Spin-injection Terahertz Radiation in Magnetic Junctions

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**Abstract.** Electromagnetic radiation of 1 – 10 THz range is observed at room temperature in a structure with a point contact between a ferromagnetic rod and a thin ferromagnetic film under electric current of high enough density. The radiation is due to nonequilibrium spin injection between the components of the structure. By estimates, the injection can lead to inverted population of the spin subbands. The radiation power exceeds by orders of magnitude the thermal background (with the Joule heating taking into account) and follows the current without inertia. Efficiency of the oscillator depends strongly on the material used and quantum efficiency may exceed the unity. It means the stimulated radiation processes play an important role.

**Experimental approach.**

The structure in study is an inhomogeneous magnetic junction. It consists of two main ferromagnetic components: a hard magnetic rod of hardened steel and a soft magnetic (Permalloy) thin film of nanosize thickness (Fig.1). To simplify realization and calculations, the whole structure has cylindrical form. The rod is sharpened at the end down to diameter of $2R = 10 – 100 \, \mu m$, the film thickness is $h = 10 – 100 \, nm$. The structure has an important property. Because of the current continuity, a high spin-polarized current density exceeds by $2R/h >> 1$ times the current density in the rod. Then an energy minimum for majority electrons appears in the rod center (Fig.1). Such electrons concentrate near the minimum. With the current increasing, the Fermi quasilevel $\varepsilon_F$ rises and the electrons from the minimum tend to penetrate into the film outside the rod. At the distance $0 < r < R < l$ from the rod edge smaller than the spin diffusion length $l \sim 20 – 30 \, nm$, the majority spins are directed opposite to $\textbf{M}_2$, this means inverted spin population. The inversion is promoted by an energy maximum for the electrons with minority spins which appears near the rod axis (see Fig.1). The energy maximum leads to withdrawal of such electrons from the rod. Thus, spin separation occurs in the junction because of its inhomogeneity, so that the electromagnetic radiation power may be gained under interband transitions.

To detect radiation, we placed the receiver on the substrate side within $L \geq 100 \, \text{mm}$ distance from the substrate, such a way that the receiver could rotate around the radiation source.

The problem of the current-driven spin population in ferromagnetic films and observing radiation under interband transitions evokes great interest for a long times [1, 2]. Theoretical estimates of the expected THz frequencies have been made in a number of works. So, a Golay cell was used as a detector and two filters to fix the frequency range, namely, a metal grid with $125 \times 125 \, \mu m^2$ meshes for low frequencies and a standard TYDEX filter for high frequencies. As a result, the studied frequency range was 1 – 10 THz. The receiver was in the wave zone, because $L >> \lambda$ condition was fulfilled, $\lambda$ being the radiation wavelength.
Observation of THz radiation.

We start with the measuring dependence of the radiation intensity on the observation angle $\varphi$, i.e., on the angle between the rod axis and the normal to the objective plane. A typical situation is the radiation has no pronounced directivity, so that an average power $W \sim 2.5 \, \mu W$ falls on the objective at any angle. With the objective diameter about 6 mm, this gives the total radiation power $W_{\text{total}} \sim 10 \, \text{mW}$ to the complete solid angle $4\pi$. It is interesting to estimate the effective absolute temperature $T$ of a body that radiates such a power. In the frequency range in study, the Rayleigh–Jeans law is fulfilled. So, we may estimate $T \gtrsim 3000$ K. Such high temperatures were absent in the experiment. Hence, the power of the receiving radiation is too high to be explained in terms of the radiator heating.

Efficiency of the oscillator.

Energy efficiency in terahertz range is evaluated experimentally for a spin-injection oscillator based on a ferromagnetic rod-film structure with point contact between the components. Very significant feathers of the specimen were established. Choice of the film material influences substantially the efficiency. A magnetic flux concentrator is used to improve the efficiency. It is found from the measurements that the quantum efficiency can exceed unity. The latter indicates substantial contribution of stimulated radiative transitions.

Estimations of efficiency. Measurements of the voltage drop $U$ in the magnetic junction and current $I$ allow to evaluate the power released by the current $W_e = UI$ and the energy efficiency of the radiator $\eta = W/W_e$, where $W$ is the radiation power. Such efficiencies for two film types are shown in Fig. 3. The maximal efficiency reaches of 0.15% with the magnetite film, and 0.06% with the Py film. The difference is due to equilibrium spin polarization $P$ that is about 0.4 for Py and is near to 1
for $Fe_3O_4$ [3]. Also it should have in mind that magnetite properties are closer to semiconductor compounds than $Py$ so spin diffusion length may be similar to magnetite one [3]. Therefore, the radiation length may be larger for magnetite than for permalloy.

**Role of material.** Epitaxial ferromagnetic films of two types were grown on the r plane of single crystalline sapphire by pulsed laser evaporation, namely, polycrystal Permalloy ($Py$) films 30 nm thick and epitaxial magnetite ($Fe_3O_4$) films 250 nm thick. Epitaxial $Fe_3O_4$ film was grown at $340\,^0C$ on a sapphire ($Al_2O_3 - 1012$) with $MgO$ (001) underlayer 10 nm thick by laser evaporation of a $Fe$ target in molecular oxygen at $9 \times 10^{-5}$ Torr pressure. The oscillators with the films indicated were studied. The radiation power as a function of the current was measured. The maximal values of the currents in the experiments were restricted with breakdown in the film to rod contact. It is seen that the maximal radiation power was about 5 mW for both curves. However, to reach such a power, half as large current is required with $Fe_3O_4$ film, as with $Py$ film. It is interesting to compare corresponding current values needed to observe radiation. It appears that the currents are three times less with using magnetite film in comparison with $Py$ film. It shows that magnetite allows more effective operation of the oscillator than $Py$.

![Fig. 3.](image)

**Magnetic flux concentrator.** There is a possibility to control the radiation power and energy efficiency by varying backward (closing) magnetic flux in the oscillator. The flux depends substantially on the magnetic core under the substrate 2. The magnetic flux may be carried away from the sample completely with a layer of soft magnetic (transformer) steel. As a result, the spin-injection driven radiation disappears. It is possible, also, to enhance the radiation with such a magnetic core by concentrating the closing magnetic flux on the sample. For example, we made a magnetic concentrator in the form of a ring with diameter $D = 1.5$ mm of an iron wire with diameter $d = 1$ mm. The concentrator decreases the current under a given power and leads to increasing the power under a given current value. The presented data are not optimal ones, but they merely illustrate possible influence of the concentrator. All the results indicate that the magnetic flux concentrator can enhance efficiency of forming negative spin polarization in the magnetic junction and increase the radiation power.

**Quantum efficiency.** Here, the quantum efficiency $\theta$ means the number of radiated photons per a current carrier. This quantity is interesting because it shows “radiative capability” of the relaxation processes in the device and characterizes intensity of radiative processes. It can be calculate from experimental data as a ratio

$$
\theta = \frac{W}{[I/e]\omega\hbar},
$$

where $e$ is the electron charge, $\omega$ is the radiation angular frequency, $\hbar$ is the Planck constant. By substituting to Eq. 1 the data for $Fe_3O_4$ from Fig. 3, namely, $W = 4.8$ mW, $I = 72$ mA, $\omega = 2 \times 10^{13}$ s$^{-1}$, we obtain $\theta = 1.7$. Thus, the quantum efficiency appears to be more than unity. For the $Py$ film, this parameter is lower, but may be close to unity. It should have in mind that non-radiative
processes also take place at room temperature. So, it may be concluded that a regular cause should exist of the enhancement of the quantum efficiency. In our opinion, such enhancement may be due to substantial contribution of stimulated processes, which are induced by the electromagnetic energy stored in the oscillator. The energy accumulation is a result of reflection the waves radiated earlier from the interfaces. It may be expected that placing the radiator into a selective resonator will amplify stimulated processes and lead to monochromatic coherent THz generation. The spin-polarized current tends to sustain nonequilibrium spin distribution in the junction. Under such conditions, the stimulated radiative transitions add power to the spontaneous ones. This leads to enhancement of the quantum efficiency $\theta$.

**Summary.** Electromagnetic radiation of $1 - 10$ THz range was observed for the first time in ferromagnetic junctions due to current driven spin injection at room temperature. We have evaluated the efficiency of the oscillator. It has been shown that:

- The material choice influences substantially the efficiency. The magnetite films give higher efficiency than Permalloy ones.
- An additional element, namely, magnetic flux concentrator, has been proposed to improve efficiency.
- The quantum efficiency has been evaluated from the measurements, that appeared to be more than unity for magnetite films. This fact is interpreted as a manifestation of the stimulated radiative transitions.

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