



Integrity ★ Service ★ Excellence

ELECTROMAGNETICS

07 March 2012

**Dr. Arje Nachman
Program Manager
AFOSR/RSE**

Air Force Research Laboratory

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 07 MAR 2012		2. REPORT TYPE		3. DATES COVERED 00-00-2012 to 00-00-2012	
4. TITLE AND SUBTITLE Electromagnetics				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory, Wright Patterson Air Force Base, OH, 45433				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the Air Force Office of Scientific Research (AFOSR) Spring Review Arlington, VA 5 through 9 March, 2012					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 33	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			



2012 AFOSR SPRING REVIEW 3001K PORTFOLIO OVERVIEW



NAME: Dr. Arje Nachman

BRIEF DESCRIPTION OF PORTFOLIO:

**Interrogation (Modeling/Simulation) of Linear/Nonlinear
Maxwell's Equations**

LIST SUB-AREAS IN PORTFOLIO:

Theoretical Nonlinear Optics

Wave Propagation Through Complex Media

Fundamentals of Antenna Design/Operation

Fundamentals of Effects of EM Exposure on Circuitry



Scientific Challenges



- **Wave Propagation Through Complex Media**

Details of time-domain dynamics of EM pulses through Dispersive, Conductive, and/or Random/Turbulent media

Research provides optimism that the class of waveforms termed Precursors have the potential to upgrade imaging quality.

- **Antenna Design/Operation**

Suitable *PARTNERSHIPS* of MATERIALS and GEOMETRY can deliver man-made composites which exhibit novel EM attributes.

Such **METAMATERIALS** include: NIMs, PBGs, and “Unidirectional” composites.

Growing reliance on small UAVs drives the need to miniaturize antennas and make them more responsive.



Scientific Challenges



- **Nonlinear Optics**

Fundamental modeling/simulation research which addresses concerns with femtosecond filament arrangements and plasma channel characteristics.

Advances in modeling/simulation of fiber and solid state lasers to guide the development of compact, high energy systems.

- **RF Effects on Circuitry**

Identification of waveforms which produce various realizations of circuit upset (includes chaos).

Complicated by the fact that effects are likely to be dictated by the activity of the circuit (eg, routines being run by laptop).



MURIs



This portfolio has an existing MURI (Ultrashort Laser Pulses) which just completed its 1st year.

**Two more MURIs supportive of the portfolio subarea
“Wave Propagation Through Complex Media”
will be starting:**

- “Deep Optical Turbulence Physics”**
- “High Power, Low-Loss, Artificial Materials for Transformational Electromagnetics”**



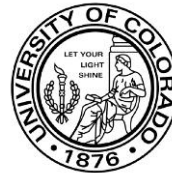
Mathematical Modeling and Experimental Validation of Ultrafast Nonlinear Light-Matter Coupling Associated with Filamentation in Transparent Media



MURI PMs---Dr Arje Nachman and Dr Enrique Parra



J.V. Moloney	ACMS/OSC
M. Kolesik	ACMS/OSC
P. Polynkin	ACMS/OSC
S.W. Koch	OSC
N. Bloembergen	OSC
A.C. Newell	ACMS/Math
K. Glasner	ACMS/Math
S. Venkataramani	ACMS/Math
M. Brio	ACMS/Math



A. Becker
A. Jaron-Becker
H. Kapteyn
M. Murnane



C. Durfee
J. Squier



W.P. Roach AFRL/RD



D. Christodoulides



R. Levis



A. Gaeta



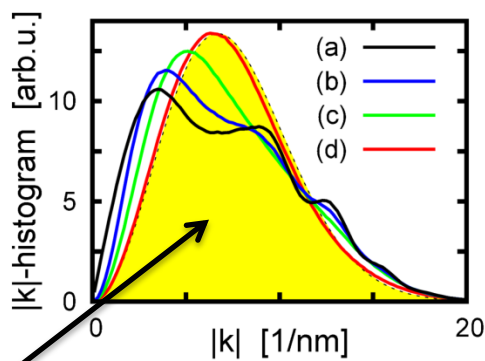
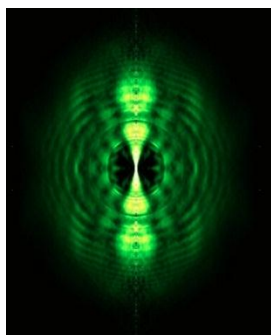


New State of Matter: Uncorrelated Electrons to Plasma Transition

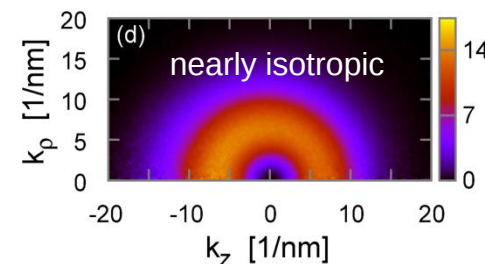
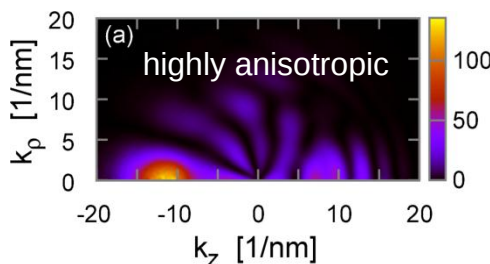


B. Pasenow, M. Brio, J.V. Moloney, S. W. Koch, S.H. Chen, A. Becker, and A. Jaron-Becker

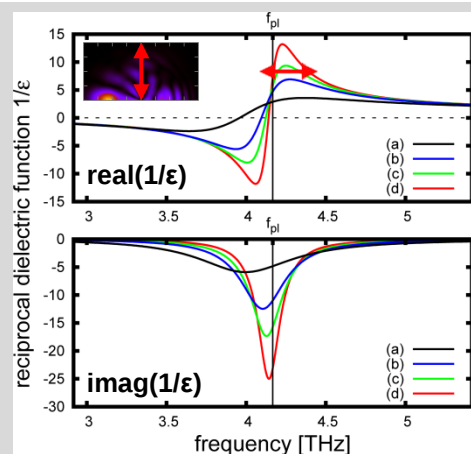
- MURI collaboration between University of Arizona and University of Colorado
- USP ionization: highly anisotropic uncorrelated electron distributions
- Relaxation/isotropization of non-equilibrium distributions due to Coulomb scattering
- THz EM response: evolution of loss of anisotropy and carrier density (plasmon pole)



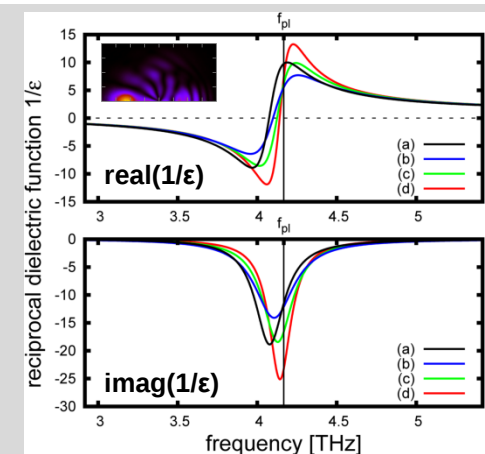
Fermi-Dirac electron momentum distribution in isotropic plasma



x-linear pol. THz pulse



z-linear pol. THz pulse



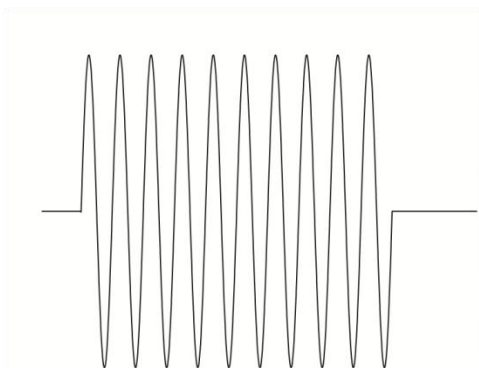


FORMATION of PRECURSORS and their ALGEBRAIC DECAY with DISTANCE into DISPERSIVE MEDIA



Dr Kurt Oughstun/UVt and Dr Natalie Cartwright (YIP)/SUNY-NewPaltz

AIR

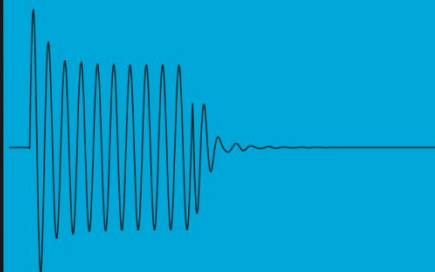


Electric field component
before incidence:
SQUARE-WAVE MODULATED SINE

Note: The CW version of
the above sinusoid would
experience exponential
decay!

$Z = 0$

MATERIAL
water, etc



Electric field
component of the
transmitted pulse.



Electric field component
of the propagated pulse.
This precursor decays
as the inverse square
root of z and contains a
generous bandwidth.

$Z > 0$



THE PROPAGATED PULSE



how they did it

The electric field component of the propagated pulse on any plane $z > 0$ is given by

$$E(z, t) = \frac{1}{2\pi} \operatorname{Re} \left\{ i \int_{ia-\infty}^{ia+\infty} T_E(\omega) \tilde{E}(z < 0, \omega) e^{i\tilde{k}(\omega)z - i\omega t} d\omega \right\},$$

where $\tilde{k}(\omega) = \frac{\omega}{c} n_2(\omega)$ is the complex wave number of the dielectric material.

$$T_E(\omega) = \frac{2}{1 + n_2(\omega)} \quad n_2(\omega) = \sqrt{1 - \frac{\omega_p^2}{\omega^2 - \omega_0^2 + 2i\delta\omega}}$$

For values of $ct/z = \theta \leq 1$ the contour may be closed in the upper half plane and application of Jordan's lemma gives $E(z, t) = 0$, $t < z/c$.

This integral representation of the field has no known exact solution when $ct/z > 1$

Asymptotic methods, such as saddle point methods, may be used to find an approximation to the propagated pulse.

These methods require the deformation of the Bromwich contour through the valleys of the accessible saddle points of the complex phase function

$$\phi(\omega, \theta) = i\omega[n(\omega) - \theta], \quad \theta = \frac{ct}{z}$$

which is completely characterized by the dielectric material.



ACTIVE **INFRARED** IMAGING THROUGH SPARSE DISCRETE MEDIA



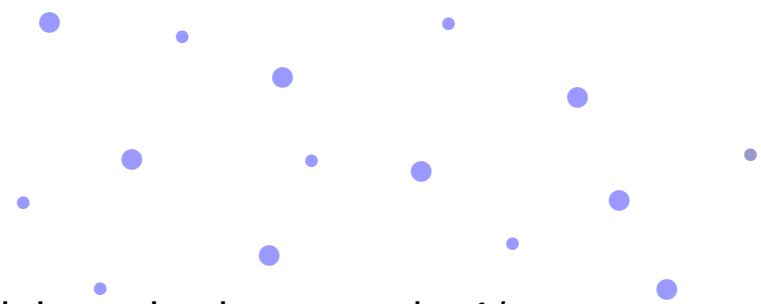
Drs. Elizabeth and Marek Bleszynski
Monopole, Inc

PROJECT OBJECTIVE

*investigate possibility of using wide-band, **infrared (IR)** pulses
in imaging through media composed of sparsely distributed
discrete particles, such as clouds, fog, dust, or smoke*

“sparse” medium: mean-free path* much larger
than average separation between scatterers

*mean free path is the penetration depth over which intensity decreases by $1/e$
so sparse=mean free path corresponding to the highest frequencies in the pulse
spectrum is much larger than average separation between scatterers.





PROPAGATION OF A WIDE-BAND **IR** PULSE THROUGH SPARSE DISCRETE MEDIA



example: a trapezoidally modulated **IR** pulse propagating through a cloud

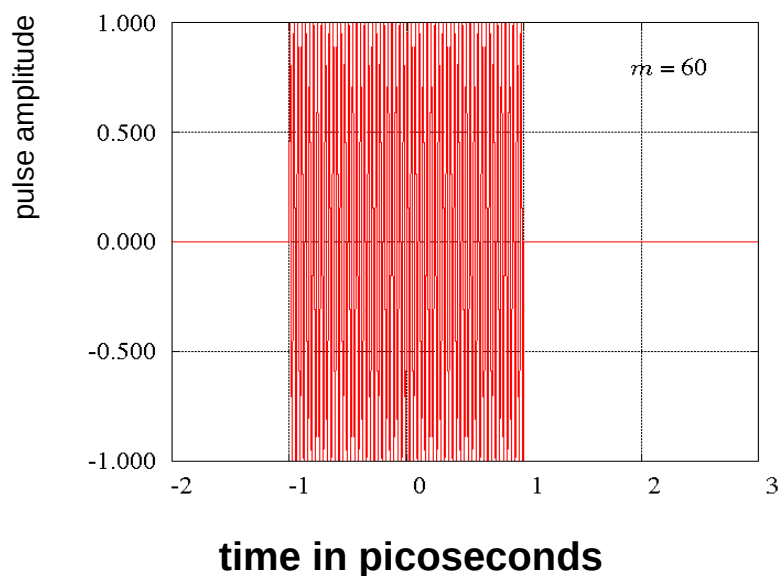
pulse parameters:

- carrier wavelength: $\lambda = 10\mu\text{m}$ ($\nu = 30\text{ THz}$)
- number of cycles in the pulse: $m = 60$
- rise/fall time: 0.05 of the carrier period

cloud parameters:

- average droplet radius: $a \sim 5\mu\text{m}$
- average droplet-droplet distance: $R \sim 1\text{ mm}$

transmitted pulse



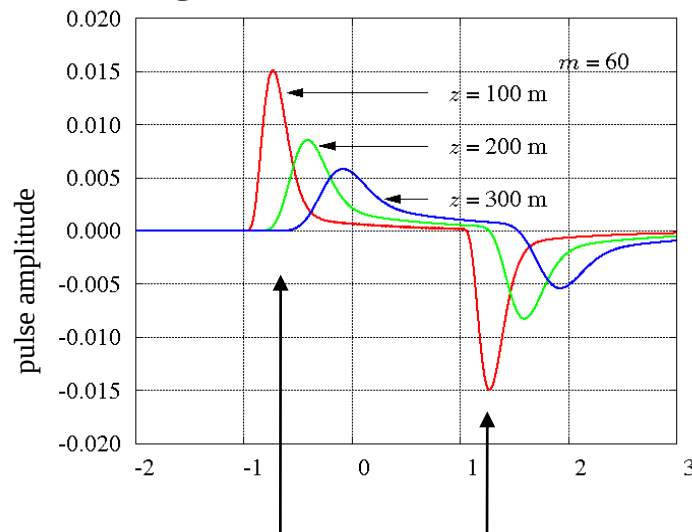


PROPAGATION OF A WIDE-BAND **IR** PULSE THROUGH SPARSE DISCRETE MEDIA



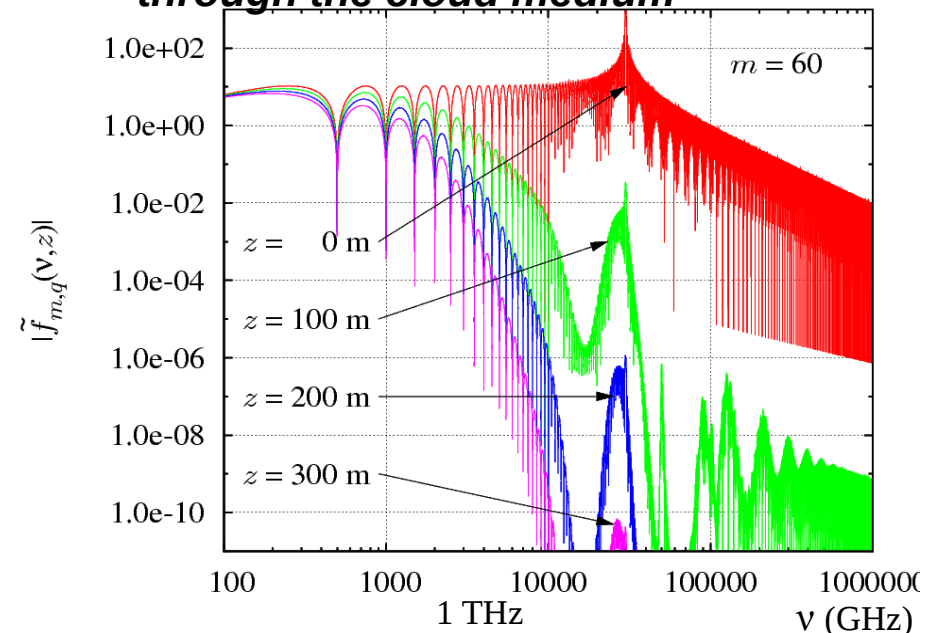
- medium as a filter attenuating high frequencies
- evolution of the propagating pulse into a Brillouin precursor

**pulse amplitude after propagating
 $z = 100\text{m}, 200\text{m}, 300\text{m}$
through the cloud medium**



**Brillouin precursor-type structures
associated with the leading and
trailing edges of the transmitted pulse**

**pulse spectrum after propagating
 $z = 100\text{m}, 200\text{m}, 300\text{m}$
through the cloud medium**



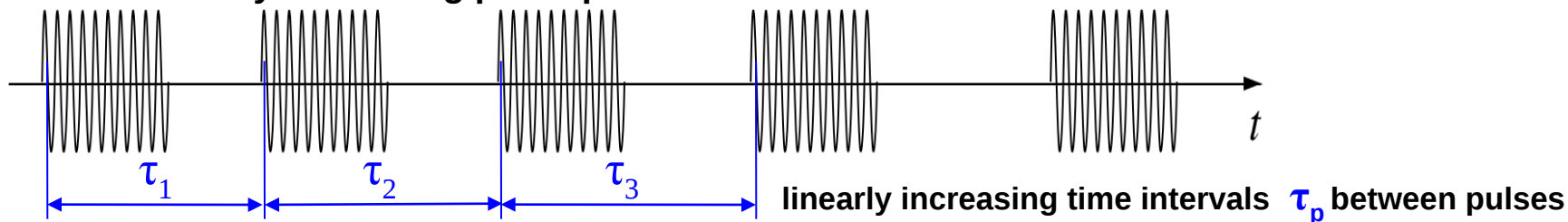
- the transmitted pulse spectrum has a **significant amount of low-frequency components**
- the **high-frequency part** of the spectrum is **attenuated very strongly** as the pulse propagates
- the **low-frequency part** of the spectrum is **weakly attenuated**



PROPAGATION OF A “CHIRPED TRAIN OF PULSES”



generate a coherent train of N pulses (with small rise/fall times) emitted at linearly increasing pulse-pulse intervals

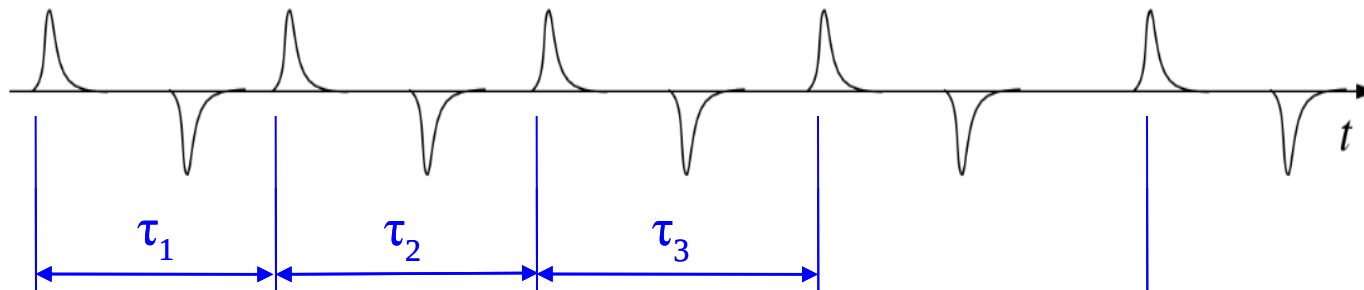


chirped train characterized by: effective **center frequency** and effective **bandwidth**

$$\nu_C = \frac{1}{\langle \tau \rangle}$$

$$B_C = \frac{1}{\tau_{\min}} - \frac{1}{\tau_{\max}}$$

after passing through clouds the pulse train becomes a **train of precursor-type pulses** associated with leading and trailing edges of the transmitted trapezoidal pulses and attenuated approximately **algebraically** (not exponentially)





PRECURSOR SUMMARY



- For MW (radar) imaging, it is difficult to produce square-wave modulated sinusoids.
But it is possible for modern radars to produce PRECURSORS!
 1. These interesting waveforms contain greater bandwidth than conventional narrow-band radar pulses,
 2. Decay algebraically with depth,
 3. Experience reduced “flash” at any media interface,
 4. Allow for easier Matched Filtering.
- None of this is seriously modified by oblique incidences.
- For laser imaging through clouds (ladar) it is very easy to produce (nearly) square-wave modulated sinusoids, but not precursors. The cloud produces the precursor, which decays algebraically with depth. In order to compensate for the loss of the high IR frequencies (and thus detailed spatial resolution) the notion of chirping the pulse train was invented.



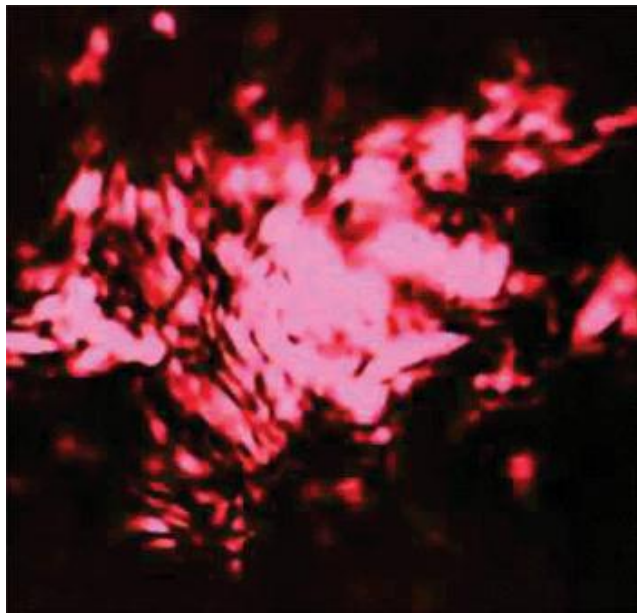
Laser Beams & Turbulence



Dr Greg Gbur/Electrical Engineering
University of North Carolina, Charlotte

Optical beam propagation in the atmosphere is hindered by atmospheric turbulence: random fluctuations of the refractive index.

Applications such as free-space optical communications and LIDAR are adversely affected by atmospheric turbulence, which induces intensity fluctuations (scintillations).



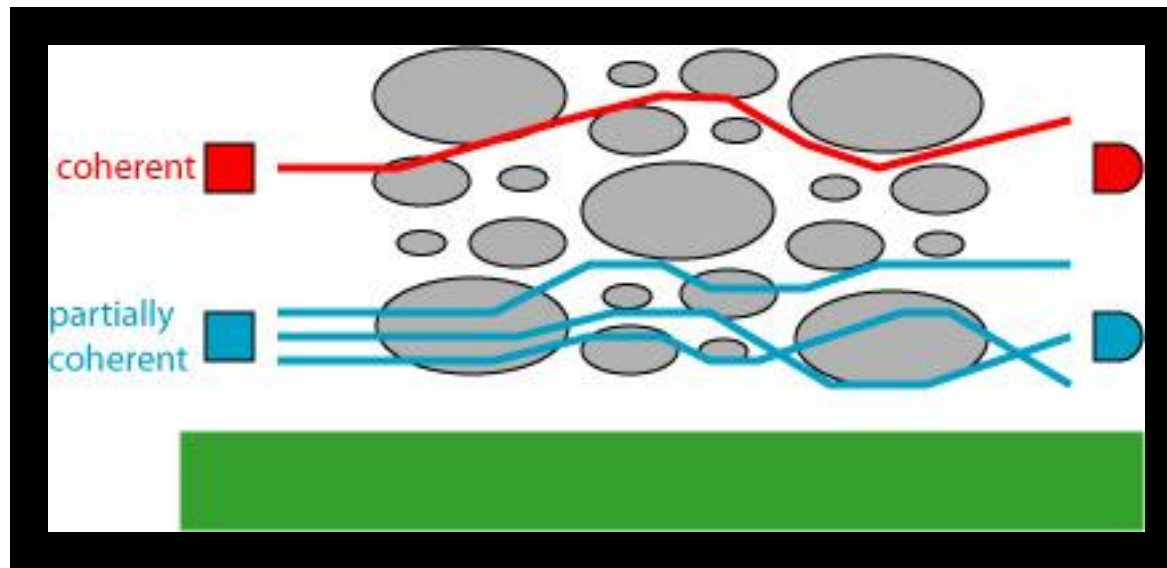
Laser beam distorted by turbulence



'Heat shimmer' (mirage) on a hot day



Partially Coherent Beams in Turbulence



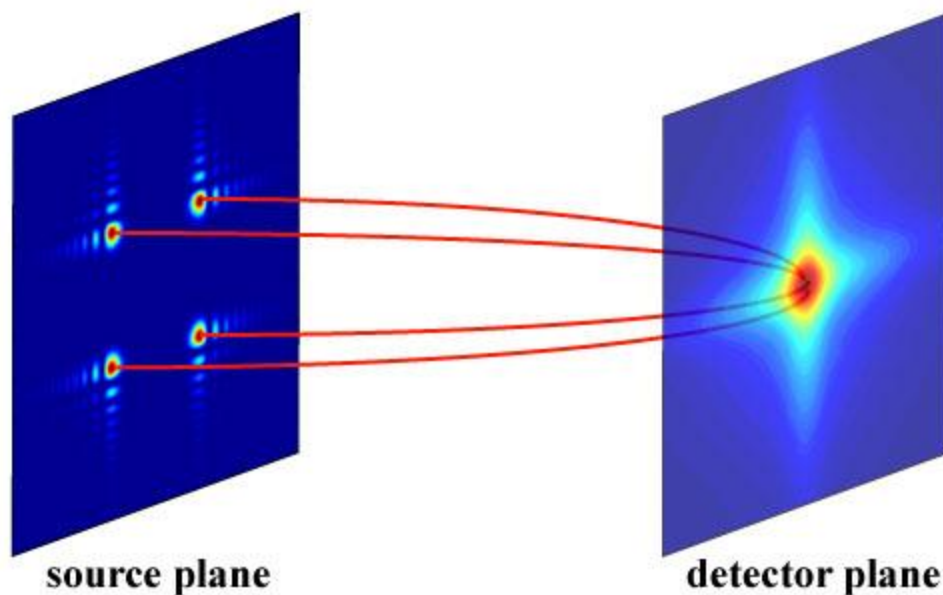
- A coherent laser essentially propagates its energy through a single coherent beam, which may partly or wholly miss detector
- The partially coherent beam sends its energy through multiple beamlets, increasing the likelihood of hitting a detector and smoothing out fluctuations
- Beamlets need to be significantly different, or diverse



Airy Beams in Turbulence



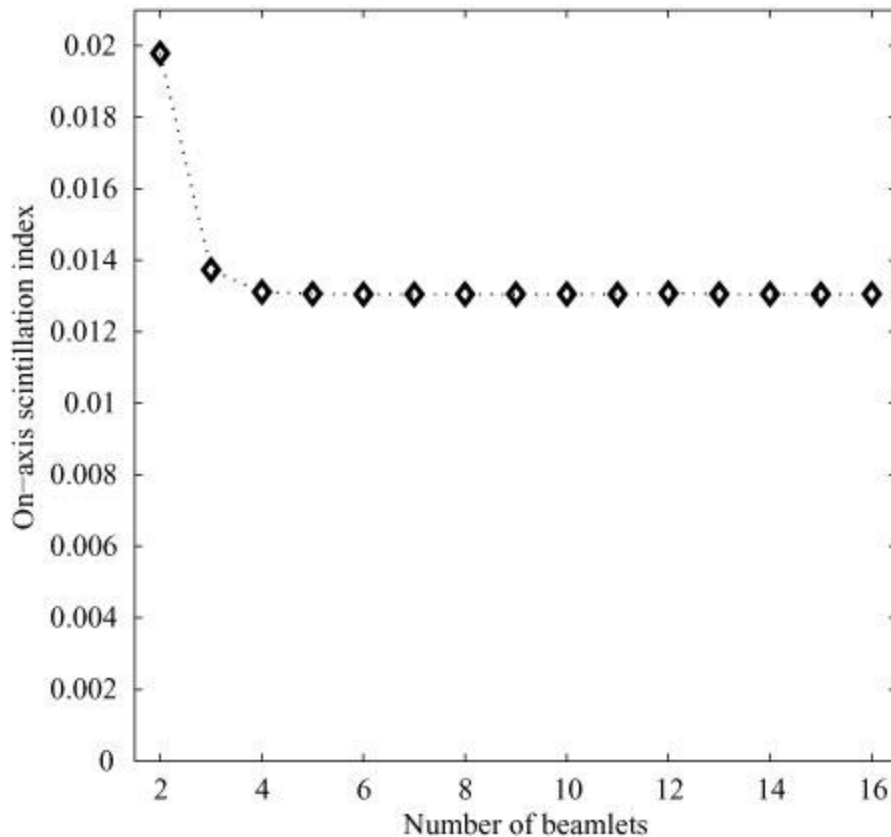
A spatial filtering system, with an appropriate phase mask, can produce an Airy beam



**Try four beamlets designed to curve together at target:
each beamlet sees different turbulence but average peak
intensity is at center of detector**



Scintillation vs. # of Beamlets



Scintillation reaches its minimum possible value with only four beamlets!

Evidently four beamlets is “good enough” for reducing intensity variance!

Additional beamlets are not diverse enough to provide additional improvement

Nonuniformly *polarized* beams another idea



Imaging with Spatial Nonlinearity

Dr Jason Fleischer
Electrical Engineering, Princeton



- Scalar field ψ obeys nonlinear Schrödinger equation.
- Numerical solution via split-step Fourier method.

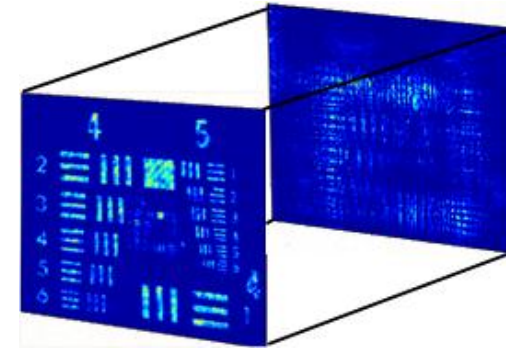
$$\frac{\partial \psi}{\partial z} = \left[\underbrace{i \frac{1}{2k} \nabla_{\perp}^2}_{\text{Linear}} + \underbrace{i \Delta n(|\psi|^2)}_{\text{Nonlinear}} \right] \psi \equiv [\hat{D} + \hat{N}(|\psi|^2)] \psi$$



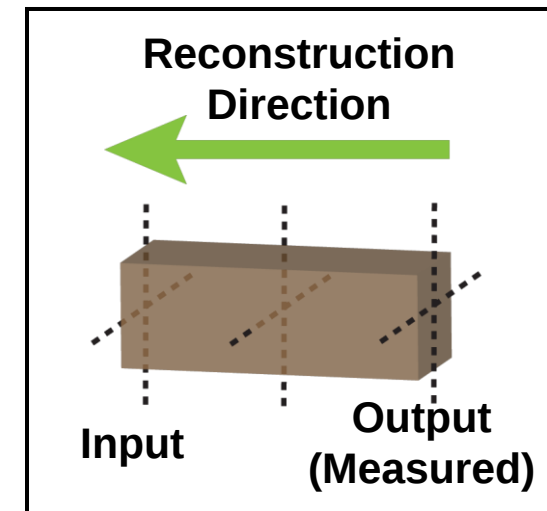
$$\begin{aligned} \psi(x, y, z + dz) &= e^{\hat{D}dz + \hat{N}dz} \psi(x, y, z) \\ &\approx e^{\hat{D}dz} e^{\hat{N}dz} \psi(x, y, z) \end{aligned}$$

Back-propagation gives $\psi(z)$ if we know $\psi(z + dz)$:

$$\psi(x, y, z) \approx e^{-\hat{N}dz} e^{-\hat{D}dz} \psi(x, y, z + dz)$$

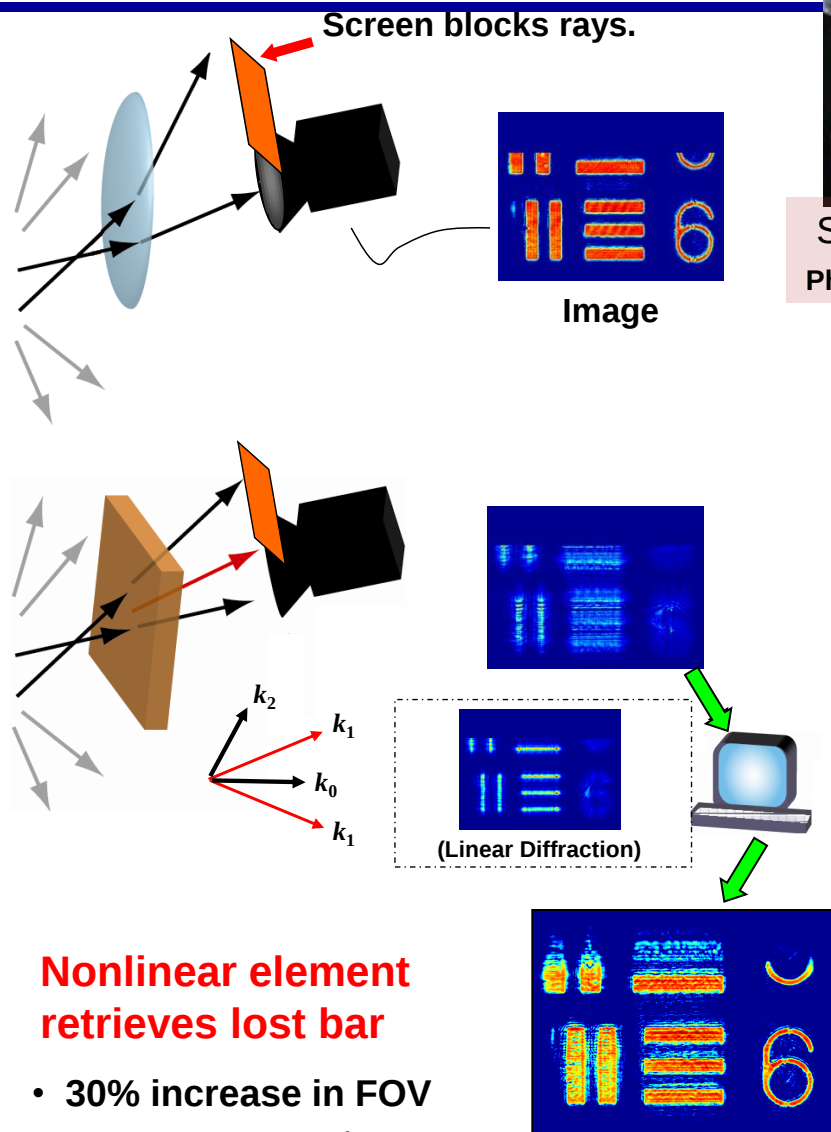


Initial value problem

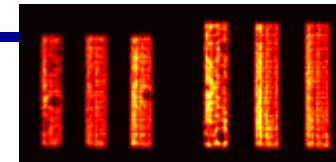




Improved imaging with NL: *field of view and resolution*

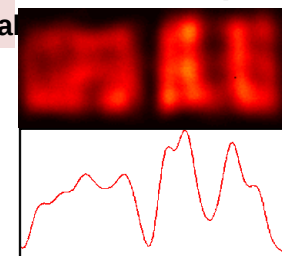


$\text{Sr}_{0.75}\text{Ba}_{0.25}\text{Nb}_2\text{O}_6$
Photorefractive crystal

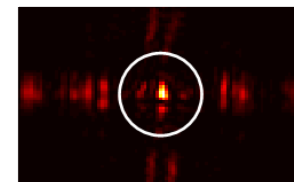
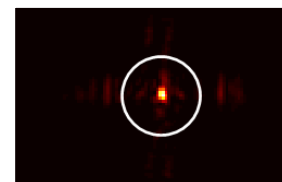
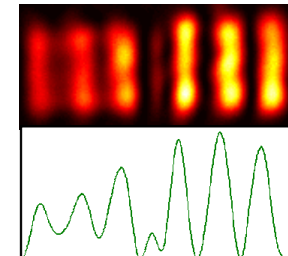


200 μm

Linear Output

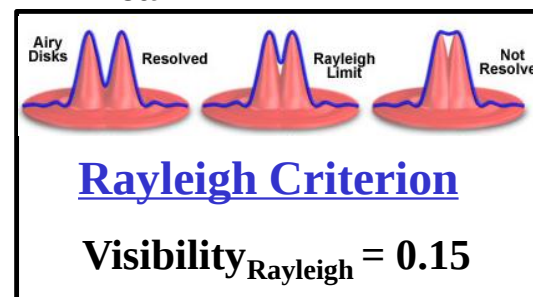


Nonlinear Output



$V_{\text{linear}} = 0.095$

$V_{\text{NL}} = 0.32$

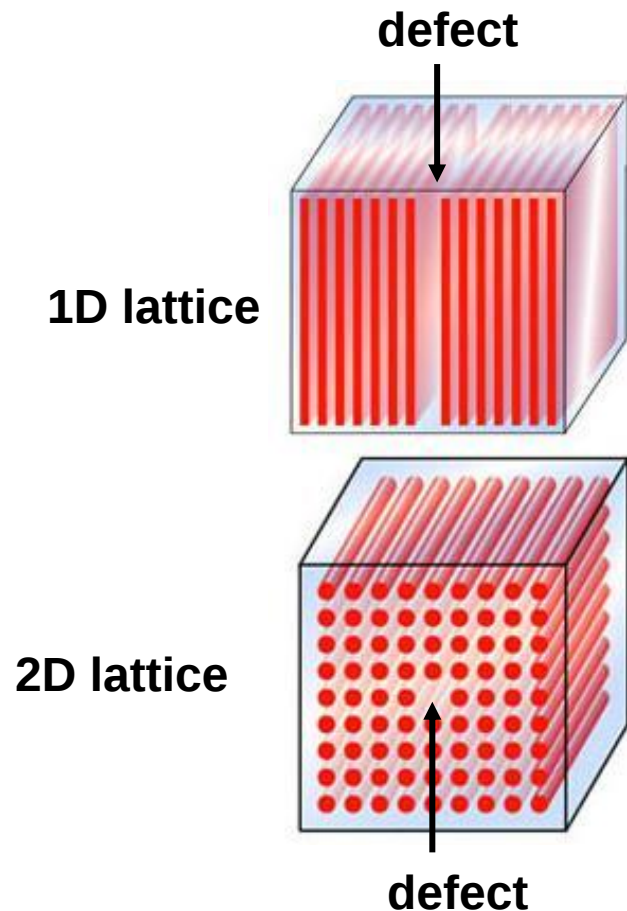




Nonlinear Beam Deflection in Photonic Lattices with Defects



Optically-induced photonic lattice with defects:
lattice spacing ~ 10 microns



A defect is a local abnormality inside a periodic lattice. Experimentally created 1D and 2D lattices with single-site defects are shown in the left figures.

Experimental procedure to optically “write” lattices with defects:

- (1) let a laser beam pass through an amplitude mask
- (2) use frequency filtering to remove half of the spatial frequencies
- (3) slightly tilt the resulting beam

Dr Jianke Yang (Math, Univ Vermont)

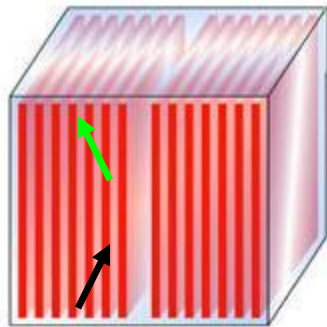
DISTRIBUTION A: Approved for public release; distribution is unlimited.



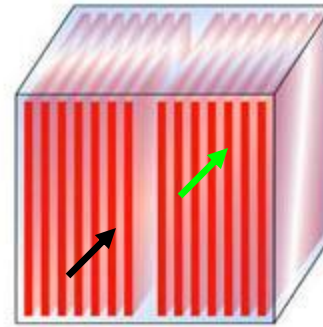
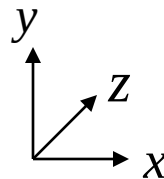
Nonlinear Beam Propagation Inside Lattices with Defects, cont'd



When a nonlinear beam is launched into a lattice with a defect one finds, both theoretically and experimentally, that at small incident angles the beam is reflected by the defect but at large incident angles, the beam passes the defect.



small angle:
reflection



large angle:
transmission

z: propagation direction

black arrow: probe-beam direction before reaching defect

green arrow: probe-beam direction after hitting the defect

Result shows a way to use a beam's incident angle to control its propagation direction in a lattice network.



Theoretical Modeling



$$i \frac{\partial U}{\partial z} + \frac{1}{2k_1} \left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) - \frac{1}{2} k_0 n_e^3 r_{33} \frac{E_0}{1 + I(x, y) + |U|^2} U = 0,$$

$$I = I_0 \cos^2 \frac{\pi x}{d} (1 - e^{-x^2/d^2}), \quad 1D \text{ case} \quad I = I_0 \cos^2 \frac{\pi x}{d} \cos^2 \frac{\pi y}{d} (1 - e^{-(x^2+y^2)/d^2}), \quad 2D \text{ case}$$

U : electric field; E_0 : applied dc field; r_{33} : electro-optic coefficient;

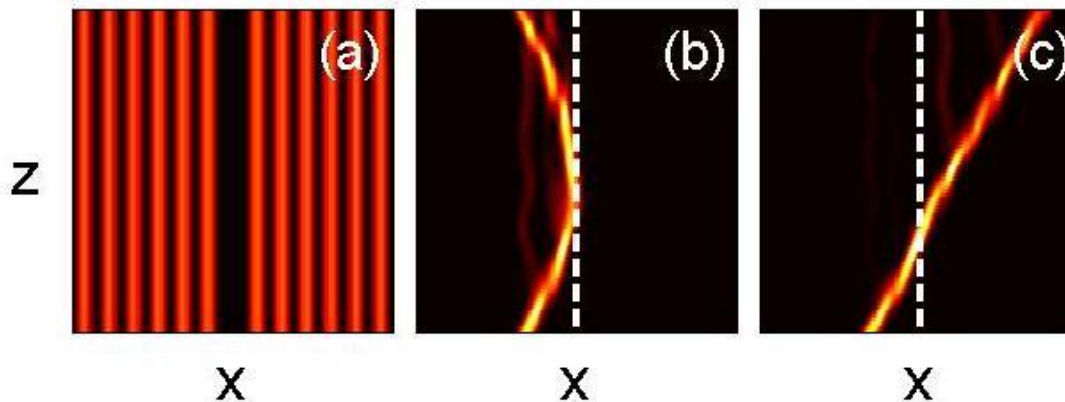
I_0 : lattice intensity; d : spacing; k_0, k_1 : wave numbers; n_e : refractive index

Simulation result:

lattice with defect

reflection at
small angle

transmission at
large angle





Can a non-Hermitian operator exhibit real spectra?



VOLUME 80, NUMBER 24

PHYSICAL REVIEW LETTERS

15 JUNE 1998

Real Spectra in Non-Hermitian Hamiltonians Having $\mathcal{PT}$ Symmetry

Carl M. Bender¹ and Stefan Boettcher^{2,3}

¹Department of Physics, Washington University, St. Louis, Missouri 63130

²Center for Nonlinear Studies, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

³CTSPS, Clark Atlanta University, Atlanta, Georgia 30314

(Received 1 December 1997; revised manuscript received 9 April 1998)

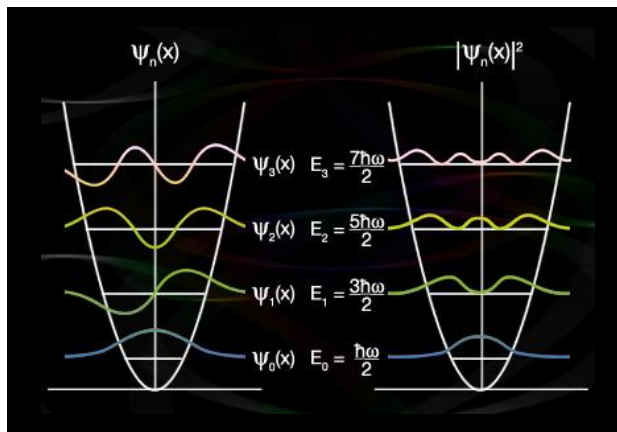
The answer is yes as long as the Hamiltonian respects $\mathcal{PT}$ -symmetry!

$$\hat{P}: x \rightarrow -x \quad ; \quad \hat{T}: t \rightarrow -t$$

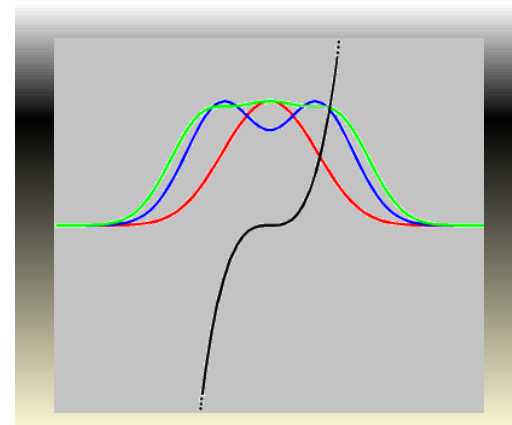
$$i\hbar \frac{\partial \Psi}{\partial t} + \frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} - V(x)\Psi = 0 \quad \text{PT symmetry} \longrightarrow$$

$$V(x) = V^*(-x)$$

Quantum mechanical oscillator



PT pseudo-Hermitian oscillator



$$V = ix^3$$



$\mathcal{PT}$ symmetry in Quantum Mechanics and Optics



Schrodinger Equation

$$i\hbar \frac{\partial \Psi}{\partial t} + \frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} - V(x)\Psi = 0$$

Time

t

Planck's constant

$\hbar$

Probability amplitude

$\Psi(x, t)$

Complex Potential $V(x) = V_R(x) + iV_I(x)$

The imaginary part $n_I(x)$ corresponds

to gain (if $n_I < 0$) or loss (if $n_I > 0$)

Paraxial Equation

$$i\hat{\lambda} \frac{\partial E}{\partial z} + \frac{\hat{\lambda}^2}{2} \frac{\partial^2 E}{\partial x^2} + n(x)E = 0$$

Propagation distance

z

wavelength

$$\hat{\lambda} = \frac{1}{k}$$

Electric field envelope $E(x, z)$

Complex refraction $n(x) = n_R(x) + in_I(x)$

So n_R is even
and n_I is odd

$\mathcal{PT}$ symmetry condition
 $V(x) = V^*(-x)$

$$n(x) = n^*(-x)$$

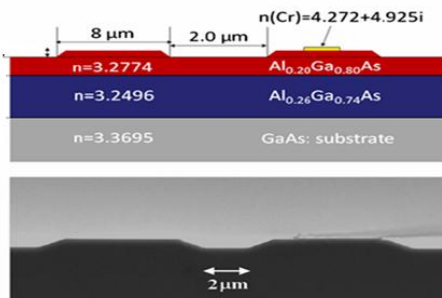


PT symmetric structures and devices

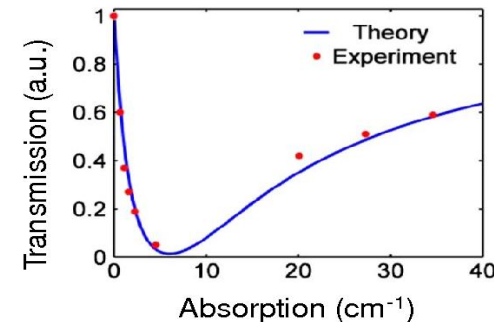


PT symmetry in optics can be readily established by deliberately involving gain and loss.

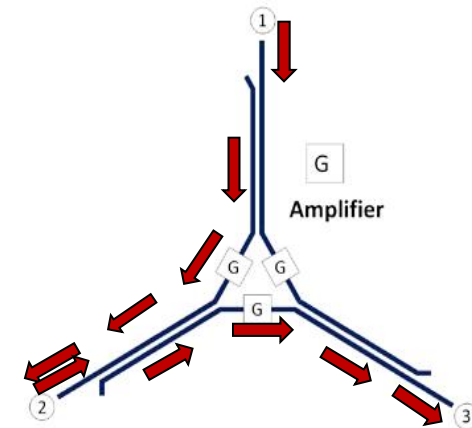
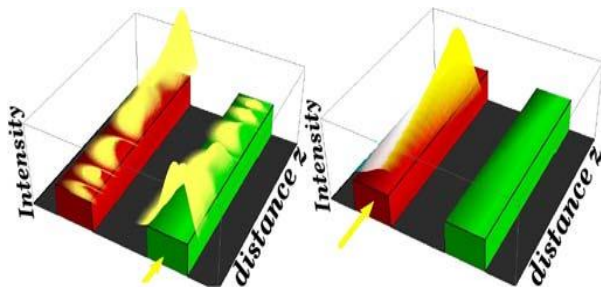
By doing so, new PT -symmetric structures and materials with useful functionalities can be envisioned.



Loss-induced transparency
due to PT -symmetry breaking



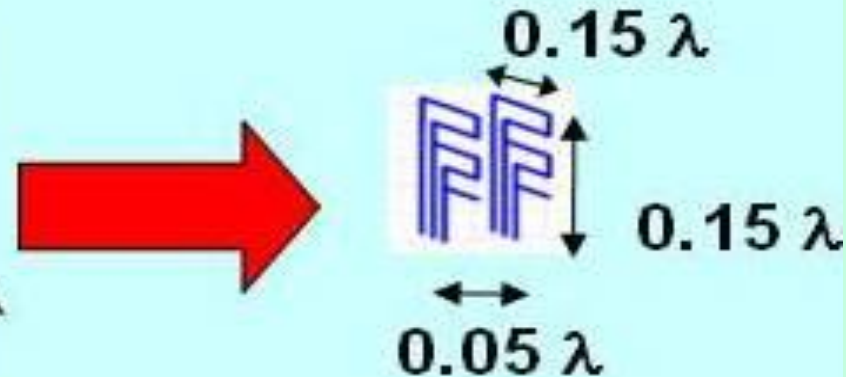
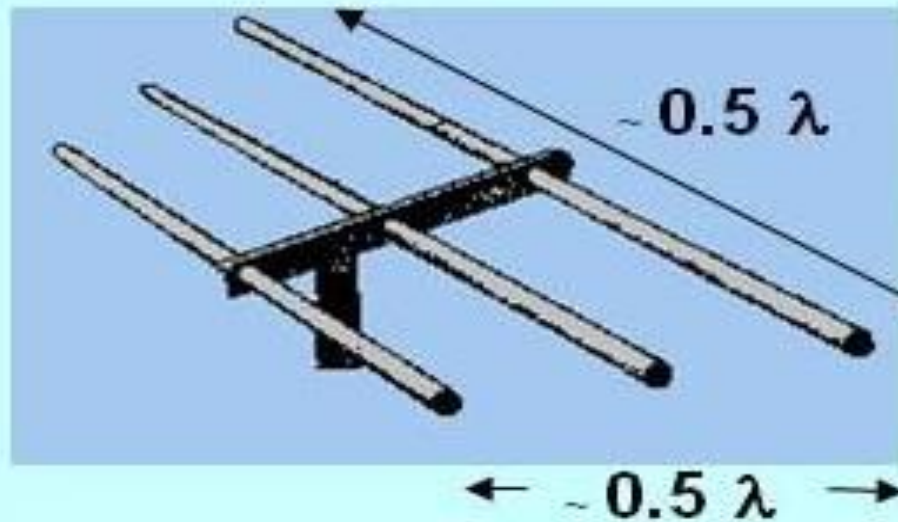
On-chip optical isolators and circulators



Dr Tsampikos Kottos (Physics/Wesleyan) and Dr Demetrios Christodoulides (Optics/UCF)



Electrically Small Supergain Arrays



Patent Awarded-Dec 2011
(Yaghjian, Altshuler, O'Donnell, Best)

- Electrically Small (ES) arrays attain 7 dB realizable gain, 5 dB higher than any previous ES antenna.
- Can be used to replace much larger Yagi antennas.
- Paves the way for 3 or more element endfire arrays with higher gains & for multiband supergain arrays.
- Future research to increase bandwidth is desirable.



RF Metamaterials for FOPEN Application

An Emulation of Anisotropy Degenerate Band Edge Tx Line Using Standard Printed Circuit

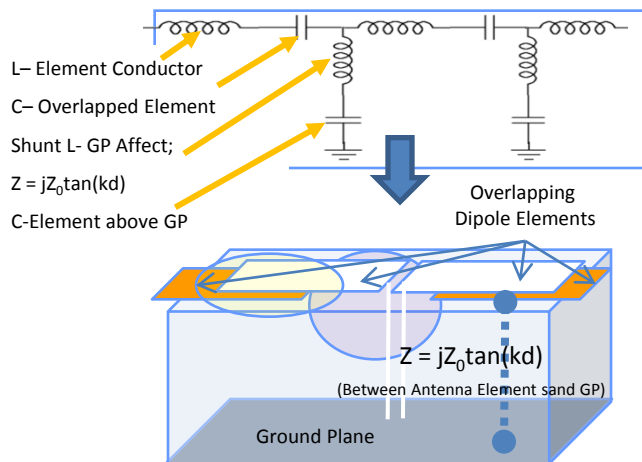


Lockheed Martin and OSU

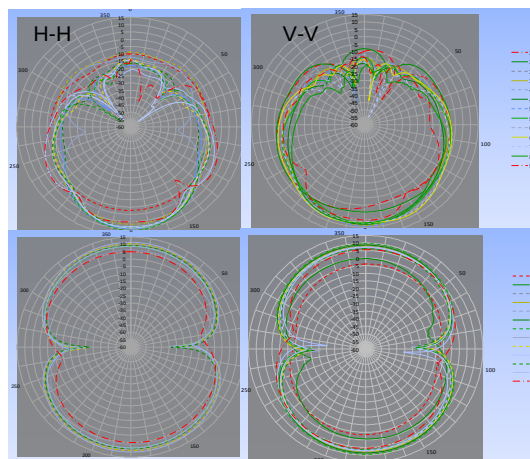
Meta FOPEN Antenna achieved the following performance (230 to 900 MHz):

- Bandwidth > 3X of State of the Art (SOA)
- Half size of SOA (24" x 24" area x 6" height)
- Light weight (5.6 Lbs)
- Dual polarized with < 20 dB cross-pol isolation
- High power capability and electronic beam steering
- Simple and low cost construction, standard PC and manufacturing method

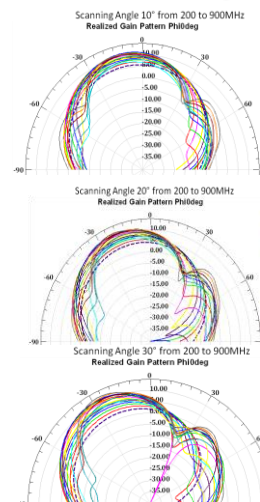
**Metamaterial Equivalent Circuit
Degenerate Band Edge (DBE)**



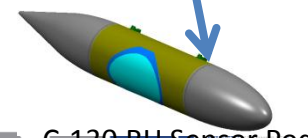
Measured Radiation Patterns



**Predicted and measured
Beam Steering**



**Integration to Shadow
Harvest Sensor Pod**



C-130 RH Sensor Pod



ELECTROMAGNETICS LAB TASKS



Dr. Brad Kramer(AFRL/RV), “Electromagnetic Materials and Antennas” *

1. Model Electromagnetically Small Antennas: superdirective, wide-band, conformal

Dr. Ilya Vitebskiy (AFRL/RV) “Metamaterials for the Enhancement of Light-Matter Interaction” *

1. Performance enhancement of various transceivers

Dr. Saba Mudaliar (AFRL/RV), “EM Scattering Studies”

1. Predict scattering from clutter and rough surfaces

Dr. Kris Kim (AFRL/RV), “Predict Far-Field RCS via Near-Field Data”

(Dr.) Jason Parker (AFRL/RV), “Moving Target Radar Feature Extraction”

Dr. Nicholas Usechak (AFRL/RV), “Dynamics of Reconfigurable/Agile Quantum Dot Lasers” **

1. Investigate control of amplitude-phase coupling in Quantum Dot laser systems

Dr. Timothy Clarke (AFRL/RD), “Modeling of HPM Effects on Digital Electronics” **

1. Derive mathematical model predicting effects (upset) on digital electronics when exposed to various incident EM pulses

Dr. Danhong Huang (AFRL/RV), “Models for Ultrafast Carrier Scattering in Semiconductors”

1. Model IR amplifier for extremely weak signals and distant targets

Dr. Analee Miranda (AFRL/RV), “Detection and Imaging of Underground Facilities Using SAR Data” *

Dr. Matthew Grupen (AFRL/RV), “Electronic Band Structure for High Speed Quantum Electron Device Simulation”

1. Modeling/Simulation of quantum tunneling devices

Dr. Iyad Dajani (AFRL/RD), “Time Dynamics of Stimulated Brillouin Scattering in Fiber Amplifiers with Frequency Modulation”

1. SBS suppression research to realize higher power in narrow linewidth fiber amps

Dr. Erik Bochove (AFRL/RD) “Modeling of Large Nonlinear Passively Phased Fiber Laser Arrays” **

***=New for FY12 **=Renewal for FY12**



Subareas Funding Trends



- Wave Propagation Through Complex* Media 

* Dispersive, Conductive, Random/Turbulent, Man-Made Composites

- Antenna Design/Operation 

- Effects of EM Exposure on Circuitry 

- Nonlinear Optics 

(MURI on “Propagation of Ultrashort Laser Pulses through Transparent Media” began 1 Oct 2010)



Connections with Other Organizations



- **ARO**

Extensive interaction with Dr Richard Hammond/ARO on UltraShort Laser Pulse propagation through air

- Dr Hammond served on my FY10 USLP MURI evaluation panel and I served on his FY11 USLP MURI panel

- **JTO**

I manage the JTO MRI “High Power Lasers Using Optically Pumped Semiconductor Laser (OPSL) Concepts” which ends in Aug 2012

- **NRO**

- Extensive discussions/visits regarding impact of 6.1 research on NRO needs
- Arranged for 2 PIs to participate in the FY12 NRO Seminar series



Connections with Other Organizations



- **ONR**

MURI (U Maryland) “Exploiting Nonlinear Dynamics for Novel Sensor Networks” managed by Dr. Michael Shlesinger, ONR

I serve on this ONR MURI panel

Negative Index Media MURI

Attended review of ONR (Dr. Mark Spector) NIM Metamaterials MURI