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# Dynamic emission and absorption of THZ signals by the array of double-layer nanowires

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THz-radiation sources based on spintronics principles using heterostructures formed by arrays of bilayer Fe/Ni and Ni/Co nanowires grown in polymer matrices (track membranes) are considered. In the frequency range of 12−30 THz, a comparative analysis of their response to the current flowing through them and separately to external THz radiation was carried out. The correspondence between the frequency ranges of spin-injection (dynamic) THz-radiation excited by current, injecting spins in the layers of heterostructures, and the area of intense absorption of electromagnetic oscillations of an external source has been established. This suggests the possibility of using structures with an array of nanowires to register THz-signals.

**Keywords:** spin current injection, external THz radiation, spin unbalance, dynamic THz radiation, THz radiation absorption.

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## Introduction

The development of the terahertz frequency range (1−30 THz), including the study of its still unknown potential, requires an expanded range of research. However, the lack of publicly available, low-cost, compact, small-sized and light-weight, reliable and easy-to-operate signal sources and receivers, determined by the complexity of their manufacturing technology and the materials and components used, makes these studies difficult. Existing sources of THz radiation (backward-wave tube (BWT), free electron laser (FEL), quantum cascade laser (QCL), etc.), as well as applied broadband detectors such as the Golay cell or bolometers based on superconductors, almost completely overlap the specified THz frequency range. However, they all fall far short of meeting the above requirements.

Thus, these machines require magnetic fields of up to 10 kG or more for their operation, which complicates their design and increases the weight and cost of the product. FEL require auxiliary vacuum equipment, which increases their size and weight. QCL operate mainly at low temperatures, and the stability of their operation strongly depends on the temperature of the generator. THz sources based on nonlinear crystals have been developed and used in recent years, but they operate only in pulsed mode, since they use powerful pulsed electromagnetic radiation. This significantly limits the scope of their application. Taking all this into account, it still relevant to continue the search for new principles for the construction of THz receiving and transmitting devices.

Spintronics offers promising opportunities in this area [1–10] — a new field of electronics that examines the processes of electron-wave interaction during the transport of not only the charge of electrons, but also their spins in multilayer thin-film magnetic heterostructures. The effects observed in this case are already being used in practice, for example, when creating computer hardware elements or sensors [11,12]. The study is underway to create both coherent and incoherent sources and receivers of electromagnetic radiation, including THz-band [13–15].

One of the promising methods of spin transport for these purposes is spin injection by high-density current $j > 10^6$ A/cm$^2$ in magnetic heterostructures formed by ferromagnetic or antiferromagnetic films of nanoscale thickness [16]. Currently, work is underway for creation of incoherent sources and receivers of the THz band using this method. However, a coherent THz laser-type source can be also created in the future. The advantage of the spin-injection method lies in the simplicity of the manufacturing technology of heterostructures for its implementation. One of the technological processes is shown below.

The operation of spin injection sources does not require any special temperature conditions, vacuum or an external magnetic field. It is also important to use the current as a working organ. The stability of the current-voltage curve is practically not affected by external conditions.

In our opinion, the power of the generated oscillations is determined by the volume of the working area in the heterostructure and can presumably reach units of W. The radiation power in experimental models reaches hundreds of $\mu$W presently. The highest power level we have received is 10 mW.

Arrays of single-layer and multilayer nanowires (NW) formed in track membranes are of interest among various designs of magnetic heterostructures [17–19]. Multilayer NWs consist of several alternating layers of various magnetic metals or alloys [20,21] in contact with each other. Such structures as active elements of quantum generators are attractive because their use can provide good heat dissipation from the working area when generating high-power signals.

It is possible to assume the opposite effect based on the results of the study in Ref. [22]— a change of the electrical characteristics of the nanowire array under the impact of external electromagnetic radiation. This effect is interesting for receiving THz signals, especially considering the possibility of using a large-area absorbing surface. Therefore, it is of interest to evaluate the possibility of using structures with an array of NW to record THz signals.

To date, the results of „hot" experiments have been obtained (in which the electromagnetic emission is excited by a high-density electric current — more than $10^6$ A/cm$^2$), confirming the possibility of using an array of magnetic NW as active elements incoherent THz quantum generators [23]. The response of heterostructures with an array of nanowires to an external signal („cold" measurements, which consider the reaction of magnetic heterostructures to an external THz signal), including in the THz range has been studied [24,25]. The results obtained suggest that both the excitation and absorption of THz signals in arrays of magnetic nanowires is associated with the occurrence of spin imbalance in them [16]. The spectra of „hot" and „cold" measurements for a single array of nanowires are considered and compared in this paper to confirm this thesis.

The obtained results suggest that the spin injection mechanism that we study can be considered as one of the possible fundamentally new mechanisms for constructing incoherent sources and receivers of THz signals.

## 1. Diagram of the THz emitter used

Radiator designs were proposed in the early studies of the authors in which heterojunctions were created when one-dimensional structures (thin rods or nanowires in a matrix) were in contact with a two-dimensional surface, a thin foil or metal film on the surface of the matrix. However, these designs had a number of disadvantages. Firstly, even the thin conductive film was solid, which made it difficult to remove THz radiation from the sample. Secondly, all NW in the array were connected in parallel in the design proposed in [23], since they were located between two contact films. The electrical resistance of such an emitter was extremely low as a result. The latter made it impossible to pass current

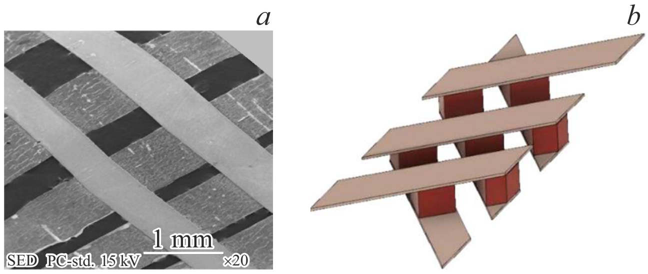


**Figure 1.** Emitter used with an array of nanowires: *a* — SEM image of a part of the emitter sample after removing the polymer matrix film (stripes with gaps are visible; stripes applied to opposite sides of the film are perpendicular to each other); *b* — diagram of the ribbon emitter, where the pink „cubes" are bundles of NW arrays located between the contact strips. Photomicrographs were obtained by scanning electron microscopy. JEOL–JSM 6000 plus microscope with an accelerating voltage of 15 kV was used, the work was conducted with magnifications of 500–10000x.

with controlled parameters, and also led to the burning of a thin contact layer.

A design was used in this paper that partially eliminated the described disadvantages. In general, the novelty consisted in the synthesis of layered (instead of homogeneous) NW, the application of sufficiently thick contact layers in the form of alternating strips, and the sequential connection of NW beams arising between strip contacts applied to opposite surfaces of the polymer matrix, which significantly increased the electrical resistance of the structure.

Magnetic transitions were created directly in the pore channels. For this purpose the pores were sequentially filled with layers of various metals or alloys during electrodeposition, between which a heterojunction occurred. Each NW consisted of two parts of different composition in the simplest case and, accordingly, one heterojunction. Contact layers were created on the surface of the polymer matrix in the form of separate strips ($0.2-0.5\,\mu$m thick and $0.5-1$ mm wide), regularly alternating with non-metallized gaps ($0.3-1$ mm). The directions of these strips on the opposite surfaces of the polymer matrix were perpendicular. The SEM image of the created radiator is shown in Fig. 1, *a* — general view with the polymer removed.

A ribbon was cut from the resulting composite (metal–polymer–contact strips) at the last stage. The „cut" direction was 45° to the direction of the contact strips, and the width of the ribbon was $1-2$ mm (the ribbon is schematically shown in Fig. 1, *b*. The contacts were attached to the ends of the ribbon. The described design of the radiator made it possible to organize a series-parallel connection of individual NW bundles. In this case the current applied to the ribbon passed through a circuit of several series-connected NW bundles. It should be noted that the area of the „bundle" was determined by the area „superposition" of the upper and lower strips of current leads. With a ribbon length of 2 cm, the number of „bundles" in the circuit was $12-20$ pieces. This connection scheme ensured a sample resistance acceptable for stable operation of the radiator. Usually, the operating voltage was up to 10 V in experiments, and the current passing through the NW was in the range of 300 mA.

In this case THz radiation exits through the gaps between the contact planes of the — current leads. This design made it possible to increase the efficiency of radiation output (despite the fact that only a smaller part of the NW was involved in the generation process) and increase the electrical resistance of the sample.

The described design made it possible to conduct both „hot" and „cold" experiments, since a significant part of the NW grown in the pores of track membranes is not shielded by current-carrying elements and turns out to be „suspended", which allows for their irradiation by an external electromagnetic signal during „cold" measurements. They do not participate in the formation of dynamic radiation.

## 2. Experiment

A detailed description of the measurements, the results of which are used below, is provided in Ref. [23–26]. It should be noted that the spectral analysis was performed using Bruker „Vertex80v" IR Fourier spectrometer in the air within the frequency range of 12–30 THz, where the most interesting effects related to our study were observed. The boundaries of the study range were chosen in each case in such a way as to highlight the observed effect. The source of the external signal was the globar — MIR thermal emitter. The globar signal was formed into a narrow beam in „cold" measurements, which was transmitted through a sample area free of band contacts using a Hyperion microscope laser sight, where the NW were in a „suspended" state.

The measuring chain of the spectral analyzer was used when conducting „hot" experiments, but instead of radiation from a thermal source, a signal from a spin-injection radiator

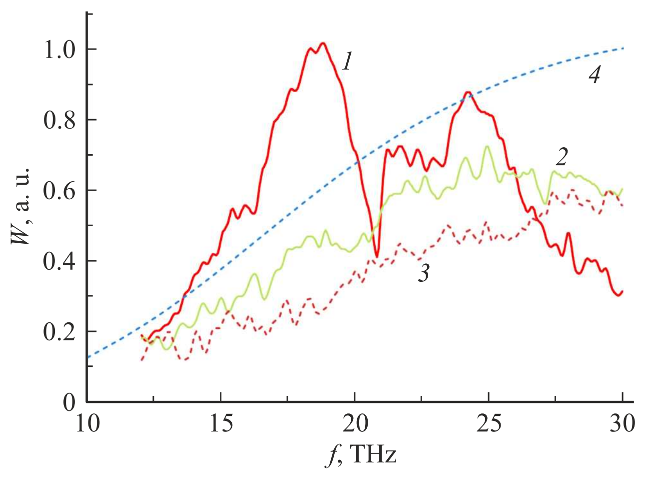


**Figure 2.** The spectrum of the recorded signal at different current values: I, mA: *1* — 85, *2* — 30, *3* — 0, *4* — calculated Planck's curve for 300 K.

with an array of NW was transmitted into it through the input. A microscope was not required in this case. The radiator's power source was a stabilized DC power source, which, if necessary, could provide an emitter current of up to 1 A.

To confirm the non-thermal nature of the observed spin-injection THz radiation, Figure 2 shows the spectral characteristics of the radiator in the frequency range of 12–30 THz as a dependence of the radiation intensity $W$ on the frequency measured at currents $I = 0$ and 30 mA before the occurrence of dynamic radiation (curves *2, 3* in Fig. 2) and $I = 85$ mA, which ensured the excitation of this radiation (curve *1* in Fig. 2). The radiation intensity $W$ was estimated in conventional units determined by the division price of the measuring oscilloscope. The signal intensity in the studied frequency range monotonously increased before the occurrence of dynamic radiation to a maximum value at $f \sim 30$ THz. This behavior of the spectrum corresponds to the character of the Planck's curve (curve *4* in Fig. 2) for the radiation of a „hot" body. The radiation power concentration is observed at a current value of 85 mA as a peak in the frequency range of 17–20 THz at the level of 3 dB and its significant dip in the frequency range of 30 THz, corresponding to the maximum of thermal radiation according to Planck's law. This dip, as shown in Ref. [26,27], is related to the competition of dynamic and thermal radiation. The excitation of THz radiation in a relatively narrow frequency range only when a certain starting current value is exceeded indicates the non-thermal, dynamic nature of the observed radiation.

Let us consider the behavior of the NW array in the frequency range of 15–30 THz in case of irradiation of samples with a signal from an external source — globar. The results of these measurements are shown in Fig. 3. It should be emphasized that in this range, the globar spectrum had a monotonous character (curve *4* in Fig. 3) and thus could not significantly affect the studied spectra. The spectra of the transmitted signal were measured when irradiating arrays of two-layer Fe/Ni, Co/Ni nanowires and a pure track membrane. The use of two samples allowed us to draw more general conclusions.

The impact of the atmosphere on the appearance of the spectrum was observed at higher frequencies (not given here), where the spectral characteristic of the globar in some areas had a strongly indented appearance. Given the absence of atmospheric impact in the studied range, the observed change in the spectrum of the external signal should be attributed to the influence of NW and the track membrane (curves *13* in Fig. 3). It can be seen that the amplitude characteristics of the spectrum depend on the materials of the NW layers, and the frequency characteristics determined by its roughness have some similarities in some areas.

Thus, two regions can be distinguished analyzing the signal spectra shown in Fig. 3. This is the region of low frequencies (up to 22 THz), where the spectra have a strongly ragged amplitude, and the region of higher frequencies, where the spectra for both magnetic transitions have a more monotonous appearance with characteristic peak dips for both samples at frequencies $\sim 25$ and 27 THz, which they correspond to the dips in the spectrum of the pure membrane. This suggests that the materials of the transitions in NW mainly affected the amplitude of the signals in this range, and the frequency characteristics were determined by the spectrum of the pure membrane.

The spectra of transmitted signals shown in Fig. 3 show their identity for different pairs of ferromagnets (as well as for the spectra of reflected signals) in the range 22–30 THz, and these spectra are identical to the spectrum of the signal transmitted through the membrane, differing only in amplitude. This suggests that spectra are determined by absorption by the track membrane in the frequency range of 22–30 THz, and NW arrays passively affect electromagnetic radiation, which undergoes only thermal interaction with NW, which does not lead to a change of the spectrum (peak dip frequencies do not change). An active interaction of electromagnetic radiation is observed at lower frequencies (15–22 THz), leading to a significant change of the spectrum of the signal transmitted through the array of nanowires. The strong raggedness of the spectrum may indicate fluctuation processes leading to the appearance of spin-unbalanced electrons that perform interband oblique quantum transitions with phonon absorption.

The comparison of the radiation spectrum of a structure obtained by us with an array of NW when a current is passed through it with the spectrum of an transmitted external signal of the same structure is of interest for development of the understanding of radiative interband spin transitions and expand their possible practical application. This comparison is shown in Fig. 4.

It can be seen from Fig. 4 that the frequency range in which non-thermal, dynamic radiation is formed corresponds to the area of the amplitude dip of the transmitted signal spectrum with the greatest roughness, i.e. here the greatest interaction of the external signal with the array is observed. At the same time, a strong peak dip at the frequency of $\sim 26$ THz in the „cold" spectrum and its absence in the „hot" spectrum confirms the passivity of NW in the range above 22 THz. The coincidence of the spectra may indicate that the absorption of external electromagnetic radiation is also associated with interband spin transitions and disturbances of spin equilibrium in magnetic transitions. This suggests the possibility of expanding the scope of such structures, in particular, for recording THz signals.

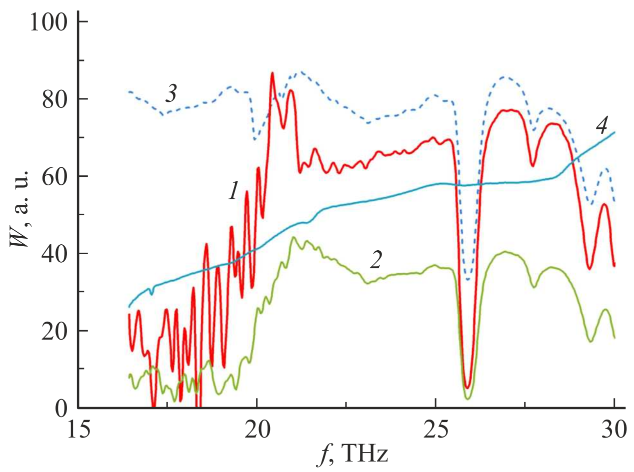


**Figure 3.** The spectrum of the transmitted signal during irradiation of an NW array consisting of two layers: *1* — Fe/Ni, *2* — Ni/Co. *3* — spectrum of the signal transmitted through a clean membrane, *4* — the spectrum of the globar — the source of the external signal.

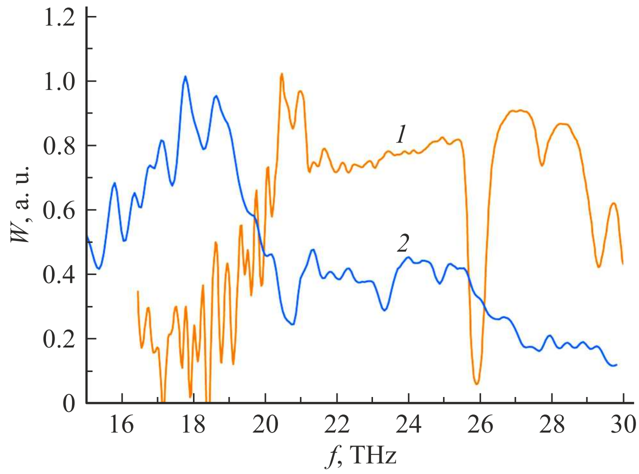


**Figure 4.** The comparison of the dynamic radiation and absorption spectra of an array of two-layer Fe/Ni nanowires. *1* — spectrum of the signal transmitted through the NP array, *2* — spectrum of dynamic radiation at a current of 85 mA.

## Conclusions

The analysis of the spectra of emitters with an array of multilayer NW showed a coincidence of the frequency ranges of observation of spin-injection radiation and intense absorption of an external signal. The nature of the absorption of an external signal shows the possibility of extending the concepts of spin imbalance introduced in the study of spin injection by current in an NW array to the process of absorption of an external signal in it. From a practical point of view, the coincidence of the frequency ranges of absorption and generation of the THz signal in the structure with an array of NW shows the possibility of creation of both generators and receivers of this range based on them.


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## Conflict of interest

The authors declare that they have no conflict of interest.

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