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Optical magnetic flux generation in superconductor

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Abstract. The generation of the magnetic flux quanta inside the superconductors is studied as a new effect to destroy superconductivity using femtosecond (fs) laser. The vortices are successfully generated in the $YBa_2Cu_3O_{7-\delta}$ thin film striplines by the fs laser. It is revealed that the vortex distribution in the strip reflects the fs laser beam profile.

Keywords. Ultrafast phenomena; femtosecond laser; optical magnetic flux generation.

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1. Introduction

Excitation and observation of ultrafast phenomena in solid states are of essential interest in the field of condensed matter physics. Recent femtosecond (fs) laser technology is now stimulating such research fields, and a variety of new physics is coming in sight. As one of the attractive fields, one can study the ultrafast phenomena in quantized system by means of the fs optical excitation. Superconductivity can provide an excellent stage to open the new field as the transient quantum physics because of its macroscopic quantized states. In a series of our recent reports, we proposed and studied the optical generation and control of magnetic flux quanta (MFQ) in superconductors [1–7]. When a part of superconductive thin film loops or striplines carrying transport supercurrent is illuminated by the fs laser, the magnetic flux is generated and it is controllable with the laser power, bias currrent, and other excitation parameters. The generation is itself regarded as new ultrafast phenomena breaking the conventional rule of superconductivity. The origin of the optical process can be understood as an ultrafast supercurrent modulation without phase transition: optical pair breaking, hot quasiparticle scattering, and recombination [8,9]. Till now, the following notable performances have been achieved: MFQ's are generated by even a single shot of the fs pulse, and the fs optical beam profile is transferred into the 2D vortex distribution in the superconductive strip. In the present work, optical magnetic flux generation in the superconductive striplines is reviewed.

2. Idea

Suppose that the superconductive thin film stripline is carrying transport current as shown in the upper panel of figure 1. The supercurrent distributes in the middle of the line even in a Meissner state. When a small area is excited with the fs laser, the incident photons break the pairs which scatter with the other carriers in several femtoseconds. The scattered particles, hot quasiparticles, cannot carry the supercurrent anymore, and cause further pair breaking. Thus, the avalanche process reduces greatly the number of the pair density. In the general picture of the optically-excited superconductor, the remaining pairs are accelerated and the total current is kept constant. However, the compensation is not an instant process but requires certain time. Thus, the supercurrent at the optically excited area decreases so that the ultrashort electromagnetic wave is emitted into free space in proportion to the time derivative of the supercurrent. Note that the reduced supercurrent distribution reflects the optical beam profile as illustrated in the middle panel.

Once this scenario is accepted, it means that inside the stripline, there exists magnetic flux induced by the surrounding supercurrent; the reduced current at the optically excited

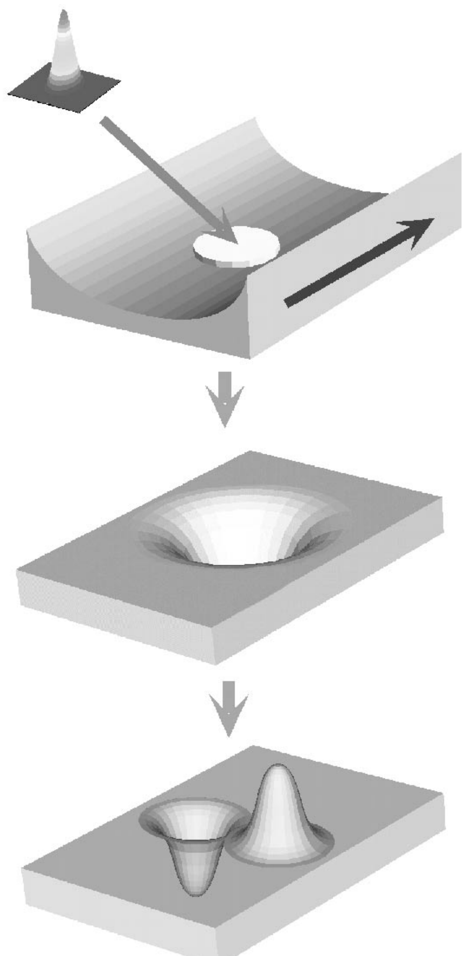

Figure 1. Idea for the optical magnetic flux generation principle.

area cannot block its penetration. Now, the initial conditions are changed and the system relaxes into the equilibrium state of superconductivity. During the relaxation, the magnetic flux quantizes into the vortices, which are expected to be trapped at the pinning centers. In other words, vortex and anti-vortex bundle pairs can be generated and the distribution of the vortices may reflect the laser beam profile. This is the basic idea for the present research.

3. Experimental

Figure 2 shows a schematic illustration of the experimental set up. The fs pulses with a pulse width of about 50 fs, a center wavelength of about 800 nm, and a repetition rate of 82 MHz, produced by a mode-locked Ti : sapphire laser are used to generate and control the magnetic flux in the loop. The sample is illuminated by laser pulses at pulse energies between 20 and 70 mW while carrying transport current. The beam profile of the pulses at the sample surface has a full-width at half-maximum (FWHM) of 25 μm. Pulses can be selected by triggering the pulse selector in this system. After the removal of the bias current, the supercurrent distribution is visualized by the THz radiation imaging technique at a typical laser power of 2 mW, which is low enough to avoid the optical influence on the generated flux, with a pixel size of 5 mm$\times$5 mm. The details of the THz beam generation and detection system, and the imaging system can be found elsewhere [10,11]. We observe only the x-component of the supercurrent distribution in the present work.

$YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films are patterned into a stripline structure using conventional photolithographic techniques and Ar ion milling. Figure 3 shows an example of the prepared sample, which consists of a 114-μm-wide by 100-nm-thick YBCO thin film strip.

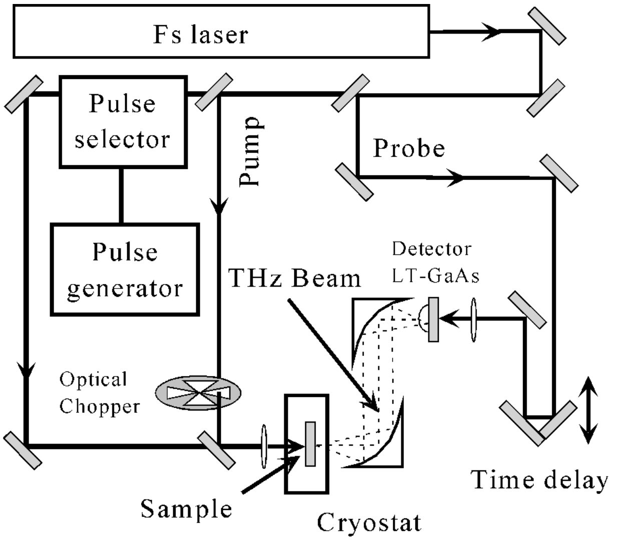

Figure 2. Experimental set up for optical pulse illumination of the sample with a fs laser and magnetic flux observation by THz radiation imaging.

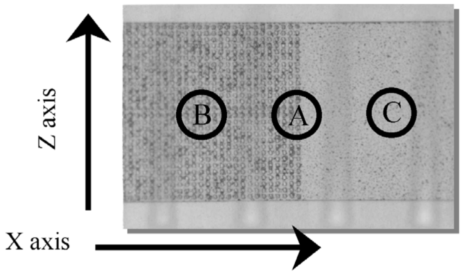

Figure 3. Photograph of a 114-μm-wide YBCO strip. The positions A, B, and C correspond to the spots illuminated by the fs laser. Orientation of the coordinates is also explained.

Half of the area in this sample has the ordered array of the antidots with a diameter of 1 μm at an interval of 4 μm.

4. Results and discussion

The positions A, B, and C in figure 3 are illuminated one-by-one at a bias current of 200 mA and a laser power of 30 mW. Figure 4 shows the two-dimensional images of the supercurrent distributions. After the illumination at position A, it is observed that the clockwise and counterclockwise supercurrents circulate in the upper and lower part of the excited area, respectively. This indicates that a bundle of vortices with different polarity is generated near the excited area. The generation is also confirmed when the positions B and C are excited. The distributions at the area with the antidots are more clear than the area without them.

The magnetic field distributions calculated by solving Biot–Savart's law indicate that the distance from the maximum position for the positive magnetic field to the one for the negative coincides with a full-width at a half-maximum of the laser beam profile regardless of the positions. This suggests that the vortices are generated by the supercurrent modulation and frozen at the generated areas. The persistent current at the edges of the strip is generated by the trapped vortices near the edges after the removal of the bias current. Sim-

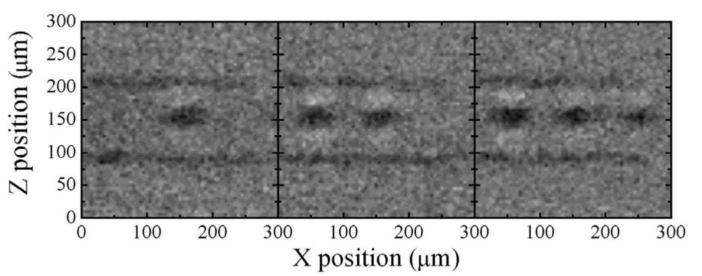

Figure 4. Images of the supercurrent distributions. Vortex-generation process was done at positions A, B, and C, in order, and images were observed after each process.

ilar experiments with different beam diameters proved that the optically generated vortex distributions are closely correlated to the laser beam profile [7]. This vortex generation inside the YBCO thin stripline was also demonstrated using a single shot femtosecond laser, which will be reported elsewhere [12]. The amount of the magnetic flux quanta generated in the strips is roughly estimated to be around $100\phi_0$.

5. Summary

The generation of the magnetic flux quanta inside the superconductor is studied as a new effect in superconductivity using femtosecond laser. The vortices are successfully generated in the YBCO thin film striplines by the fs laser. It is revealed that the vortex distribution in the strip reflects the fs laser beam profile. The results presented here could open a new research field in the superconductor photonics.

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