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Vortex state in thermally-induced pinning patterns in superconducting film

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ABSTRACT

We propose a way to manipulate the landscape of the superconducting condensate in thin films via stripe-like (1D) and checkerboard (2D) periodic patterns. Our approach is based on the spatially localized heating of the superconductor, which is reflected in sinusoidal variations of the local temperature, which can be produced via, e.g., a focused laser beam or nanoheaters. This simple approach provides a very good alternative for modulation of the vortex collective, emerging in the type-II superconductors as a natural response to the applied magnetic field and the transport current, which was, up to now, controlled mainly via nanofabricated static pinning centers, whose distribution cannot be changed once the landscape is defined.

1. Introduction

The design of pinning configurations and control of the pinning interaction with vortices are fundamental for creating functional new devices with superconductors [1–3]. The pinning centers play a crucial role in providing highly efficient anchoring of vortices in thin superconducting films with artificially patterned nanoperforations [4,5], variations of sample composition or/and thickness [6–8], and atomic vacancies [9]. Nanoengineered superconducting systems can also utilize a variety of artificial magnetic traps [10–25], leading to a pinning system with a high degree of tunability. The pinning centers, as well as the modification of the shape of the site and the lattice, can strongly affect all relevant properties of the superconductors, including a metamorphosis of undeformed Abrikosov vortices into anisotropic Abrikosov–Josephson vortices, moving at significantly higher velocities, which offers an insight into the fundamental character of the dynamics of the superconducting condensate at high current densities, which is crucial for many applications [26]. The theoretical framework shows relevant changes of the properties of sample, such as spatial and temporal variations of the critical temperature (T_c) in the time-dependent Ginzburg–Landau model, as reported in recent papers [27–34]. In the presence of a tunneling current, suppression (or even depletion, in the extreme case) of superconductivity occurs in the confined area below the scanning tunneling microscopy (STM) tip, which can serve as a pinning mechanism for nearby vortices [35]. Recently, a dynamic thermal pinning landscape was proposed, based on the interaction of the condensate with a pulse laser [36,37], where temporal commensurability phenomena are found to arise due to the locking between the frequency of the dynamic pinning and the frequency of the characteristic condensate dynamics. These stroboscopic states are quite robust, persisting in wide parameter space (magnetic field, current, temperature, magnitude of the dynamic pinning), and can serve either as a basis for a local velocimetry technique or for probing different vortex phases (Abrikosov, Abrikosov–Josephson) [37]. Moreover, local heating of the superconductor with a focused laser beam can be used to carry out a fast and precise manipulation of individual vortices [38], which opens up a novel research field that could be called optofluxonics, to be applied in quantum computation based on the braiding and entanglement of vortices in optically controlled elements of rapid single flux quantum logic. Another interesting feature of the arrays of the pinning center is that these structures are sometimes able to provide nonuniform current density distribution, which can favor vortex–antivortex (V–AV) pair generation at the place where the current reaches deparing current [39]. Calculations based on the Ginzburg–Landau theory have been carried out for arrays in a superconducting film, predicting a plethora of V–AV ionic molecules and composite V–AV lattices [40–43]. Optical traps of vortices are also relevant in rotating Bose–Einstein condensates (BEC), as realized by a geometric arrangement of laser beams at a smaller scale compared to vortices [44]. Therefore, optical pinning structures go beyond the traditionally used permanent pinning centers, which once constructed cannot be further modi-

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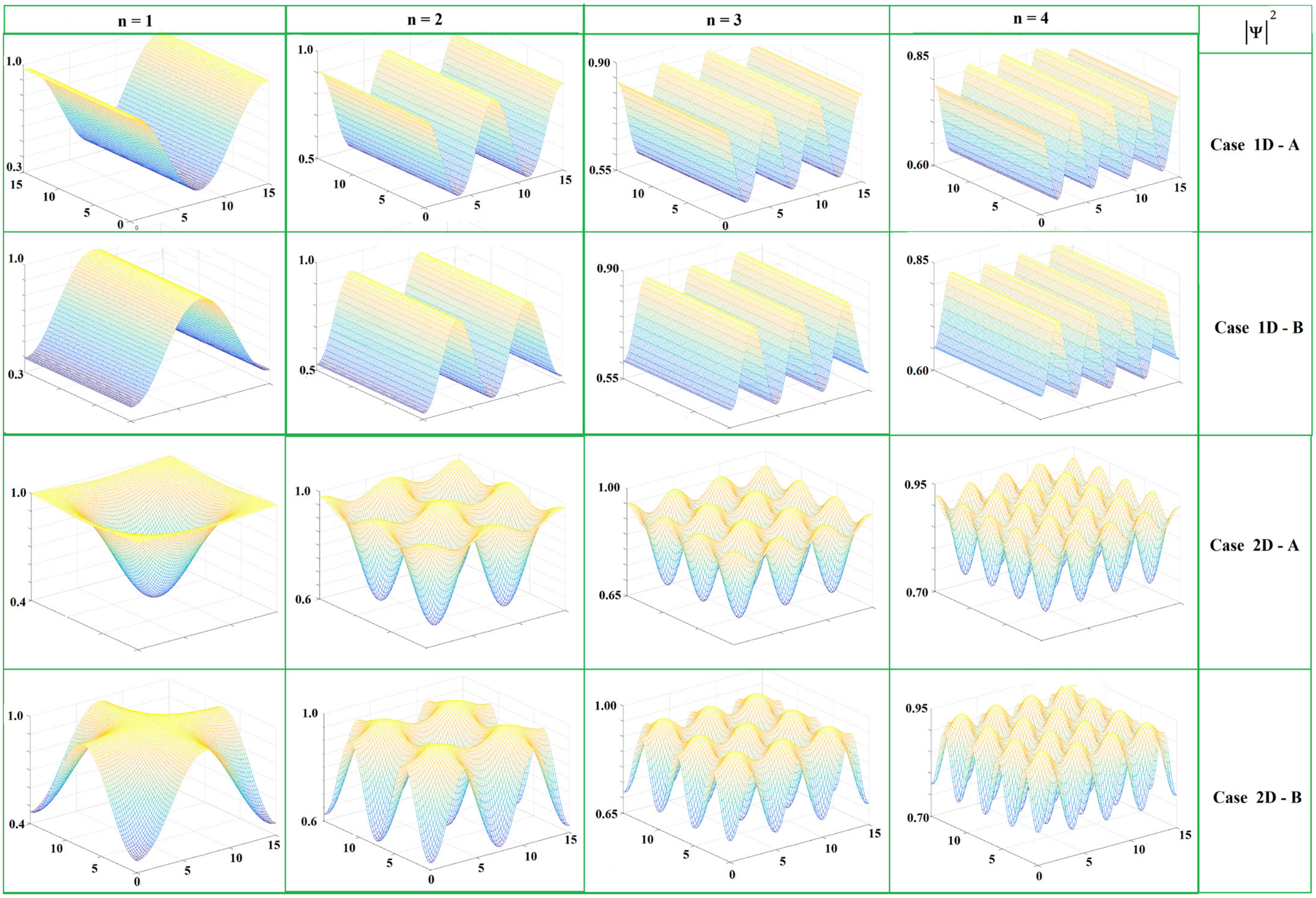

Fig. 1. (Color online.) Spatial pattern of the Cooper-pair density, $|\psi|^2$ in absence of magnetic field.

fied. Certainly the added degrees of freedom in terms of different possible optical patterns could open new phenomena unattainable in the studied superconducting systems, which is the main motivation for the present investigation. The interaction of light with superconductivity in most cases leads to local heating of the condensate [45–51]. This paper describes the usage, for the above mentioned goals, of an optical device to create a one dimensional (1D) stripe of sinusoidal spatially dependent temperature T [see two top rows in Fig. 1], in order to create a spatial pattern of the order parameter, but also two-dimensional (2D) (checkerboard) cases, shown in the two bottom rows in Fig. 1. We consider how such pinning patterns, which can be modified in-situ with an optical excitation on the sample, change in characteristic critical fields H_1 (field value for the first vortex entry) or H_2 (field at which the superconductivity is destroyed), as well as in the magnetization and the Cooper-pair density profiles arising as a result of the local interaction of vortices with the thermal configurations studied in this investigation. The paper is organized as follows: The model system, the theoretical approach, the numerical details, and the main characteristics of the sample are given in Section 2. The results of our numerical simulations are presented in Section 3, where we study the response of thin superconductors with an array of pinning centers created by a sinusoidal spatial profile of the thermal excitations. Our findings are summarized in Section 4.

2. Theoretical formalism

In the present investigation, we consider a very thin square superconducting bridge, of thickness $d \ll \xi$. So, for the determination of ψ, we consider the magnetic field to be uniform everywhere. In fact, within this limit, the demagnetization effect can be neglected and the magnetization can be calculated with the magnetic moment definition [52,53]. We considered a sample in Cartesian coordinates, of size $L_x \times L_y = 15\xi(0)$, with a Ginzburg–Landau parameter $\kappa = 1.3$, exposed to an external magnetic field $\mathbf{H} = H\mathbf{z}$, with regions of depleted superconductivity created by local heating. We considered a uniform mesh grid with a resolution of 5 points per $\xi(0)$, that is, $\delta = 0.2\xi(0)$. The form of the time-dependent Ginzburg–Landau equation in dimensionless units is given by [54–56]:

$$\frac{\partial \psi}{\partial t} = -\left(i\nabla + \mathbf{A}\right)^2 \psi + (1 - T(x, y))\psi \left(1 - |\psi|^2\right) \qquad (1)$$

$$\frac{\partial \mathbf{A}}{\partial t} = (1 - T(x, y)) Re\left[\bar{\psi}\left(-i\nabla - \mathbf{A}\right)\psi\right] - \kappa^2 \nabla \times \nabla \times \mathbf{A} \qquad (2)$$

with the Neumann boundary condition at sample boundaries:

$$\mathbf{n} \cdot (i\nabla - \mathbf{A})\psi = 0 \qquad (3)$$

We simulated n (1D) rows and (2D) checkerboard pattern of heat sources ($n = 1, 2, 3, 4$) in the sample, via the temperature function $T(x, y)$ defined as:

$$T(x, y) = T_0 \begin{cases} \sin^2(n\pi x/L_x)\,, & \text{Case1D} - \text{A} \\ \cos^2(n\pi x/L_x)\,, & \text{Case1D} - \text{B} \\ \sin^2(n\pi x/L_x)\sin^2(n\pi y/L_y)\,, & \text{Case2D} - \text{A} \\ \cos^2(n\pi x/L_x)\cos^2(n\pi y/L_y)\,, & \text{Case2D} - \text{B} \end{cases} \qquad (4)$$

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