Transport theory is the key foundation of the theoretical design of metamaterials-metamaterial is artificial phase transition

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Abstract. This is a revisit of my PhD thesis work in which I coined the term transport theory. In 1966. This is the first introduction of transport theory into condensed matter physics. Transport theory is today the key foundation of the theoretical design of materials. Since metamaterial is a new material, naturally it will fall under this category of work. Recently I discovered that metamaterial is in fact, artificial phase transition. Permeability, permittivity, effective bulk modulus, effective mass density are transport properties. The transport property also shows a singularity behavior at the critical point of phase transition in metamaterial same as that of the singularity behavior of transport property during condensation at phase transition. The successful fabrication of quantum metamaterial producing artificial superconductivity and metamaterial interpretation of high temperature superconductivity further confirms that metamaterial is artificial phase transition. Being artificial phase transition, one is able to control the degree of phase transition by tuning the resonance frequency of the transport properties.

1. PhD work revisited --introduction of transport theory into condensed matter physics

In 1966 W. S. Gan coined the term transport theory during his PhD work in the physics department of Imperial College London. His PhD thesis (1969, Imperial College London) Transport Theory in Magnetoacoustics [1] is the first to introduce transport theory into condensed matter physics. Since then transport theory has undergone tremendous development in linear transport theory, electronic transport theory, nonlinear transport theory, quantum transport theory etc. Today transport theory is the key foundation of the theoretical materials design [2]. It is the most important theory in condensed matter physics. The status of transport theory in condensed matter physics is equivalent to that of Yang Mills Theory [3] in particle physics. Also in 1967 Philip Warren Anderson and Volke Heine coined the term condensed matter physics when they changed the name of the solid state theory group to condensed matter physics group at Cavendish Lab, Cambridge, to combine liquid state physics with solid state physics and to reflect the important role of phase transition. Today condensed matter physics group has the largest membership in the American Physical Society. Thus his PhD thesis also played a role in the founding of the field of condensed matter physics.
2. Discovery of metamaterial as phase transition – metamaterial is a branch of condensed matter physics

In this paper, my PhD thesis will be revisited. It will be illustrated that metamaterial in fact is a phase transition and metamaterial is a branch of condensed matter physics. The double negativity of permeability and permittivity of electromagnetic metamaterial and double negativity of the effective bulk modulus and the effective mass density of the acoustic metamaterial is phase transition from the positive phase material to the negative phase material. Permeability, permittivity, bulk modulus and mass density are transport properties. Based on the backbone of the transport properties, one is able to discover new forms of metamaterials beyond the electromagnetic metamaterial and the acoustic metamaterial. Metamaterial is a branch of condensed matter physics Metamaterial is a transport phenomenon. Hence transport theory which describes transport properties and transport phenomena is the key foundation of the theoretical design of metamaterials. Metamaterial is a new material and transport theory is the key foundation of the theoretical design of new materials. Besides this, one does not have to use analogy to extend electromagnetic metamaterial to acoustic metamaterial. One can base on transport properties, the root of the problem.

3. Singularity behavior of transport properties at the critical point of phase transition

The description of metamaterial as a phase transition can be further confirmed by the singularity behavior of the transport properties of permeability [4], permittivity [5] and effective bulk modulus [6] during the critical point of phase transition, during the resonance frequency. (Please refer to the plots in Figs. 1, 2, 3, 4) There is a common behavior of the transport properties: permeability, permittivity, effective bulk modulus at the critical point of phase transition that at this critical point of resonance frequency they will have a sudden increase in value followed by a sudden drop to a huge negative value and then followed by a gradual rise in value in the negative region. The metamaterial is used in the phase transition of high temperature superconductivity further confirmed that metamaterial is a phase transition.

![Figure 1. Singularity behavior of permeability in magnetism at the critical point of phase transition [4].](image1)

![Figure 2. Singularity behavior of permittivity in high temperature superconductivity at the critical point of phase transition [5].](image2)
4. Discovery of other forms of metamaterials beyond electromagnetic and acoustic metamaterials

In this paper, based on transport properties, two new forms of metamaterials are introduced. One is the artificial piezoelectricity and another is artificial ferromagnetism based on the transport properties of dielectric constant and dipole moment respectively. The dielectric constant of the piezoelectricity is found to have the singularity mentioned in the previous paragraph [7]. An immediate fabrication of this form of metamaterial is to use the split ring resonator (SRR) as the unit cell of the piezoelectric metamaterial. The material of the unit cell will be made of piezoelectric material. This allows one to
manipulate and control the piezoelectricity. Piezoelectricity provides the physical basis for almost all practical applications of acoustic fields. This is because they provide an effective means for electrically generating and detecting acoustic vibrations.

I am in the process of investigating the singularity behavior of the dipole moment, the transport property of ferromagnetism versus frequencies during phase transition, the critical point or the resonance frequency.

5. Discovery of other forms of metamaterials beyond electromagnetic and acoustic metamaterials
The double negativity of electromagnetic metamaterial and acoustic metamaterial and the singularity of the dielectric response function of high temperature superconductivity are first examples of the use of transport properties to discover new forms of metamaterials.

5.1. Artificial elasticity
The singularity behavior of the effective bulk modulus at the resonance frequency or critical point of phase transition can be exploited to fabricate acoustic metamaterial [6]. Here there is a sudden increase of the effective bulk modulus to a very high value at the resonance frequency followed by a sudden drop to very high negative value and a gradual increase in value in the negative region. This singularity behavior can be exploited to fabricate acoustic metamaterial using the geometric structure of split ring resonator (SRR) with the unit cell made of elastic material. This enables the control and manipulation of the elasticity of the material. This is artificial elasticity.

5.2. Artificial magnetism
Pendry et al [4]'s paper on magnetism from conductors and enhanced nonlinear phenomena is an example of artificial magnetism. Here the permeability which is a transport property shows a singularity behaviour at the critical point of phase transition with a sudden rise at the resonance frequency to positive infinite value followed by a sudden drop to negative infinite value and then a gradual rise in the negative region. The negative values of permeability is used to fabricate the negative electromagnetic metamaterial using the SRR geometric structure as the unit cell of the metamaterial and the material of the unit cell is made of magnetic material. This enables the achievement of an electromagnetic metamaterial experimentally and the manipulation and control of magnetism. This is artificial magnetism.

5.3. Artificial high temperature superconductivity
Smolyaninov et al [5] proposed that high temperature superconductivity can be achieved using metamaterial. This is because dielectric response function governing electron-electron interaction can be used to increase the critical temperature of high temperature superconductivity according to Kirzhnits et al [8]. It is found that the dielectric response function which is a transport property has singularity behavior (hyperbolic shape) at the resonance frequency or the critical point of phase transition. The dielectric response function versus frequencies plot shows a sudden increase to high positive value and then a sudden drop to large negative value followed by a gradual increase in value in the negative region. This behavior can be exploited in the fabrication of high temperature superconductor by using a geometric structure of SRR for the unit cell made of high temperature superconductor. This enables one to manipulate and control high temperature superconductivity. Hence the name high temperature superconductivity metamaterial.

5.4. Artificial piezoelectricity
Piezoelectricity is an important phenomenon in acoustics. It provides the physical basis for almost all practical applications of acoustic fields. This is because they provide an effective means for electrically generating and detecting acoustic vibrations. It is found by Legrand et al [7] that the permittivity also has a singularity behavior at the resonance frequency or point of phase transition with a sudden increase to a very high value followed by a sudden drop to negative value then a gradual
increase in value in the negative region. This singularity behavior can be used to fabricate artificial piezoelectricity by using a SRR as geometric structure of the unit cell made of piezoelectric material. This will enable the manipulation and control piezoelectricity. This is artificial piezoelectricity.

5.5. Artificial ferromagnetism
In ferromagnetism, according to Joseph Mayer [9], there is some sort of mathematical singularity at the condensation point. The transport property of ferromagnetism is magnetization or dipole moment. It is of interest to investigate the singularity behavior of the dipole moment at the critical point of phase transition or condensation point. There will be a temperature dependence of the dipole moment besides the frequencies dependence. One will have to plot the dipole moment versus the frequencies at a series of temperatures. There will be no singularity behavior of the dipole moment versus frequencies plot at other temperatures. However, at the critical temperature of second order phase transition, there will be a hyperbolic shape behavior of the dipole moment versus dipole moment versus frequencies plot at other temperatures. However, at the critical temperature of second order phase transition, there will be a hyperbolic shape behavior of the dipole moment versus frequencies plot similar to that of the cases of the artificial elasticity, artificial magnetism, and artificial piezoelectricity.

6. Metamaterial as phase transition as breakthrough to a new world of artificial materials
Double negativity electromagnetic metamaterial and double negativity acoustic metamaterial are manifestations of artificial magnetism and artificial elasticity. This will be a starting point for the exploration of various new artificial materials based on metamaterial and phase transition. Immediate examples are artificial piezoelectricity and artificial ferromagnetism. This will open to a new world of new materials based on other transport properties besides permeability, permittivity, effective bulk modulus and effective mass density.

7. Phase transition approach to metamaterial
Phase transition approach to metamaterial will enable a deeper understanding of metamaterial. The advantage of using metamaterial in phase transition is to enable to adjust the degree of phase transition from full phase transition to partial phase transition by tuning the resonance frequencies of the transport property as phase transition arises from the singularity behavior of the transport property at the critical point.

8. Conclusions
Transport theory has come a long way in tremendous development in condensed matter physics since the term was coined by me in 1966. It has now become the key foundation of theoretical materials design. Hence it has become the most important theory in condensed matter physics. Since metamaterial is a new material, it will naturally fall under the category of design using the transport theory.

9. References
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