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Development of an automated prototype of THz filter based on magnetic fluids

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ABSTRACT

We report on the fabrication of liquid automated filter capable of controlling the intensity of terahertz radiation in the range of 0.4-1.4 THz. The filter is a cell with a magnetic fluid (5% dispersion of 5BDSR particles in 80W-90 synthetic oil) placed on the path of THz radiation between a pair of crossed Helmholtz coils. The prototype created allows achieving an extremely high attenuation coefficient, up to 35 dB. Automatic start-up and stirring system make filter operation repeatable, even with multiple on/off filter state changes. All this allows us to speak about the operability of the presented technology and the possibility of further development of the prototype, the use of similar filters in any THz photonics systems, in which it is required to control the intensity of polarized radiation.

Keywords: THz polarizers, THz attenuation, magnetic nanoparticles, synthetic gear oil, anisotropy

1. INTRODUCTION

To date, there are not many works demonstrating the use of an external magnetic field to control liquid THz filters[1,2]. These works consider filters based on dispersions of magnetic nanoparticles - ferrofluids. It is known that the efficiency of modulation of THz radiation by magnetic particles is not high. Achieving high attenuation coefficients when switching the modulator, usually requires the creation of significant optical paths. This, in turn, leads to an increase in the initial transmission losses, especially in the short-wavelength part of the THz range. Thus, due to the limited size and initial transmission of the filter in the open state, it is necessary to select in detail the parameters of the external field, the characteristics of the filter, including the type of magnetic particles used and their concentration[4].

Nevertheless, the creation of simple inexpensive systems with variable properties in the THz range, based on magnetoactive materials, is very attractive and actual. Previously, we considered a filter consisting of a cuvette with a ferromagnetic liquid and two pairs of Helmholtz coils[5]. The magnetic field created by the Helmholtz coils is able to orient the magnetic particles of the filter into line structures. Different direction of particle orientation leads to different effects of the filter on linearly polarized terahertz radiation. Thus, while orientating the clusters of magnetic particles parallel to the amplitude of the electric field of THz radiation, the attenuation coefficient is equal 1-20 dB in the range 0.4-1.6 THz with an attenuation peak at 1.4 THz. In this paper, we present an improved broadband liquid THz filter. We have added the function of automatic mixing and changing the filter states. Also improved the technical characteristics by increasing the magnetic field generated by the coils by ~2 times (from 3.7 mT to 8 mT). As a result, we achieved a shift in the absorption maximum from 1.4 THz to 0.7 THz, while the attenuation coefficient increased by 50 times. The proposed modification of the filter with adjustable attenuation of THz radiation has a sufficient degree of reliability and good reproducibility. It makes it possible to use it not only from the point of view of fundamental studies of the interaction of matter with THz radiation, but also as an applied device (along with polymer films[6]) for problems of THz photonics[7].

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2. MATERIALS AND METHODOLOGY

We used magnetic fluids based on 5% dispersion of magnetic submicron 5BDSR particles (analogue of FINEMET[8] alloy). Particles were obtained by ball mill twice grinding. A detailed analysis of the morphology and magnetic properties of 5BDSR particles is given in the work[9]. A uniformly mixed dispersion of particles in 80W-90 synthetic oil, which has a high transparency in the THz range[5]. It was placed into a standard 10 mm thick quartz cuvette or was poured into a thin cell with a controlled gap thickness, made of two glass slabs and silicone gaskets. The prepared cuvettes were fixed in special holders and placed inside the Helmholtz coils, which form a uniform magnetic field. Under the action of a uniform constant external magnetic field, linear stable agglomerates of particles are formed in the cuvette. These agglomerates are an anisotropic medium for THz radiation[10]. For an ordinary wave (THz polarization orthogonal to cluster orientation) the damping decreases and, accordingly, the transmission increases with respect to the isotropic state. For an extraordinary wave (THz polarization parallel to cluster orientation), the transmission decreases due to absorption of radiation by imaginary electric polarization in a medium induced by the field[1].

As shown by preliminary experiments, after a single formation in a magnetic field, the resulting line agglomerates are difficult to reorient. This is due to their larger size compared to individual particles. For the same reason, agglomerates in dispersion are less stable. Therefore, when the external magnetic field is removed, the formed agglomerates tend to precipitate, thereby sharply reducing the effective concentration of the active substance in the dispersion. Figure 1 shows photomicrographs of a ferromagnetic liquid droplet with a single orientation of the particles by an external magnetic field and with multiple changes in the orientation of the magnetic field.

Figure 1. Micrograph of a ferromagnetic liquid in a uniform magnetic field (left), with multiple changes in the orientation of the magnetic field (right).

Thus, with repeated use, the magnetic particles agglomerate into large clusters. The structures formed have only a conventionally ordered orientation and cannot be further effectively controlled by an external magnetic field.

To prevent the formation of agglomerates, the destruction of already formed and stabilize dispersions, surfactants[11] are added to them, or initially complex structures are created in which magnetic particles are protected with a special non-magnetic layer[12]. However, such structures would be poorly suited for creating THz filters, which require the formation of linear agglomerates of micron thicknesses. Another solution to the problem can be a complete replacement of the magnetic fluid with each change in the state of the filter, but this approach is impractical.

In this paper, we examined methods for restoring the working media directly during operation. Common used magnetic stirrer is obviously not possible in the case of magnetic particles. Vibration exposure with frequencies from 100 Hz to 5000 Hz, as well as the use of ultrasonic waves did not lead to the required result. The most effective and accessible method in our case turned out to be mechanical stirring of the dispersion.

Electronic control circuit and a cuvette with a motorized prop were developed and manufactured to control filter states and change THz transmittance. The control circuit and motorized cuvette are shown in Figure 2.

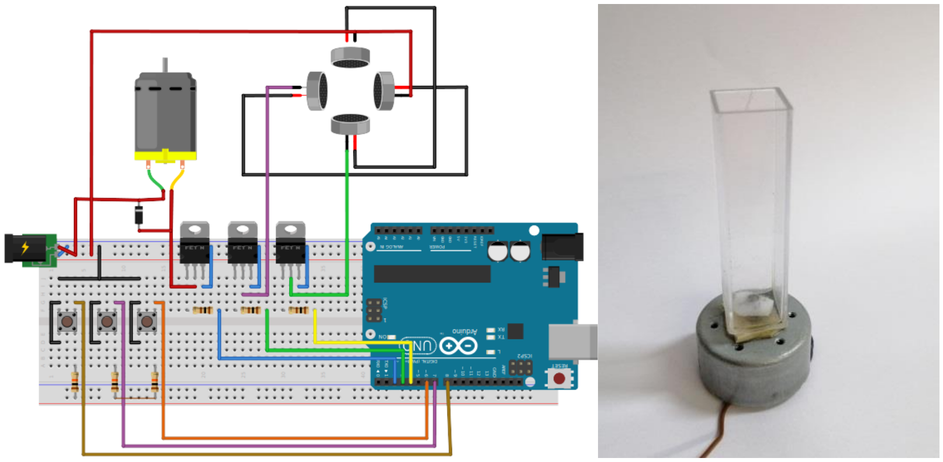

Figure 2. Electrical diagram of a prototype automated THz attenuator (left) and a photo of a motorized cell (right).

The control circuit of the coils allows changing the state of the filter at the required times to achieve the required transmission/attenuation characteristics. Each time the filter is switched, the magnetic fluid is pre-mixed. In the process of mixing, large agglomerates of magnetized particles are destroyed, and the active medium passes into its original state.

The developed automated THz attenuator was placed inside the THz-TDS spectrometer T-Spec 1000. Spectral characteristics of the radiation after passing through this device were investigated.

3. RESULTS AND DISCUSSION

The results of studying the spectra of the filter characteristics are shown in Figures 3-5. Figure 3 shows the recorded series of dispersion spectra after repeated mixing without an external magnetic field and an overview of the filter in the spectrometer.

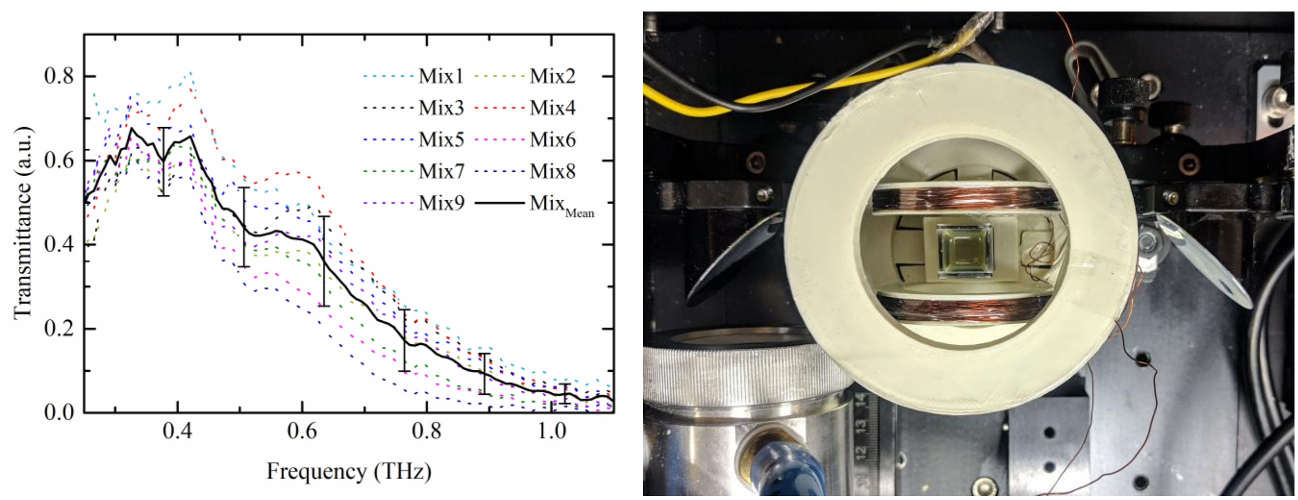

Figure 3. Transmission spectra of a cuvette with dispersion for chaotic orientation of particles with repeated stirring (left), general view of a liquid filter in the cuvette compartment of the spectrometer (right).

The transmittance of the filter with non-oriented particles change quite strongly after the end of the mixing process: the spread is ~20%. Such a transmittance spread can be associated with the appearance of inhomogeneities due to the comparability of the dimensions of the prop blades to the sizes of the cuvette.

Spectra of different filter states with oriented particles were also recorded. Fig. 4a shows spectra of opaque or “off” state when the direction of the particles is parallel to the THz polarization (current is applied to the external coils). The maximum transmission or "on" spectra Fig. 4b refers to the orthogonal orientation of particles (current is applied to the internal coils). The transmittance spectrum of dispersion in the initial isotropic state is shown for reference.

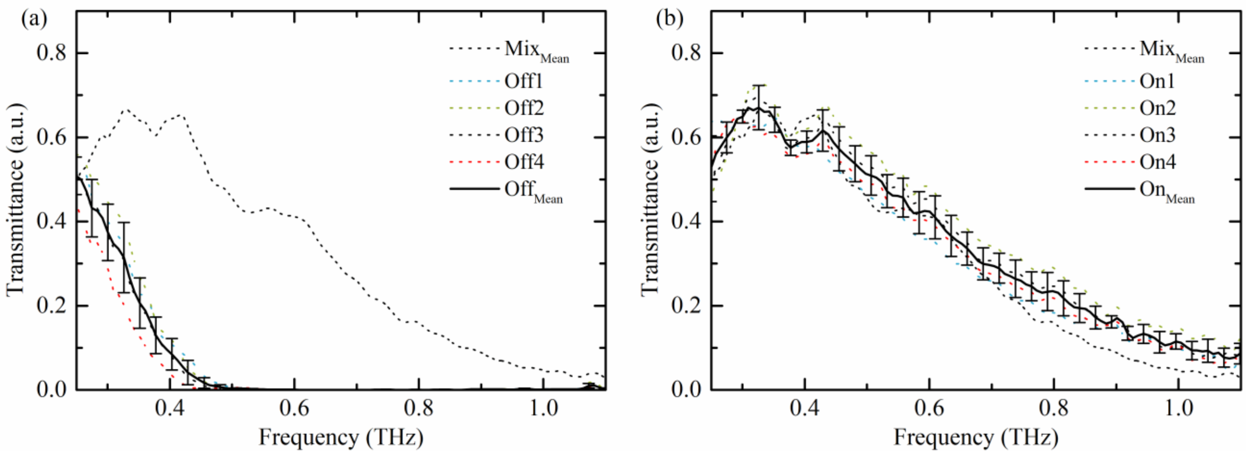

Figure 4. Filter spectra in opaque (left) and transparent (right) states.

As can be seen from the presented spectra, the spread in the filter transmission in the "on" state, when the magnetic field is kept constant, is much less and does not exceed 5-10%. Moreover, the spread of transmittance is even lower in the closed state of the filter. It should be noted that the transmission of the filter in the initial state (non-oriented particles) and in the open state (particles are oriented orthogonally to the THz electric field polarization) are very close. At the same time, in the open state, the reproducibility of the results increases significantly (comparing Fig 3 and Fig 4). This behavior is explained by the greater ordering of particles in space when a magnetic field is applied.

It has been shown that the presence of an acting magnetic field during the operation of the filter additionally solves the problem of gradual sedimentation of particles under the influence of gravity, thereby increasing the stability of measurements.

To achieve higher filter attenuation values, the concentration of magnetic particles (5 wt.%) in the active filter fluid and the coil voltage have been optimized. Helmholtz coils responsible for creating a uniform field have been tested for stability and heating with increasing supply voltage. In optimal operating conditions, a magnetic field of about 8 mT was achieved for the filter in the opaque state and 4 mT for the filter in the "on" state. Further increase in the magnitude of the magnetic field in the filter is associated with excessive heating of the used coils. Larger diameter coils cannot be placed in the housing of the T-Spec 1000 spectrometer. However, even in their current form, optimization of the experimental conditions made it possible to achieve a damping factor of more than 1000 rel. units as shown in Figure 5.

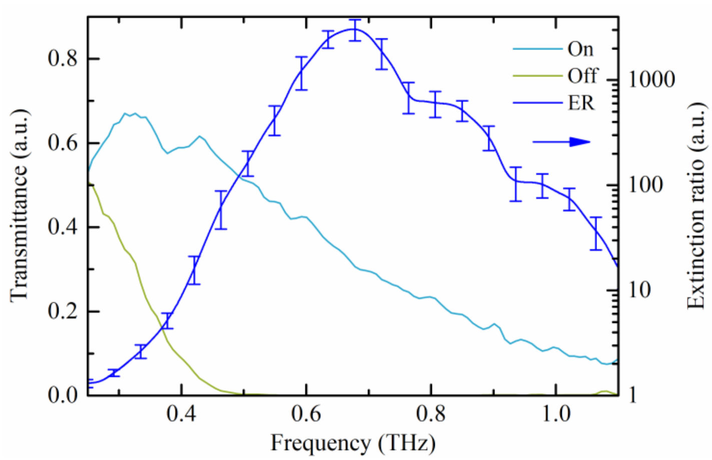

Figure 5. Average transmission spectra of the filter in the open and closed state, attenuation coefficient when switching the filter (logarithmic scale).

Compared to the early results that we obtained for a filter of similar geometry[5], optimization of the solution density and coil parameters made it possible to increase the filter efficiency by a factor of 500 without significant losses in the initial transmission. It makes the efficiency of the new prototype comparable to industrial THz polarizers[13].

4. CONCLUSION

Thus, a prototype of an automated filter that could effectively control the intensity of THz radiation was developed. The selected optimal parameters of the ferromagnetic fluid and the control magnetic field made it possible to achieve an extremely high attenuation coefficient, up to 35 dB. Using a digital current control system has increased the repeatability of the measurement results, so the filter opens and closes reliably even with multiple changes of states. All this allows one to speak about the operability of the presented technology and the possibility of further development of the prototype, the implementation of such filters as attenuators or switches in any THz photonics systems, in which it is required to control the intensity of polarized radiation.

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