Prospective solid-state photonic cryocooler based on the "phonon-deficit" effect

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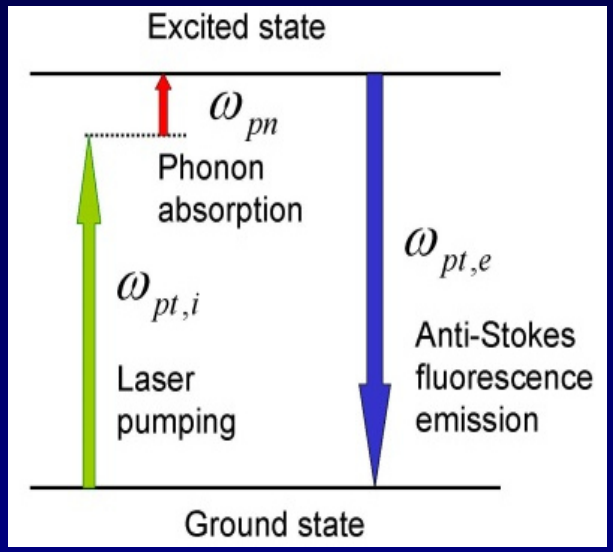
US ONR support is acknowledged

Problems of deep photonic cooling

With laser light tuned to the frequency $\omega_{pt,i}$ a little below the fluorescent emission frequency $\omega_{pt,e}$ of the transition, a simultaneous ω_{pn}-phonon absorption is required for a subsequent fluorescence blue-shift: $\omega_{pt,e}=\omega_{pt,i}+\omega_{pn}$.

Efficiency of cooling: $E_c \sim \omega_{phonon}/\omega_{incident\ photon}$.

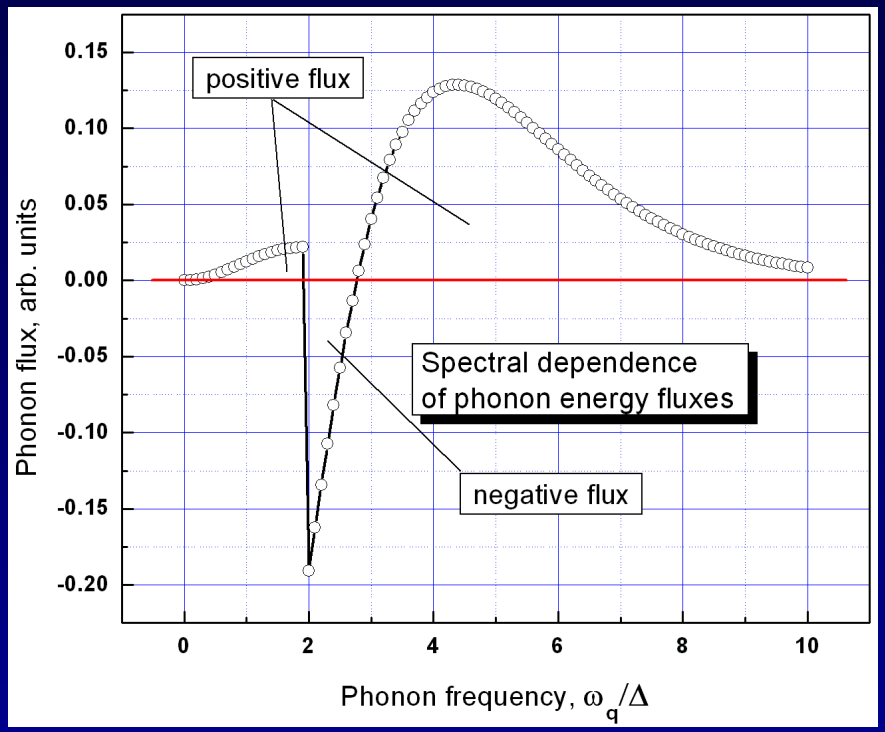


- At room temperature and infrared pumping, $E_c \sim (1/40)eV/1eV \sim 0.02$.
- At 4K, E_c is smaller by two orders of magnitude, and parasitic absorption becomes an issue.
- Even at one parasitic event per ten thousand successful phonon-assisted radiative transitions the net cooling is absent!

What is the solution?

- For low temperatures, one can consider lower energy pumping photons, for example, using 10 μm-wavelength/THz photons.
- However, in this case atomic transition levels should be separated by 0.1eV, in which case the multiphonon non-radiative decays are becoming very likely (Hehlen, 2009), thus denouncing the cooling opportunities.
- New ideas for photonic cooling at low-temperatures are required.
- One of opportunities may be related to the so called “phonon deficit” effect.

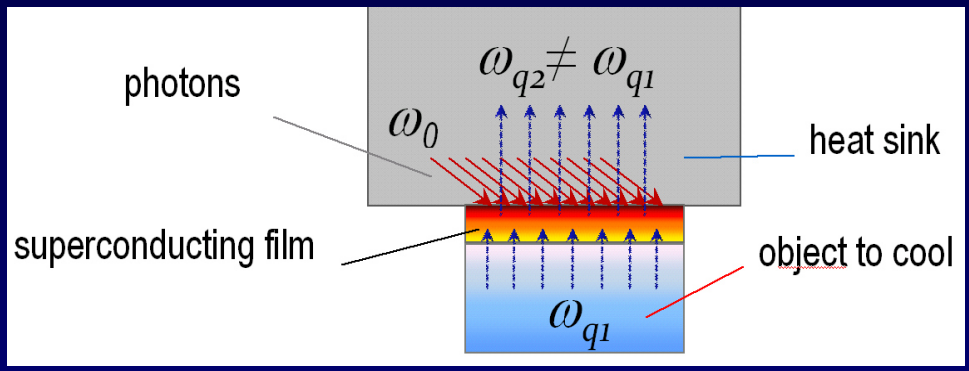
The Phonon Deficit Effect (PDE)



Phonon deficit effect in terms of the phonon energy flux.

Frequency of the photon pump is chosen $\omega_0=1.5|\Delta|$.

Explaining the Concept of the Cooler

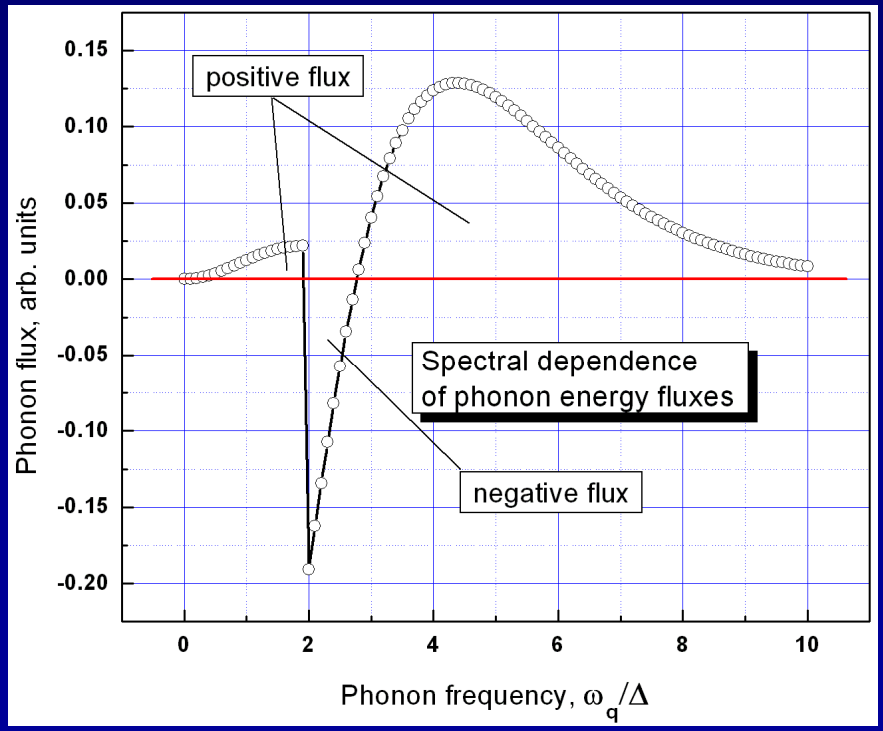


- The top medium is transparent to ω_0-photons.
- It also accepts freely phonon fluxes from superconductor, thus serving as a heat sink.
- Second medium, the "object to cool", designed not to accept these phonons, but rather serve as a phonon source in the range of negative flux frequencies.
- The nonequilinbrium superconducting film absorbs phonons from the object to cool for compensating the deficit, and transfers excess phonons (at different energies) to the sink.
- Thus, PDE in this situation acts as a heat pump.

PDE serves as a double discriminator:

a) It is selective in frequency domain

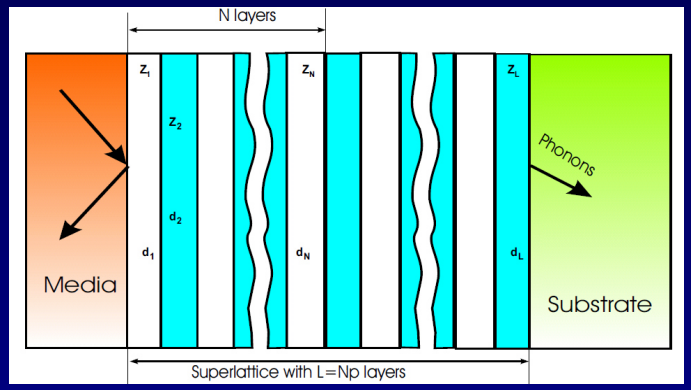
b) It is selective by direction of phonon fluxes

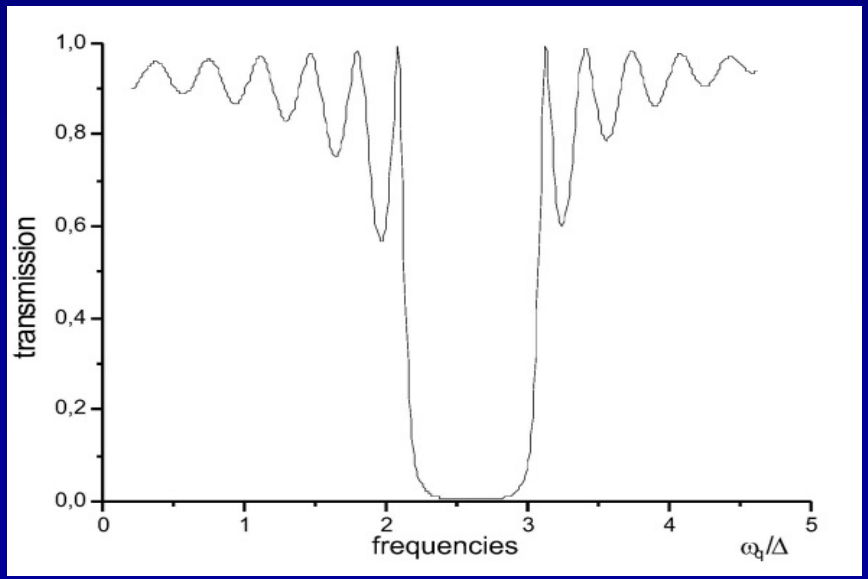


Phonon filtering can be used to take advantage of the frequency selectivity

Bragg multilayers as a selective phonon filter.

Both stop-band and bandpass filters are possible.



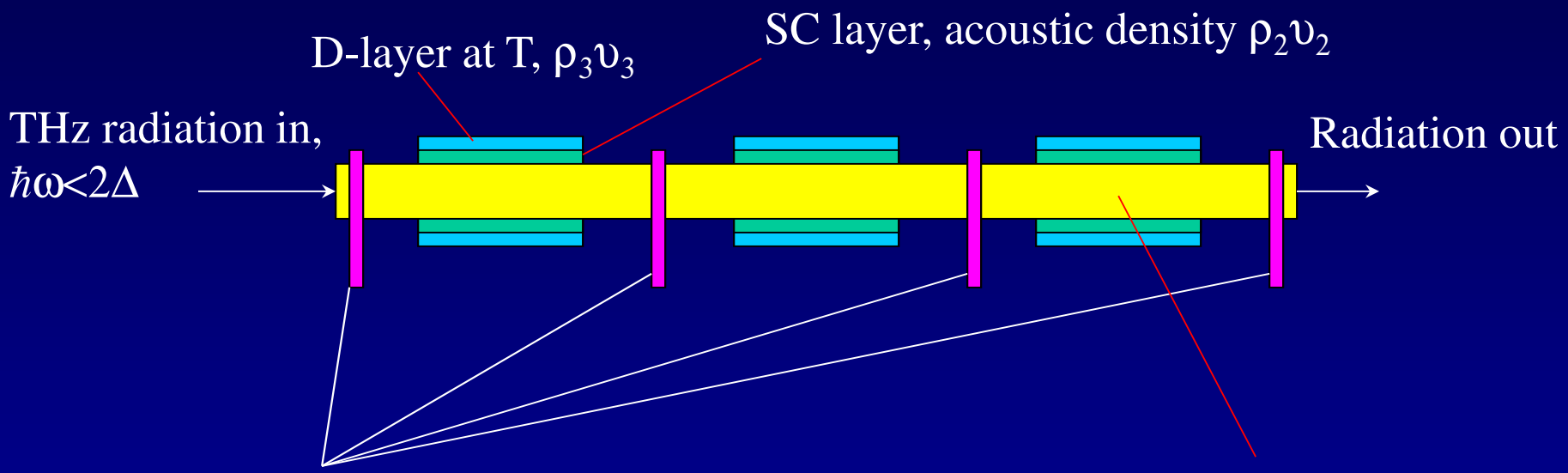


Designed stop-band filter.

Phonon rectification (thermal diode) can be used to take advantage of the directional selectivity

- First observation by Starr (1936).
- "Kapitza resistance".
- A lot of attention recently to thermal diodes.
- Close analogy with geometrical optics.
- "Optical density" →"acoustic density", ρu.
- Level of rectification sometimes comes close to 5 and even higher.
- Our calculations revealed that it is close the PDE cooler operability requirement.

General layout of the concept



Thermal anchoring at $T_0=T_{bath}$ (copper holders)

Sapphire fiber:
- transparent for THz
- excellent heat conductor
- acoustic density $\rho_1\upsilon_1$

Cooling at $\rho_3\upsilon_3<\rho_2\upsilon_2<\rho_1\upsilon_1$: $T<T_0$

Conclusions

The topic is “hot” enough to be considered as a “cool” opportunity for cooling by heating