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Modeling On-chip Nanoscale Trap and Enhance Device for Quantum Photonics Using Comsol Multiphysics

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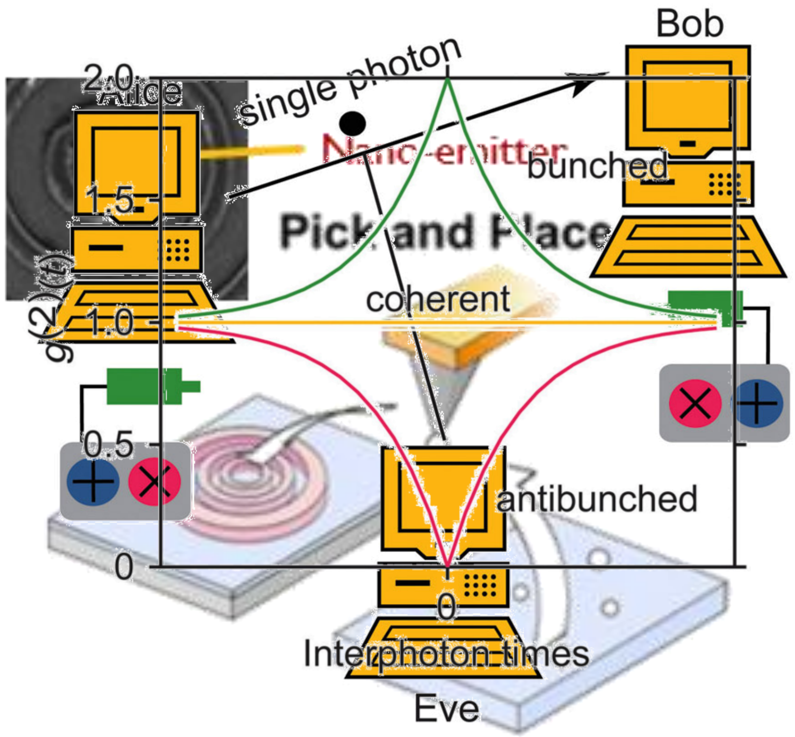
C. H. Bennett and G. Brassard. "Quantum cryptography: Public key distribution and coin tossing". In *Proceedings of IEEE International Conference on Computers, Systems and Signal Processing*, volume 175, page 8. New York, 1984

Single Photon Source in Quantum Optics

- General idea
  - Emits only one photon at a time (antibunched)
  - Emitted photons are indistinguishable
  - Example: Q-dots, crystal NV center etc.
- Application
  - Quantum cryptography
  - Quantum computation
- Development challenge
  - Separate enhancement medium required
  - Complex to fabricate and integrate
  - <u>Time consuming, non-scalable process</u>



Difference between antibunched (SPS), coherent (laser), and bunched (thermal/classical) light sources

Quantum key distribution with single photon

ACS Photonics, 5, 3, 692–698 (2018)

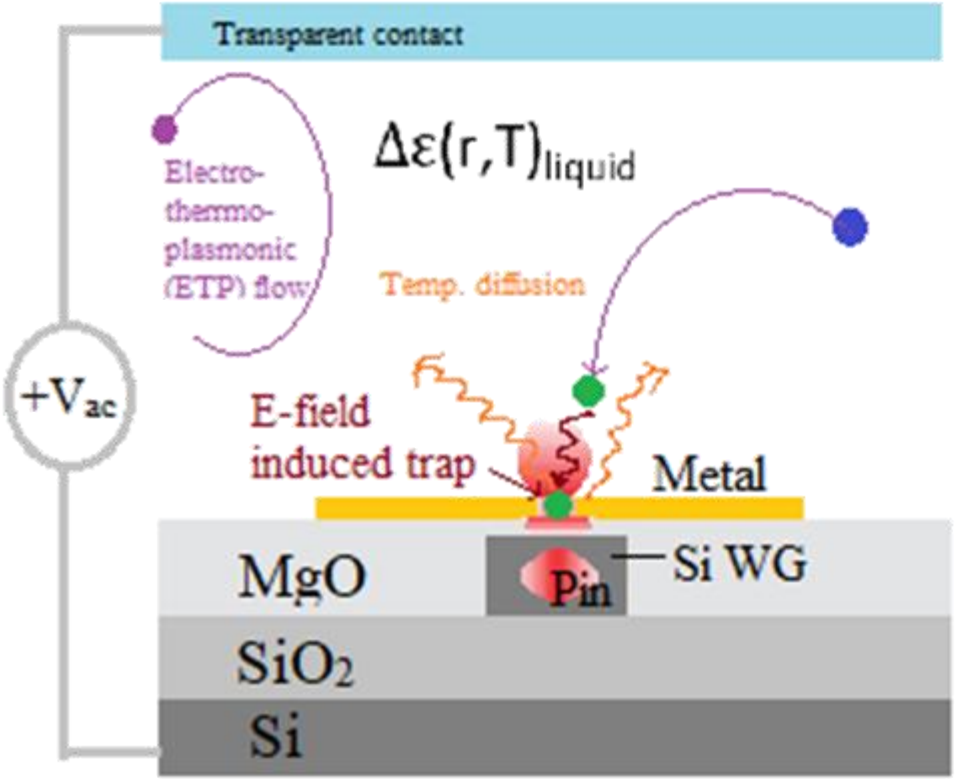
** J. C. Ndukaife et al, Long-range and rapid transport of individual nano-objects by a hybrid electro-thermo-plasmonic nano-tweezer, Nature Nanotechnology, 11, 1, 53–59 (2016).*

Proposed Scheme

Waveguide excitation and plasmonic coupling to nanogap → Localized & enhanced field in gap creates gradient around → Local fluid temp. rise around metal

→ AC bias→ $\Delta\,\varepsilon \propto \Delta T$ → On-demand fluid vortex = ETP flow * → Suspended nano-particles dragged near gap by ETP flow → Field gradient induced force drags nano-particles to hotspot

→ AC→ DC → Particle gets locked at stable trapping potential well * → Particle (emitter) gets trapped! → Emission enhanced by Purcell effect and routed through WG



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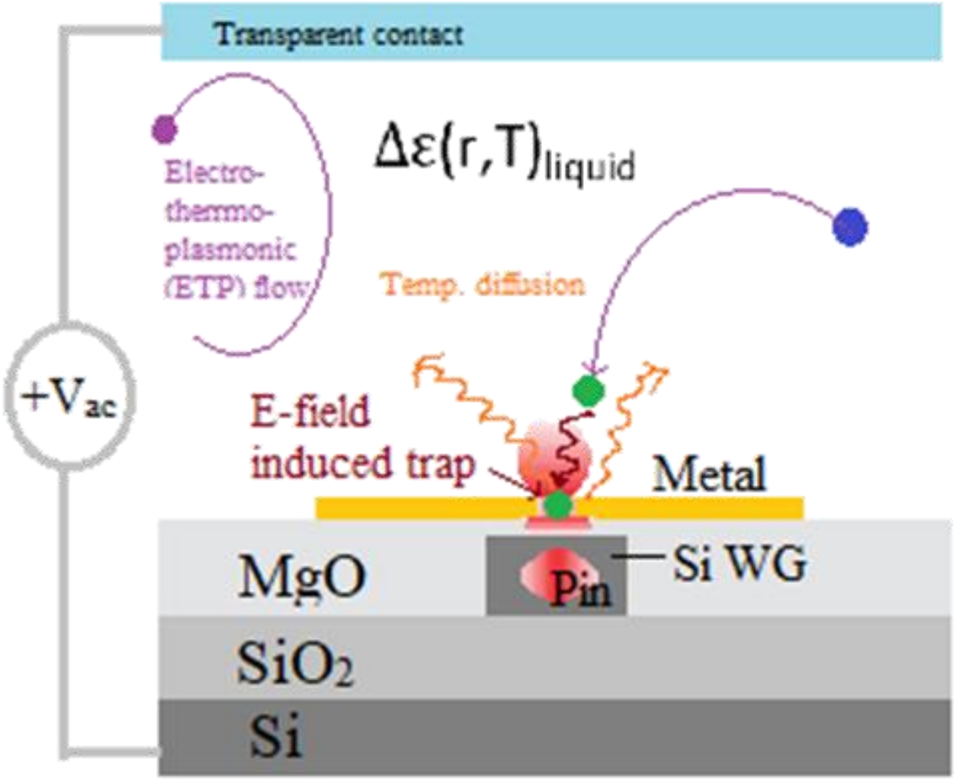


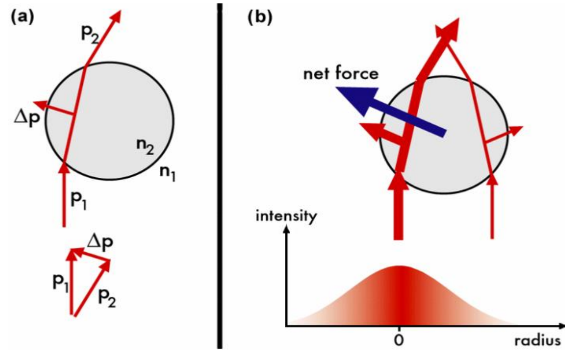
Goals and Challenges

- Investigate particle trapping ability
  - Trade off between power consumption, field strength confinement and particle size

$$\textbf{Trapping potential} = \int_{-\infty}^{r} \mathbf{F.dr} \propto \frac{\textbf{Input power} \times \textbf{Particle size} \times \textbf{Field gradient}}{\textbf{Gap size}}$$

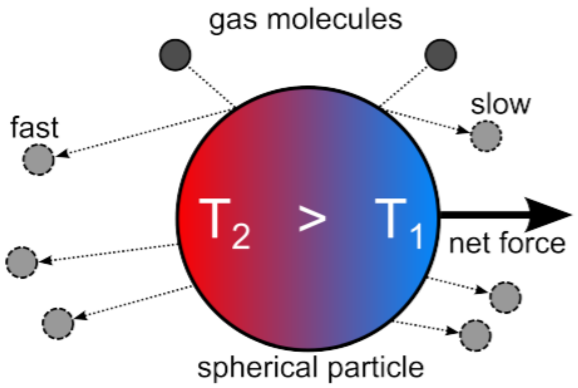
(Note: The above equation only represents general dependence, not exact relation)

  - Required trapping potential depth $\geq 10K_BT$ for stable trapping



Gradient optical force

- Check thermal feasibility of system operation
  - High excitation power → higher plasmonic loss → High temperature rise (ΔT) → convective flow or thermophoretic force(big particle) acting oppositely → reduces trap stability



Thermophoretic force

Simulation set up

COMSOL Multiphysics module components:

i. Wave optics module
- Scattering boundary condition
- Full wave study
- Used mesh control faces

ii. Heat transfer in Solid
- Convectional flow neglected
- Liquid considered as solid

Material choice

i. Aluminum as metal (initially used TiN)
- Smaller screen depth, more metallic

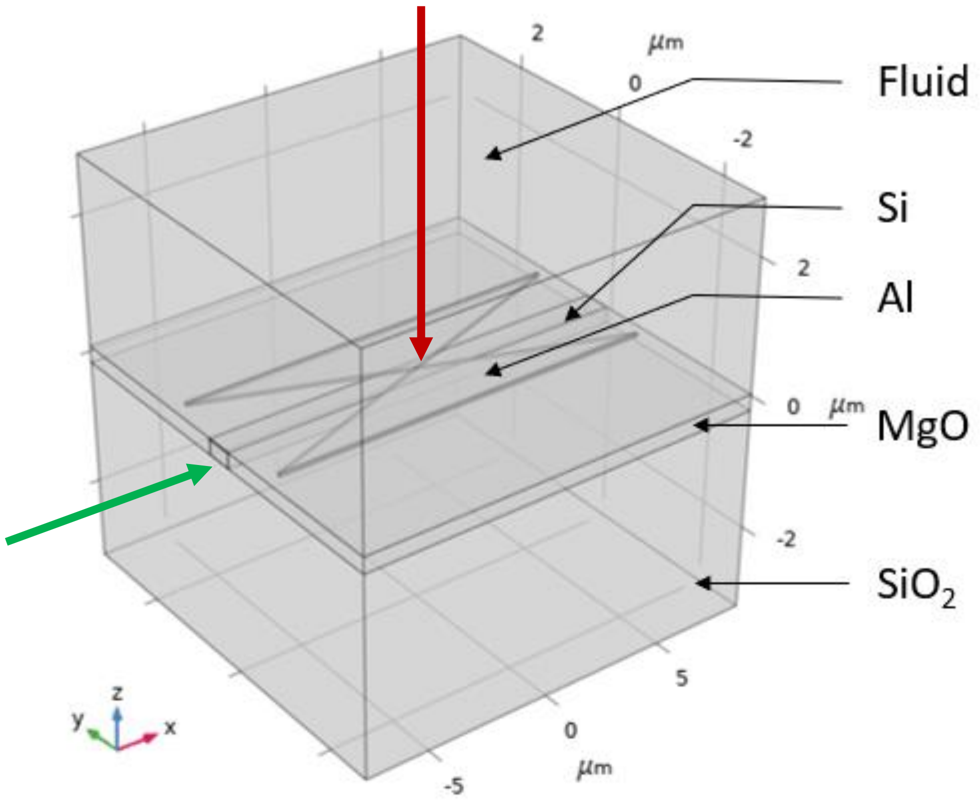
  (ε_{Al} (1.55 μm)= -242+49i, δ_{Al} = ~8 nm;

  ε_{TiN} (1.55 μm)= -24+36i, δ_{TiN} = ~21 nm)
- Thermally conductive, better heat dissipation

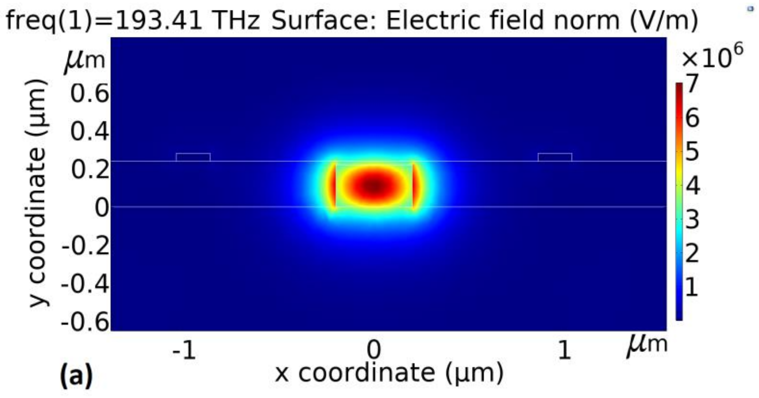
  (κ_{Al} = 237 W/m/K ; κ_{TiN} = 29 W/m/K)

ii. Polystyrene as nano-particle
- Good polarizability
- Simplicity

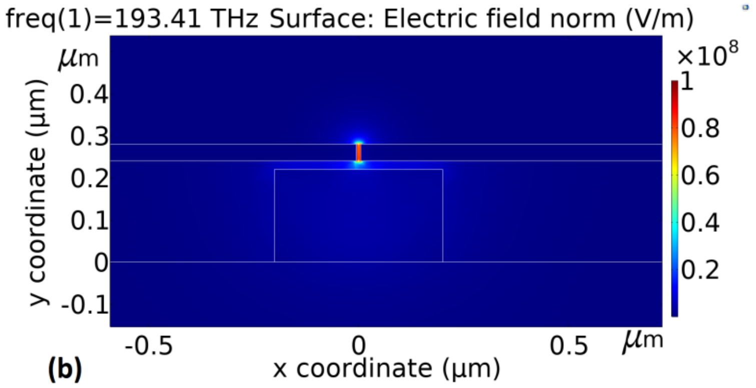
Mode coupling with hybrid waveguide



Photonic mode

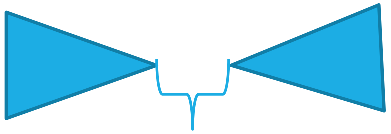


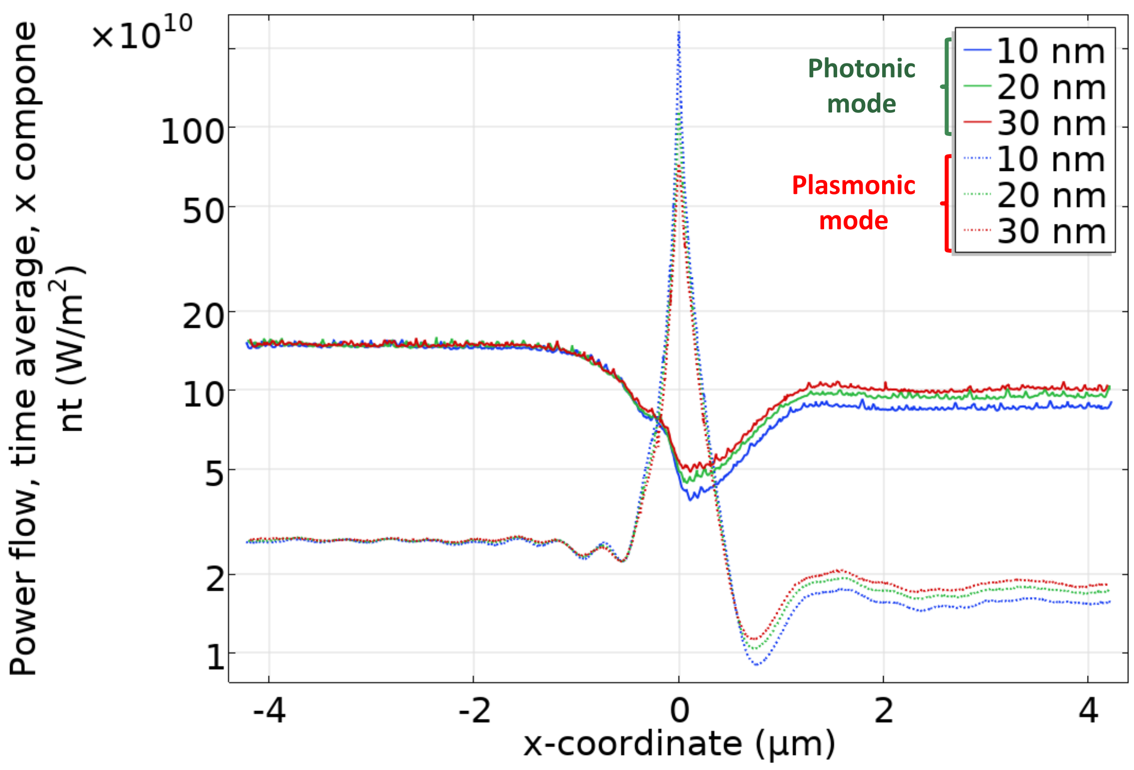
Plasmonic/ hybrid MIM mode



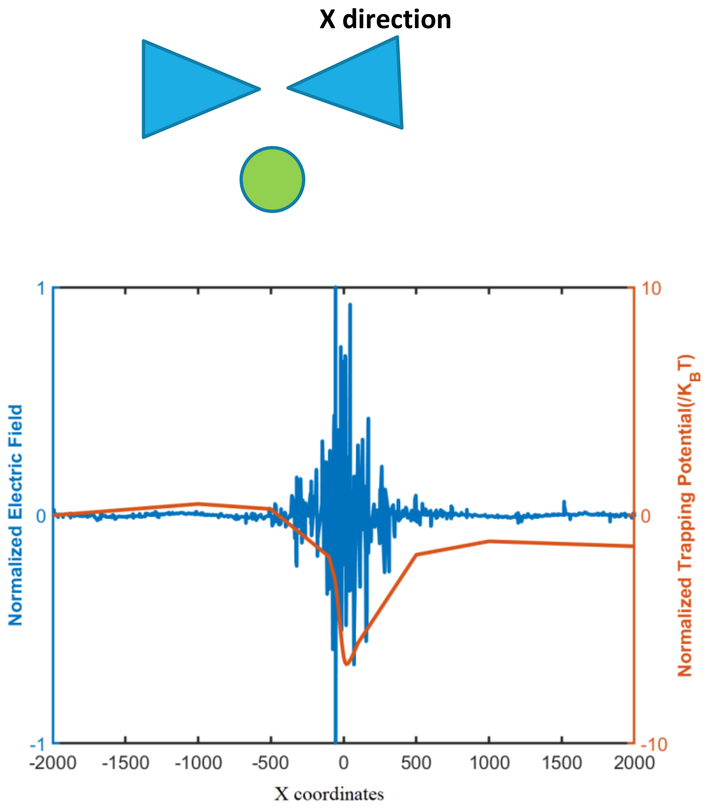
Power coupling efficiency

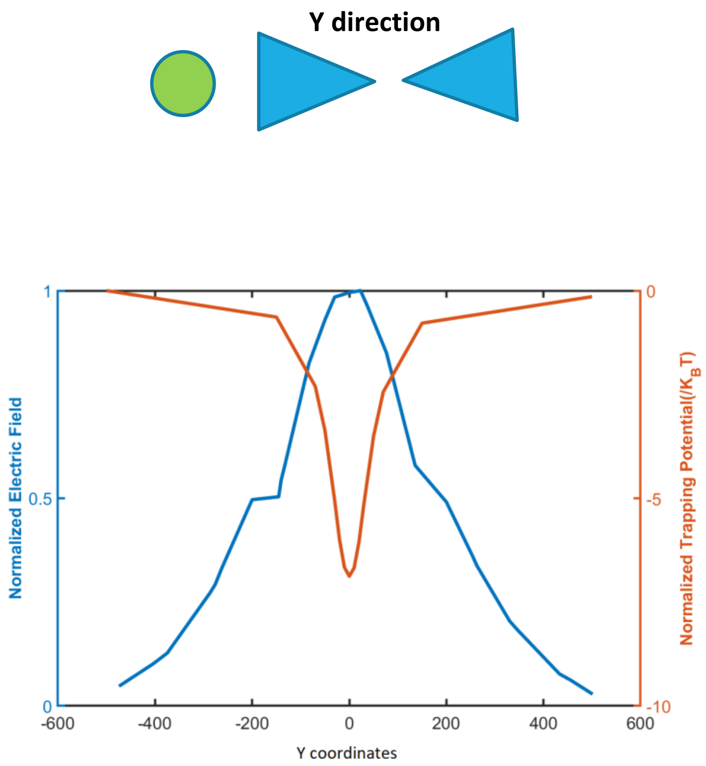
- Power transition gives an approximate idea of mode coupling strength
- Sharp, >10x enhancement of plasmonic mode power for smaller gap
- Insertion loss is between 30% to 50% for decreasing gap size (power input 8mW)
- Can be further optimized by tuning structure parameters

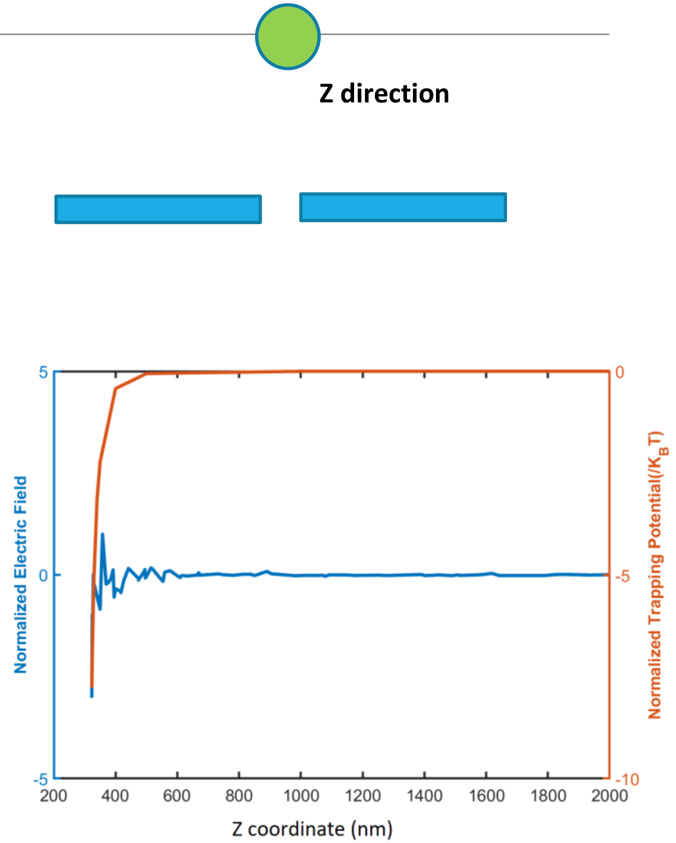




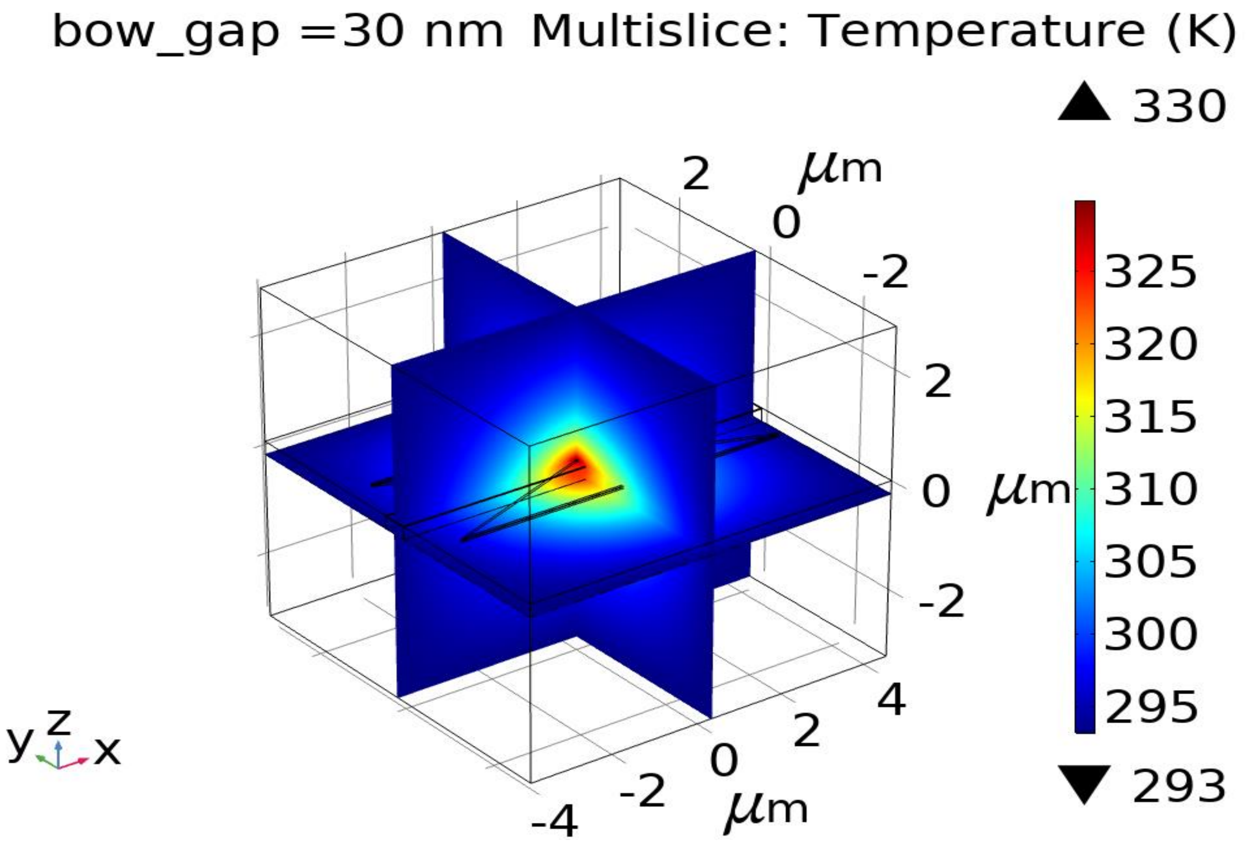
Field induced trap for nano-particle







Temperature profile



Conclusion

- ✓ Effective adiabatic conversion of injected photonic mode to highly confined and enhanced MIM mode is achieved with the geometry.
- ✓ The confined enhancement of field creates sharp field gradient leading to stronger force ($\propto E^2$).
- ✓ Capability to trap nano particles with support of ETP flow verified.
- ✓ Power flow transition between the distinguished modes indicative to effective emitter-waveguide coupling.

<u>Future schemes:</u>

- ➢ Efficient power coupling with lower input power (→lower temperature)
- ➢ Investigation of Purcell factor and emission coupling
- ➢ Structural modification to accommodate additional heatsinks if required.
- ➢ Full process implementation in COMSOL Multiphysics combining AC/DC ,Fluid mechanics along with wave optics and heat transfer modules.

Thank you