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METAMATERIALS FOR MINIATURIZATION OF OPTICAL COMPONENTS

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Final Report**

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14. ABSTRACT Our work for reported period is related to two major areas: (i) Neoclassical theory of electromagnetic interactions with special features at nanoscale; (ii) Dissipative properties of magnetic composite (meta) materials. In our joint work with Dr. Welters we have developed a theory of dissipative properties of composite (meta) materials composed of high-loss and low-loss components. In our joint work with Dr. Babin we advanced the relativistic and spinorial aspects of our neoclassical electromagnetic theory.					
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Dear Dr. Nachman,

Please find below my final report for

AFOSR Contract No. FA9550-11-1-0163 from June 30, 2011 to June 30, 2014.

Alex Figotin.

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1. Title: "METAMATERIALS FOR MINIATURIZATION OF OPTICAL COMPONENTS".
 2. AFOSR Contract No. FA9550-11-1-0163.
 3. Annual Report for the period June 30, 2011 to June 30, 2014.
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I. OBJECTIVES.

- Studies of fundamental aspects of electromagnetic interactions at nanoscale.
- Advancement of the our neoclassical electromagnetic theory for elementary charges including atomic nanoscales relevant to metamaterials and miniaturization of optical components.
- Studies of dissipative properties of composite (meta) magnetic materials

II. STATUS OF EFFORT

Our work for reported period is related to two major areas:

- (i) Neoclassical theory of electromagnetic interactions with special features at nanoscale;
- (ii) Dissipative properties of magnetic composite (meta) materials.

I. Neoclassical theory of electromagnetic interactions with special features at nanoscale.

The neoclassical electromagnetic theory is constructed based on a relativistic Lagrangian with the following properties:

- (i) elementary charges interact only through their elementary EM potentials and fields;
- (ii) the field equations for the elementary EM fields are exactly the Maxwell equations with proper conserved currents;

(iii) a free charge moves uniformly preserving up to the Lorentz contraction its shape;

(iv) the Newton equations with the Lorentz forces hold approximately when charges are well separated and move with non-relativistic velocities. Since an overwhelming number of EM phenomena are explained within the CEM theory by the Maxwell equations and the Lorentz forces our neoclassical theory is equally successful in explaining the same phenomena.

Our theory has a very special and specific feature - the size of the free electron $a_{\{e\}}$ - which has no counterpart in either classical nor in quantum theories where an electron is a point-like object. Our current assessment of $a_{\{e\}}$ is 5 nm. When entertaining an idea of the size of free electron of approximately 5 nm being a new fundamental spatial scale we expect this scale to manifest itself in electron transitions to its free state and, maybe, in situations when electron confined or bound to spaces of dimensions comparable with 5 nm. With that in mind we have identified three areas where the free electron size can be of a critical importance.

The first area is the field emission physics when an electron subjected to external electric field leaves the surface of a cathode and becomes free.

The second area is relatively new one - plasmonics. Recent remarkable advances in nano-technology allowed to probe electromagnetic interactions at nano-scale and provided new challenges to the electromagnetic theory.

The third area is the plasma physics or more specifically the concept of "charge cloud" related to the Particle-in-Cell (PIC) method. Some plasma experiments "demonstrate that the physical interpretation of the numerical spatial charge and force sharing goes beyond simple smoothing of point particles and clearly supports the concept of finite-size particles".

II. Dissipative properties of magnetic composite (meta) materials.

An important motivation and guiding examples for our studies come from two-component dielectric media composed of a high-loss and lossless components. Any dielectric medium always absorbs a certain amount of electromagnetic energy, a phenomenon which is often referred to as loss. When it comes to the design of devices utilizing dielectric properties very often a component which carries a useful property, for instance, magnetism is also lossy. So the question stands: is it possible to design a composite material/system which would have a desired property comparable with a naturally occurring bulk substance but with significantly reduced losses. In a search of such a low-loss composite it is appropriate to assume that the lossy component, for instance magnetic, constitutes the significant fraction which carries the desired property. But then it is far from clear whether a significant loss reduction is achievable at all.

It is quite remarkable that the answer to the above question is affirmative, and an example of a simple layered structure having magnetic properties comparable with a natural bulk material but with 100 times lesser losses in wide frequency range is constructed in Ref. 6. The primary goal of this paper is to find out and explain when and how a two component system involving a high-loss component can have low loss for a wide frequency range.

We have studied dissipative properties of systems composed of two components one of which is highly lossy and the other is lossless. A principal result of our studies of is that all the eigenmodes of such a system split into two distinct classes characterized as high-loss and low-loss. Interestingly, this splitting is more pronounced the higher the loss of the lossy component. In addition, the real frequencies of the high-loss eigenmodes can become very small and even can vanish entirely, which is the case of overdamping.

Advancing further our first results we used a Lagrangian mechanics approach and have developed a framework to study the dissipative properties of systems composed of two components one of which is highly lossy and the other is lossless. An important result of this approach is that for any such dissipative Lagrangian system, with losses accounted by a Rayleigh dissipative function, a rather universal phenomenon occurs, namely, selective overdamping: The high-loss modes are all overdamped, i.e., non-oscillatory, as are an equal number of low-loss modes, but the rest of the low-loss modes remain oscillatory each with an extremely high quality factor that actually increases as the loss of the lossy component increases. We prove this result using a new time dynamical characterization of overdamping in terms of a virial theorem for dissipative systems and the breaking of an equipartition of energy.

III. ACCOMPLISHMENTS/NEW FINDINGS.

- In our joint work with Dr. Welters we have developed a theory of dissipative properties of composite (meta) materials composed of high-loss and low-loss components.
- In our joint work with Dr. Babin we advanced the relativistic and spinorial aspects of our neoclassical electromagnetic theory.

IV. FACULTY AND GRADUATE STUDENTS SUPPORTED:

Dr. A. Babine

V. PUBLICATIONS:

1. Babin A. and Figotin A, Electrodynamics of balanced charges, *Found. of Phys.*, 41, 242--260, (2011).
2. Babin A. and Figotin A. Relativistic dynamics of accelerating particles derived from field equations, *Found. of Phys.*, 42, 996--1014, (2012).
3. Figotin A. and Welters, Dissipative properties of systems composed of high-loss and lossless components, *Journal of Mathematical Physics*, 53, 123508, (2012).
4. Babin A. and Figotin A, Relativistic Point Dynamics and Einstein Formula as a Property of Localized Solutions of a Nonlinear Klein-Gordon Equation, *Commun. Math. Phys.*, 322, 453--499, (2013).
5. Figotin A. and Vitebskiy I., Electromagnetic Unidirectionality in Magnetic Photonic Crystals, Chapter 3 in Inoue et al. (eds.), *Magnetophotonics*, Springer Series in Materials Science 178, 2013, (with I. Vitebskiy).

6. Babin A. and Figotin A, Neoclassical Theory of Elementary Charges with Spin of $1/2$, Journal of Mathematical Physics, 55, 082901 (2014).
7. Babin A. and Figotin A, Newton's law for a trajectory of concentration of solutions to Nonlinear Schrodinger equation, Communications on Pure and Applied Analysis, 13, No.5, 1685-1718, (2014).
8. Figotin A. and Welters, Lagrangian framework for systems composed of high-loss and lossless components, Journal of Mathematical Physics, 55, 062902 (2014).
9. Babin A. and Figotin A, Electrodynamics of elementary distributed charges. A single theory for Macroscopic and Microscopic Scales, Book, in preparation, to be published by Springer, 95% complete.

VI. CONFERENCES and INVITED TALKS:

- AIMS Conference, Madrid, Neoclassical Theory of Electromagnetic Interactions, July 2014.
- Continuous models and Discrete systems, Salt Lake City, Utah, Lagrangian Framework for boundary value problems, July 2014.
- SIAM conference, Philadelphia, Lagrangian Treatment of Systems Composed of High-Loss and Lossless Components, June 2013.
- Mathematical Physics of Disordered Systems -- A Conference in Honor of Leonid Pastur, Hagen, Germany, Some Mathematical Problems in a Neoclassical Theory of Electric Charges, 2013.
- Electromagnetics Workshop, Brooks Air Force Base, San Antonio, Lagrangian Treatment of Systems Composed of High-Loss and Lossless Components, January, 2013
- ICOPS, Dissipation in Composites with High-Loss and Lossless Components, July 2012.
- Electromagnetics workshop, San Antonio, Dissipative Properties of Systems Composed of High Loss and Lossless Components, January 2012.
- AMS Western Section Meeting, Salt Lake City, Some Mathematical Problems in a Neoclassical Theory of Electric Charges, October, 2011.