Magneto-optical transmission measurements of thin NbN superconducting films in Faraday and Voigt orientation at THz frequencies

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Introduction

The terahertz transmission of a thin NbN superconductor layers with the critical temperatures 16 K and 10.8 K at several frequencies within the (0.40 – 2.52) THz range was observed in Faraday and Voigt orientation for several magnetic fields up to 10 T. Both temperature scans in a fixed static magnetic field and magnetic field scans at fixed temperature have been measured. In addition, for several temperatures down to 10 K without magnetic field complex conductivity have been measured by time-domain terahertz spectroscopy. Transmission observed in zero magnetic fields can be explained by the theoretical model based on the BCS theory [1]. Superconductor in magnetic field $H$ ($H_{c2}>H>H_{c1}$) is in Abrikosov state which can be thought of as inhomogeneous state with the presence of vortex lattice which greatly influences superconductor behavior. Transmission of THz radiation presents suitable tool for investigating this system. In order to describe Abrikosov state Clem model [2] was used to describe single vortex. Vortex core can be thought as normal-state inclusion of cylindrical shape in superconducting matrix. Such composite system can be effectively described by Bruggeman theory [3]. The mentioned model does not include the vortex motion due to the interaction with THz radiation which leads to absorption and consequently affecting transmission as well. Even without vortex dynamics the model successfully describes the basic features of experimentally observed transmission even for the highest magnetic fields.

Abstract for poster

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Introduction

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Introduction

Outline

- Introduction
- **Experimental technique**
  Laser thermal spectroscopy and laser magnetospectroscopy
- Experimental results
- Theoretical description
- Model vs experimental results
- Conclusions
Laser thermal spectroscopy & laser magnetospectroscopy

- is not real spectroscopy but it is very similar and this technique is based on same physical principle
- Let’s demonstrate it on a studies of the properties of semiconductors at low temperatures and high magnetic fields under the excitation of Far Infrared (FIR).

http://www.grimes.demon.co.uk/thesis/index.htm
Is it convenient for superconductors?

Is there some energy level in SC dependent on temperature or magnetic field?

YES, IT IS!

Optical gap

\[ \Delta(T) = \Delta(0) \sqrt{ \cos \left( \frac{\pi}{2} \left( \frac{T}{T_c} \right)^2 \right) } \]

\[ 2\Delta(0) = 3.53k_B T_c \]

Numerical factor 2 corresponds to fact that Cooper pair consists from two electrons.
As a name of lecture suggests we are working at THz frequencies. What is that?

Spectrum of electromagnetic radiation

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>THz</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^12</td>
<td></td>
</tr>
<tr>
<td>10^11</td>
<td></td>
</tr>
<tr>
<td>10^10</td>
<td></td>
</tr>
<tr>
<td>10^9</td>
<td></td>
</tr>
<tr>
<td>10^8</td>
<td></td>
</tr>
<tr>
<td>10^7</td>
<td></td>
</tr>
<tr>
<td>10^6</td>
<td></td>
</tr>
<tr>
<td>10^5</td>
<td></td>
</tr>
<tr>
<td>10^4</td>
<td></td>
</tr>
<tr>
<td>10^3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Wavelength (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio- and TV-waves</td>
<td>10^3</td>
</tr>
<tr>
<td>Microwaves</td>
<td>10^2</td>
</tr>
<tr>
<td>THz</td>
<td>10^1</td>
</tr>
<tr>
<td>Infrared</td>
<td>10^2</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>10^1</td>
</tr>
<tr>
<td>Visible</td>
<td>10^0</td>
</tr>
<tr>
<td>X-rays and γ</td>
<td>10^{-1}</td>
</tr>
</tbody>
</table>

1 THz ↔ 1 ps ↔ 33 cm⁻¹ ↔ 0.3 mm ↔ 48 K ↔ 4.1 meV
Why THz region?

Let`s take following definition of THz range

<table>
<thead>
<tr>
<th>300 GHz – 30 THz</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 µm – 1mm</td>
</tr>
<tr>
<td>1.24 meV -12.4 meV</td>
</tr>
</tbody>
</table>

If we take into account BCS formula for optical gap \( 2\Delta(0) = 3.53k_B T_c \),

then terahertz region coresponds to optical gap \( 2\Delta(0) \) of superconductor with

**Tc from 4 to 400 K!!**

These measurements can provide information on the single-particle excitations, as well as on the response of the Cooper pairs.
**Experimental technique**

**Our Experimental Setup**

- Coherent, **linearly** polarized, monochromatic radiation
- Discrete wavelengths from 40 μm to 1 mm
- Transmission - Bolometer signal / Pyrodetector signal
- Light modulation – typically 130 Hz, 100 μs pulse width
- Lock-in detection method
- Temperatures from 3 K to 300 K
- Magnetic fields up to 11 T
- Two different field configurations
- Simultaneous monitoring of the dc resistance

Advantages: high intensity, low ratio noise/signal, monochromatic radiation

Disadvantages: only few frequencies available, measurement of transmission, not conductivity
### NbN thin layer

- **Classical II. Type superconductor**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Polycrystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>≈80 nm</td>
</tr>
<tr>
<td>( T_c )</td>
<td>10.8 K</td>
</tr>
<tr>
<td>( \Delta T_c )</td>
<td>0.4 K</td>
</tr>
<tr>
<td>( \sigma_N(0) )</td>
<td>( 0.45 \times 10^6 , \Omega \cdot m^{-1} )</td>
</tr>
<tr>
<td>Substrate</td>
<td>Si</td>
</tr>
<tr>
<td></td>
<td>250 ( \mu )m thick</td>
</tr>
</tbody>
</table>

Origin: S. Benačka  
We measure transmission of the thin NbN film in its normal and superconducting state while sweeping temperature (or magnetic field).

Output power of the FIR laser is monitored by the pyroelectric detector.

Laser radiation transmitted through the sample is detected by the bolometer.

Transmission of the sample is proportional to the ratio of signals from bolometer and pyrodetector.

This method effectively eliminates any possible time instabilities in the FIR laser power.
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Experimental results

- Normalized transmission $T / T_N$
- Transmission $T$
- Normal state transmission $T_N$
- It is convenient to analyze the temperature dependences of the far-infrared transmission $T$ normalized to that in the normal state $T_N$, taken slightly above the critical temperature.
Experimental results

Zero magnetic field

NbN Benačka
Silicon, \( T_c = 10.8 \) K

NbN Illin
Sapphire, \( T_c = 16 \) K
Experimental results

**Faraday orientation**

- B

**Voigt orientation**

- horizontal polarisation

---

Experiment

NbN Benacka

field perpendicular to the layer

- 0 Tesla
- 1 Tesla
- 2 Tesla
- 3 Tesla
- 4 Tesla
- 5 Tesla
- 6 Tesla
- 7 Tesla
- 8 Tesla
- 9 Tesla

---

Temperature [K]

Transm [a. u.]

---

Teplota [K]

Transm [a. u.]

---

0 Tesla
-1 Tesla
-2 Tesla
-3 Tesla
-4 Tesla
-5 Tesla
-6 Tesla
-7 Tesla
-8 Tesla
-9 Tesla
-10 Tesla
Transmission - interference effects

We account for interference effects in NbN film as well as in sapphire substrate, although interference effects are partially suppressed due to surface roughness.

Transmission, $T$, can be explicitly expressed using transfer matrix method.

$$T = \frac{I_t}{I_0} = |t_{03}|^2$$
Theoretical description

Normal state – DRUDE MODEL

\[ \sigma(\omega) = \frac{\sigma_0}{1 - i\omega\tau} \]

\[ \sigma_0 = \frac{ne^2\tau}{m} \text{– DC conductivity} \]

\[ \omega \text{– circular frequency} \]

\[ \tau \text{– momentum scattering time} \]
Superconducting state – BCS theory

Explicit formula for the complex optical conductivity and a fast self-contained program.
Formula applies to isotropic homogenous BCS superconductors with arbitrary purity and spherical Fermi surface.


\[ \omega = 0 \quad \delta\text{-function in conductivity} \]
\[ \omega > 0 \quad P = \sigma_1 E^2 \]
\[ \hbar \omega < 2\Delta \text{ low dissipation} \]
\[ \hbar \omega > 2\Delta \text{ dissipation increases with } \omega \]
\[ \hbar \omega >> 2\Delta \quad \sigma_n \equiv \sigma_s \]
Theoretical description

Zero magnetic field

![Graphs showing theoretical data for transmission and temperature.](image)
Theoretical description

Zero magnetic field

Better agreement is achieved by treating our real sample not as a homogeneous SC with sharp transition but as a mixture of superconductors with different $T_c$. 
Theoretical description

Non-zero magnetic field

Ginzburg-Landau model

Clem model
Bruggeman`s theory

Local field
\[ E_{loc} = E + E_s + E_{near} \]

Effective permittivity

Generalized Bruggemann`s formula for elipsoidal inclusions

\[ \tilde{\varepsilon}_{eff} = \frac{1}{2(P_i^{-1} - 1)} \left( \beta + \sqrt{\beta^2 + 4(P_i^{-1} - 1)\varepsilon_s\varepsilon_n} \right) \]

\[ \beta = (P_i^{-1}f_s - 1)\varepsilon_s + (P_i^{-1}f_n - 1)\varepsilon_n \]

\[ P_x + P_y + P_z = 1 \quad P_i - \text{shape factor} \]

\[ f_n = V_n \frac{V}{V} - \text{vortex fraction}, \quad f_s = 1 - f_n \quad \text{SC fraction} \]

\[ f_n \sim N_v\pi\xi^2(T) \]

Continuous medium

Sphere
\( P=1/3 \)

Ellipsoid

Cylinder
\( P_x=P_y=1/2 \)
\( P_z=0 \)
Faraday orientation

\[
\tilde{\mathcal{E}}_{\text{eff}} = \frac{1}{2} \left( \beta + \sqrt{\beta^2 + 4 \tilde{\mathcal{E}}_S \tilde{\mathcal{E}}_N} \right)
\]

\[
\beta = (2f_S - 1) \tilde{\mathcal{E}}_S + (2f_N - 1) \tilde{\mathcal{E}}_N
\]
Voigt orientation

\[ \vec{\mathcal{E}}_{\text{eff}} = \int_s \vec{\mathcal{E}}_s + \int_n \vec{\mathcal{E}}_n \]
Conclusions

- We have systematically measured temperature-dependent transmission of NbN superconducting films in both parallel and perpendicular magnetic fields up to 10 T.
- Zero-field transmission is well understood in frame of the BCS based model.
- Good semi-quantitative agreement with the observed data suggests that our phenomenological model is capable of capturing all essential physics.
- Vortex interaction and dynamics was not discussed.

Acknowledgments

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