

Gigantic Tellegen responses in metamaterials

Corresponding Author: Professor Shuang Zhang

This manuscript has been previously reviewed at another journal. This document only contains information relating to versions considered at Nature Communications.

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I have read the revised manuscript now entitled "Gigantic Tellegen responses in metamaterials" and I support my previous conclusion that this work is timely and interesting. However, the conclusions drawn here are not sufficiently supported and some statements in the manuscript are misleading. In my opinion, more careful and thoughtful work is needed to make this manuscript suitable for publication.

1. My key question which I have raised previously is the possibility to describe the metamaterial with bulk effective parameters. Unfortunately, the author's response to that question is unsatisfactory. Please, show not only Tellegen coefficient, but rather all extracted material parameters (permittivity and permeability). Are they physical? How resonances in permittivity and permeability align with the resonance of the Tellegen coefficient? This should be discussed in the main text as well.

2. The authors correctly say that their metamaterial exhibits isotropic response only in the x-y plane, while the electromagnetic response in the z-direction is different. However, analysis of oblique incidence scenario is crucial for the correct identification of the type of electromagnetic response present here. As shown in the literature, probing only normal incidence geometry may lead to the confusion, see an example of this sort in [Phys Rev B 92, 085107 (2015)]. Naively, I would expect just ϵ_{zz} and μ_{zz} components for the response in z direction. With this assumption, does the effective medium calculation match simulation/experiment? Is the model of anisotropic Tellegen medium consistent? Without such analysis I do not think that the claim of anisotropic Tellegen response is sufficiently justified.

3. The authors added a statement "and the direct observation of axion response in the latter [condensed matter] has yet to be realized". This is absolutely misleading, see the experimental paper [L. Wu, et al. Science 354, 6316, 1124-1127 (2016)] where experimentalists measure exactly the same quantities as the authors, but for the topological insulator and in the THz domain.

4. The authors' claim that their system "opens up significant opportunities for the experimental exploration of novel concepts related to axion electrodynamics" is an exaggeration. As I said, this physics is known and experimentally verified in condensed matter. So, the novelty statement here should be more precise and limited to the microwave spectral range where, indeed, such structures have not been realized previously.

5. Finally, at p.5 the authors write about 4 classes of bianisotropic coupling. It seems they missed two more classes of bianisotropy: pseudo-Tellegen and pseudo-chiral response.

Reviewer #2

(Remarks to the Author)

I've read the authors' reply to the Referees, and in my opinion they have addressed carefully and very satisfactorily all the raised points. I strongly recommend the publication of the article in its present form.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have significantly improved the manuscript addressing all essential questions. I have just a couple of minor comments which the authors may wish to implement:

1. The imaginary part of the extracted effective permittivity shown in Fig. S3a of Supplementary Materials changes its sign. It means that at some frequencies the metamaterial behaves as an active medium which is unphysical. I believe this issue should be commented by the authors in the text.
2. The authors analyzed the scenario of oblique incidence and, through the simulations, revealed the impact of nonlocality (spatial dispersion). This should be mentioned in the manuscript to provide a broader picture and highlight the limitations of effective medium description in this case.

After these minor corrections, I believe, the manuscript is suitable for publication.

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1 Reviewer 1

Comment 1

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Reply 1:

We appreciate the reviewer’s insightful comments for further improving our work. Below we will carefully address each question from the reviewer.

Comment 2

1. My key question which I have raised previously is the possibility to describe the metamaterial with bulk effective parameters. Unfortunately, the author's response to that question is unsatisfactory. Please, show not only Tellegen coefficient, but rather all extracted material parameters (permittivity and permeability). Are they physical? How resonances in permittivity and permeability align with the resonance of the Tellegen coefficient? This should be discussed in the main text as well.

Reply 2:

We apologize for the oversight in our previous response. We have now provided the extracted effective permittivity and permeability, as shown in Fig. R1(a) and Fig. R1(b) respectively. The pronounced Tellegen response of the metamaterial results from the engineered resonance of the saddle-shaped metallic resonators and the YIG rod. As a result, the resonances observed in the permittivity and permeability spectra are aligned with the resonance of the Tellegen coefficient, as shown in Fig. R1(c).

With the extracted effective parameters ε , μ , and ξ , we can put them back into Comsol model (Electromagnetic Waves, Frequency Domain) to calculate the transmission parameters of an effective medium slab. The Tellegen slab has the same effective thickness $d_0 = 12\text{mm}$, and is illuminated by a E_y -polarized plane wave (Fig. R2(a)). As shown in Fig. R2(b) and Fig. R2(c), the calculated transmission spectra of such an effective medium slab (denoted by lines) match well with the simulated results of the designed metamaterial (denoted by symbols), showing the validity of the effective parameters extracted from the metamaterial.

In addition, we provide a microscopic perspective of the Tellegen response by investigating the magnetic and electric dipole moments. As schematically shown in the

upper panel of Fig. R3(a), the metamaterial slab is normally illuminated by a standing wave with the electric field polarized along the y -axis. When the slab is placed at the node of magnetic field ($H_x = 0$), the magnetic dipole induced by the incident magnetic field is expected to be zero ($M_x \propto H_x = 0$), while the Tellegen response gives rise to the in-phase magnetic dipole moments induced by the electric field ($M_y \propto E_y$). For our metamaterial, the magnetic dipole moment can be calculated through the integration of the current density $\mathbf{j}$ of the unit-cell: $\mathbf{M} = \frac{1}{2c} \int (\mathbf{r} \times \mathbf{j}) d^3r$, where $\mathbf{r}$ is the coordinate vector and c is the speed of light. The simulated magnetic dipole is shown in the lower panel of Fig. R3(a), where M_x, M_z are near zero across the whole range as expected, while M_y exhibits a resonating spectrum. In addition, M_y has nearly the same phase as the incident wave E_y at the resonance frequency around 9.5GHz, verifying the in-phase cross-coupling. Similarly, when the metamaterial slab is placed at the node of electric field ($E_y = 0$), the simulated electric dipole $\mathbf{P} = \frac{1}{i\omega} \int \mathbf{j} d^3r$ in Fig. R3(b) shows a nearly zero $P_y \propto E_y = 0$ and a resonating $P_x \propto H_x$, indicating the in-phase electric dipole moment induced by the magnetic field. Therefore, the microscopic dipole analysis further verifies the pure Tellegen response of the metamaterial.

For this comment, we have now provided more detailed information in the Supplementary Materials Sec. 5 and added a new section about the dipole moments of the metamaterial (Supplementary Materials Sec. 2).

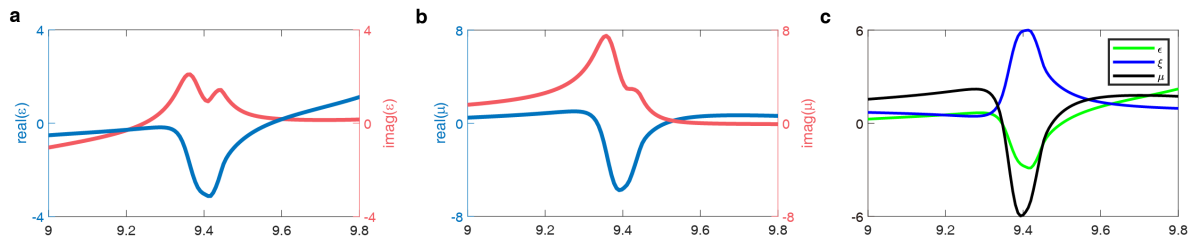


Fig. R1 The extracted effective permittivity ϵ (a) and permeability μ (b) of the metamaterial. Blue and red lines represent the real and imaginary parts, respectively. (c) The aligned resonance of the real part of ϵ , μ , and ξ spectrum.

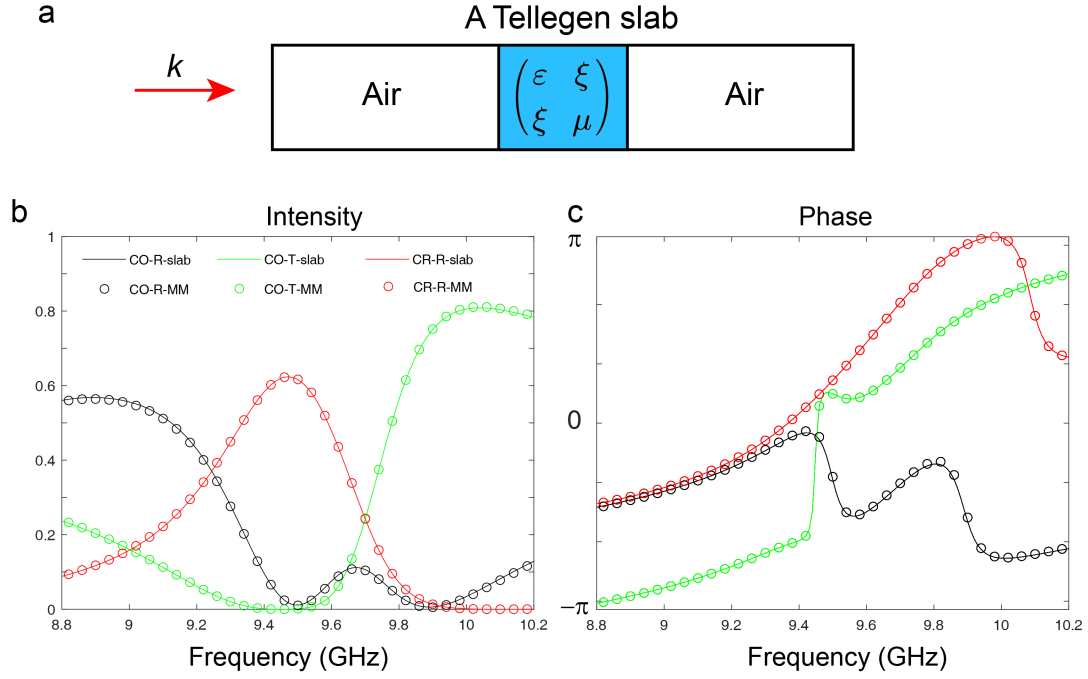


Fig. R2 (a) A Tellegen slab has the same effective thickness and effective parameters as the metamaterial, and is illuminated by a E_y -polarized incident wave. The intensity (b) and phase (c) of the transmission and reflection waves. Lines and symbols respectively represent the simulated results from the Tellegen slab and the metamaterial.

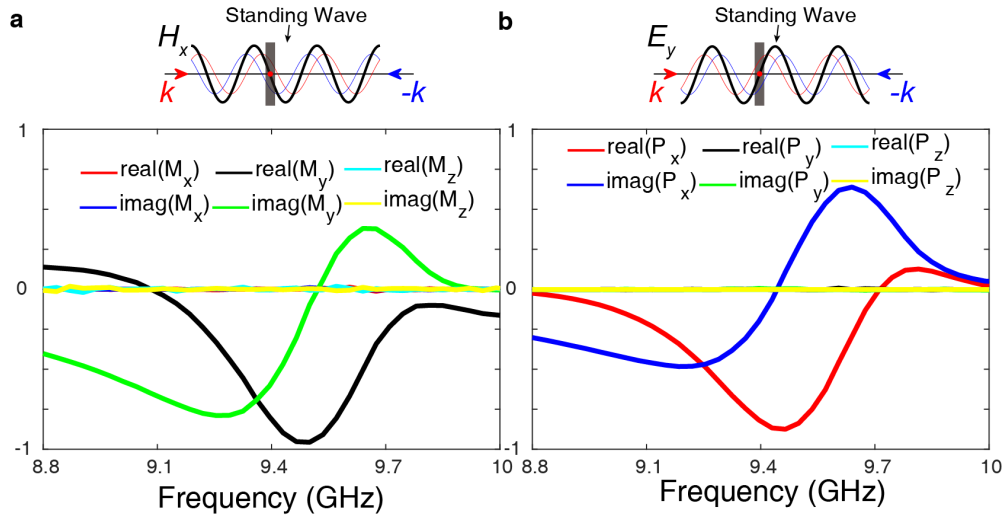


Fig.R3. The dipole moments in the Tellegen metamaterials under E_y polarized incidence. (a) The magnetic dipole component at the node of magnetic field. (b) The electric dipole component at the node of electric field. The unit of y-axis is arbitrary. The upper figures show the configurations of the excited standing wave (black), created by the superposition of a right traveling (red) and left traveling (blue) wave.

Comment 3

2. The authors correctly say that their metamaterial exhibits isotropic response only in the x-y plane, while the electromagnetic response in the z-direction is different. However, analysis of oblique incidence scenario is crucial for the correct identification of the type of electromagnetic response present here. As shown in the literature, probing only normal incidence geometry may lead to the confusion, see an example of this sort in [Phys Rev B 92, 085107 (2015)]. Naively, I would expect just ϵ_{zz} and μ_{zz} components for the response in z direction. With this assumption, does the effective medium calculation match simulation/experiment? Is the model of anisotropic Tellegen medium consistent? Without such analysis I do not think that the claim of anisotropic Tellegen response is sufficiently justified.

Reply 3:

Thank you for the comment. First of all, similar to most demonstrated metamaterials, our metamaterial exhibits nonlocal responses, as pointed out by the reviewer in the last report. As a result, spatial dispersion exists, meaning the effective parameters are expected to depend on the wavevector. In other words, the same set of parameters retrieved under normal incidence would not rigorously explain the electromagnetic responses (transmission and reflectance) at oblique incidence.

Our numerical results show that the effective medium calculation matches with the simulation results under the normal incidence or the oblique incidence with small incident angles, as shown in Fig. R4. As shown in Fig. R4(a) and Fig. R4(b), for small incident angles (4° and 8°), the simulated scattered parameters of the metamaterial (solid lines) match quite well with that of the homogenous slab (dash lines). However, for larger incident angles (20° and 24°), the transmission parameters of the metamaterial deviate from that of the homogenous slab (Fig. R4(c) and Fig. R4(d)), indicating that local effective medium description is not valid. Nonetheless, our main claim of the Tellegen response of the metamaterial is still valid, despite that the response of the metamaterial is nonlocal, which is a common feature of metamaterials.

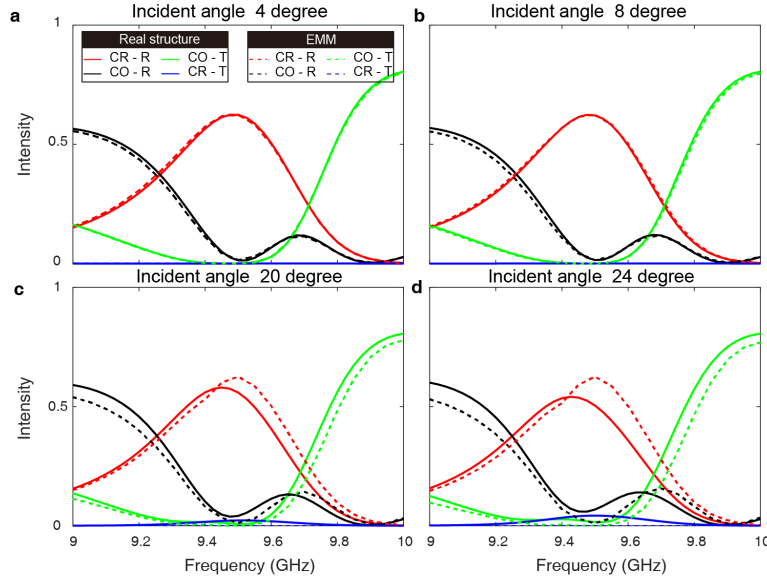


Fig.R4. Comparison of the transmission parameters of the metamaterial and a homogenous Tellegen slab for oblique incidence scenario. The labels “CO-” and “CR-” indicate co-polarization and cross-polarization respectively, and “T” and “R” present transmission and reflection respectively.

4. The authors added a statement “and the direct observation of axion response in the latter [condensed matter] has yet to be realized”. This is absolutely misleading, see the experimental paper [L. Wu, et al. Science 354, 6316, 1124-1127 (2016)] where experimentalists measure exactly the same quantities as the authors, but for the topological insulator and in the THz domain.

Reply 4:

Thanks for the comment. The axion response has indeed been experimentally reported in antiferromagnetic crystals like Cr_2O_3 (Tellegen coupling parameter ξ about 10^{-4}) and in topological insulators (with a quantized axion response in terms of the fine-structure constant, like the Science paper the reviewer mentioned). Our Tellegen metamaterial demonstrates a much stronger axion response (Tellegen coupling parameter ξ about 4), several orders of magnitude higher than that of natural materials, which can be flexibly engineered by designing the metamaterial unit cell. To avoid misleading, we have now changed the text into

“Although axion response has been extensively studied in condensed matter physics^{20,21} and has been experimentally reported in some antiferromagnetic crystals²² and electronic topological insulators²³⁻²⁸, the experimental realization of a strong and flexibly tunable axion response has remained elusive.”

5. The authors' claim that their system "opens up significant opportunities for the experimental exploration of novel concepts related to axion electrodynamics" is an exaggeration. As I said, this physics is known and experimentally verified in condensed matter. So, the novelty statement here should be more precise and limited to the microwave spectral range where, indeed, such structures have not been realized previously.

Reply 5:

Thanks for the comment. For the previous experiments in condensed matter, the angle of polarization rotation that can characterize the axion electrodynamics is generally within the range of mrad (about 2°). This indicates the intrinsically small electromagnetic response in the natural axion materials, which presents a significant challenge for experimental measurements and practical application. In our works, the key feature of Tellegen response - Kerr rotation reaches 90° at the resonance frequency, indicating gigantic responses in metamaterials which is very hard to achieve in natural materials. Meanwhile, with the advantage of metamaterials, the axion-coupling term can be flexibly engineered by tuning the artificial structures, thus opening up opportunities for the experimental exploration of novel concepts related to axion electrodynamics. We now change it into

"opens up significant opportunities for the experimental exploration of novel concepts related to axion electrodynamics in microwave range³⁹."

6. Finally, at p.5 the authors write about 4 classes of bianisotropic coupling. It seems they missed two more classes of bianisotropy: pseudo-Tellegen and pseudo-chiral response.

Reply 6:

Thanks for the comment. We agree that the bianisotropic coupling encompasses pseudo-Tellegen and pseudo-chiral responses. In cases where only the trace-free symmetric component of the nonreciprocal (reciprocal) polarizability is non-zero, the bianisotropic coupling corresponds to the pseudo-Tellegen (pseudo-chiral) response. In our work, we focus on an in-plane isotropic response, thus following the widely used classification [PRB 94, 195432 (2016), Nanophotonics, 7, 1069-1094 (2018)] in which the bianisotropic coupling can be classify four basic types. To avoid misleading, we changed the text into

"For the metamaterial with isotropic in-plane response, the bianisotropic coupling can be categorized into four basic classes – two that are reciprocal (chiral and omega), and two that are nonreciprocal (Tellegen and moving)."

1 Reviewer 1

Comment 1

The authors have significantly improved the manuscript addressing all essential questions. I have just a couple of minor comments which the authors may wish to implement: 1. The imaginary part of the extracted effective permittivity shown in Fig. S3a of Supplementary Materials changes its sign. It means that at some frequencies the metamaterial behaves as an active medium which is unphysical. I believe this issue should be commented by the authors in the text.

Reply 1:

We appreciate the reviewer's acknowledgement of our revised paper. Yes, a slightly negative imaginary part of the extracted permittivity is observed. This phenomenon can be attributed to the finite spatial periodicity of the metamaterial, a topic extensively discussed in metamaterial literature (like Phys. Rev. B 71, 245105 (2015); Phys. Rev. E 68, 065602 (2003)). Note that although the effective permittivity exhibits slightly negative imaginary part, the positive imaginary parts of permeability and Tellegen terms ensure that it is overall a lossy medium without gain (*Optics express*, 11(7), 649-661). In response to this comment, we have included the detailed information in Supplementary Materials Note 5 to provide a comprehensive and coherent discussion.

"In Fig. S3(a), a slightly negative imaginary part of the extracted permittivity is observed, which can be attributed to the finite spatial periodicity of the metamaterial [1,2]. Note that although the effective permittivity exists slightly negative imaginary part, the complex response of permeability and Tellegen terms ensure that it is overall a lossy medium without gain."

Comment 2

2. The authors analyzed the scenario of oblique incidence and, through the simulations, revealed the impact of nonlocality (spatial dispersion). This should be mentioned in the manuscript to provide a broader picture and highlight the limitations of effective medium description in this case.

Reply 2:

We appreciate the reviewer's comment and have incorporated a pertinent discussion in the main text to highlight the limitations of effective medium description in this case.

"Here we would like to note that, due to the presence of spatial dispersion in the metamaterial, the retrieved parameters under normal incidence cannot rigorously explain the electromagnetic responses at oblique incidence with significant incident angles."

Comment 3

After these minor corrections, I believe, the manuscript is suitable for publication.

Reply 3:

We appreciate the reviewer's time and effort to improve the quality of our manuscript.