White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	S
• Turbulence and transport	
• Interactions of plasmas and waves	P
• Plasma self-organization	S
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Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	X
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Title:	Microplasmas as an Effective Media for Electromagnetic Waves
Corresponding Author:	Michael H. Helle
• Institution:	Naval Research Laboratory
• email:	Mike.helle@nrl.navy.mil
Co-Authors:	Benjamin Rock, Joseph Penano, John Palastro, and Antonio Ting

**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

- ***Describe the research frontier* and importance of the scientific challenge.**

There is great interest in microplasmas, plasmas with dimensions less than a millimeter, because their increased surface-to-volume ratio can lead to new physics and chemistry when compared to large-scale plasma[1]. Microplasma are typically formed from moderate pressured gases and can exhibit local electron densities, n_e, from 10^{10} cm^{-3} to 10^{16} cm^{-3}. These values correspond to plasma frequencies $\omega_{pe}/2\pi$ ranging from GHz to THz. It could be possible to engineer complex resonant frequencies by manipulating the size and shape of these microplasmas. A collection of such microplasmas could exhibit even more complex behavior. If individual microplasmas were significantly sub-wavelength, the composite material would appear as a continuous effective medium with regard to incident electromagnetic waves. Such a material, with complex engineered resonances, is typically considered a metamaterial [2]. Microplasmas range in size from millimeters to microns, thus a microplasma metamaterial would be an ideal device for frequencies from ~100 MHz to THz.
Current metamaterials rely on geometric factors to define the resonant frequency of the effective media. The characteristics of the resonance, width and amplitude, are entirely dictated by the resistivity per unit area of the material used. Typical metamaterials consist of metallic elements that have low resistivity, and therefore small features sizes are required in order to achieve an appreciable resonance width. These small feature sizes mean that the effective plasma frequency is often too low and additional structures such as

metallic rods have to be added to obtain a negative permittivity. Microplasmas however have a higher resistivity, and therefore larger features sizes would be needed. The increased fractional volume automatically satisfies the requirement for the effective plasma frequency and no additional structures are needed, simplifying the overall design.
A microplasma also provides the unique benefit of controlling its electrical properties through the plasma density n_e and the collisional frequency υ. For instance it could be possible to shape the microplasma such that an equivalent magnetic dipole moment and a magnetic resonance frequency ω_m is generated. Combining this with a negative permittivity material (e.g. a effective macroplasma with $\omega_{pe} < \omega$) leads to a material that exhibits a negative refractive index at a frequency $\omega = \omega_m$.
This possibility illustrates why microplasma based metamaterials are so attractive. Current metamaterials are static devices that are designed with fixed properties that are always "on." Microplasma metamaterials provide the ability to actively control the resonant properties on demand through the manipulation of n_e and ν. For example, on either side of the resonance, the plasma metamaterial acts as a positive or negative index material. By detuning the system, the material can act as a high dB filter. And finally, if the plasma is turned off the material acts as a normal transparent dielectric. No other metamaterial can provide such on demand control. Additionally, a microplasma based metamaterial could operate in high field environments where normal materials would ordinarily breakdown.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

The idea of using microplasmas as discretized elements to function as an effective medium is a recent development and has yet to be fully understood and verified [3]. Early devices use either rudimentary electrodes or hybrid designs that use metallic structures to generate a magnetic permeability. Both designs use the plasma only as a means to obtain a negative permittivity. These devices are generally planar, with the research focused on producing EM band gaps. A claim of generating a negative refractive index has been made, however the error bars cloud its validity [4,5]. These works also rely on simplistic 1D models. No 3D effective media theory that includes relevant plasma physics has been developed. Also, parameters such as microplasma coupling, chemistry, lifetimes, heating effects, validity of effective media theory, etc. have yet to be investigated. To date this field has been approached from a material science point of view and lacks a detailed plasma physics understanding.

The fundamental questions that need to be to answered within this field are:

1) How does modifying the microplasma parameters change the bulk electromagnetic properties?

2) How are the electromagnetic properties modified as the electron mean free path approaches the individual feature size?

3) What are the limits to effective media theory and to what extent do realistic systems deviate?

4) To what degree does coupling between the microplasmas and the electromagnetic radiation lead to nonlinear effects?

A purely microplasma based device without metallic components would be the ideal platform to understand the underlying physics of such a system. One could envision various ways in which this could be achieved, however any such investigation would need to follow an approach in which individual microplasma are first fully characterized and then their bulk behavior is examined. From a simulation point of view, initially the output of codes used to model the microplasma elements should be coupled

into electromagnetic field solvers. Eventually, codes using similar approaches to those developed for molecular dynamics should be developed to model the whole system.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

This research points toward the development of a whole new field of materials for which electromagnetic waves can be modified by tuning the plasma properties. Put another way this represents a new type of active, adjustable metamaterial that is not well understood [3,6], but has many potential applications, e.g., ultrafast optical switching, energetic materials, transformative optics, electromagnetic mode shaping, and enhanced beam focusing (superlens). Studies of the fundamental interactions of electromagnetic radiation with sub-wavelength plasma structures are needed. The end result of which would be the development of an effective medium theory describing how these microstructured plasmas affect macroscopic media properties such as permittivity and permeability.

References

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[3] Osamu Sakai et al 2007 Plasma Phys. Control. Fusion 49 B453
[4]Osamu Sakai, Teruki Naito, Takuya Shimomura, Kunihide Tachibana Thin Solid Films 518 (2010) 3444–3448
[5] Osamu Sakai, Takuya Shimomura, and Kunihide Tachibana Phys. Plasmas 17, 123504 (2010).
[6] Osamu Sakai and Kunihide Tachibana 2012 Plasma Sources Sci. Technol. 21 013001