3D DESIGN AND PERFORMANCE ANALYSIS OF NANO-SIZED SQUID-ON-TIP

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Abstract

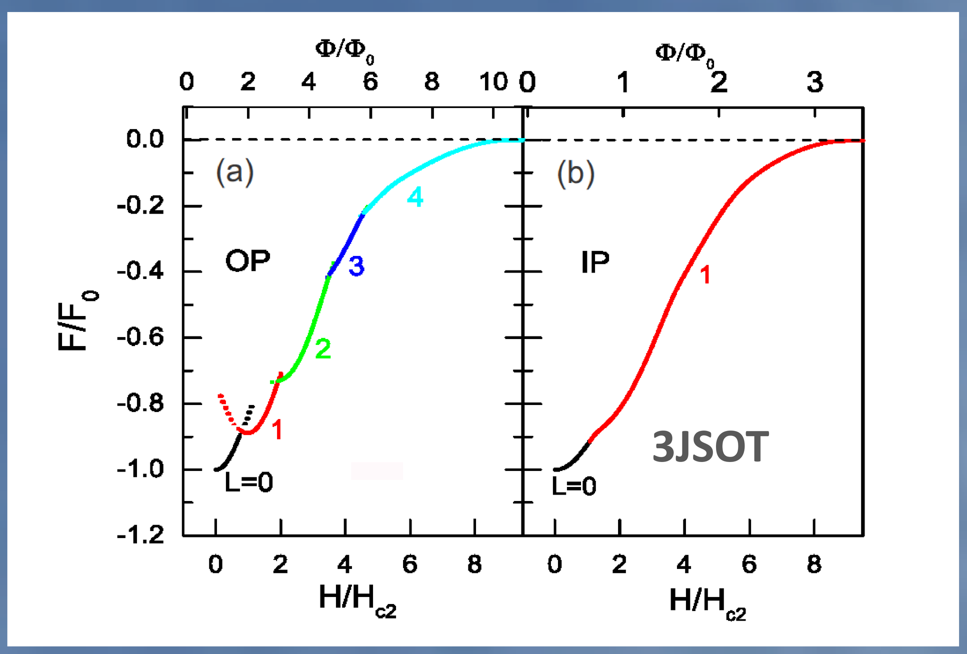
SQUID-on-tip (SOT) is the most sensitive detector of small magnetic moments to date [1]. We analyze the performance of such nano-sized SOT in the presence of the magnetic field, using the state-of-the-art three dimensional (3D) simulations within the phenomenological Ginzburg-Landau (GL) theory. Based on the observed behavior of the superconducting order parameter in the SOT, the distribution of the Cooper-pair density and the behavior of the circulating supercurrents, we propose engineering solutions at the nanoscale to improve the sensitivity of the device. By introducing the constriction in the arms of the SQUID loop, the gradient of phase of the order parameter is largely enhanced in the constriction of the SOT in the Meissner and first vortex state. This is expected to facilitate the interference pattern of the critical current of the SOT and reduce the noise. Furthermore, wedge shaped three junction loop of SOT (3JSOT) enables the tunability of the device and its selective response to both the in-plane and out-of-plane components of magnetic field [2]. We further discuss the other realizations of the SOT with engineered 3D shapes of the SQUID itself [3] and show the relation of those geometries to sensitivity to 3D magnetic field.

Free energy

- Using the mathematical transformation, Gauss theorrem and London gauge the dimensionless free energy (in units of $H_c^2 V/8\pi$) for a finite sample can be expressed as:

$$F = V^{-1}\int_V [2(\vec{A}-\vec{A}_0).\vec{J}_{3D} - |\psi|^4]d\vec{r}$$

- The stability range of the even states with vorticities larger due to symmetry.
- Wedge-shaped loop of the 3JSOT is also sensitive to the in-plane component of the magnetic field.

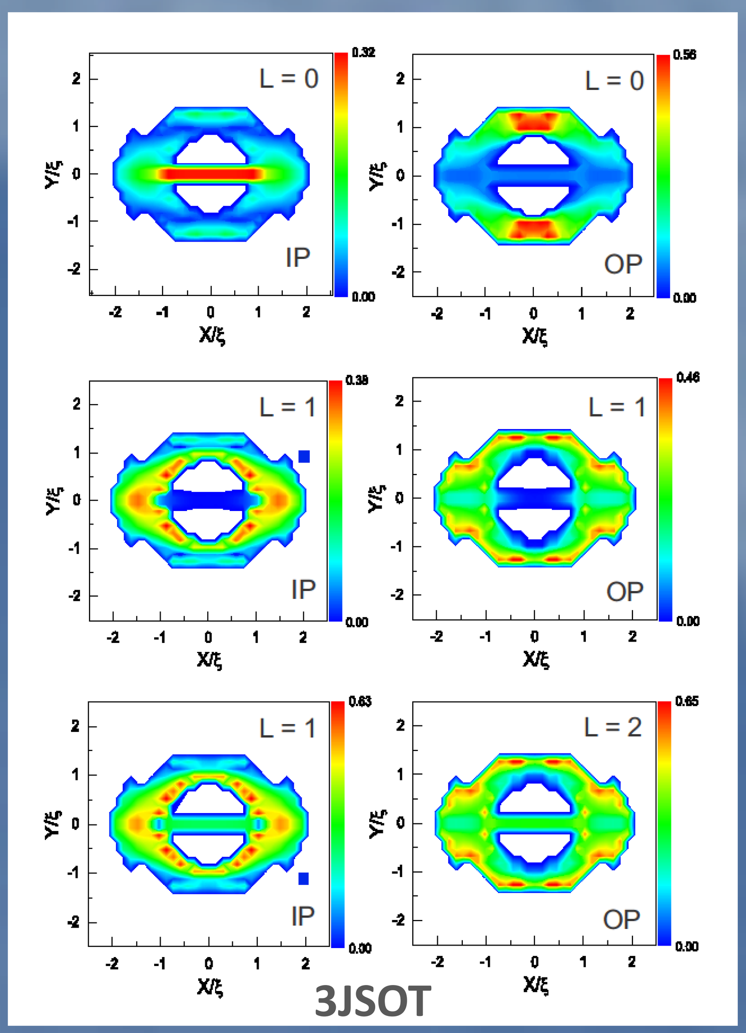


Total screening current

- Screening current is calculated by:

$$\vec{J}_{3D} = \frac{1}{2i}(\psi^*\vec{\nabla}_{3D}\psi - \psi\vec{\nabla}_{3D}\psi^*) - |\psi|^2\vec{A}$$

- Screening current density is larger in the connecting arm than in the side arm of the loop of 3JSOT of the IP case in the Meissner state, whereas in the OP case the current is lower in the connecting arm and greater in the side arm.
- Screening current density (also Cooper pair density) in the connecting arm of the loop alternate from low to greater values respectively due to switching from superconducting to normal state and vice-versa.



References

[1] D. Vasyukov, Y. Anahory et al., A scanning superconducting quantum interference device with single electron spin sensitivity, Nature Nanotech **8**, 639-644 (2013).

[2] Y. Anahory, J. Reiner et al., Three-Junction SQUID-on-Tip with Tunable In-Plane and Out-of-Plane Magnetic Field Sensitivity, Nano Letters **14**, 648-6487 (2014).

[3] C. Granata, & A. Vettoliere, Nano Superconducting Quantum interference device: A powerful tool for nanoscale investigations, Physics Reports, In press (2015).

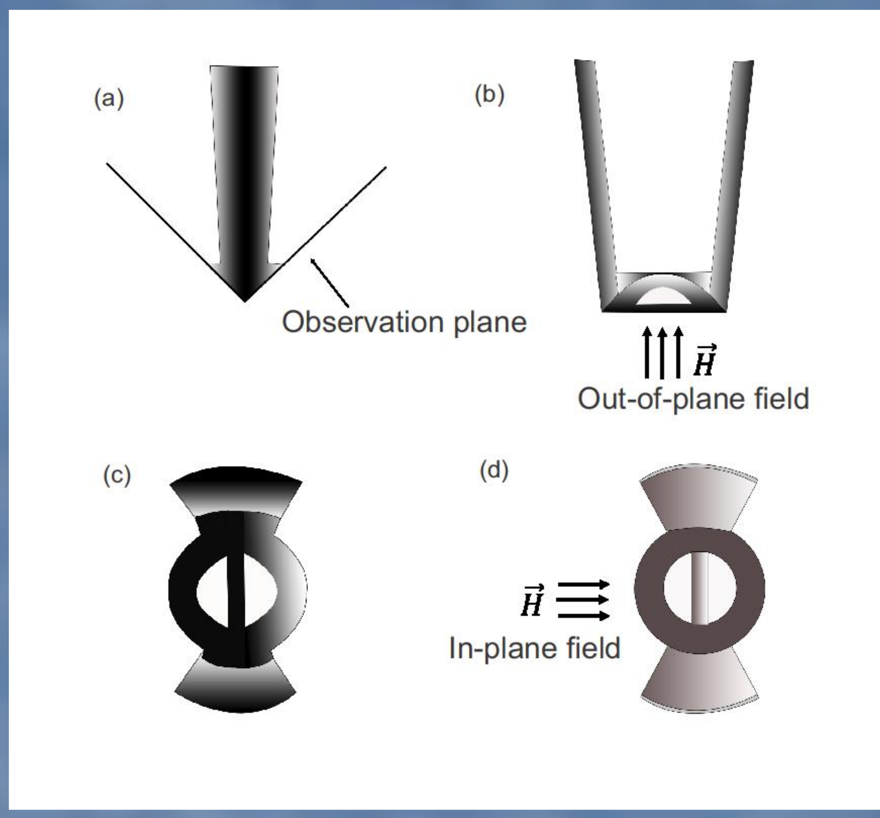
System of interest

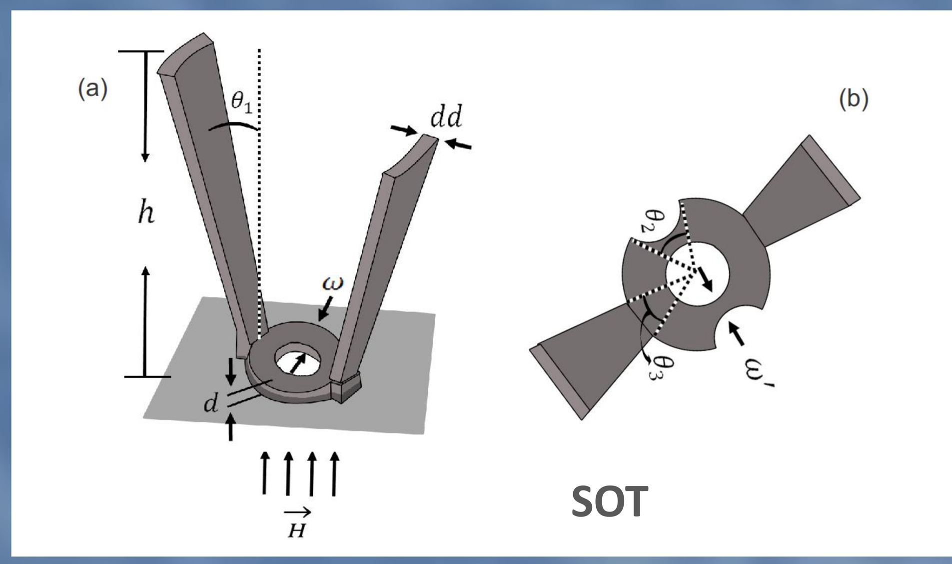
Using dimensionless variables and the London gauge for the vector potential $\vec{A}$, the 3D GL equation can be expressed as :

$$(-i\vec{\nabla}_{3D} - \vec{A})^2\psi = \psi(1 - |\psi|^2),$$

with the boundary condition,

$$\vec{n}.(-i\vec{\nabla}_{3D} - \vec{A})\psi\Big|_{boundary} = 0.$$



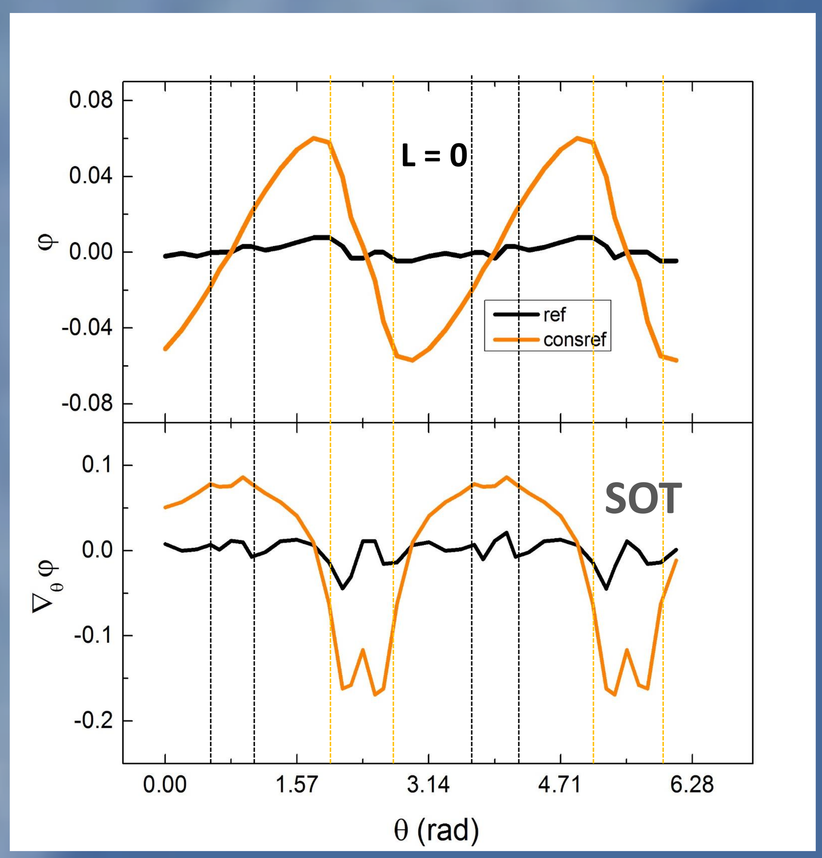


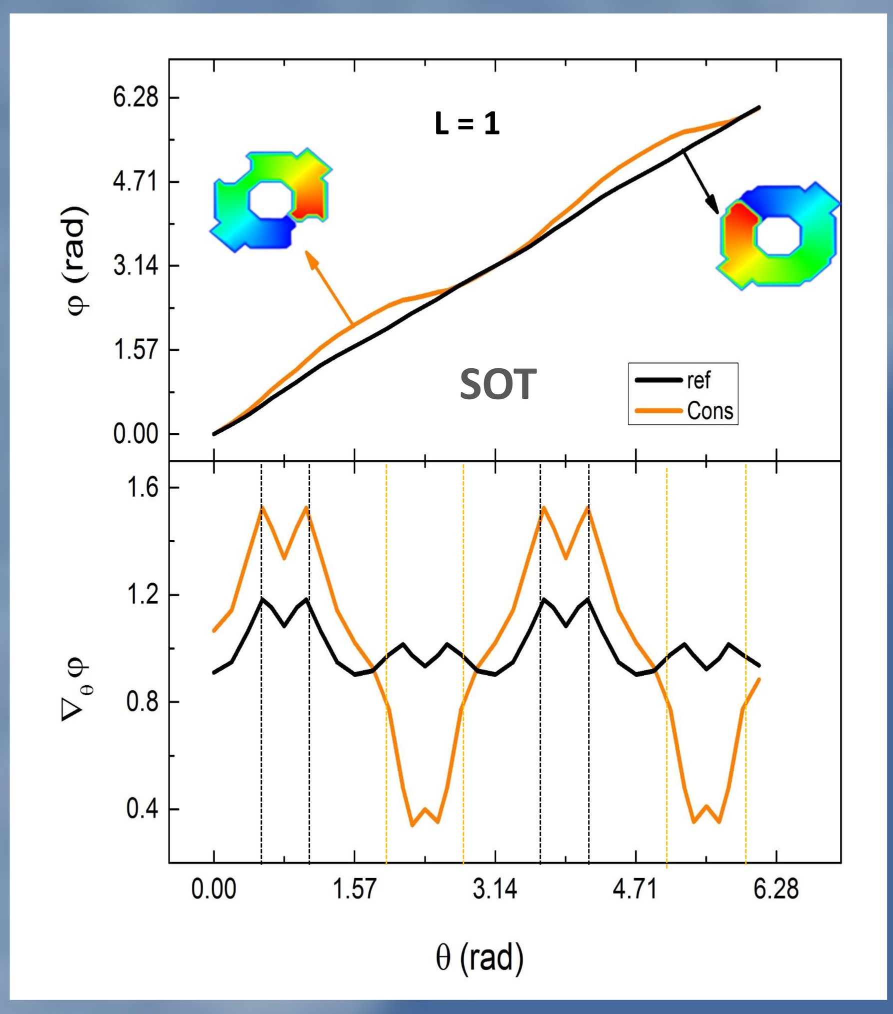
In the above figure, oblique view of SQUID-on-tip (SOT) device is shown, (a) without and (b) with constriction in the pick-up loop, with indicated relevant geometric parameters and applied magnetic field.

Oblique view of the 3JSOT sample is shown in the left figure: (a) side view from y-axis, (b) side view from x-axis (c) bottom view, and (d) top view, with indicated relevant geometric parameters and applied magnetic field.

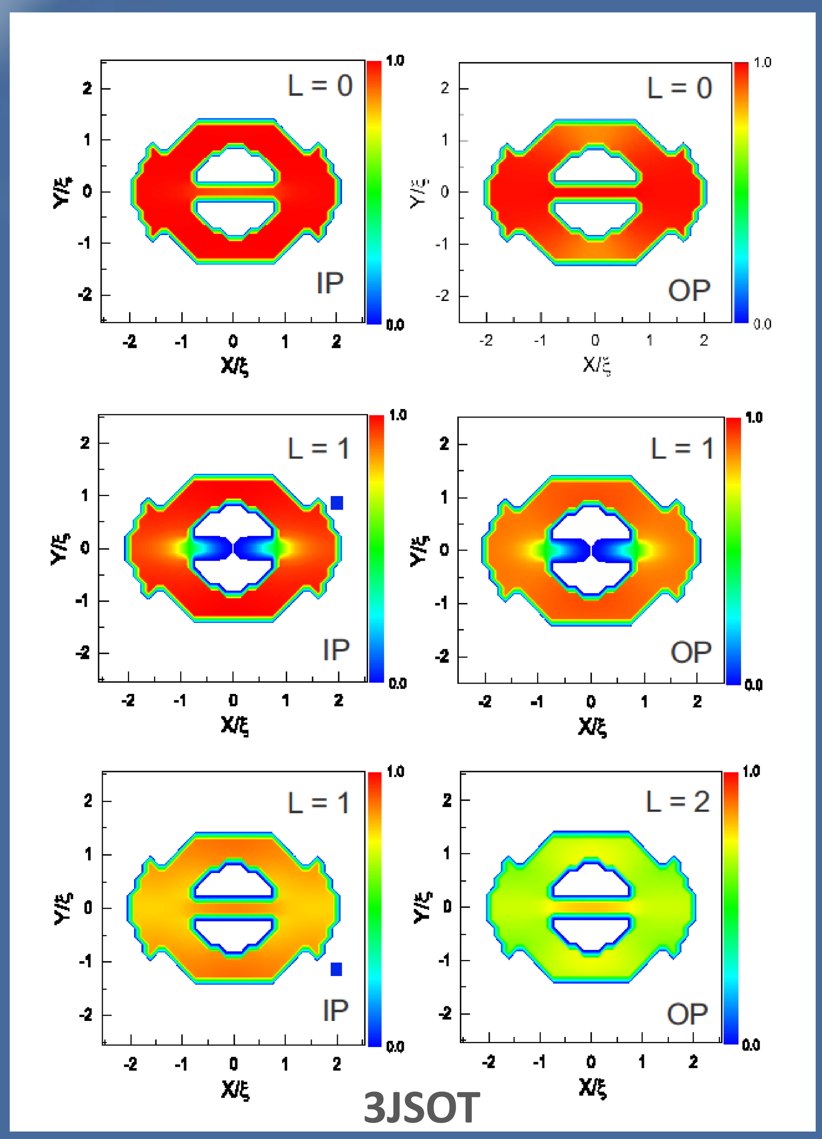
Results

- Using 3D GL simulation, I characterize the behavior of SOT in applied magnetic field. Phase of the order parameter is calculated according to the **de Moivre's formula**.
- Clearly the phase of the order parameter of SOT with constriction in the Meissner state at inner edge of the loop, alternates with respect to the angle around the loop. Phase change is observed with the noticeable split at the constriction region in the arm of the loop of SOT in the L = 1 state. Phase of the order parameter is important for sensitivity of the SOT which can be optimized by varying the length of the constriction region of the loop.





- Connecting arm of the 3JSOT loses and regains its superconducting state for vorticity odd and even respectively in the OP case.
- This distinct shape of the SOT persists its performance even in higher magnetic field.



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Conclusions

- We investigated theoretically the influence of the constriction of the loop of SOT on the properties of the device.
- The phase of the order parameter and the screening current are strongly influenced by the constriction in the Meissner state and in the first vortex state.
- The distinct 3D shape of the 3JSOT persists its performance even in higher magnetic field and is sensitive to both in-plane and out-of-plane components of the magnetic field.