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Microwave chirality discrimination in enantiomeric liquids

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Chirality discrimination is of fundamental interest in biology, chemistry, and metamaterial studies. In optics, near-field plasmon-resonance spectroscopy with superchiral probing fields is effectively applicable for analyses of large biomolecules with chiral properties. We show possibility for microwave near-field chirality discrimination analysis based on magnon-resonance spectroscopy. Newly developed capabilities in microwave sensing using magnetoelectric (ME) probing fields originated from multiresonance magnetic-dipolar-mode oscillations in quasi-2D yttrium-iron-garnet disks provide potential for unprecedented measurements of chemical and biological objects. We report on microwave near-field chirality discrimination for aqueous *D*- and *L*-glucose solutions. The shown ME-field sensing is addressed to deepen our understanding of microwave-biosystem interactions. It can also be important for an analysis and design of microwave chiral metamaterials. *Published by AIP Publishing*. [http://dx.doi.org/10.1063/1.4994273]

I. INTRODUCTION

Many molecules in chemistry and biology are chiral. Biologically active molecules in amino acids (the building blocks of proteins) and sugars are chiral molecules. Chiral discrimination in a mixture of chiral molecules is among the most important and difficult tasks in biophysics and chemistry. In this connection, the development of a technique that offers improved chiral analysis and a better understanding of interactions of electromagnetic (EM) fields with chiral materials remains an important goal. Traditional chiroptical spectroscopy arises from the effect of interference between the electric-dipole transition moment and the weak magneticdipole transition moment that is detected when a chiral molecule is irradiated with alternating right- or left-circularly polarized light.^{1–3} For localized (subwavelength) chiroptical biosensing, special plasmonic structures with left- and righthanded probing fields are effectively used.^{4–6}

The measured forms of chiroptical intensity are inversely proportional to the wavelength of the probing radiation. That is why the use of microwave radiation to detect chirality was considered as a non-solvable problem. Microwave circular dichroism would be expected to be too small for detection using modern spectrometers. Surprisingly, a new microwave technique based on chirality-sensitive three-wave mixing to identify the enantiomers of chiral molecules was demonstrated in Ref. 7. This technique departs from traditional (optical) electromagnetic methods of detecting and identifying the handedness of molecules. Because it does not depend on a weak magnetic-dipole transition moment, the chiral signal is nearly as large as that of the applied microwaves.^{7,8} This conceptually new method to detect chirality is applicable, however, to cold gas-phase molecules. The three-wave technique for molecules sampled in the gas phase shown in Ref. 7 cannot be used to study the handedness properties of liquid structures in microwaves. Such a study is especially attractive for biological applications. In general, the use of microwaves for biological applications is very important

because of the sensitivity of this electromagnetic radiation to water and dielectric contrast. As a problem of great importance in biophysics and chemistry, this may concern, in particular, an analysis of the molecular mechanisms of nonthermal microwave effects.^{9,10} While microwave absorption is considered as an effective tool for observing and measuring different kinetic processes in biological structures, the existing standard microwave techniques are not applicable for sensing and monitoring enantiomeric liquids.

In this paper, we report the first experimental observation of microwave chirality discrimination in liquid samples. In the room-temperature experiments, we use the aqueous D- and L- glucose solutions of different concentrations. Our microwave spectroscopy technique determines the rotational energy levels of chiral molecules with the aim of being applied for the localized measurement of different biological liquids and biological tissue. In the literature, rotational spectroscopy for enantiomer-specific detection and separation is presented in many aspects. The Rabi frequency describing an electric dipole transition between rotational states of a chiral molecule differs in sign for opposite enantiomers.^{11,12} In the method used in Ref. 7, for identifying molecular chirality, the measured quantity depends on the handedness of three mutually orthogonal electric-dipole rotational transition moments, which are associated with the three rotational degrees of freedom of a molecule. When microwave radiation interacts with these moments, energy transfer changes the rotational state of the molecule, generating a spectroscopic signal. The sign of a scalar triple product depends on the order of the electric-dipole-moment vectors. This sign (being changed under spatial inversion and unchanged under time reversal) is a measure of molecule chirality. In 1978, Baranova and Zel'dovich¹³ predicted the "propeller effect" in which a racemic mixture of chiral molecules is separated into left and right fractions when subjected to a radio frequency electric field of rotating polarization. The sense of rotation is given by the circularity of the electric field.

Opposite enantiomers will 'screw' in opposite directions and thus separate along the direction about which the electric field rotates. In Ref. 14, it was shown that when exposed to a rotating electric field (at the frequency of 900 kHz), the leftand right-handed chiral molecules rotate with the field and act as microscopic propellers. Owing to their opposite handedness, they propel along the axis of field rotation in opposite directions. The results of chiral separation are detected using the chromatographic absorption profiles.

For enantiomer-specific detection, in our technique of microwave rotational spectroscopy, neither Rabi-frequency molecule rotational resonances nor "propeller effect" are used. The observed effect of chirality discrimination in liquids is due to the dependence of interactions between magnetic-dipolar-mode (MDM) resonances and microwave radiation on the handedness properties of a sample loading an yttrium iron garnet (YIG) disk. Similar to Ref. 7, a chiral particle is modeled as three mutually orthogonal electricdipole moments and the handedness is identified by the sign of the triple product of these dipole moments. When a probing field originated from a MDM spectrum in a quasi-2D YIG disk is applied to a biological sample, electric dipoles of chiral molecules will have both spin and orbital angular momentums about a ferrite disk axis. The direction of molecule rotation is determined by the direction of a bias magnetic field. For a given direction of a bias field, transitions between rotational states of a chiral molecule are different for opposite enantiomers.

Recently, collective spins in YIG sub-millimeter spheres were explored to achieve their strong couplings to microwave radiation.^{15–17} In such spheres, the couplings of the microwave photons to collective spin modes with nonuniform precession of magnetization-the MDMs^{18,19}have also been observed. The spectrum of MDM oscillations in a quasi-2D YIG disk, however, is much stronger and richer than that in a YIG sphere.^{20,21} Quantization of the microwave fields due to quasi-2D YIG disks with multiresonance MDM oscillations appears as an interesting and unique effect.^{22,23} It was shown that a small quasi-2D ferrite disk with a MDM spectrum behaves as a source of specific quantized fields in vacuum termed magnetoelectric (ME) fields.^{24,25} The electric and magnetic fields of the ME fields carry both spin and orbital angular momentums. The ME fields originated from a MDM ferrite disk are strongly localized (subwavelength) fields with quantized topological characteristics, such as power-flow vortices and field helicities. A sign of these topological parameters depends on a direction of a bias magnetic field. This allows effective distinguishing of the "right" and "left" enantiomeric structures placed in close proximity to a MDM ferrite disk.

II. EXPERIMENTAL RESULTS FOR D- AND L-GLUCOSE AQUEOUS SOLUTIONS

An experimental structure is shown in Fig. 1. Figure 1(a) shows the experimental setup for microwave near-field chirality discrimination based on MDM resonances. In Fig. 1(b), one can see a device-under-test (DUT): a microstrip structure with a MDM ferrite sensor and a loading sample. A



FIG. 1. (a) Experimental setup for near-field characterization of chiral parameters based on MDM ferrite sensors. (b) A device-under-test (DUT): a microstrip structure with a MDM ferrite sensor and a loading sample. A ferrite disk is loaded by a cylindrical capsule with aqueous *D*- or *L*-glucose solutions. (c) Cross-sectional view of the capsule. The capsule base thickness of w = 300 um gives a gap between a ferrite disk and glucose solution necessary to avoid strong damping of MDM resonances by a load.

ferrite disk is loaded by a cylindrical capsule with aqueous D- or L-glucose solutions. Figure 1(c) shows the cross-sectional view of the capsule with glucose solutions.

In experiments, we use a disk sample of diameter D = 3 mm made of the YIG film on the gadolinium gallium garnet (GGG) substrate (YIG film thickness t = 49.6 um, saturation magnetization is $4\pi Ms = 1880 \text{ G}$, linewidth $\Delta H = 0.8 \text{ Oe}$; the GGG substrate thickness is 0.5 mm). The microstrip structure is realized on a dielectric substrate (Taconic RF-35 with the permittivity $\varepsilon_r = 3.52$ and thickness of 1.52 mm). The characteristic impedance of a microstrip

line is 50 Ω . A bias magnetic field \vec{H}_0 is produced using an electromagnet. A power supply (LAMBDA dc power supply) feeds the electromagnet with a dc current that can be adjusted (manually or automatically by Labview software) to produce the desired bias magnetic field. The bias field is measured using a gaussmeter (2010T, Magnetic Instrumentation Co) with an accuracy of 0.05 Oe. As the microwave source, we used a vector network analyzer (Agilent 87050, power level of $-15 \, \text{dBm}$, Agilent Co). Spurious signals are negligible since there are no active devices in our setup. The accuracy of the microwave measurements is 100 kHz. In the present experiment, a ferrite disk is loaded by a capsule with $10 \,\mu$ l capacitance of aqueous D- or L-glucose solutions. The capsule is a small cylinder (internal diameter of 3.2 mm, wall thickness of 0.1 mm, and height h = 1.2 mm) made of polypropylene with a permittivity of $\varepsilon_r = 2.2$. The capsule base thickness of w = 300um gives a gap between a ferrite disk and glucose solution necessary to avoid strong damping of MDM resonances by a load. The S-matrix parameters were measured using the vector network analyzer. With the use of a current supply, we established a quantity of a normal bias magnetic field H_0 , necessary to get the MDM spectrum in a required frequency range. The transmission (S_{21}) and reflection (S_{11}) spectra of a microstrip structure with an unloaded MDM ferrite disk are similar to the spectra shown in Ref. 26. At the MDM resonances, a ferrite disk becomes slightly entangled in the reflected microwave radiation, while it becomes strongly entangled in the transmitted microwave radiation. For this reason, one observes Lorentz-type resonances in the reflection spectrum and Fano interference in the transmission response.

When a ferrite disk is loaded by a sample, the MDM spectrum is transformed: The spectrum stretches on the frequency axis and shifts to lower frequencies. At different parameters of the samples, we observe different transformations of the spectra. To exclude the multifactorial character of the spectrum transformations, in evaluation of the sample parameters, we *superpose* the first resonance peaks of all the spectra at the same frequency. This is possible by the variation of a value of the bias magnetic field. The resonance

frequencies of the MDM resonator are effectively tunable by an external parameter: a bias magnetic field. With such a tuning, we can shift the frequency of a certain resonance peak at any given point on the frequency axis (certainly, in the frequency range of the material ferromagnetic resonance).

Figure 2 shows the experimental results of the MDM transmission spectra in a microstrip structure for the D- or Lglucose solutions in two opposite directions of a bias magnetic field. In both cases of the solutions, the glucose concentration is 538 mg/ml. For better illustration of the effect, the spectra are normalized to the background (when a bias magnetic field is zero) level of the microwave structure. The reflection spectra for the D- or L-solutions in two opposite directions of a bias magnetic field are shown in Fig. 3 for the two types of glucose solutions at the glucose concentration of 538 mg/ml. The spectra are normalized to the background level of the microwave structure similar to the normalization used for the transmission spectra. The resonance peaks, both in Figs. 2 and 3, are classified as the radial and azimuthal modes.²² In the spectra shown in Figs. 2 and 3, the first radial resonance peaks are put at the same frequency. This allows analyzing the spectral modification due to different glucose solutions. For two types of glucose solutions (right- and lefthanded) and two opposite directions of the bias magnetic field, the first peak frequency was 7.726 GHz. At this frequency, the quantity of a bias magnetic field is $H_0 = 4210$ Oe. The resonance frequencies are sampled by the computer every one second, and a deviation (100 kHz max) from the given value is corrected by changing the current supply until the first resonance frequency is returned to its value. This process is done automatically using Labview software, by monitoring the received signal and controlling the current supply simultaneously.

From Figs. 2 and 3, one can observe specific symmetry relationships in the spectra. There are evident relationships between the sample handedness and directions of a bias magnetic field. For the transmission coefficients, these symmetry relationships for all the MDM resonances in the spectra can be expressed conditionally as



FIG. 2. Experimental results of the MDM transmission (S_{21} parameter) spectra of the *D*- or *L*-glucose solutions in two opposite directions of a bias magnetic field. In both cases of the solutions, the glucose concentration is 538 mg/ml. The spectra are normalized to the background (when a bias magnetic field is zero) level of the microwave structure. The results give evidence for a specific chiral symmetry: simultaneous change in the glucose handedness and the direction of bias of the magnetic field keeps the system symmetry unbroken. The resonance peaks are classified as the radial and azimuthal modes.²¹ The frequency f = 7.726 GHz is the resonance frequency of the 1st radial MDM.



FIG. 3. The MDM reflection spectra of the *D*- or *L*-solutions in two opposite directions of a bias magnetic field for the concentration of 538 mg/ml for the two types of glucose solutions. The spectra are normalized to the background level of the microwave structure similar to the normalization used for the transmission spectra. The resonance peaks are classified as the radial and azimuthal modes.²¹ The frequency f = 7.726 GHz is the resonance frequency of the 1st radial MDM.

$$(S_{21}^{H_0\uparrow})^{(D)} \iff (S_{21}^{H_0\downarrow})^{(L)} \text{ and } (S_{21}^{H_0\downarrow})^{(D)} \iff (S_{21}^{H_0\uparrow})^{(L)}, (1)$$

where *R* and *L* denote the right-handed and left-handed enantiomers and the arrows $\uparrow\downarrow$ indicate the bias magnetic field directions along the disk axis (see Fig. 1). For the reflection coefficients, one has

$$(S_{11}^{H_0\uparrow})^{(D)} \iff (S_{11}^{H_0\downarrow})^{(L)} \quad \text{and} \quad (S_{11}^{H_0\downarrow})^{(D)} \iff (S_{11}^{H_0\uparrow})^{(L)}.$$
 (2)

In Ref. 26, it was shown that the transmission spectrum of the microstrip MDM sensor itself (the structure without any loads of a ferrite disk) is sensitive to the direction of a bias magnetic field, while the reflection spectrum is the same in two opposite directions of a bias field. This sensitivity of the transmission coefficient of an unloaded sensor is due to the field chirality of a MDM ferrite disk and azimuthal inhomogeneity of a microstrip structure. For our present study of enantiomer discrimination, there is a parasitic effect. Since this "structure effect" is very sensitive to the frequency region, we succeeded in eliminating it by shifting the spectra to higher frequencies. In the frequency region of the present experiment, from 7.5 GHz to 8.0 GHz, the differences in the peak levels in the transmission spectra of an unloaded sensor for two opposite directions of a bias field were less than 0.2 dB. To make sure that the spectral differences in Fig. 2 are due to the enantiomeric properties of the samples, we also analyzed the transmission spectra for two opposite directions of a bias field when a ferrite disk was loaded by a capsule with $10\,\mu$ l of distilled water. In this experiment, we also observed that the differences in the peak levels were less than 0.2 dB. Regarding the reflection coefficient in our microstrip structure, the present experiments clearly show that (similar to the results in Ref. 26) there are no differences in the spectra of an unloaded sensor in two opposite directions of a bias field. In addition, when a ferrite disk was loaded by a capsule with $10 \,\mu$ l of distilled water, we found that the reflection coefficients were absolutely insensitive to the direction of a bias field.

For a quantitative analysis of chirality discrimination in glucose solutions, we use the MDM reflection spectra in our microstrip structure. This is because of two reasons. First, the forms of Lorentz resonance peaks in the reflection spectra (compared to the Fano resonance peaks in the transmission spectra) allow us to calculate differences between the scattered-matrix parameters more clearly. Second, the reflection spectra in the structure are much stronger than the transmission spectra. It is also important that for the reflection spectra of a structure without enantiomer samples, we definitely have $S_{11}^{H_0\uparrow} = S_{11}^{H_0\downarrow}$. Based on the results in Fig. 3, we calculated, for every type of a glucose solution, the differences between the scattered-matrix parameters obtained in two opposite directions of a bias magnetic field

$$\Delta S = S_{11}(H_0\uparrow) - S_{11}(H_0\downarrow). \tag{3}$$

The enantiomer-dependent results are shown in Fig. 4. It is evident that for all the resonant peaks, the quantities of ΔS have definite antisymmetric forms with respect to frequency. These antisymmetric forms are oppositely oriented for the *D*- and *L*-glucose. A quantitative characteristic of the sample chirality is made by the estimation of the frequency differences Δf between the peaks of parameters ΔS . We can see that for different types of MDMs in the spectrum, such frequency differences are different.

In the present study, we also made a relative estimation of the liquid chirality via the variation of concentration of the glucose solution. Figure 5 shows the results of enantiomerdependent parameters Δf for two concentrations, 420 mg/ml and 538 mg/ml, of the glucose solutions. In the supplementary material, we show microwave near-field chirality discrimination in metamaterial chiral structures.

III. PROPOSED MODELS OF INTERACTION OF ME FIELDS WITH CHIRAL OBJECTS

Symmetry principles play an important role in the laws of nature. Maxwell added an electric displacement current to put into a symmetrical shape the equations coupling together the electric and magnetic fields. The dual symmetry between electric and magnetic fields underlies the conservation of energy and momentum for electromagnetic fields.²⁷ Recently, it was shown that this dual symmetry determines the conservation of optical (electromagnetic) chirality.^{28,29}





FIG. 4. The enantiomer-dependent parameter $\Delta S = S_{11}(H_0 \uparrow) - S_{11}(H_0 \downarrow)$ obtained in two opposite directions of a bias magnetic field for the D- and L-glucose solutions. For all the MDM resonant peaks, the quantities of ΔS have definite antisymmetric forms with respect to frequency. These antisymmetric forms are oppositely oriented for D- and L-glucose. A quantitative characteristic of the sample chirality is obtained by the estimation of the frequency differences Δf between the peaks of parameters ΔS for the Dand L-glucose solutions. For different MDMs, the frequency differences Δf are different.

Based on an analysis of the interaction of chiral light and chiral specimens, new mechanisms of enantiomer discrimination and separation in optics have been proposed.^{6,28–33} In these works, the chiral particles are considered in the dipolar limit with a cross-polarization term coupling the electric and magnetic dipole moments. It is well known, however, that in a subwavelength region [the region with sizes much less than a free-space electromagnetic (EM) wavelength], the fields originated from local electric and magnetic dipoles are separate potential electric and magnetic fields without any dual symmetry. Moreover, no special near-field structures originated from the presumed cross-polarization terms are observed in classical electrodynamics.^{27,34} In this connection, it is worth noting that optically active media are considered as non-local (spatially dispersive) media.³⁵ All this means that the dipolar-limit model with cross-polarization terms for chiral samples is hardly applicable in a subwavelength region. The model of cross-polarization coupling becomes much more questionable for chiral samples in microwaves, where the difference between EM wavelength and specimen sizes is more considerable.

To obtain an interaction of small chiral objects with microwave fields in a subwavelength region, another



FIG. 5. Enantiomer-dependent parameters Δf for two concentrations, 420 mg/ml and 538 mg/ml, of the glucose solutions. For *D*-glucose solution, $\Delta f > 0$, and for *L*-glucose solution, $\Delta f < 0$.

mechanism of the field-matter interaction, different from that used in optics, should be considered. This mechanism arises from the properties of near fields originated from a ferromagnetic sample. In a small ferrimagnetic sample (with sizes much less than the free-space EM wavelength), one has a negligibly small variation of electric energy and microwave dynamical processes are described by "incomplete" Maxwell equations with neglect of an electrical displacement current. In spite of breaking of Maxwell's symmetry, specific unified-field (with coupled electric- and magnetic-field components) retardation effects exist in small ferrite samples. There are so-called magnetostatic (or magnetic-dipolar) oscillations.^{19,35} In the case of a quasi-2D ferrite disk, these oscillations are characterized by topological properties. At the MDM resonances, both the fields inside and in close proximity outside a ferrite disk have spin and orbital angular momentums. In vacuum, the near fields originated from MDM oscillations-the ME fields-are different from EM fields.²⁵ The topological properties of ME fields allow using a model of a triple of electric dipoles for a chiral molecule in our study of microwave chirality discrimination. It is worth noting here that there can be an infinite number of chiral parameters that characterize a chiral object, and each of these chiral parameters is a pseudoscalar.³⁶ The vector triple product of electric dipoles, modeling a chiral molecule $\vec{d}_1 \cdot (\vec{d}_2 \times \vec{d}_3)$, is a simple case of such a pseudoscalar. This pseudoscalar has opposite signs for the right and left chiral molecules.

We consider the specific topological properties of ME fields based on quadratic forms of the fields. The models of interaction of ME fields with chiral objects can be introduced based on an analysis of these quadratic forms. There are two types of quadratic forms characterizing ME fields. The first quadratic form is power-flow density. At the MDM resonances ($\omega = \omega_{MDM}$), one has active and reactive power flows.³⁷ The active power flow

$$\vec{P} = \frac{1}{2} \operatorname{Re}(\vec{E} \times \vec{H}^*) \tag{4}$$

has a vortex topology. Both inside and outside a ferrite disk, one observes the orbital angular momentum of the field. This angular momentum of the field is expressed as



FIG. 6. Power-flow distributions on a vacuum plane above a ferrite disk in a microstrip structure. A bias magnetic field is directed normally to a disk plane. One can observe strong subwavelength localization of energy and vortex behavior of the microwave fields near a ferrite disk. For opposite directions of a bias magnetic field, there are opposite rotations of the power-flow vortices.

$$\vec{L} = \frac{1}{2} \operatorname{Re}[\vec{r} \times (\vec{E} \times \vec{H}^*)], \qquad (5)$$

where \vec{r} is a radius from the disk axis. Figure 6 shows the power-flow distribution on a vacuum plane above a MDM ferrite disk at the first-mode resonance. This is the region where a capsule is situated. The distribution was obtained numerically with the use of ANSOFT HFSS EM Simulator. One can observe strong subwavelength localization of energy and vortex behavior of the microwave fields near a ferrite disk.

At the MDM resonance, both the electric and magnetic fields rotate around a disk axis. The frequency of these rotations of the fields is the same as the frequency of the magnetization precession in YIG.²⁵ The spin-orbit interaction, resulting in electric polarization for magnetic-dipole dynamics, produces a rotating electric field. In a laboratory frame, one observes not only magnetization but also electric-polarization properties of a ferrite disk. Since the electric dipoles rotate at the same frequency as the magnetic dipoles, an electric displacement current is still negligibly small. When an achiral dielectric sample is placed above a ferrite disk, every electric dipole in a sample will rotate. The direction of rotation is determined by the direction of a bias magnetic field. The mechanical torque exerted on a given electric dipole is defined as a cross-product of the MDM electric field \vec{E} and the electric moment of the electric dipole d

$$\vec{N} = \vec{d} \times \vec{E}.$$
 (6)

Figure 7 shows a MDM ferrite disk with rotating electric field \vec{E} loaded by an achiral dielectric sample with electric polarization \vec{p} . The "spin" defined by Eq. (6) is accompanied by the orbital rotation by virtue of an angular momentum expressed by Eq. (5). The torque exerted on the electric polarization due to the MDM electric field should be equal to the recoil torque exerted on the magnetization in a ferrite disk.²⁵

At the MDM resonances, the rotating electric fields cause the rotation of electric dipoles of chiral molecules. In distinguishing the "right" and "left" enantiomeric properties of samples, a torque of the ME field plays an important role. The ME field chirality results in unidirectional transfer of angular momenta through a subwavelength vacuum region. With modeling a chiral molecule as a triple of electric dipoles (right-handed or left-handed), transitions between rotational states of a chiral molecule are different for opposite enantiomers for a given direction of a bias field. Because of this reaction torque, the precessing magnetic moment density of the ferromagnet will be under additional mechanical rotation at certain frequencies $\Omega^{(R,L)}$, where R and L denote the right-handed and left-handed enantiomers. The frequencies $\Omega^{(R,L)}$ are defined based on both, spin and orbital, momentums of the fields of MDM oscillations. When a dielectric sample loads a ferrite disk, modification of the magnetization motion in a disk can be characterized by the introduction of an effective magnetic field. In the case of



FIG. 7. An electric field inside a ferrite disk has both orbital and spin angular momentums. When an electrically polarized dielectric sample is placed above a ferrite disk, electric dipoles in a dielectric sample precess and accomplish an orbital rotation. A bias magnetic field is directed normally to a disk plane. For opposite directions of a bias magnetic field, one has opposite rotations of the electric field and opposite directions of precession of electric dipoles.

enantiomer samples, this effective magnetic field is expressed as

$$\vec{H}_{eff}^{(R,L)} = \vec{H} - \frac{\Omega^{(R,L)}}{\gamma}, \qquad (7)$$

where γ is a gyromagnetic ratio which relates the electron spin angular momentum and the electron magnetic moment. The Larmor frequency of a ferrite structure with a dielectric loading should be lower than such a frequency in an unloaded ferrite disk. The quantities $\vec{H}_{eff}^{(R,L)}$ are different for different types of enantiomers. Since these quantities are also different for different MDM resonances, one has different stretching of the spectra for the right-handed or left-handed enantiomers. As a result, we observe different *S*-matrix characteristics of a microwave structure when the *D*- and *L*- glucose solutions are used.

It is worth noting that the torque exerted on the electric polarization due to the MDM electric field and the recoil torque exerted on the magnetization in a ferrite disk are not observed as the propeller effect. In the propeller effect, when the external RF electric field is applied to the liquid solution, an enantiomer is affected by a certain translational force. The movement of the enantiomer in liquid is modelled as the movement of a screw in a nut. The right- and left-handed molecules move in the opposite directions. Enantiomers separate along the direction about which the electric field rotates.^{13,14} While one assumes that the effect of translational forces arising in a capsule with glucose solutions. Importantly, the torsion effect observed in our experiments concerns the

relationship between the symmetry properties of ME fields and the symmetry properties of chiral molecules.

The symmetry properties of ME fields are characterized by helicity density. There is the second quadratic form of ME fields. The ME-field helicity density is defined as²⁵ $F = \frac{e_0}{2}\vec{E} \cdot \nabla \times \vec{E}$. Formally, this parameter can be considered as a particular case of the EM-field chirality²⁸ $\chi = \frac{e_0}{2}\vec{E} \cdot \nabla$ $\times \vec{E} + \frac{1}{2\mu_0}\vec{B} \cdot \nabla \times \vec{B}$, when an electrical displacement current is negligibly small ($\nabla \times \vec{B} = 0$). The helicity parameter of a ME field is calculated as

$$F = \frac{\omega_{MDM}\varepsilon_0}{4} \operatorname{Re}(\vec{E} \cdot \vec{B}^*) = \frac{\omega_{MDM}}{4c^2} \operatorname{Re}(\vec{E} \cdot \vec{H}^*), \quad (8)$$

where *c* is the light velocity in vacuum. A sign of the helicity parameter depends on a direction of a bias magnetic field: $F^{\vec{H}_0\uparrow} = -F^{\vec{H}_0\downarrow}$. An integral of the ME-field helicity over an entire near-field vacuum region of volume *V* should be equal to zero

$$\mathcal{H} = \int_{V} F dV = \frac{\omega_{MDM}}{4c^2} \int_{V} \operatorname{Re}(\vec{E} \cdot \vec{H}^{*}) dV = 0.$$
(9)

The ME-field helicity appears only at the MDM resonances. The "helicity neutrality," expressed by Eq. (9), can be considered as a specific conservation law of helicity.³⁷ The helicity parameter *F* is a pseudoscalar: to come back to the initial stage, one has to combine a reflection in a ferrite-disk plane and an opposite (time-reversal) rotation about an axis perpendicular to that plane. This property is illustrated in Fig. 8. The vector triple product of electric dipoles, modeling a chiral molecule $\vec{d}_1 \cdot (\vec{d}_2 \times \vec{d}_3)$, is a pseudoscalar as well.



FIG. 8. The field topology near a ferrite disk at the MDM resonance frequency and in two opposite directions of a bias magnetic field. The electric and magnetic fields outside a ferrite disk are rotating fields which are not mutually perpendicular. The helicity parameter F is a pseudoscalar: to come back to the initial stage, one has to combine a reflection in a ferrite-disk plane and an opposite (time-reversal) rotation about an axis perpendicular to that plane.

So, the field interacting with chiral molecules is distinguished by the same topological property. When an enantiomer sample loads a ferrite disk, the "helicity neutrality" is violated. This "helicity neutrality" is restored by the modification of the magnetization distribution in a ferrite disk. Such a modification, different for two types of enantiomers (the right-handed or left-handed ones), result in different transformations of the MDM spectra and so different *S*matrix characteristics of a microwave structure.

IV. CONCLUSION AND DISCUSSION

Direct inspection of biological structures at microwave frequencies is a problem of great importance in many aspects. In particular, it concerns understanding of the molecular mechanisms of microwave nonthermal effects. While microwave absorption is considered as an effective tool for observing and measuring different kinetic processes in biological structures, the existing standard microwave techniques are not applicable for sensing and monitoring enantiomeric liquids. Nowadays, standard methods of microwave biosensing lack the spatial resolution to probe structural characteristics of chemical and biological objects.

In this paper, we demonstrated a conceptually new form of spectroscopy of enantiomeric liquids based on a microwave technique. The method determines the chiral properties of molecules with the aim of being applied for the localized measurement of different biological liquids and biological tissue at room temperature. In the shown technique of microwave rotational spectroscopy, neither Rabi-frequency molecule rotational resonances nor "propeller effect" are used as models for enantiomer-specific detection. The roomtemperature effect is observed due to the dependence of interactions between MDM resonances in a YIG disk and a sample with handedness properties. At MDM resonances in a ferrite disk, one has rotational energy levels of the precessing elementary magnetic dipoles. When an electrically polarized dielectric sample is placed above a ferrite disk, electric dipoles in a sample precess and accomplish an orbital rotation. At MDM resonances, one has rotational energy levels of the elementary electric dipoles. This effect, described in our previous publications,^{25,26} is well-illustrated in Fig. 7 in the present paper. The effect is related to the rotational behavior of chiral molecules. The energy levels are determined by energy levels of MDM oscillations.²² The fact that the symmetry properties of ME fields are related to the symmetry properties of chiral molecules plays an important role in the field-matter interaction.

The main purpose of this paper is to present a novel microwave technique for chirality *discrimination* in enantiomer liquids, that is the technique allowing us to observe different microwave responses for the right-handed and left-handed enantiomer samples. We showed that the differences between the scattered-matrix parameters obtained in two opposite directions of a bias magnetic field give us the necessary information to discriminate the two types of chiral objects: the D- and L-glucose solutions. We showed also that the degree of such a discrimination depends on concentrations of enantiomeric liquids. There exists a correlation

between the parameters defined from Figs. 2–4 and the electric dipole moments of a sample. Also, these parameters are correlated with the rotational properties (with the spin and orbital degrees of freedom) of these electric dipole moments. In our microwave structure, the MDM azimuthal modes are excited with less amplitudes than the radial modes. For this reason, the sensitivity of the sample to the azimuth-mode excitations can be weaker than to the radial-mode excitations. So, at the present stage of the research with this kind of microwave structure, we cannot say definitely what type of mode (the azimuth or radial ones) would give more sensitive results. To answer this question, more detailed research with a special technique for the azimuth mode excitation should be fulfilled. This could be a task for future studies.

At the heart of the technique, we have a very complicated mechanism of interactions between the magnetization dynamics in a ferrite disk resonator and electric dipoles of chiral molecules in an enantiomer sample. In this paper, we considered some models of this phenomenon. These models are based on our previously published results with a theoretical analysis of the spectral problem and numerical studies. It is evident that such a complicated mechanism of interactions cannot be characterized by certain empirical formulas describing our microwave technique. So far, many aspects of strong chiral discrimination in glucose solutions observed in our microwave experiments remain unclear. Scientifically, the problem of chirality discrimination appears as a very topical and, at the same time, a very complicated problem. The problem concerns fundamental aspects of microwavebiosystem interactions. Our technique of microwave chirality discrimination in enantiomeric liquids at room temperature is a breakthrough in this problem. We demonstrate a conceptually new form of spectroscopy of enantiomeric liquids and conceptually new models describing this phenomenon. The statement that so far many aspects of strong chiral discrimination in enantiomer liquids observed in our microwave experiments remain unclear does not show that we do not understand well what we measure. Future experiments and future theoretical studies should give us more understanding in physics of interaction of microwave fields with liquid enantiomeric structures. We aim to expand the proposed technique to study different types of sugars: glucose, maltose, fructose, and arabinose solutions. The microwave study of protein structures is one of our main purposes. At present, we showed the microwave chirality discrimination in enantiomer liquids with sufficiently high glucose concentrations of 420 and 538 mg/mL. One of the main aims is a strong enhancement of the sensitivity of our technique. At the MDM resonances, the rotating electric fields cause the rotation of electric dipoles of chiral molecules. These rotating electric dipoles have both spin and orbital degrees of freedom. To increase the sensitivity of the proposed microwave technique, one should increase a spin-orbit interaction in a sample. This can be achieved with strong localization of ME fields by special field concentrators-lenses. By virtue of a "topological" nature of ME fields, these localized excitations are immune to local noise. It is also worth noting that there is no universal quantitative description of molecular chirality. The handedness is not an absolute concept but depends

on the properties being observed. We do not measure the chirality parameter. In our present study, a nonvanishing value of the observed chirality characteristic distinguishes a chiral liquid from an achiral one.

Since the study presents the chirality discrimination, we can state that the results for the racemic mixture and those for pure water should be the same. That is, the frequency difference between microwave responses, which we observe for the right-handed and left-handed enantiomer samples, will be zero for the racemic mixture. It is also worth noting that our experimental results and a model are applicable only for enantiomeric liquids. They are not applicable for dry glucose.

SUPPLEMENTARY MATERIAL

To illustrate the effect of interactions of MDM oscillations with chiral structures, we analyzed numerically (with the use of ANSOFT HFSS EM Simulator) microwave nearfield chirality discrimination in planar chiral structures. Based on our near-field technique, we study chiral metamaterials realized as a composition of the "right" and "left" planar metallic stars. In these metamaterial structures, the azimuthally rotating electric and magnetic fields of a MDM ferrite disk induce electric charges and currents on metal stars. The direction of the field rotation is determined by the direction of a bias magnetic field. For a given enantiomeric structure, the electric charges and currents induced on metal stars are different for different directions of a bias magnetic field. See supplementary material for microwave near-field chirality discrimination in planar chiral structures.

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