentrated solar thermal
- Efficient incandescence

- Emissivity
- Refractive index
- Functions of λ, θ, and T

- Structures
  - Stacks
  - V grooves
- Methods
  - Transfer matrix
  - RCWA
  - Needle optimization

Optical property measurement - emissometer

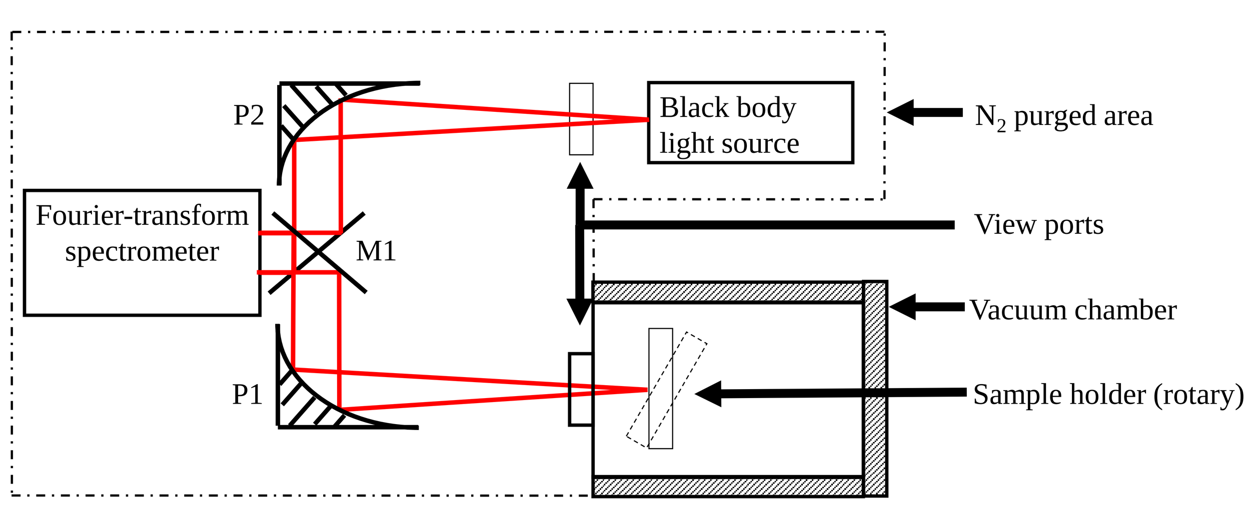


Fig. 1 Emissometer schematic

The emissometer consists of two (almost) identical light paths. The top or bottom path measures the spectrum of the black body simulator or the heated samples, respectively. In both cases, the incandescent radiation is collected by a parabolic mirror through a CaF_2 view port. Then the flip mirror M1 couples one of the beams into a Fourier-transform spectrometer. The ratio of the signals measured from the two paths can then be calculated to yield the refractive index and the extinction coefficient as outlined below.

$$\varepsilon_{sample}(\lambda,\theta,T)$$

⇩ Emissometer symmetrical-path measurement

$$\varepsilon_{sample}(\lambda,\theta,T)=\frac{I_{sample}(\lambda,\theta,T)}{I_{blackbody}(\theta,T)}=\frac{I_{sample}(\lambda,\theta,T)\cdot H_{left}}{I_{blackbody}(\theta,T)\cdot H_{right}}$$

$$R$$

⇩ Energy conservation. Kirchoff’s law. Transmission = 0

$$R(\lambda,T)=1-Tr(\lambda,T)-\alpha(\lambda,T)=1-\alpha(\lambda,T)=1-\varepsilon(\lambda,T)$$

$$r=R^{1/2}e^{i\phi}$$

⇩ Kramers-Kronig relations

$$\phi(\lambda,T)=-\frac{1}{2\pi}\int_0^\infty \ln\left|\frac{s+\lambda}{s-\lambda}\right|\frac{d\ln R(s,T)}{ds}ds$$

$$n+iK$$

⇩ Electromagnetics

$$r(\lambda,T)=\frac{n(\lambda,T)+iK(\lambda,T)-1}{n(\lambda,T)+iK(\lambda,T)+1}$$

Simulation

V-grooves and metal-dielectric stacks are among the most powerful nanophotonic techniques. Rigorous Coupled-Wave Analysis (RCWA) and the Needle Optimization are our optimization tools for the former and the latter, respectively.

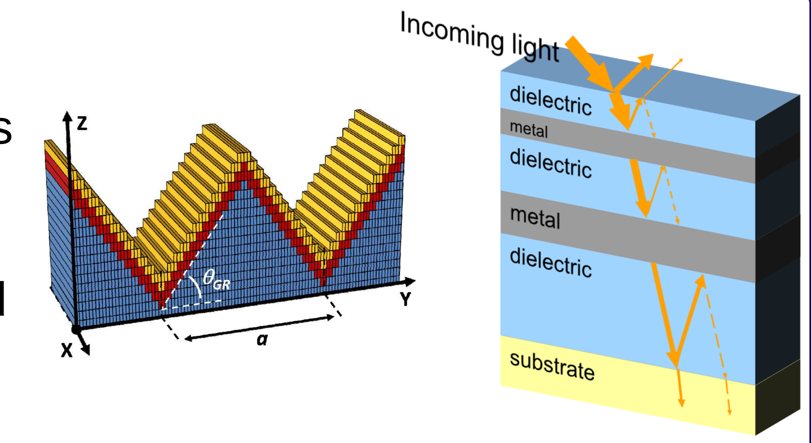
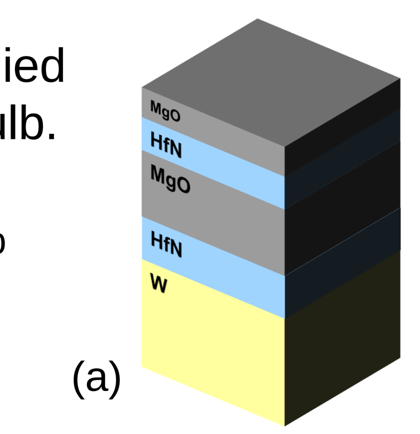


Fig. 2 Structures for spectral design. Left: V-grooves. Right: Metal-dielectric stacks.

Efficient incandescence

Our expertise in high-temperature optics can be applied to improving an old technology - the incandescent bulb. A simple 4-layer stack can increase the luminous efficacy by 92%. Another 11-layer stack shows 103% improvement, which leads to 62.5 lm/W, comparable with compact fluorescent lamps.



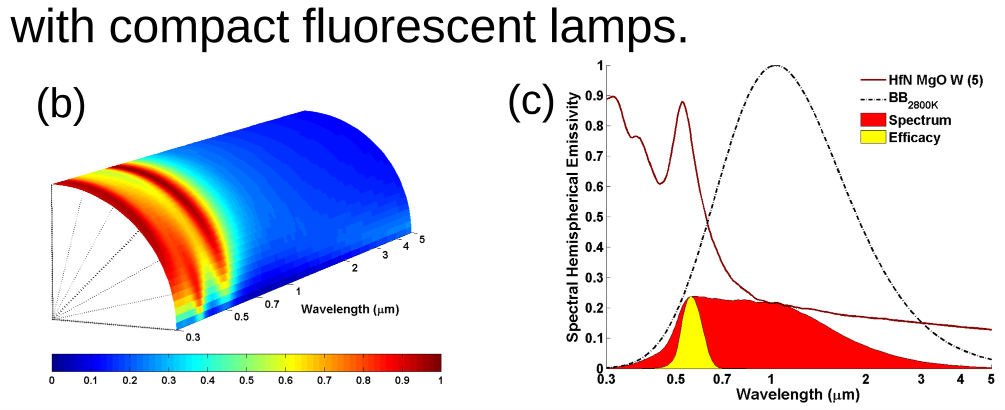
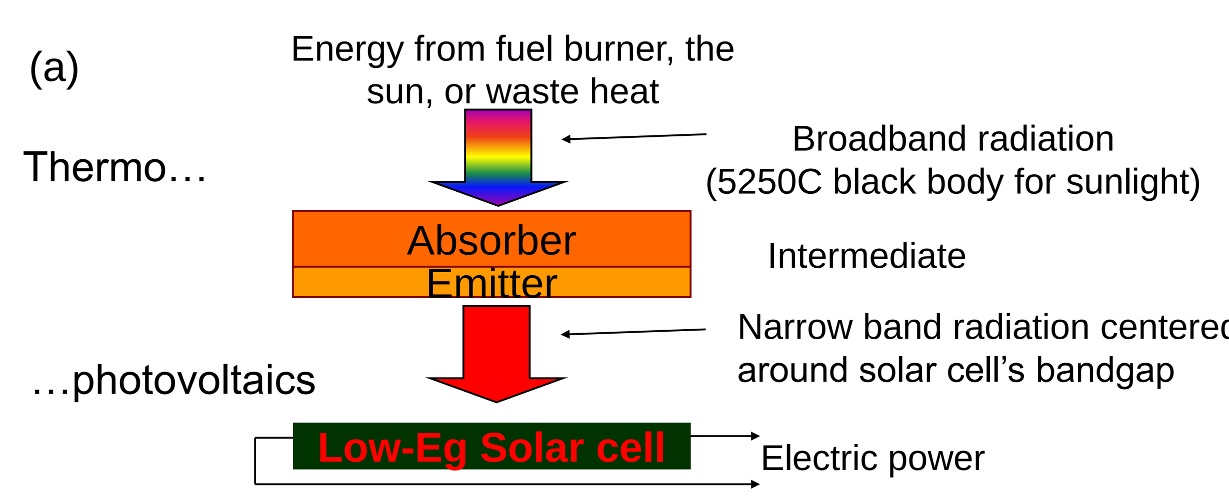


Fig. 3 Efficient incandescence design. **(a)** An optimized 4-layer stack. **(b)(c)** The spectral and angular responses of (a).

Thermophotovoltaics (TPV)

TPV is an ongoing research topic. It tries to circumvent the inherent inefficiency of photovoltaics by concentrating the power emitted to the solar cell above its bandgap. Thermodynamic limit on efficiency is 85% with full concentration and 54% without concentration.

Our nanophotonic approaches can apply to its absorber, emitter and solar cell designs



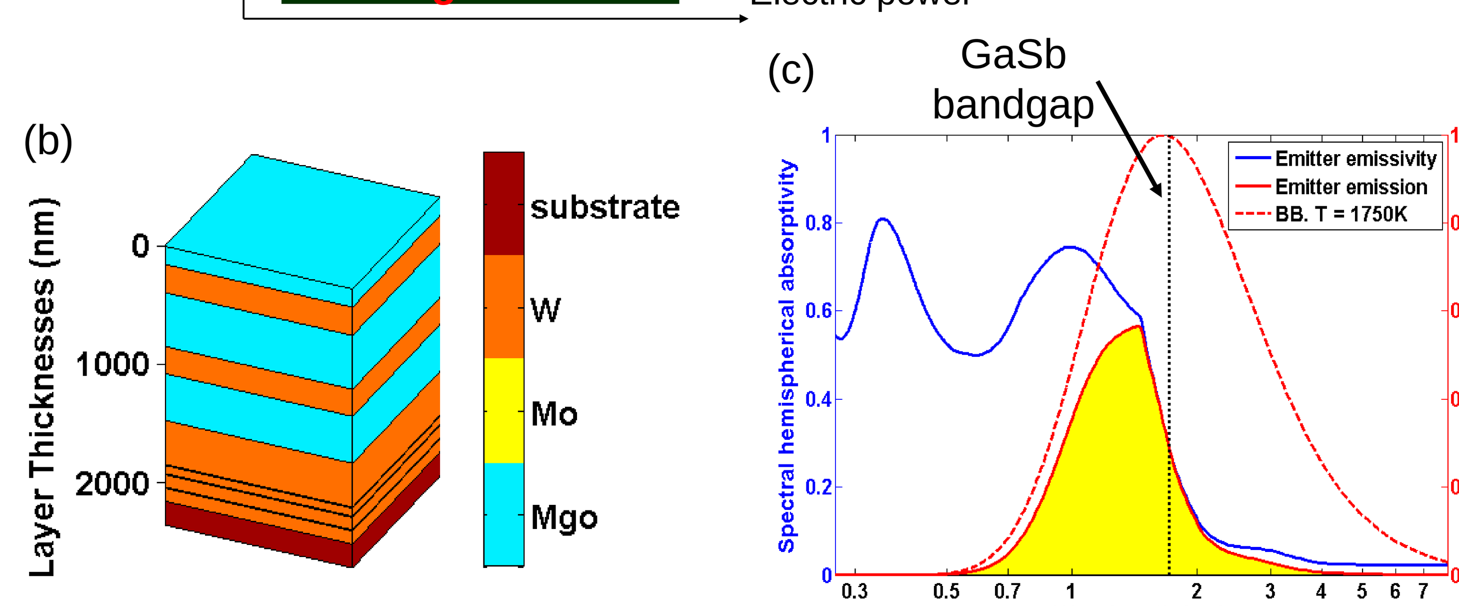
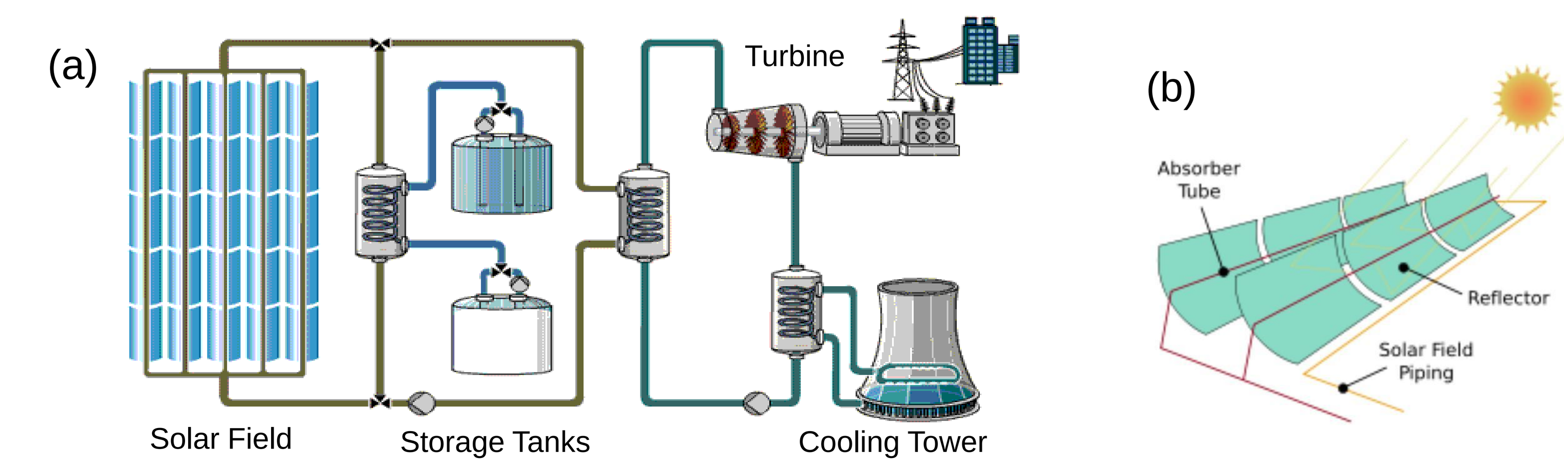
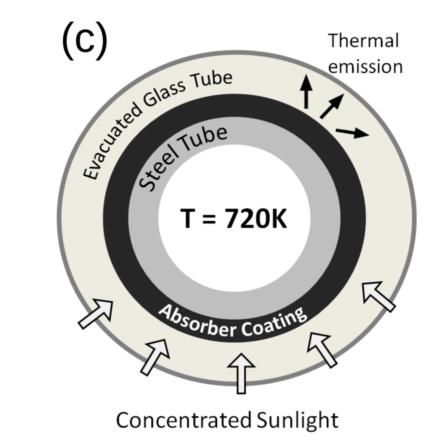


Fig. 4 (a) Block diagram of TPV. **(b)** An optimized TPV emitter. **(c)** Spectral response of (b).

Concentrated solar thermal (CST) power plants





CST is currently the dominant solar technology in terms of total capacity.Its advantages are

- converts the **full solar spectrum** into heat.
- High capacity factor (>40%)
- Cost-effective
- Lifetime > 20 years
- Utility scale (>50MW)
- can retrofit existing fueled power plants
- supplies steam for other uses (industrial or heating)

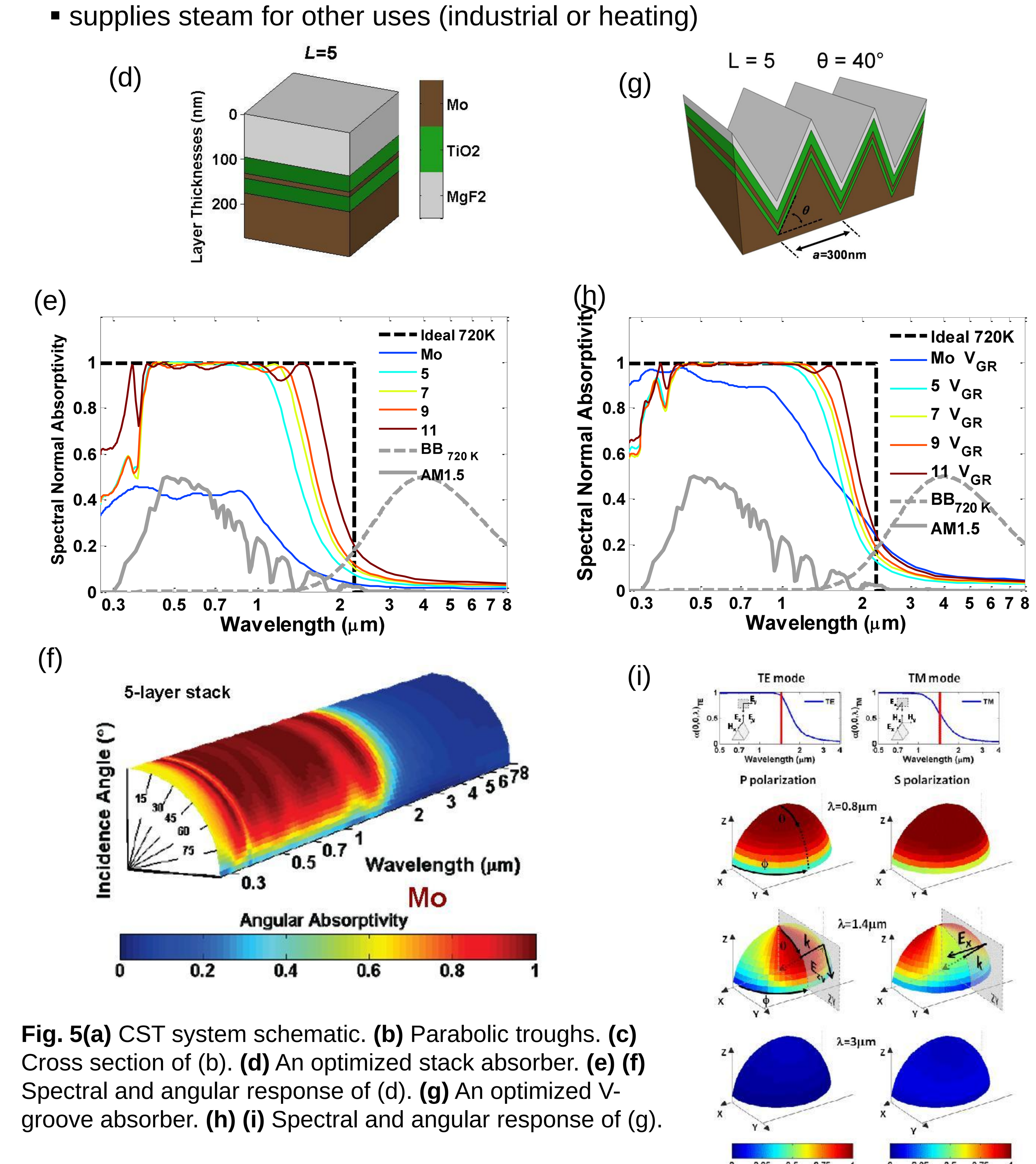


Fig. 5(a) CST system schematic. **(b)** Parabolic troughs. **(c)** Cross section of (b). **(d)** An optimized stack absorber. **(e) (f)** Spectral and angular response of (d). **(g)** An optimized V-groove absorber. **(h) (i)** Spectral and angular response of (g).

References

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2. N. P. Sergeant, O. Pincon, M. Agrawal, and P. Peumans, "Design of wide-angle solar-selective absorbers using aperiodic metal-dielectric stacks," Opt. Express **17**, 22800-22812 (2009).

Acknowledgement

The authors acknowledge support from GCEP.