Plasma-based reconfigurable photonic crystals and metamaterials

Multi-University Research Initiative

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MURI Program Review
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Plasma-based reconfigurable photonic crystals and metamaterials

**Goal:** to understand the science and engineering of integrating plasmas into an assembly of dissimilar materials so as to generate an uncommon electromagnetic response.

**Application:**
Control of mm-wave EM radiation with high bandwidth

Plasma integrated into: Ordered periodic structures (photonic crystal/ metamaterials) for control of EM waves in the mm-range (>30 GHz) of the spectrum.
MURI challenges

- Generate and integrate **high density microplasmas**
  - transient and steady-state, to control mm-waves
  - scales comparable to field wavelength (0.1 – 3 mm)
  - $\omega_p$ comparable to field frequency ($10^{13} – 10^{16}$ cm$^{-3}$)
- Achieve **high bandwidth** control (>MHz)
  - change/control plasma properties rapidly
  - understand/exploit breakdown and mode transitions
- Demonstrate **low transmission loss**
  - Need low loss tangent dielectrics at high frequency
- Demonstrate **low materials degradation**
  - Require long lifetime when integrated into device/systems
- High fidelity coupled field/plasma simulations
Significant year one accomplishments

Publications and presentations


Significant year one accomplishments

- Tunable plasma photonic crystal filters/modulators
- All-plasma photonic crystal/metamaterial
- Plasma-generating and plasma-tunable split ring resonators to 10 GHz
- All dielectric PC/MM with generated microplasma arrays
- 1D/2D (Fluid and PIC) simulations of microwave gap-driven microplasmas at high frequency (up to THz)
- Synthesized high-Q advanced dielectrics and characterized EM properties
- Performed plasma exposure studies to understand degradation mechanisms
- First demonstration of dielectric resonator-driven plasmas/plasma arrays
- Developed large-scale 3D parallel FDTD solver with coupling to full physics plasma representation for plasma PC/MM predictions
- $13N$-moment multi-fluid plasma simulations for high fidelity plasma dynamics and wave–plasma PC/MM interactions
# Professional and student training

<table>
<thead>
<tr>
<th><strong>Graduate Students</strong>*</th>
<th><strong>Post-Doctoral and Research Associates</strong></th>
<th><strong>Faculty</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ben Wang (SU)</td>
<td>A. Lucca-Fabris (SU)</td>
<td>M. Cappelli (SU)</td>
</tr>
<tr>
<td>Robert Colon (SU)</td>
<td>N. Gascon (SU)</td>
<td>J. Hopwood (TU)</td>
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<tr>
<td>David Biggs (SU)</td>
<td>J. Gregorio (TU)</td>
<td>A.R. Hoskinson (TU)</td>
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<tr>
<td>Jack Goodwin (SU)</td>
<td>R. Luo (PS)</td>
<td>M. Lanagan (PS)</td>
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<tr>
<td>Fabio Righetti (SU)</td>
<td>J. Guo (PS)</td>
<td>C. Randall (PS)</td>
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<tr>
<td>Stephen Dennison (TU)</td>
<td>K. Kourtzanidis (UT)</td>
<td>L. Raja (UT)</td>
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<tr>
<td>Zane Cohick (PS)</td>
<td>D. Levko (UT)</td>
<td>U. Shumlak (UW)</td>
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<tr>
<td>Jing Zhao (PS)</td>
<td>Taylor Matlock (UCLA)</td>
<td>R. Wirz (UCLA)</td>
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<td>Prem Kumar (UT)</td>
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<td>Dylan Pederson (UT)</td>
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<td>Iman Datta (UW)</td>
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<td>Andrew Ho (UW)</td>
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<td>Sean Miller (UW)</td>
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<td>Noah Reddell (UW)</td>
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<td>Chris Dodson (UCLA)</td>
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<td>Cesar Huerta (UCLA)</td>
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<tr>
<td>Lucas Garel (UCLA)</td>
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</table>

*Almost half of the graduate students receive fellowship support*

** List does not include the over one dozen undergraduates that have participated during the summer and academic years.
Photonic crystals (PC) are engineered bandgap materials
- exploit successive Bragg reflections from periodic surfaces
- EM wavelengths comparable to spacing
- material combinations or defects can be used to introduce propagating mid-gap modes
- plasmas used to functionalize these modes

Metamaterials (MM) are engineered pseudo-materials
- exploit mixture of dielectric and magnetic properties of composite materials
- EM wavelengths longer than mixture spacing
- Field establishes collective dipole resonances
- material combinations can be used to generate complex or negative EM $n$ or $Z$
- plasmas used to functionalize the $n$ or $Z$
Tunable plasma photonic crystal (Ku band) filter

- Alumina PC scaffold (Bandgap 11-15 GHz)
- Resonance mode at 13.8 GHz
- Functionalized tunable by discharge plasma
- FDTD simulations used for the design of filter
- Measurements of shifts in quantitative agreement with discharge model
- First demonstration of tunable filter and framework for high bandwidth modulator

Stanford
reduce size and extend frequency into the mm-range

initial measurements using alumina scaffold but the loss tangent is too high

need dielectrics with lower loss tangents (higher Q) in the Ku regime

Alumina PC scaffold
Copper confinement
Non-confined DC discharge
Bandgap at (15-20 GHz)
(Second bandgap 30-40 GHz)
Resonance modes at 18 and 36 GHz (Ku and K band)
Functionalized tunable by discharge plasma

DC microdischarge*
(triode configuration)
0.5-5 Torr Argon
Plasma density and temperature (Langmuir probes) $\sim 10^{11} \text{ cm}^{-3}$, 9eV

All plasma photonic crystals/metamaterials

Discharge plasmas (X-Ku)

- minimizes dissipation losses from dielectrics
- Strong plasma density (current) dependence

Laser plasmas

- 2D array of pulsed plasma spheres can serve as a transient MM reflector
- collective Mie resonances driven by microwave field lead to temporary high impedance surface*

- additivity models give effective $\mu$, $\varepsilon$

$$z = \sqrt{\frac{\mu_{eff}}{\varepsilon_{eff}}}$$

- HFSS simulations confirm model predictions
- experiments underway

**Tunable waveguide (Ku and C band) PC filters**

**All dielectric** tapered waveguide design (holes of diminishing size)

- Bragg-mirrors create band-gap structure
- Linear tapering of holes in a dielectric waveguide creates resonant cavity
- Plasma is produced in the center hole (AC/pulsed DC in argon at 1 Torr) to shift resonance frequency
- Compact design (all dielectric facilitates plasma introduction)

**Microstrip** design with equally-spaced holes in ground plane

- Allows microdischarge integration into centimeter-scale devices
- Bandgap degrading by the plasma
- Plasma-dielectric (Rogers laminate) material interactions leaves carbon residue
  - Limits life
  - Reduces performance

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**Graphs and Diagrams:**

- Transmission vs. Frequency for different plasma conditions
  - $n_e = 0$ cm$^{-3}$
  - $n_e = 9 \times 10^{11}$ cm$^{-3}$
  - $n_e = 2 \times 10^{13}$ cm$^{-3}$

- DC HC microdischarge
  - Future studies will integrate magnetized microdischarges
Plasma-tunable split-ring metal resonators

(Stanford/Tufts)

Split-Ring Resonators are the building blocks of most metamaterials
Ma et al., Nature Materials 8, 639 - 642 (2009)

• effective permeability passes through zero (results in negative n)
• permeability driven by ring inductance and capacitance
  • can be functionalized by plasma
  • resonance field can also drive the formation of plasma
• equivalent circuit models used to predict tuning characteristics

Design and Fabrication
• developed design and fabrication methods for plasma-tuned SRRs over range of frequencies

Independent discharge tuning of SRRs

Driven breakdown and sustained discharge plasmas

• demonstrated potential for generating high density microplasma arrays for mm-wave PPC/MM
1D/2D Fluid simulations of microwave gap-microdischarges

- **The 1-D fluid model** was developed and benchmarked over 0.5 – 12 GHz
- Validated against experimental measurements of electron density/gap voltage
- Required sustaining potential drops from 75 to less than 10 volts with increasing drive frequency
- \( n_e \) increases with frequency, \( f \)
- saturates as the collision frequency = electron energy dissipation frequency \((\sim 4 \text{ GHz})\)
- \( n_e \approx 10^{20-21} \text{ m}^{-3} \)
- good agreement with TU experiments
- note highest density near dielectric
- Surface waves excite the plasma
- Ionization concentrated at gap edges
- E-fields as high as \(10^7 \text{ V/m}\)

**2-D fluid model** developed that fully couple EM wave with structure

- \( f=1\text{GHz} \)
- \( P=1 \text{ atm} \)
- TE Mode point source

**Graphs and Diagrams**

- Peak electron density vs. excitation frequency
- Electron density contours in the gap
- Ex field at the gap with indicated plot line for Fig. 2
1D/2D PIC simulations of microwave gap-microdischarges

- **PIC simulations** can capture additional Nonequilibrium physics
- Simulations include:
  - electron field emission
  - secondary electron emission
  - metal and dielectric boundary interactions

1D PIC Results
- Breakdown depends on field frequency but only above ~ 10 µm gap widths
- Breakdown has weak frequency dependence at large gap widths

2D PIC Results
- parallel microstrip configuration
- microwave field contours concentrated near electrodes
- plasma densities comparable to experiments
- Streaks of plasma density show oscillating quasi-steady sheath characteristics
- Peak plasma densities in range seen in TU experiments
Plasma-materials interaction

PI – Plasma Interaction Facility
Facility and plasma source for plasma exposure of dielectrics/metals
• understand plasma material interactions (PMI) on $\varepsilon, Q$
• assess material and device lifetimes
• characterize morphologies
• elemental composition degradation

Material Analysis
Pre/post material examination
• Surface topology (SEM)
• Surface composition (EDS)
• Weight loss (micro-balance)
  – In-situ capabilities installed

Plasma characterization
5-hour exposures
Ion flux to target
Ion fluence $\sim 10^{22} \text{s}^{-1} \text{m}^{-2}$

Sample holder temperature
Sample ion current

EDS spectrum taken after $\text{Al}_2\text{O}_3$ sample exposure

Atomic Concentrations

$\text{O K}\alpha$
$\text{Al K}\alpha$
$\text{Mg K}\alpha$
Plasma-materials interaction

Material degradation studies
Understanding mechanisms attributed to:

Electrons & VUV photons
- break bonds, excite atoms
- adatom sublimation at high T
- VUV photon (Ar) \(\sim\) 12 eV
- Al-O bond energy \(\sim\) 5 eV

Ions \(\rightarrow\) sputtering
- Sheath > sputter threshold (\(\sim\)10-100 eV)

Plasma properties just upstream of target

<table>
<thead>
<tr>
<th>Species</th>
<th>Power (W/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion</td>
<td>0.3</td>
</tr>
<tr>
<td>Electron</td>
<td>0.5</td>
</tr>
<tr>
<td>Photons</td>
<td>0.3</td>
</tr>
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</table>

Estimated properties during Pi plasma exposure of Al₂O₃ target
Plasma-induced degradation of dielectric properties

Microstrip plasma erosion:
can result in
- device wear
- contamination
- compromised performance

Note: The serious corrosion occurred with gap size increased from 0.11mm to 0.413mm

Note: Carbon deposition during hollow cathode discharge operation in argon at high pressure

Plasma exposure testing of commercial and PSU fabricated dielectrics

Commercial materials
- Ferro
- Heraeus
- Dupont 951
- Dupont 943
- Alumina

In-house fabricated tape
- Zirconia
- Titania
- Calcium Titanate

Carbon residue was observed after exposure for all substrates.
- does not affect the permittivity but the dielectric loss increased

<table>
<thead>
<tr>
<th>Sample</th>
<th>Frequency (GHz)</th>
<th>$\varepsilon_r$</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$</td>
<td>Pre- 14.5</td>
<td>9.3</td>
<td>1,100</td>
</tr>
<tr>
<td></td>
<td>Post- 14.5</td>
<td>9.4</td>
<td>800</td>
</tr>
<tr>
<td>ZrO$_2$</td>
<td>Pre- 10.2</td>
<td>24.0</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>Post- 10.2</td>
<td>24.0</td>
<td>740</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>Pre- 15.0</td>
<td>3.8</td>
<td>2,900</td>
</tr>
<tr>
<td></td>
<td>Post- 15.0</td>
<td>3.8</td>
<td>2,300</td>
</tr>
</tbody>
</table>

Decrease in Q after plasma exposure

Note: High density plasma in direct contact with dielectric resonator surfaces
Characterization of dielectric performance

- Synthesized and/or tested dielectrics up to 20 GHz range
- Interactions between MURI team members:
  - device integration
  - plasma interaction studies

<table>
<thead>
<tr>
<th>Material</th>
<th>Frequency GHz</th>
<th>ε</th>
<th>Q</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>20</td>
<td>4</td>
<td>3,000</td>
<td>Commercial substrate to UCLA</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>15</td>
<td>9</td>
<td>1,300</td>
<td>Commercial substrate to UCLA, Ring resonator studies at PSU</td>
</tr>
<tr>
<td>ZrO₂</td>
<td>10</td>
<td>24</td>
<td>800</td>
<td>PSU synthesized Substrate to UCLA</td>
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<tr>
<td>TiO₂</td>
<td>4</td>
<td>100</td>
<td>2,500</td>
<td>PSU synthesized Substrate to UCLA</td>
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<tr>
<td>Zn₀·₈Sn₀·₂TiO₄</td>
<td>10</td>
<td>40</td>
<td>5,000</td>
<td>High power Resonator studies at PSU</td>
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<tr>
<td>CaTiO₃</td>
<td>1</td>
<td>170</td>
<td>1,000</td>
<td>PSU synthesized Resonators sent to Tufts</td>
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<tr>
<td>Ba₀·₄Sr₀·₆TiO₃</td>
<td>2 GHz</td>
<td>880</td>
<td>300</td>
<td>Future material of interest?</td>
</tr>
<tr>
<td>Li₂MoO₄</td>
<td>17 GHz</td>
<td>6</td>
<td>2,000</td>
<td>Future material of interest?</td>
</tr>
</tbody>
</table>
New plasma-materials interaction capabilities

- Direct, in-situ, and non-intrusive measurements enabled:
  - Sheath E-field (SEY)
  - Ion EDF
  - Gas constituents
  - Micro-scale features

- Ex-situ analysis
  - SEM, EDS, XRD, profilometry, mass loss

Pi v2: World-class diagnostic suite for in-situ PMI

Broadly Tunable, Narrow Linewidth Laser System
(Enables direct sputter product density measurement & plasma diagnosis)
Dielectric resonators for microplasma arrays

- Dielectric arrays can also serve as metamaterials with EM wave excitation of dipole resonances
- Strong E and H field concentrations can be obtained between dielectric elements by exciting electric and magnetic dipole resonances
- Free space EM wave excitation of resonances produce plasma discharges

High Q resonator fabricated from Zn$_{0.8}$Sn$_{0.2}$TiO$_4$  $Q = 50,000$

electric field increases by over 10x in the gap
Dielectric resonators for microplasma arrays

Simulation of a two DR system

- CaTiO₃ resonators
  - from Penn State Team
  - \( \varepsilon_R = 165 \)
  - diameter = 30 mm
  - height = 15 mm
  - HEM₁₁₁ mode: 1.14 GHz

Experiments

- experimental measurement of breakdown power
- Model used to convert measured antenna power into breakdown electric field
- DR ignited and sustained plasma
- Plasma ignition up to 60 Torr argon (antenna power <12 W)

- Plasma sustained to 760 Torr
- Breakdown field ~10-20 kV/m
- Paschen-like behavior
Arrays of Cylindrical DR Resonator Plasmas
5 x 5 array of DR resonators
- Modeling suggests EM fields between resonators can induce gas breakdown
- Microplasma impedances modify EM behavior of the photonic crystal

Electromagnetic model for a 5x5 array of dielectric resonators

Experimental Demonstration of resonator driven plasma array
5 x 1 array of DR resonator plasmas
- antenna driven
- ignited in 1 Torr argon

- The plasmas modulate the microwave power reflected back toward the antenna:

<table>
<thead>
<tr>
<th>Argon pressure (Torr)</th>
<th>Percent reflected power</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 Torr</td>
<td>25 W</td>
</tr>
<tr>
<td>731 Torr</td>
<td>10.5 W</td>
</tr>
</tbody>
</table>

(Duvts)
Dielectric resonators for microplasma arrays

Experimental demonstration of split DR antenna-driven plasma

- High Q resonator fabricated from $\text{Zn}_{0.8}\text{Sn}_{0.2}\text{TiO}_4$  $Q = 50,000$
- Resonance frequency sensitive to gap distance
- Plasma generation in atmosphere air gap
- DR subject to 300W of multimode microwaves at 2.45GHz
- $\text{Zn}_{0.8}\text{Sn}_{0.2}\text{TiO}_4$ resonator designed to resonate in TE011 at 2.45GHz
Simulating EM wave PC/MM interactions

Large-scale FDTD EM-wave solver with coupled full plasma representation

- guide understanding of interaction between EM waves and plasma arrays
- Study the non-linear behavior of the plasmas due to MW energy absorption
- Large-scale simulations are needed! Massive parallel computations are necessary

Solver and model\(^1\) principal attributes:

- C++ object-oriented programming
- MPI Parallelization
- 3D - Finite Difference Time Domain (FDTD)
- Quasi-neutral plasma - fluid model
- Coupling with EM through electron current density
- Local effective field and effective diffusion approximation

Simulating EM wave PC/MM interactions

EM waves incident on a 3D plasma array

- FDTD EM solver benchmarked on a 3D plasma array

Volume contours of $E_{\text{RMS}}$ field – standing waves between the micro-plasmas (TE plane wave excitation)

The plasma array on the X-Z plane

- $f_{\text{EM}} = 100$ GHz, $P = 760$ torr
- Periodic B.C. on Y and Z, PML B.C. on X
- $\Delta x = \Delta y = \Delta z = \lambda/200$
- $\lambda = 3$ mm
- $n_{\text{cut-off}}$ (non-collisional) $\approx 1.24 \times 10^{20}$ m$^{-3}$
- skin depth $\approx 0.5$ - 1 mm

sensitivity to plasma size

transmittance for different FWTM (Full Width at Tenth Maximum) and a constant electron density (left) and different electron densities with constant FWTM (right) (TE plane wave excitation)

sensitivity to plasma density
Simulating EM wave PC/MM interactions

**EM waves incident on a 3D plasma array**

- Parametric studies

Varying the EM excitation modes

\[ n_e = 2.5e21 \text{ (#/m}^3) \], \( a = \lambda/4 \), FWTM=\( \lambda/25 \)

- EM polarization and waveform has small effects on steady-state transmittance

Transmittance versus Frequency

\[ n_e = 2.5e21 \text{ (#/m}^3) \], \( a = 0.75\text{mm} \), FWTM=0.12mm

- Excitation with a Gaussian enveloped sinusoidal TE current source

- TM mode propagation

- Developed tools for analysis of periodic plasma photonic crystals including their frequency response and band diagrams calculation

**EM wave dispersion (band diagram)**

Band diagram of a 2D plasma photonic crystal similar to the 3D array structure presented before

\[ n_e = 2.5e21 \text{ (#/m}^3) \], \( a = 0.75\text{mm} \), FWTM=0.12mm

- TM mode propagation

Transmittance vs field frequency

Increase of transmittance as \( \omega > \omega_p \)
Simulating EM wave PC/MM interactions

13N-Moment Plasma Modeling

- Low pressure field-driven plasmas can experience departures from equilibrium in their particle distribution functions
  - fluid modeling is an approximate representation of the physics
  - usual transport relations do not provide adequate closure
- The 13N-moment multi-fluid plasma model extends fluid models towards the collisional transition regime: marginal collisionality, weakly-coupled plasmas, finite charge-separation
  - equations directly evolve the non-Maxwellian features of the plasma distribution function
Simulating EM wave PC/MM interactions

13N-Moment Simulation of microwave attenuation through plasma array

- plasma initialized in a regular rectangular lattice
- broadband (0.5 – 10 GHz) TE mode source launches from the left
- plasma has density peaks of $10^{18}$ m$^{-3}$ among a background density of $10^{14}$ m$^{-3}$ with a uniform 10 eV temperature.
- plasma is evolved using the 13N-moment multi-fluid plasma model.
- Contours of transverse electric field show the frequency filtering effect (bandgap) of the plasma structure.
Simulating EM wave PC/MM interactions

13N-Moment Simulation of plasma array disassembly/reassembly

- the 13N-moment multi-fluid plasma model is used to investigate the disassembly of coherent plasma structures to determine operating regimes for fast re-configurability
- Ion and electron species are modeled
- plasma parameters:
  \[ T_e = 2 \text{ eV} \]
  \[ T_i = 1 \text{ eV} \]
  \[ \text{Kn} = 0.01 \text{ (electrons)} \]
  \[ \text{Duration} = 1 \mu\text{s} \]
- the 13N-moment multi-fluid plasma model is valid over a large range of plasma parameters for this problem.
Plasma MURI focuses on the fundamental science necessary for the development of high bandwidth reconfigurable plasma PCs (PPC) and plasma-embedded MMs (PMM) that operate in the mm-wave range of the EM spectrum.

This broad class of materials is often referred to as terahertz (THz) materials. PPCs and PMMs that operate in the mm-wave range (or lower) require plasma resonances (e.g., plasma frequencies, \(\omega_p\)) in the extreme high frequency (EHF) and THz regimes, and hence densities in excess of \(n_e = 10^{14} \text{ cm}^{-3}\). These plasma frequencies are much lower than those in semiconductors and metals and so gaseous PPCs and PMMs are not suitable for interacting with optical radiation. However, plasma densities beyond \(10^{16} \text{ cm}^{-3}\) can be used in terahertz MM/PC devices. THz radiation is a largely unexplored component of the EM spectrum. Development of devices for its manipulation, control, harmonic generation, and amplification has potential uses ranging from imaging to remote sensing.

We have assembled a team to study: theoretical, computational, and experimental aspects of ordered microplasmas, magnetized and non-magnetized, of moderate to high densities \((10^{12} \text{ cm}^{-3} - 10^{16} \text{ cm}^{-3})\); the control of these plasmas; their interactions with materials used in PCs and MMs; the development of dielectric materials that afford lower losses at high frequencies displacing the use of metals in PMMs; and the integration of these plasmas into 2D and 3D MM and PC devices. The research brings together experts in plasma generation and simulations, metamaterials, photonic crystals, synthesis/fabrication of low-loss dielectrics, plasma-materials interactions, and EM wave-plasma simulations.

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