Isolation from external magnetic fields is a fundamental requirement that appears in various scientific experiments today. In particular, for applications where static or slowly varying magnetic fields need to be screened, enclosures made of superconductors or high magnetic permeability metal alloys are typically utilized. These are called “shields” as they isolate the inner space from the external fields. They achieve this interior shielding by either expelling the fields from or drawing the fields into the shield materials, which inevitably results in the distortion of the external field profile by the presence of the shields themselves. In this communication, we report the first experimental realization of a “cloak” for dc magnetic fields. We construct a hollow cylindrical cloak with a material consisting of an artificially patterned network of superconducting and soft ferromagnetic elements. We show that, when an external dc magnetic field is applied, the interior of the cloak is completely shielded while the field outside remains unperturbed.

A dc magnetic cloak that shields the inner region without affecting the exterior space requires a highly anisotropic medium characterized with a response that is diamagnetic in one direction and paramagnetic in the perpendicular direction.\(^1\) For the former diamagnetic property, arrays of superconducting strips have been investigated,\(^1\) and we incorporate such structures into our cloaking material. See Figure 1(a). We thermally evaporate 200 nm-thick Pb film onto 77-μm-thick polyimide sheets and pattern the film into an array network using photolithography. When the magnetic field is applied perpendicular to the superconducting structures, the Meissner effect funnels the field into the regions between the adjacent plates. When the field encounters the next layer of superconducting planes, it becomes expelled, distorted, and then guided in a direction perpendicular to the original incoming direction. The field that penetrates the second layer through the gap between superconducting structures again sees the third layer to repeat the same process, until all applied field has been guided in-plane. In this stacked superconducting meta-material, we cascade the layers so that the positions of superconducting structures do not align perfectly from layer to layer to encourage field distortion within the material.

The strength of diamagnetism (for fields perpendicular to the plates) depends on the dimension of material building blocks (i.e., superconducting structures) and the lattice spacing for their network.\(^1\) This provides us with a knob to tune the field path by using the “graded” geometry with variations in lattice parameters. The spatial variation that we prescribe is that the gap between the superconducting plates narrows as the field penetrates deeper into the material. This allows the magnetic field to enter the cloak freely with little field perturbation while forcing it to be more distorted and guided within the material as it penetrates further into it. The outermost layer has 2000 μm × 2000 μm superconducting plates with a 600 μm gap. The innermost layer has the plates of the same size with 4 μm spacing. The gap is reduced in five discrete steps. See Table 1 for the physical parameters of different superconducting layers. The superconducting plate thickness (200 nm) is chosen to be smaller than the lattice spacing but larger than the London penetration depth.

The second requirement to realizing a dc magnetic cloak is to engineer a material with a tendency to shunt the magnetic field that is in plane. To achieve this specific profile of permeability, we deposit a soft ferromagnetic material between the neighboring superconducting layers and turn the space into a low reluctance path for guided magnetic field lines. Permalloy

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**Figure 1.** (a) Schematic of the cloaking material consisting of an array of superconducting and soft ferromagnetic elements. Only four sheets of the partial size are depicted and shifted for clarity. We design the plate corners to be round so that the field in the gap does not concentrate enough to break the superconductivity easily. (b) Apparatus geometry. (c) Topview schematic showing the locations of two Hall sensors and magnetic field lines in empty space. Sensor 1 detects the field that penetrates through the cloak, and sensor 2 is positioned to capture external field perturbations due to the presence of the cloak.
(Ni/Fe/Mo/Mn) is e-beam evaporated onto the backside of the polyimide sheets. To circumvent saturation and coercive field issues,\textsuperscript{11,12} we deposit multiple layers of 50-nm-thick Permalloy films spaced by 5-nm-thick Chromium layers. (See Table 1 for parameters used for the Permalloy/Cr material.) Finally, the polyimide sheets are rolled one layer over another to form a hollow cylindrical material (approximately 24 mm OD, 55 mm height, and 3 mm wall thickness) with the artificially engineered properties that the radial component of effective permeability $\mu_r$ lies between 0 and 1 and is an increasing function of $r$, while the tangential component $\mu_\phi > 1$.

Figure 1(b) depicts our measurement apparatus. A cylindrical cloak is placed between a set of coils that produces a dc magnetic field. For the field detection, a cryogenic Hall sensor (labeled 1) is placed inside the cylinder, with its sensing vector pointing towards the incoming field. Another sensor (labeled 2) is placed outside the cylinder, as close to the cylinder as it is allowed by the sensor housing. This sensor is placed $\approx 45$ degrees to the horizontal with

<table>
<thead>
<tr>
<th>Layer</th>
<th># of polyimide sheets</th>
<th>Spacing of superconducting plates</th>
<th>Thickness of superconducting layer on single polyimide sheet</th>
<th>Thickness of ferromagnetic material on single polyimide sheet [material] = [thickness of single layer] $\times$ # of layers on single polyimide sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>4 $\mu$m</td>
<td>200 nm</td>
<td>[Permalloy/Cr] = [50 nm/5 nm] $\times$ 18</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>10 $\mu$m</td>
<td>200 nm</td>
<td>[Permalloy/Cr] = [50 nm/5 nm] $\times$ 18</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>50 $\mu$m</td>
<td>200 nm</td>
<td>[Permalloy/Cr] = [50 nm/5 nm] $\times$ 18</td>
</tr>
<tr>
<td>4</td>
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<tr>
<td>5</td>
<td>5</td>
<td>400 $\mu$m</td>
<td>200 nm</td>
<td>[Permalloy/Cr] = [50 nm/5 nm] $\times$ 18</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>600 $\mu$m</td>
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</tr>
<tr>
<td>7\textsuperscript{a}</td>
<td>1</td>
<td></td>
<td></td>
<td>[Permalloy/Cr] = [50 nm/5 nm] $\times$ 28</td>
</tr>
</tbody>
</table>

\textsuperscript{a} The last polyimide sheet (Layer 7) is only 7.6 $\mu$m-thick and is placed with the ferromagnetic material side facing inward and the polyimide side facing out.

Figure 2. (a) Schematic of field lines around a superconducting shield. (b) Sensor 1 measurements for different currents injected into the surrounding set of coils. No shield and s.c. shield indicate measurements at 77 K and 4 K, respectively. (c) Sensor 2 measurements. (d) Schematic of field lines around a Mu-metal shield. (e) Sensor 1 measurements with and without a Mu-metal shield. (f) Sensor 2 measurements with and without a Mu-metal shield.
its sensing vector tangential to the cylinder circumference to capture external field perturbations. Both scattering and shadowing can be investigated with sensor 2 by changing the polarity of the current injected in the coils. The sensor locations with respect to the cylinder as well as a schematic for the applied magnetic field are illustrated in Figure 1(c).

For comparison, we first present results obtained with cylinders (non-cloaks) that are often used in magnetic shielding applications. The first material is a hollow cylindrical shield made of pure Nb, which becomes superconducting below 9.3 K. Above the superconducting transition temperature, the field penetrates through the shield just as shown in Figure 1(c). However if the field is turned on after the shield has become superconducting, the field becomes completely expelled, distorting the field lines as illustrated in Figure 2(a). Figure 2(b) shows our sensor 1 measurements at 77 K where the shield is just a normal metal and also at 4 K where it is in a superconducting state. Measured magnetic fields are plotted against currents injected into the coils. Sensor 2 measurements at the same temperatures are shown in Figure 2(c). The bending of the external magnetic field lines at the shield surface gives rise to considerable field distortion and shadowing, resulting in the change in the magnetic field detected by the sensor 2. Although a conventional superconductor completely shields the inner region as shown in Figure 2(b), the exterior field becomes greatly perturbed, a reason why this shield is not considered a cloak. We also note that if the transition temperature is crossed with the external magnetic field on, the field becomes trapped inside the cylinder,[13] making this device not ideal for applications where the static field needs to be screened.

The second material suited for comparison is a hollow cylinder made of Mu metal. Mu metal is a soft ferromagnetic Ni/Fe/Cu/Mo alloy that is extremely effective at screening static fields. High magnetic permeability of the material pulls the field lines towards the shield surface and contains them within the material. A schematic for magnetic field lines is represented in Figure 2(d). Sensor 1 measurements with and without the shield are shown in Figure 2(e) and the same measurements for sensor 2 are shown in Figure 2(f). As in the superconducting case, the shield bends the nearby field, causing significant distortion as well as shadowing. Although Mu metal screens the inner region, the exterior field is greatly perturbed again.

Finally, we present the results of the dc cloak made of a patterned network of superconducting and soft ferromagnetic elements. The perfect cloak would shield the interior from the external field while leaving the external field completely unperturbed as shown in Figure 3(a). The magnetic field measurements

![Figure 3.](image-url)
with and without the reported cloak are shown in Figures 3(b) and (c) for sensors 1 and 2. The interior is screened just as the superconducting and Mu metal cases described above. However, unlike those two cases, sensor 2 measurements now clearly indicate that the placement of the material does not scatter or create shadows in the external field. To further confirm this result, we have relocated the two sensors to positions 3 and 4 depicted in Figure 3(a) and carried out the field measurements with and without the reported cloak. The results, which again reveal no external field perturbations, are shown in Figures 3(d) and (e) for locations 3 and 4. It is clear that the cloak and the cloaked region here behave much like an empty space to the external dc magnetic field.

As the applied field is increased further, the material can cease to behave as a cloak due to the partial breakdown of superconductivity. The field between the plates is greatly enhanced, especially for the layers with smaller gap spacing. As the applied field is increased, the field at the gap can exceed the critical field of Pb films. See Figure 3(f). A sudden onset of magnetic field in sensor 1 measurements at higher currents in the coils (and hence higher applied fields) signals such breakdown of superconductivity. It is possible to engineer thinner cloaks as the lithography processes can be carried out on much thinner substrates. However, such configuration will certainly increase the critical field within the material. This may be overcome by utilizing superconductors with higher critical fields, a soft ferromagnetic or paramagnetic material with higher magnetic permeability, and/or designing the gap variation that changes from the outer to inner layers in a more continuous manner rather than in large discrete steps as done in this experiment.

In conclusion, we have engineered a grated material composed of artificially patterned superconducting and soft ferromagnetic elements and demonstrated a device that for the first time cloaks an object from dc magnetic fields. The flexibility in designing the spatial variations to guide the field lines stems from the bottom-up approach and makes the reported cloak scalable with attention to superconducting critical fields. The interdisciplinary paradigm of material engineering has spread into many fields beyond conventional material science, optics, and condensed matter physics, with frequency range from terahertz to dc. The results obtained in this experiment not only suggest useful applications such as static magnetic field screening in nested circuits but also reveal ways to utilize engineered structures for the construction of devices with novel properties.

Experimental Section

Experimental Details: The cryogenic Hall sensors used in this experiment have a ~20 mG noise floor, and contain sensing elements (with 0.8 mm² sensing area) at the center of the housing, 2.6 mm from the edge.

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