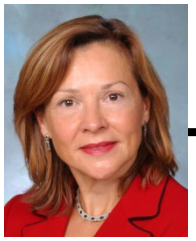
Biologically-inspired routes to sense-and-response in adaptive, intelligent metamaterials



Naomi Halas, Rice U.

Peter Nordlander, Rice U.

Stephan Link, Rice U.

Rich Baraniuk, Rice U.

John Rogers, UIUC

Roger Hanlon, Woods Hole MBL

Tom Cronin, UMBC

ONR Basic Research Challenges, 2013 Review Teleconference

RICE

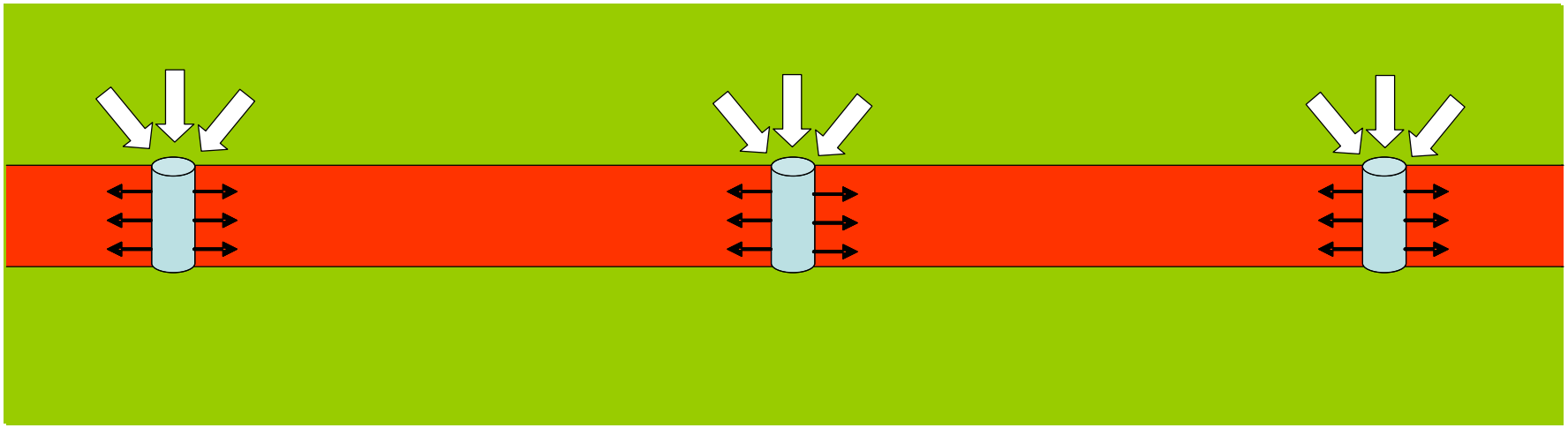
MBL Biological Discovery in Woods Hole

ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

UMBC AN HONORS UNIVERSITY IN MARYLAND

ONR Revolutionary Research . . . Relevant Results

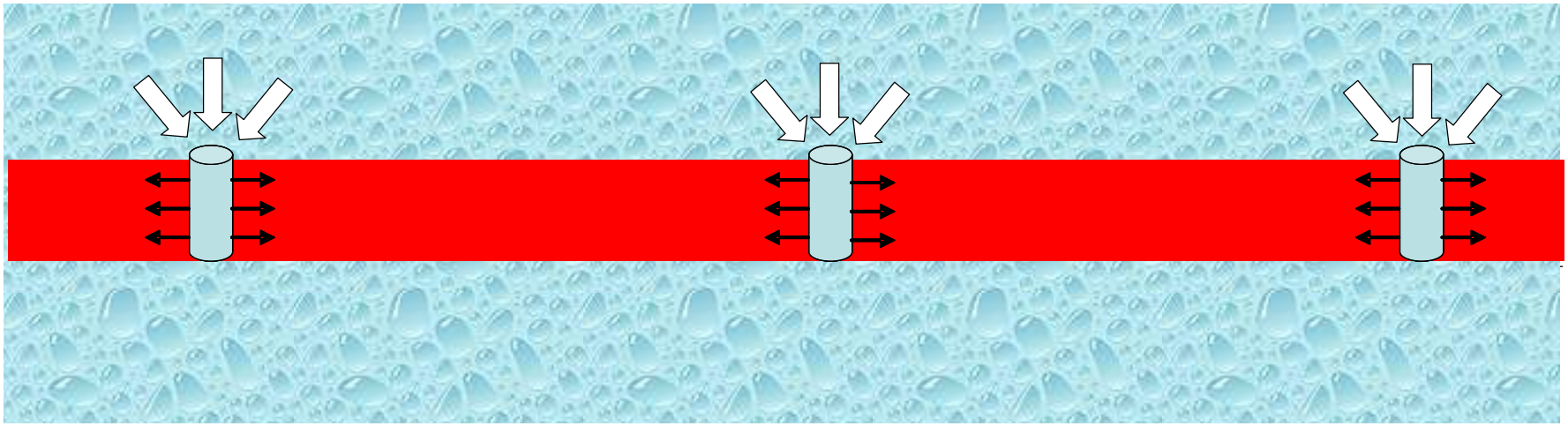
A grand challenge: color matching



Can we integrate sense-and-response into a material?

RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

A grand challenge: texture matching



Can we integrate local imaging -and-response into a material?

RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Cephalopods are nature's masters of sense-and-response:



Roger T. Hanlon

How do they accomplish this task? (cephs are color blind)
Do they have strategies we may be able to emulate?

RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Four goals of our BRC team effort:

A. to discover and study the ***underlying physical principles and mechanisms*** that can be used for the design and development of active optical/metamaterials;

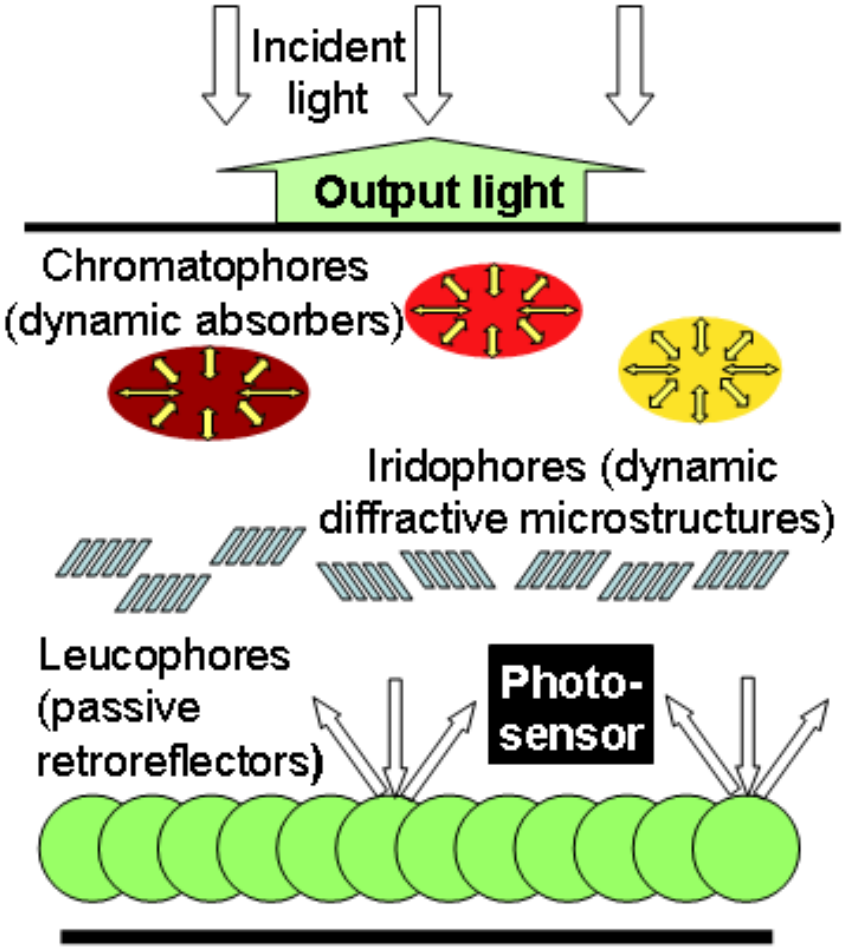
B. to advance our understanding of ***optical detection and recognition*** in cephalopods, to determine the role of skin opsins and their resultant signal in visual recognition and cephalopod response;

C. to develop ***concepts and mechanisms of compact optical detection*** that can ultimately be integrated with active composite media to facilitate an intelligent response;

D. to design ***information architecture and processing algorithms*** for synthetic, dynamic color and pattern change analogous to the camouflage response in biological systems.

RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

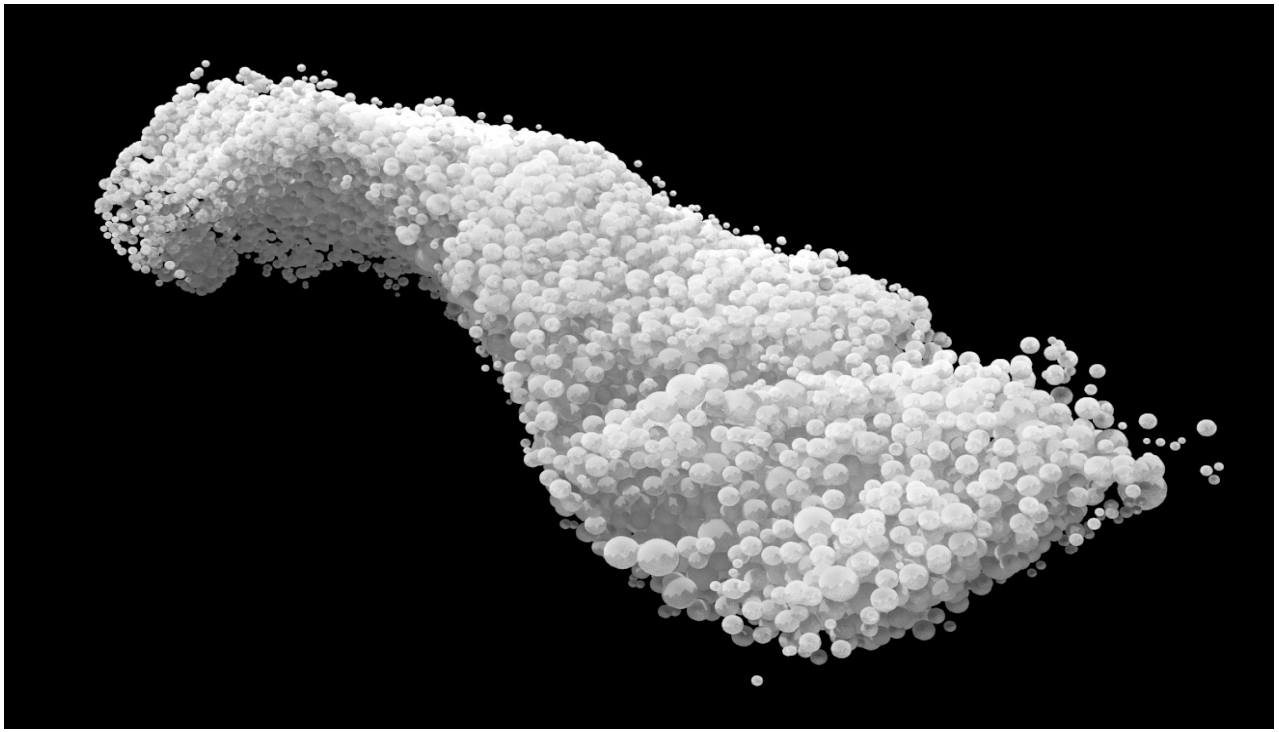
Compact optical and spectral detection: a “Grand Challenge”



RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Skin leucophores: nature's **whitest** white

Precise 3D model of a single leucophore cell containing 12,000 reflectin protein spheres



Mathger et al. 2013 Advanced Functional Materials

RICE

MBL Biological Discovery in Woods Hole

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

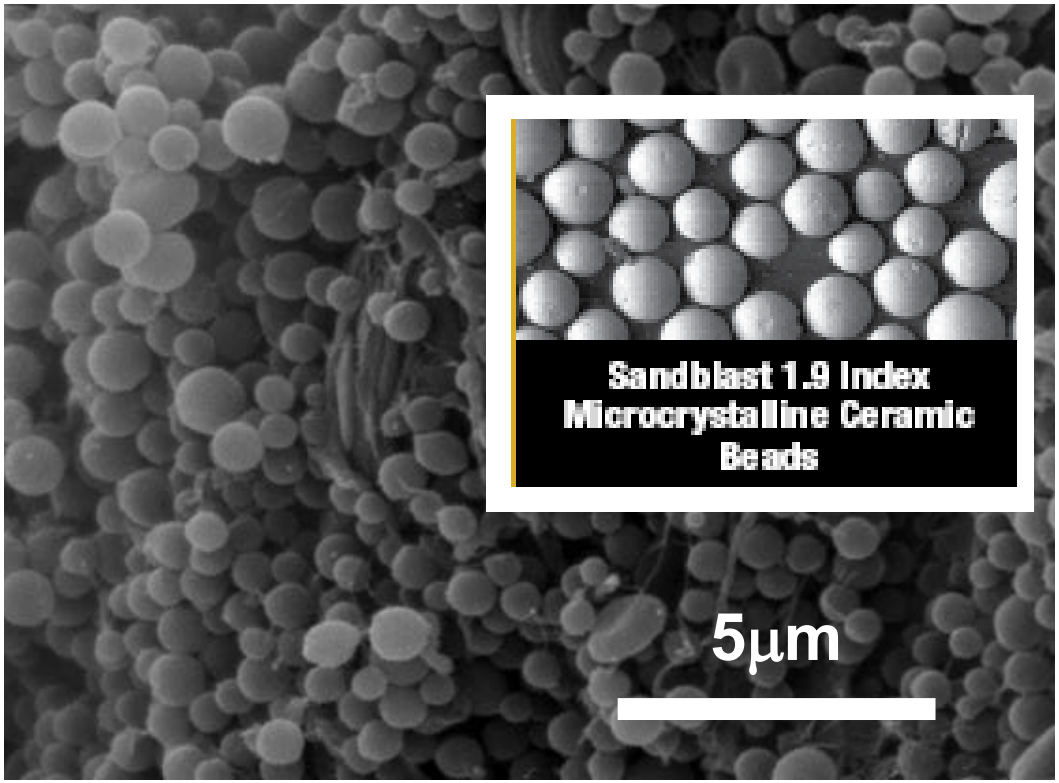
UMBC
AN HONORS UNIVERSITY IN MARYLAND

ONR
Office of Naval Research
Revolutionary Research . . . Relevant Results

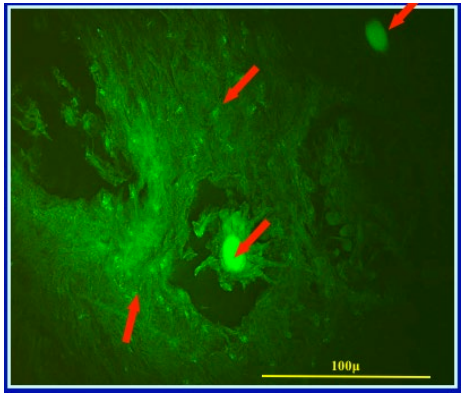
Accidental biomimicry:

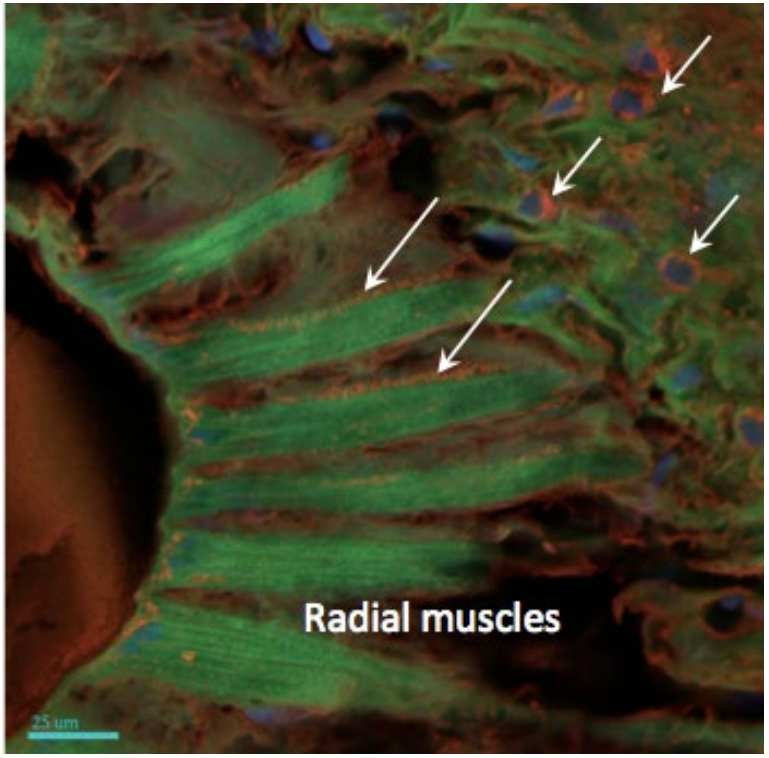
SEM image of leucophores

Inset: 3M Scotchlite ™ retroreflecting material used in transportation safety applications



Opsins: light detectors distributed in the skin?





-Numerous neurophysiological and behavioral experiments have failed to demonstrate a skin patterning response to light shone on the skin

-Thus the function of skin opsins remains unknown

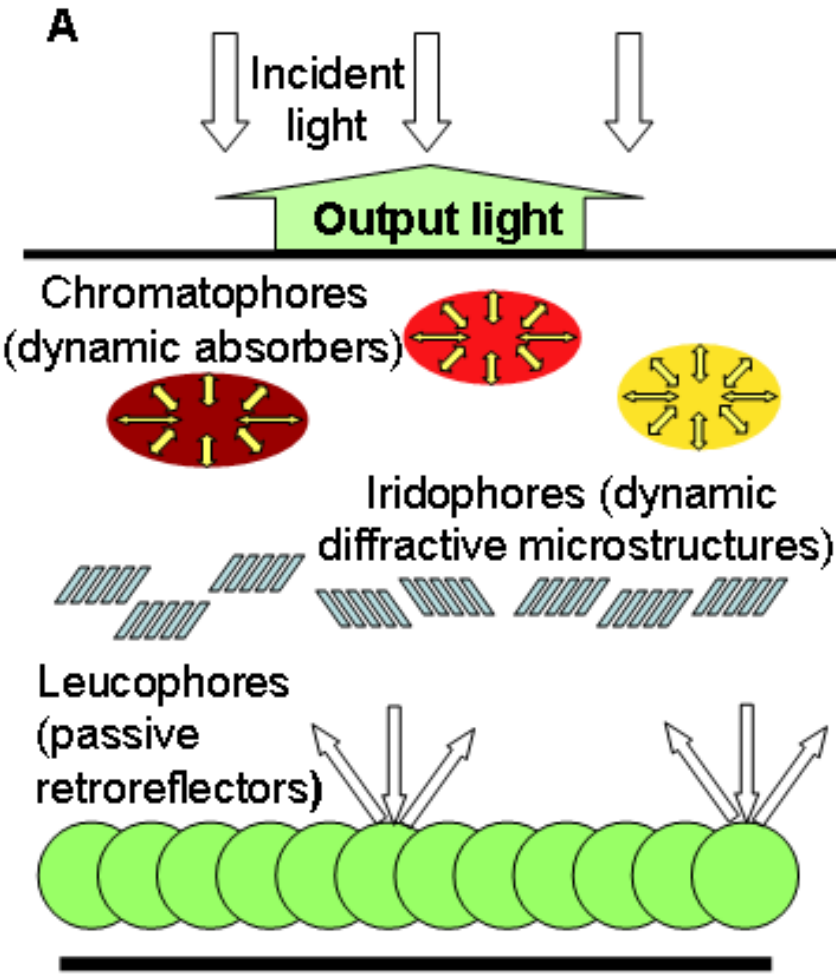
-Opsins have been detected in the skin (Tom Cronin lab with MBL)

Immunocytochemistry: opsins (arrows) co-located near chromatophores: nerves and interstitial cells

Outline

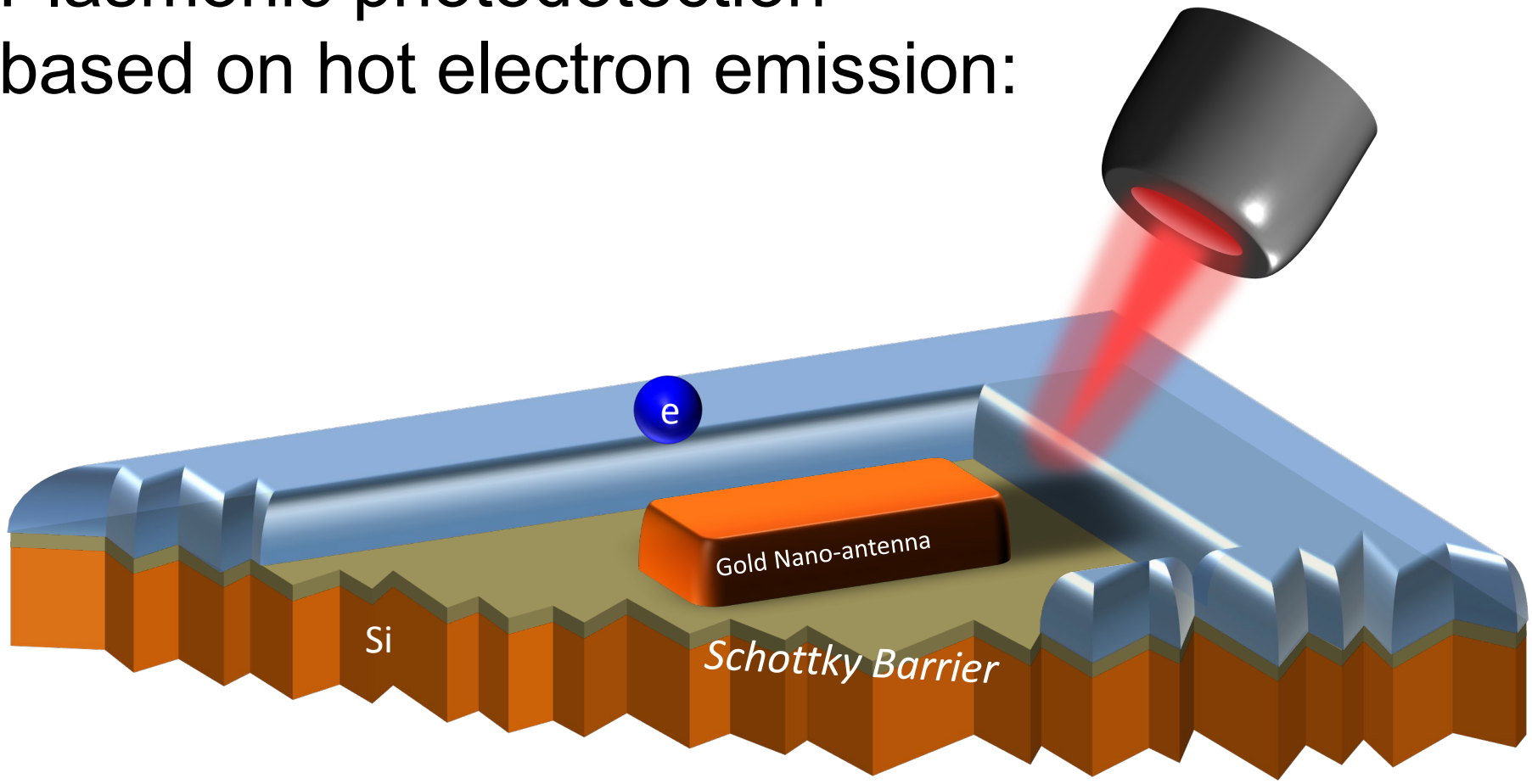
- Biology Research (Hanlon, Cronin)
- **Components Research (Halas, Link, Nordlander)**
- Platform Research/Development (Rogers)
- Sensor network-based imaging (Baraniuk)

Compact optical and spectral detection: a “Grand Challenge”



RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Plasmonic photodetection based on hot electron emission:



RICE

MBL Biological Discovery in Woods Hole

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

UMBC
AN HONORS UNIVERSITY IN MARYLAND

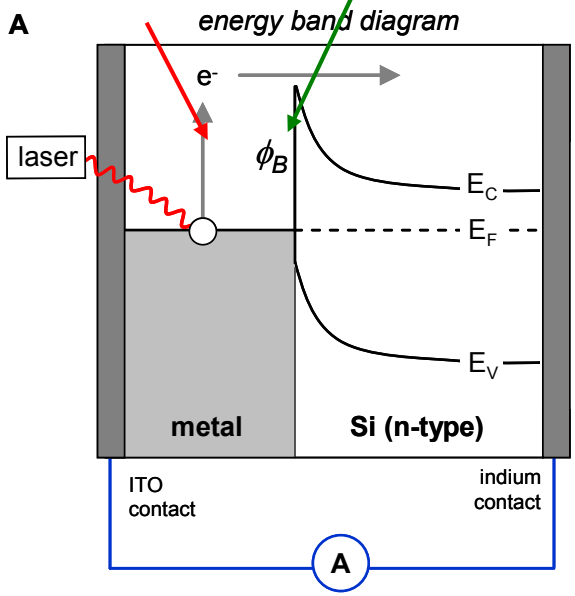
ONR
Revolutionary Research . . . Relevant Results

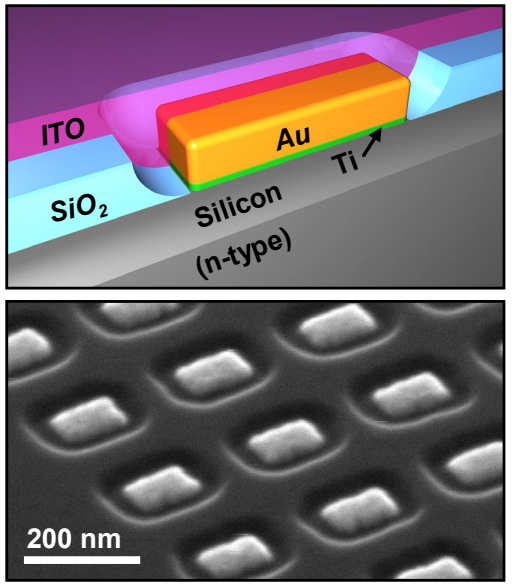
Photodetection with active optical antennas

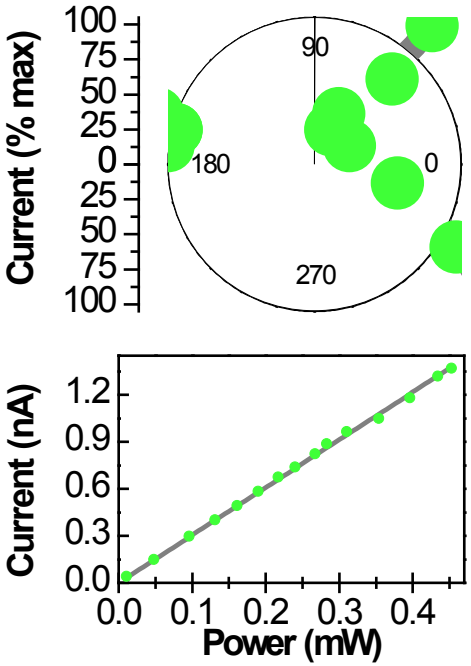
(M.W. Knight *et al.*, Science 332(2011)702)

Plasmon decay into hot electrons

Transport across the Schottky barrier







A nanoantenna-photodiode!

RICE

MBL Biological Discovery in Woods Hole

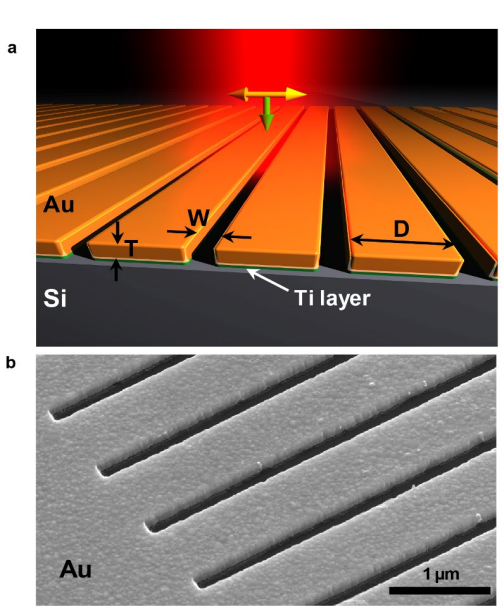
ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

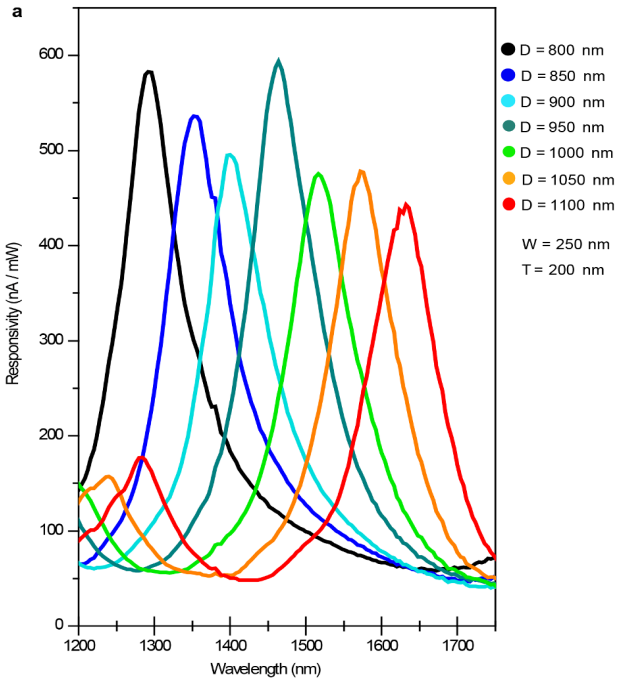
UMBC AN HONORS UNIVERSITY IN MARYLAND

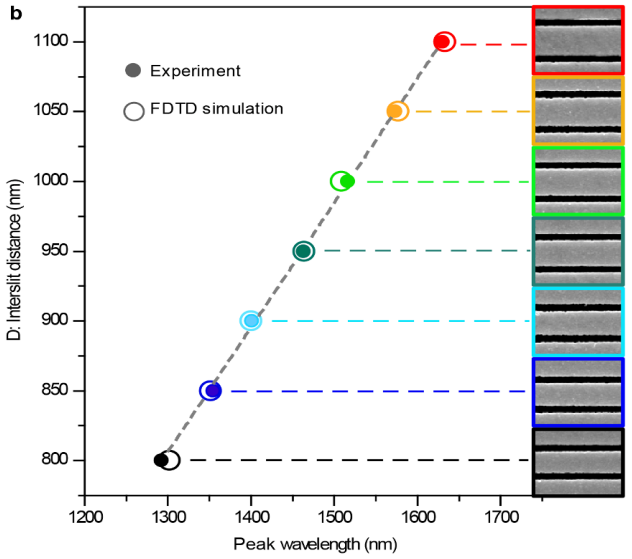
ONR Revolutionary Research . . . Relevant Results

EOT-Antenna on a semiconductor surface

(A. Sobhani et al., Nature Comm. 4(2013)1643)





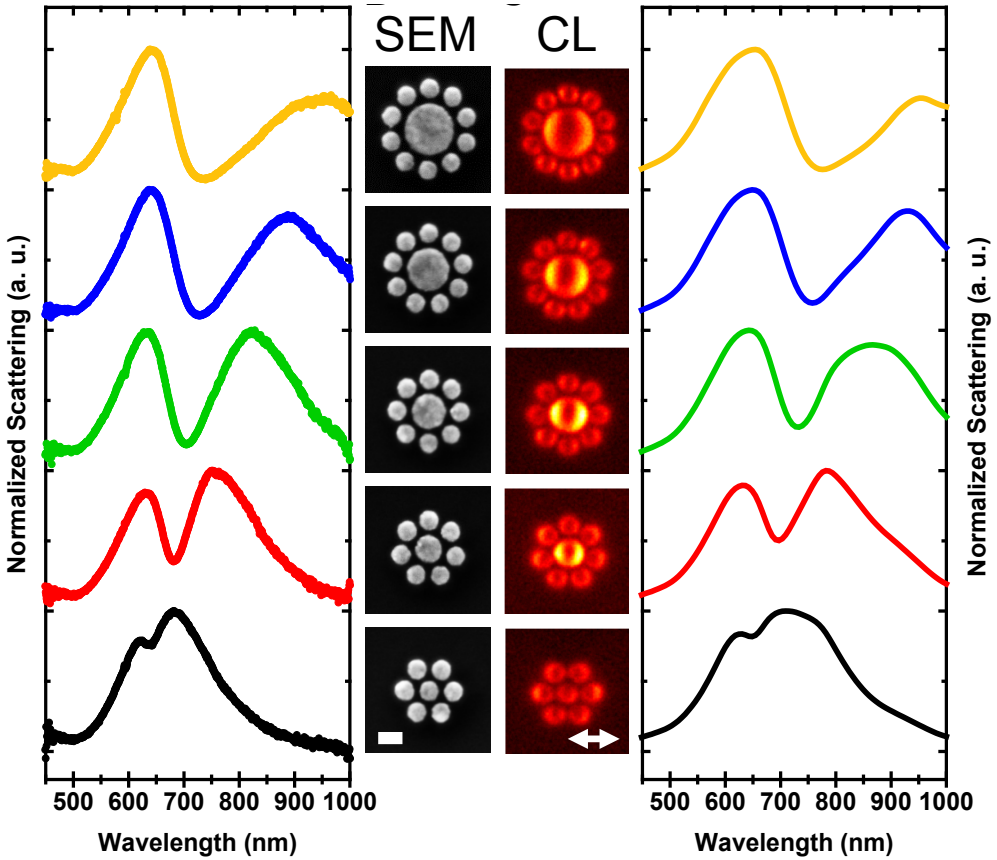


The use of a slit array enables the design of ultranarrow spectral photoresponse

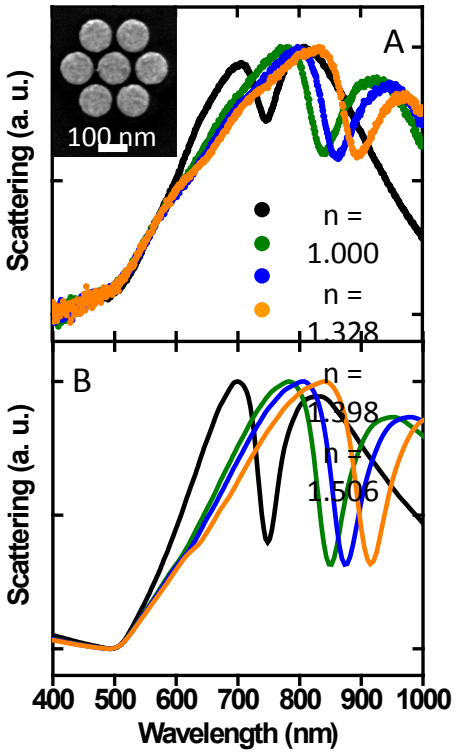
RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Lineshape Engineering of Fano “transparency windows” in broadband opaque structures

J. A. Fan, *et al.*, Science 328, 1135 (2010).
J. B. Lassiter *et al.*, Nano Lett. 12, 1058-62 (2012).



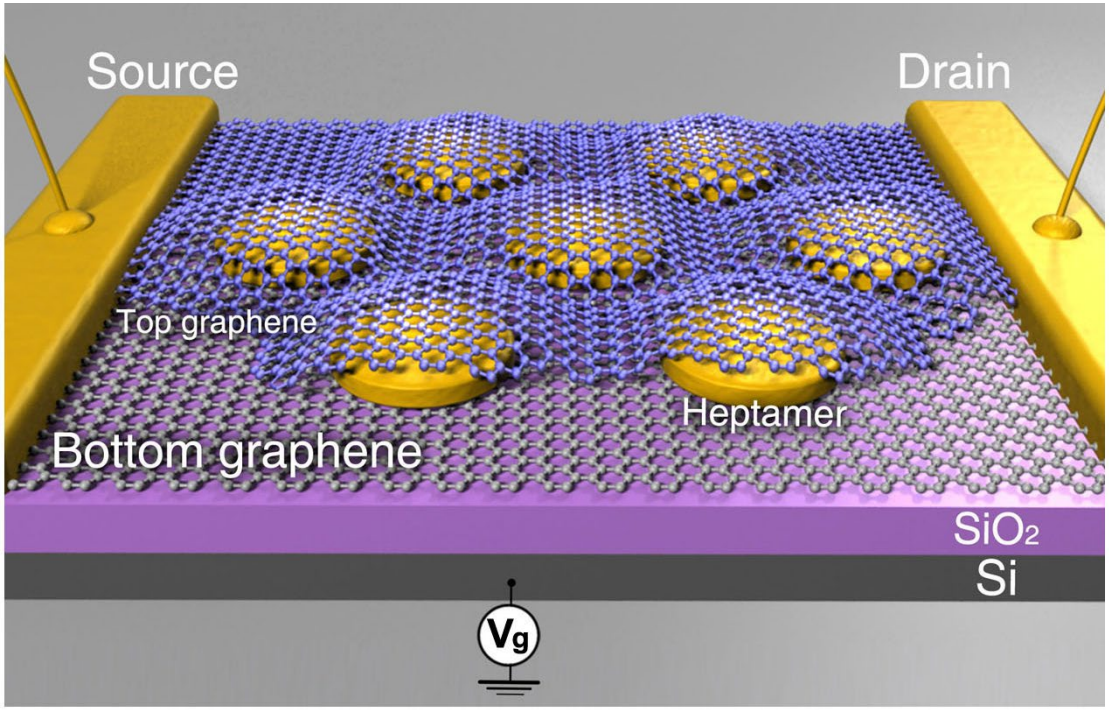
Tunable spectral window



RICE
MBL Biological Discovery in Woods Hole
ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
UMBC AN HONORS UNIVERSITY IN MARYLAND
ONR Revolutionary Research . . . Relevant Results

Graphene Sandwich Photodetector

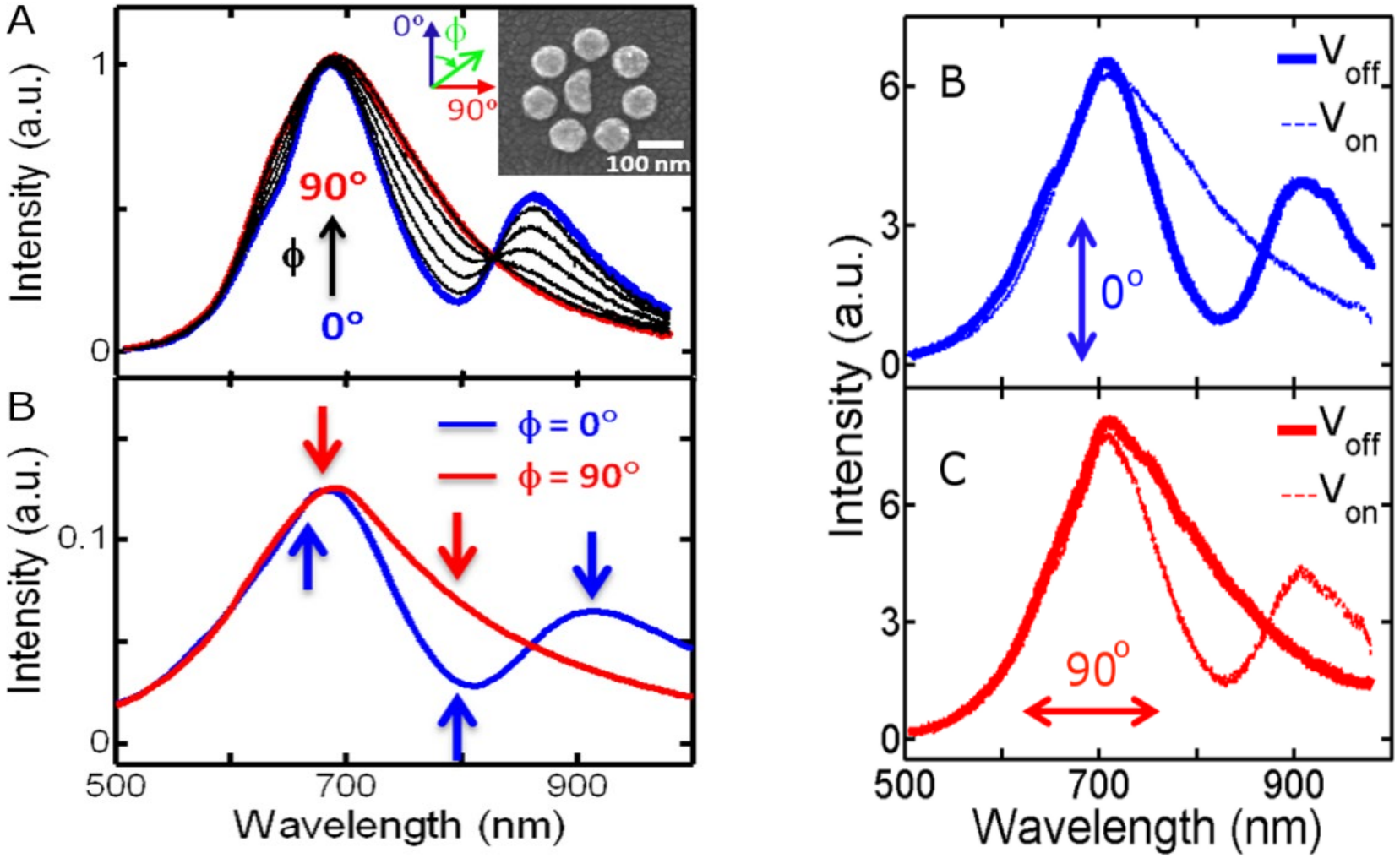
(Z.Y. Fang et al., Nano Lett. 12(2012)3808



- **Gold heptamer sandwiched by two single graphene sheets**
- **Efficient HE production at the heptamer Fano resonance**
- **Fano resonance can be tuned across the visible and NIR**

RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Active Plasmonics: a Plasmonic Fano Switch

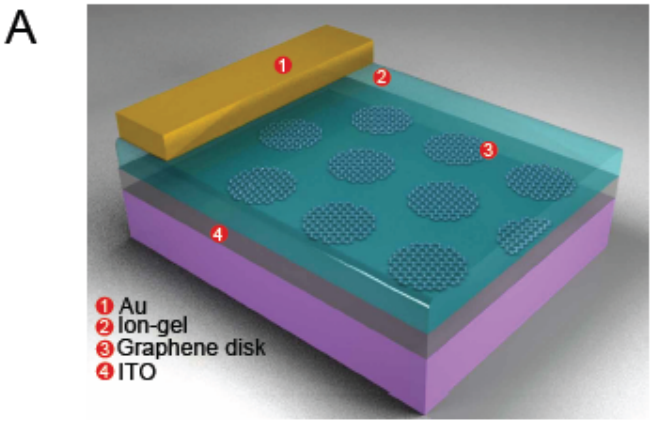


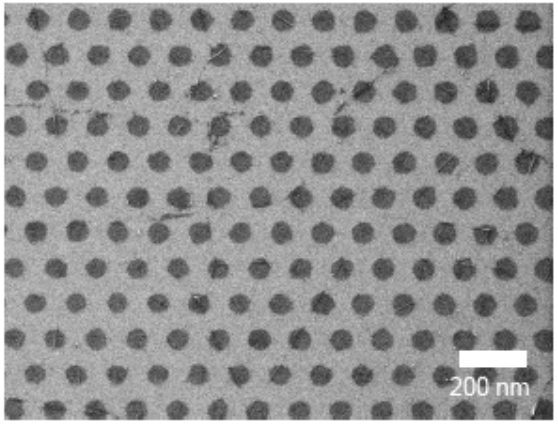
W.-S. Chang, J. B. Lassiter, P. Swanglap, H. Sobhani, S. Khatua, P. Nordlander, N. J. Halas, S. Link, Nano Lett. 12, 4977 (2012).

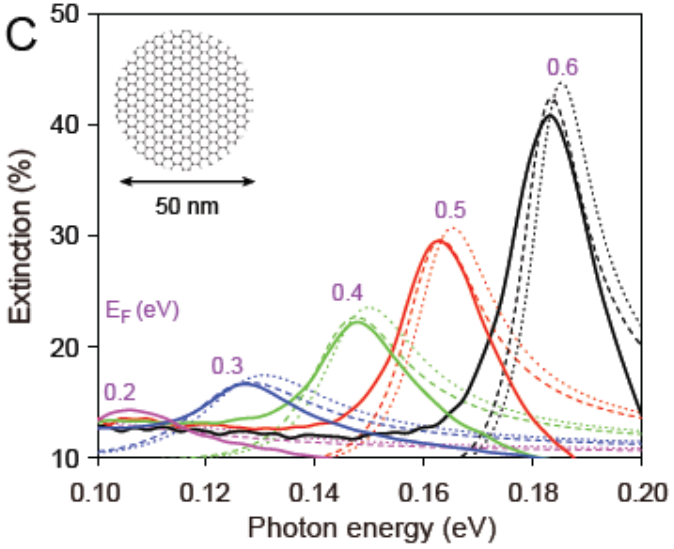
RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

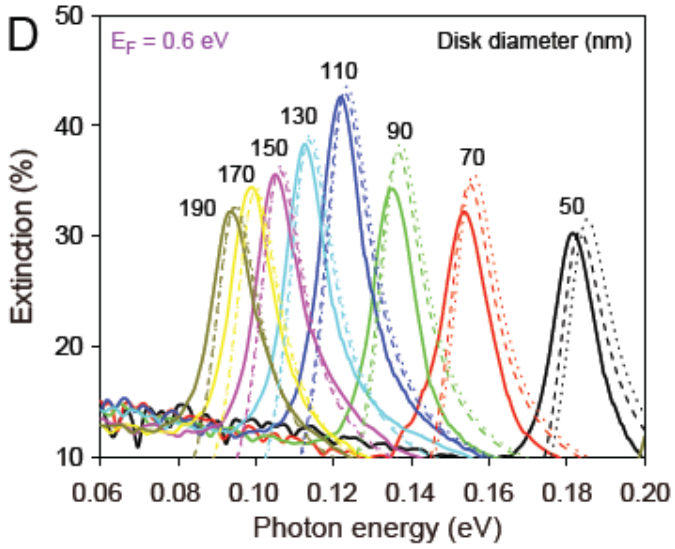
Plasmonic color actuation using Graphene

(Z.Y. Fang et al., ACS Nano 7(2013)2388)









Exp. ——————

RPA – – – –

E&M (Drude) ·····

Doping tunability

Diameter tunability

RICE

MBL Biological Discovery in Woods Hole

ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

UMBC AN HONORS UNIVERSITY IN MARYLAND

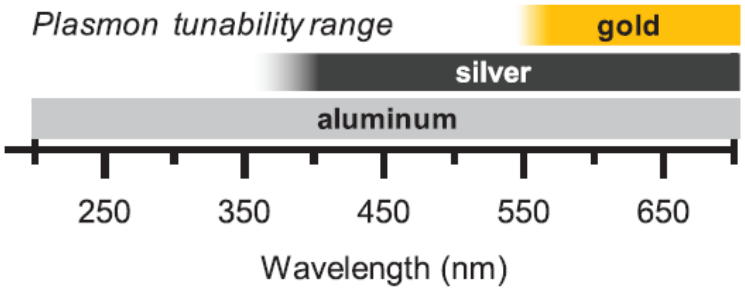
ONR Office of Naval Research S&T Revolutionary Research . . . Relevant Results

Into the visible region of the spectrum:

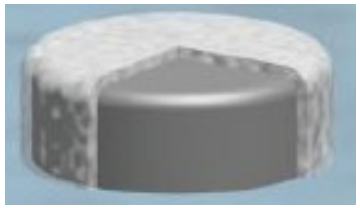
I. Aluminum plasmonics

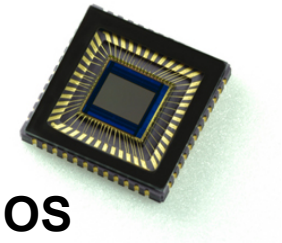
II. Molecular plasmonics

Aluminum Plasmonics



Stable



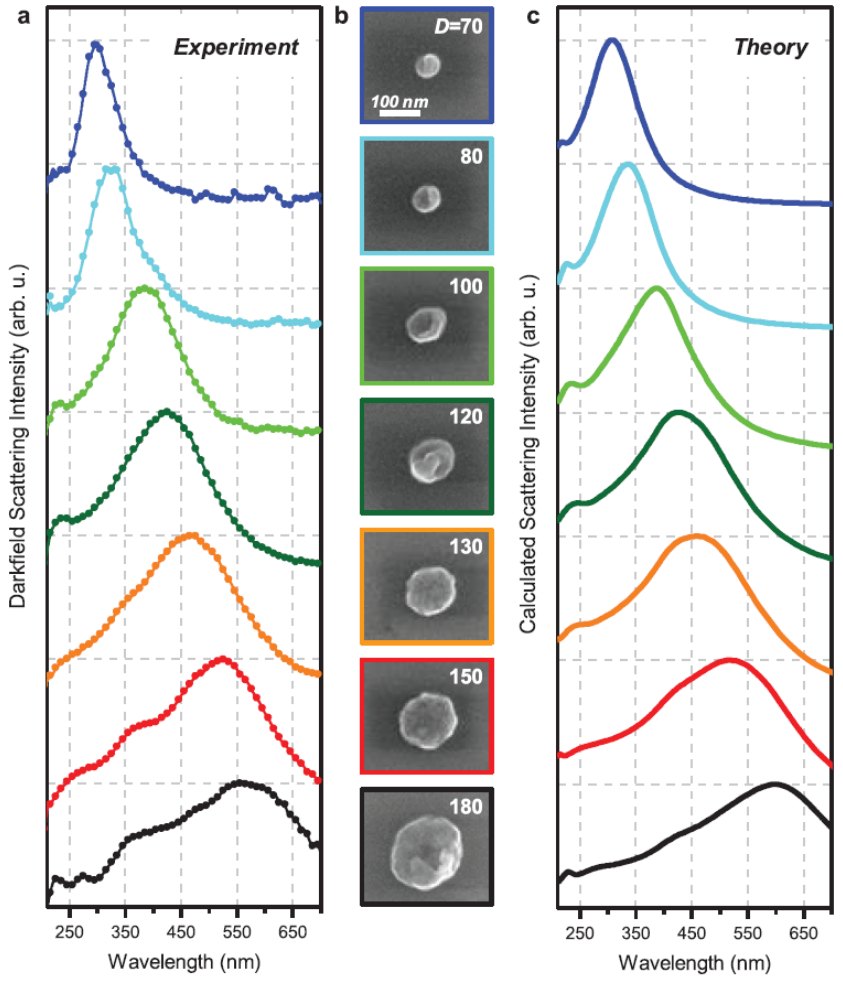


CMOS Compatible

COST (8/4/2014)

Material	$/lb	€/kg
Al	1.12	1.83
Ag	294.44	484.24
Au	18,770.00	30,850.00

"Aluminum for Plasmonics," *ACS Nano* ***2013****, 8, 834-840.*



RICE

MBL Biological Discovery in Woods Hole

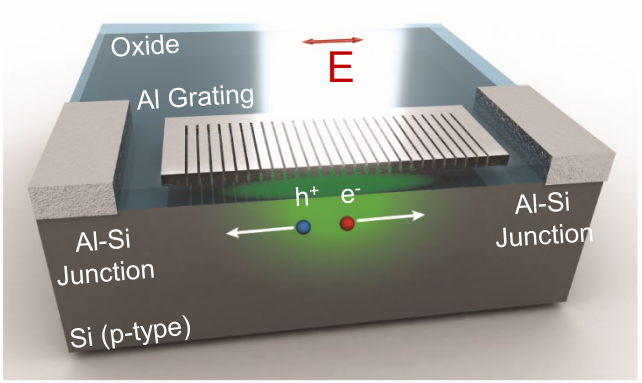
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

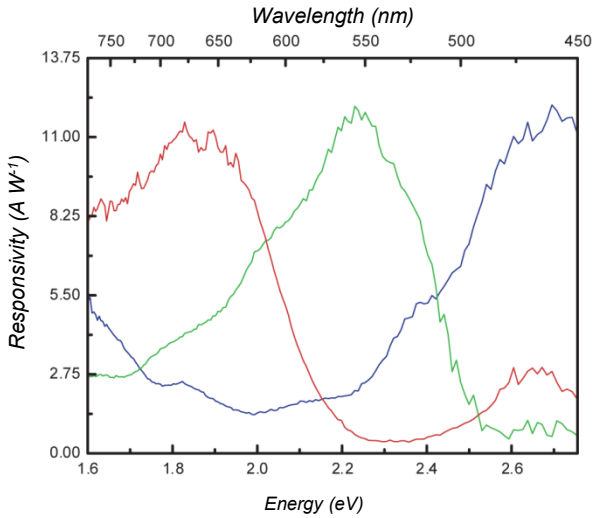
UMBC
AN HONORS UNIVERSITY IN MARYLAND

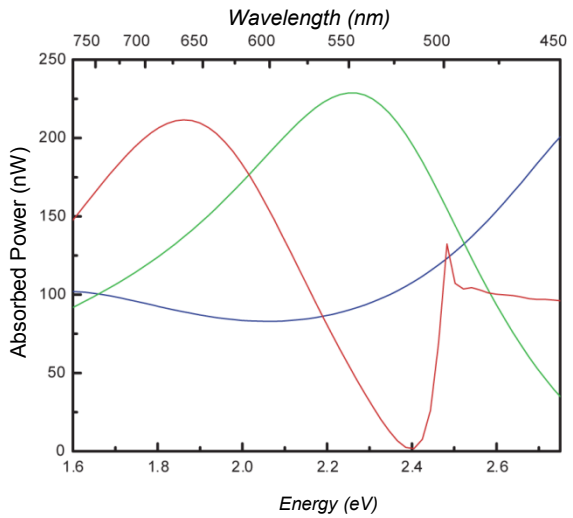
ONR
Office of Naval Research
Revolutionary Research . . . Relevant Results

An Aluminum plasmonic RGB photodetector

B. Zheng et al., Advanced Materials, ASAP.



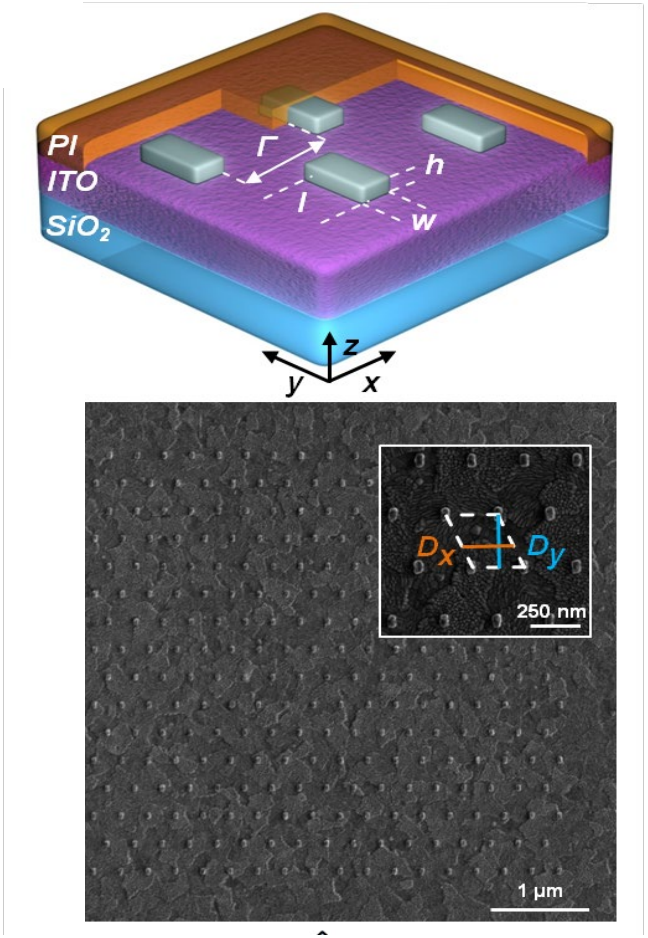


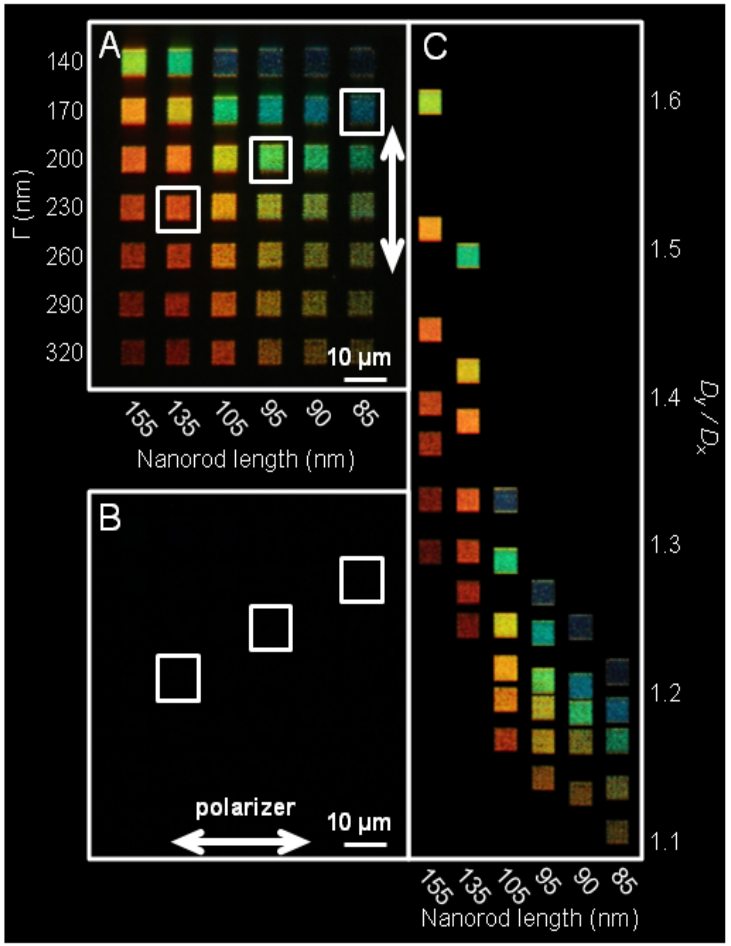


RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Aluminum Plasmonic Pixels

Olson, Manjavacas, Liu, Chang, Foerster, King, Knight, Nordlander, Halas, Link, PNAS, submitted.

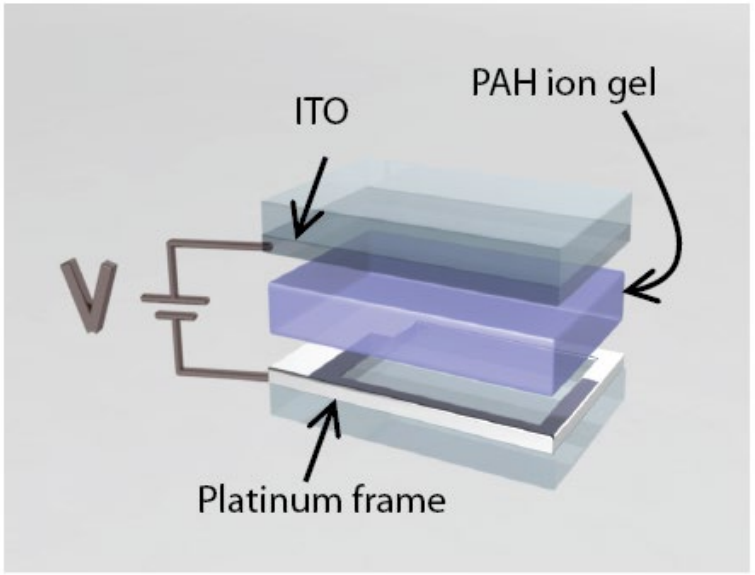


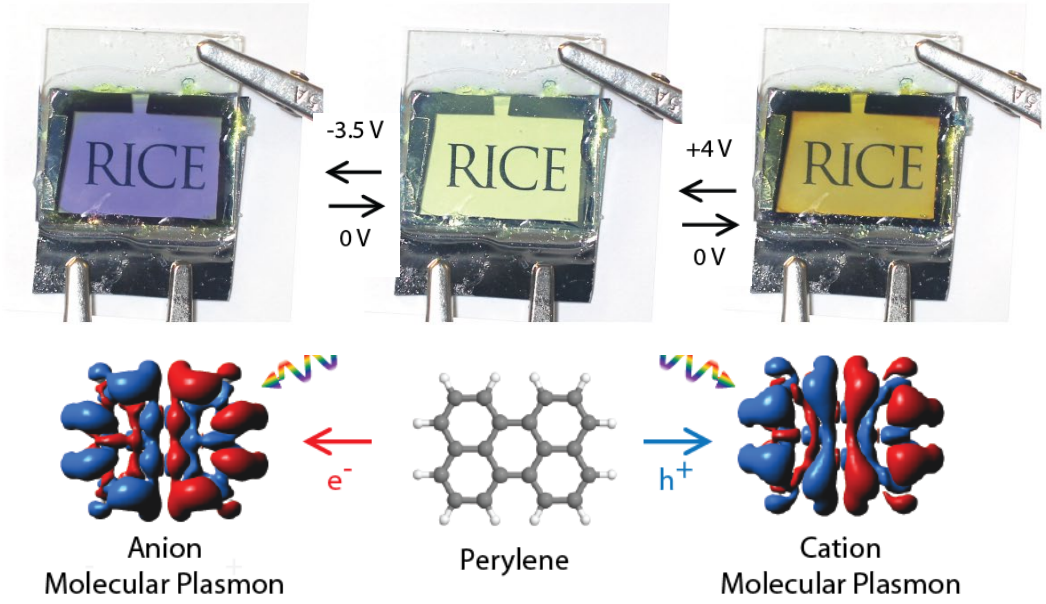


RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Molecular Plasmonic Devices

G. Stec et al., ACS Nano 11, 3254-3261 (2017).





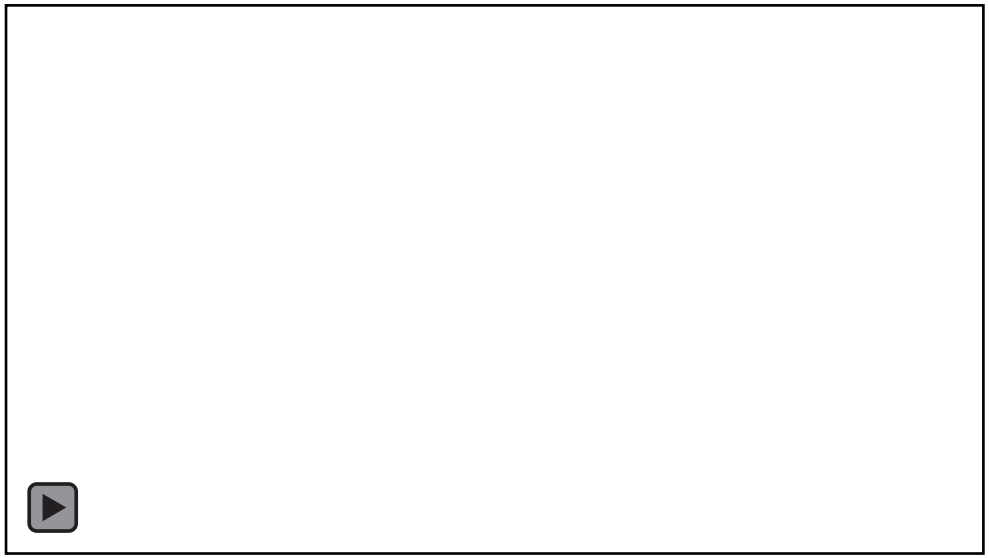
Multicolor Switching Device

Clear-to-Black Device

Multicolor Switching (Perylene)

Perylene Anion (Royal Blue) -3.5 V
Off: 0 V
Perylene Cation (Olive/Orange): 4 V
Off: 0 V

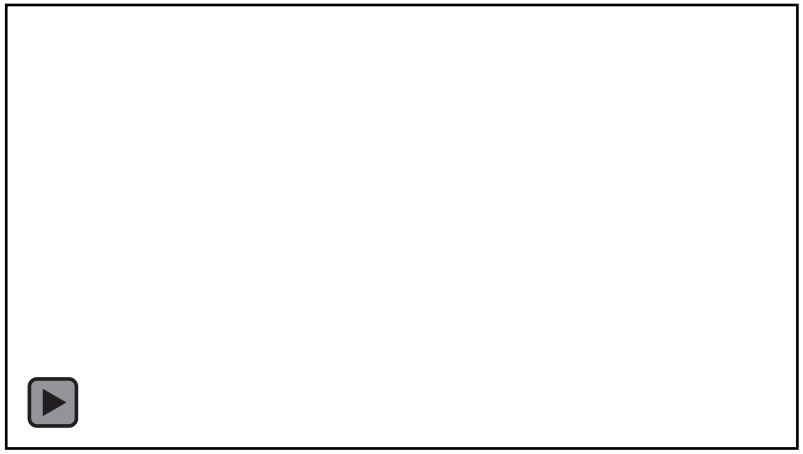
Turn on speed increased 8x
Turn off speed increased 30x



RICE
MBL Biological Discovery in Woods Hole
ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
UMBC AN HONORS UNIVERSITY IN MARYLAND
ONR Revolutionary Research . . . Relevant Results

Black Device

+4 V
Speed increased 16x



Outline

- Biology Research (Hanlon, Cronin)
- Components Research (Halas, Link, Nordlander)
- **Platform Research/Development (Rogers)**
- Sensor network-based imaging (Baraniuk)

Cephalopod-Inspired Adaptive Camouflage

deformable, adaptive, multifunctional

RICE

MBL Biological Discovery in Woods Hole

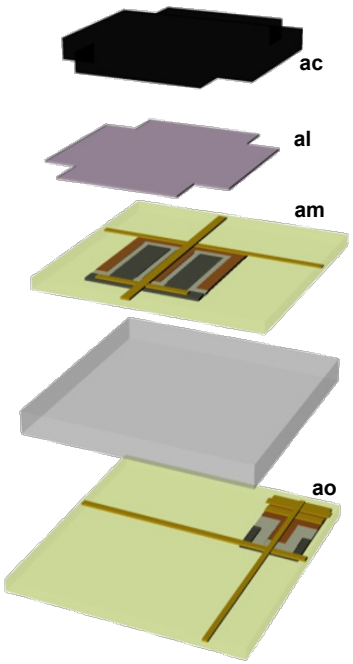
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

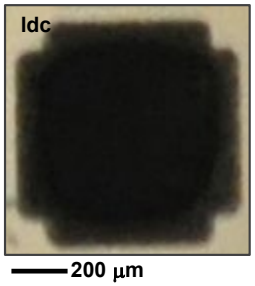
UMBC
AN HONORS UNIVERSITY IN MARYLAND

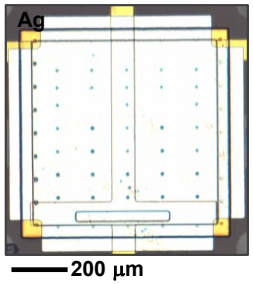
ONR
Office of Naval Research
S&T
Revolutionary Research . . . Relevant Results

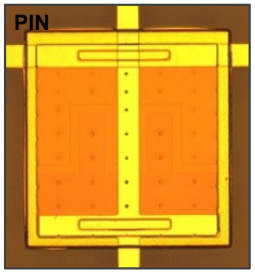
Design of a Bio-Inspired Adaptive Camouflage System

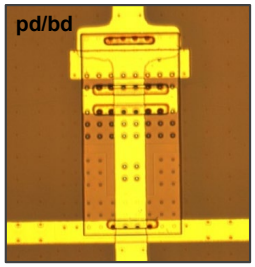
Unit Cell Design & Correspondence to Biology





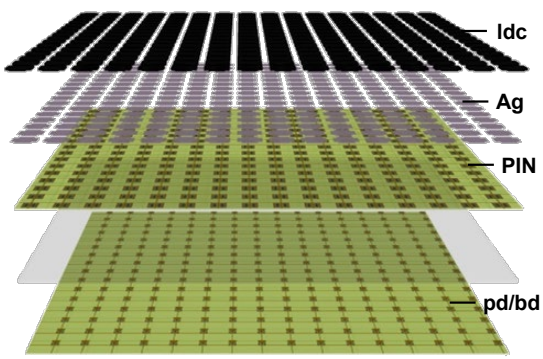


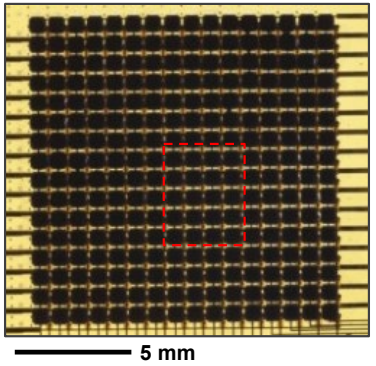


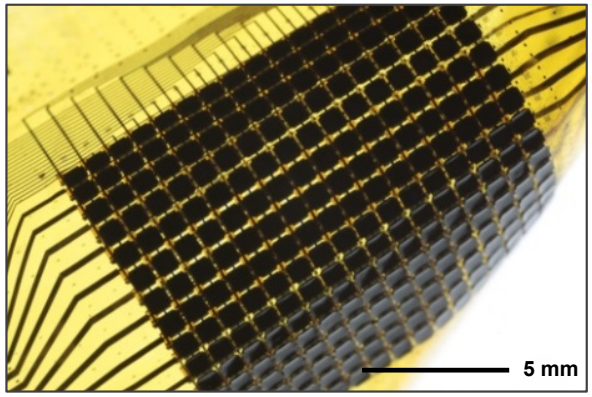


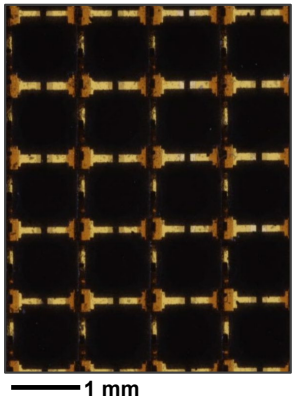
ac: artificial chromatophore
al: artificial leucophore
am: artificial 'muscle'
ao: artificial opsin

Full, Multiplexed System Architecture



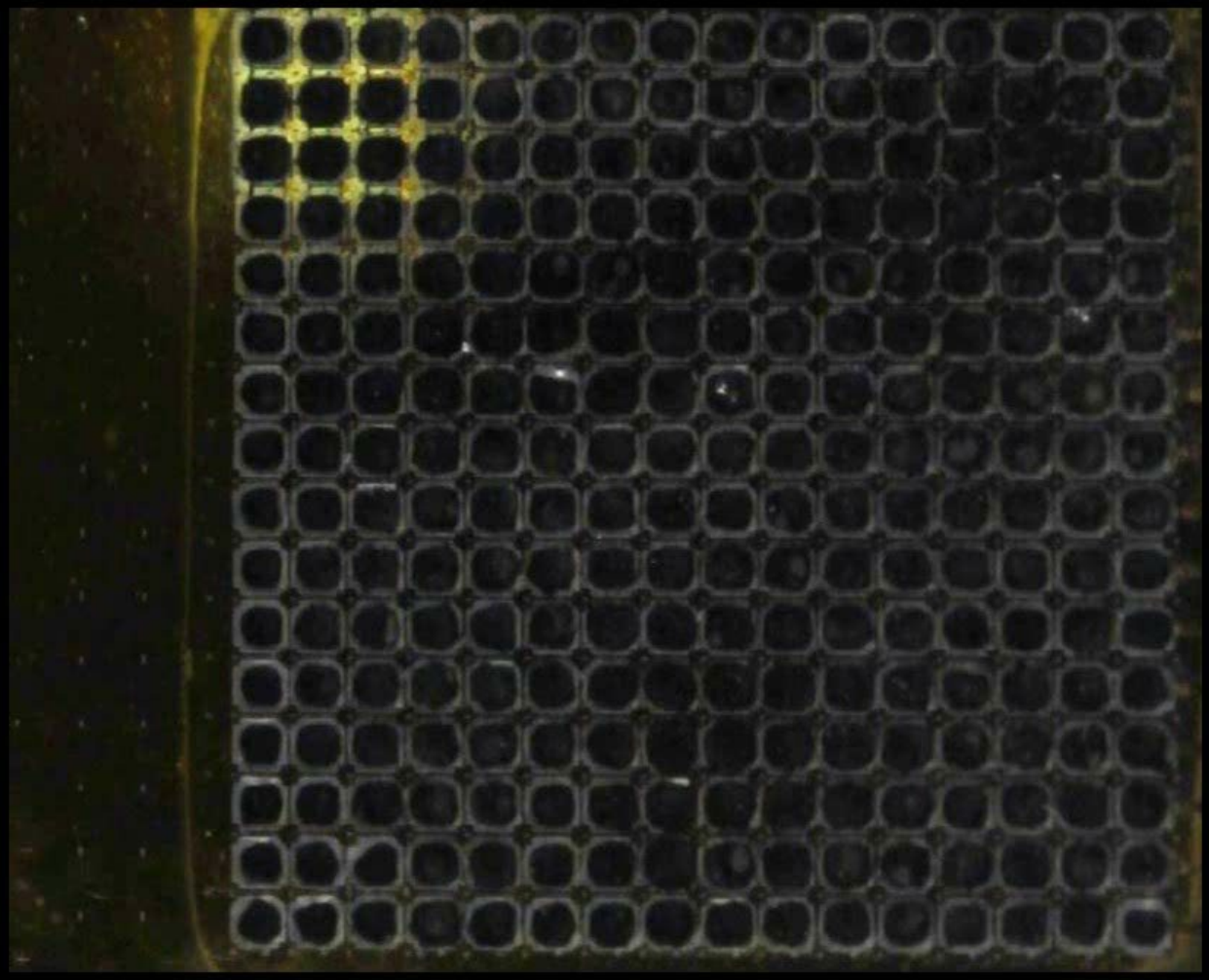






ldc: leucodye
Ag: nanostructured silver
PIN: PIN diode for thermal actuation
pd/bd: photodiode/blocking diode

RICE
MBL Biological Discovery in Woods Hole
ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
UMBC AN HONORS UNIVERSITY IN MARYLAND
ONR Office of Naval Research S&T Revolutionary Research . . . Relevant Results



RICE

MBL Biological Discovery in Woods Hole

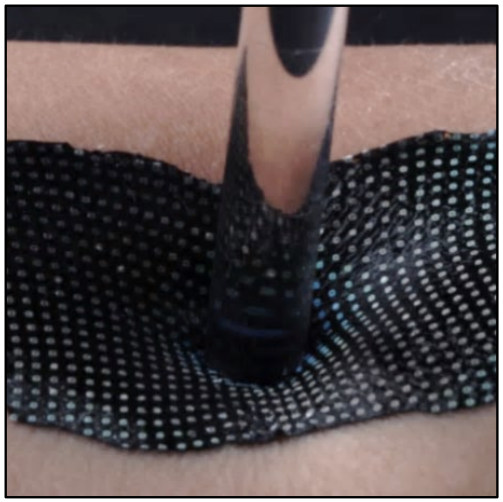
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

UMBC
AN HONORS UNIVERSITY IN MARYLAND

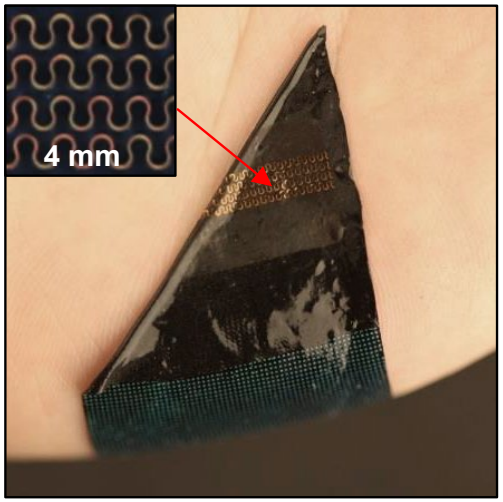
ONR
Office of Naval Research
S&T
Revolutionary Research . . . Relevant Results

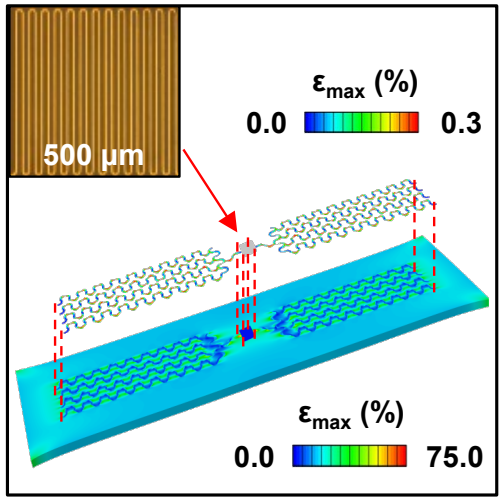
Color Changing, Thermally Responsive Electronic Skins for Physiological Status Monitoring

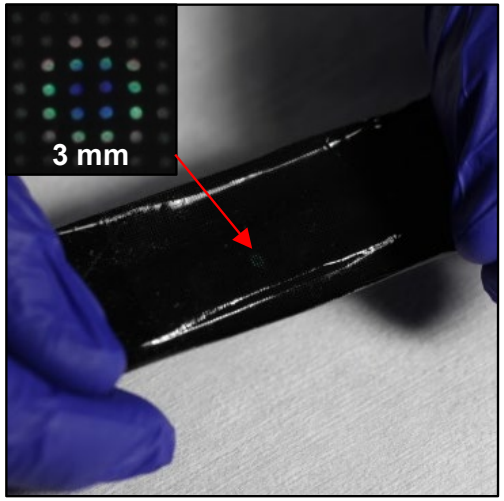
3 cm



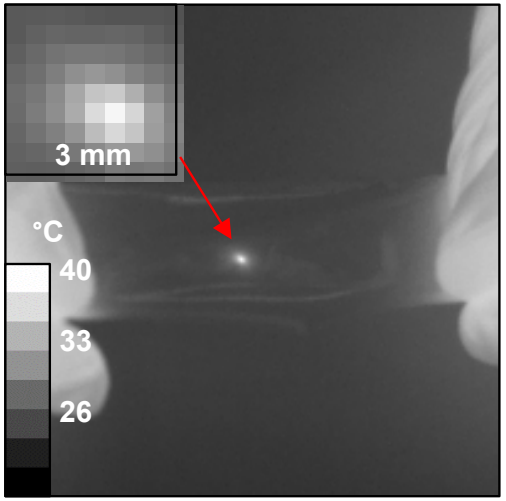
1 cm







3 cm



3 cm

RICE

MBL Biological Discovery in Woods Hole

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

UMBC
AN HONORS UNIVERSITY IN MARYLAND

ONR
Revolutionary Research . . . Relevant Results

Outline

- Biology Research (Hanlon, Cronin)
- Components Research (Halas, Link, Nordlander)
- Platform Research/Development (Rogers)
- **Sensor network-based imaging (Baraniuk)**

Lensless Imaging

- Conventional camera design
  - compact sensor array: **Uniform** and **high-resolution sampling** of the scene
  - objective lens: directs a **cone of light** into the camera
  - based on human visual system model

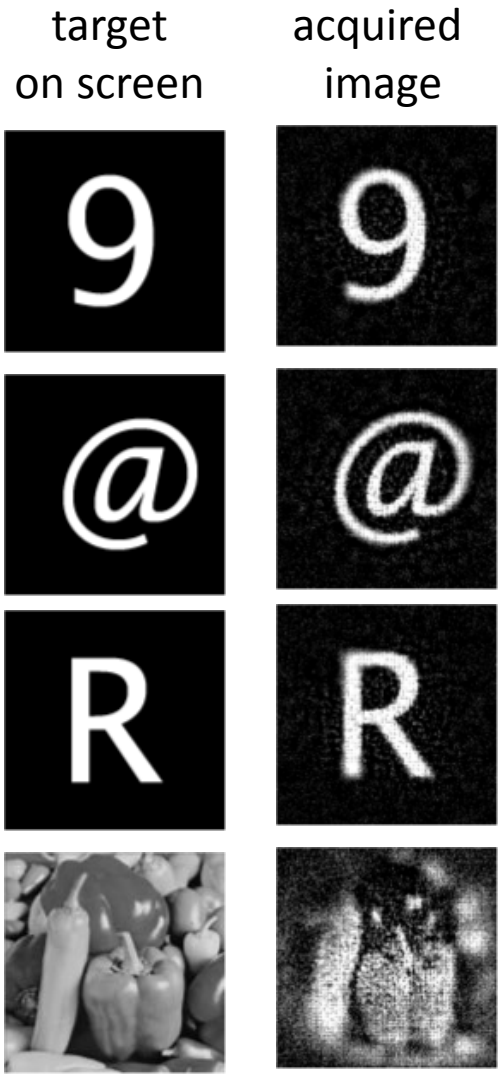
- **Goal**: A large, potentially flexible, imaging platform capable of distributed acquisition of light fields

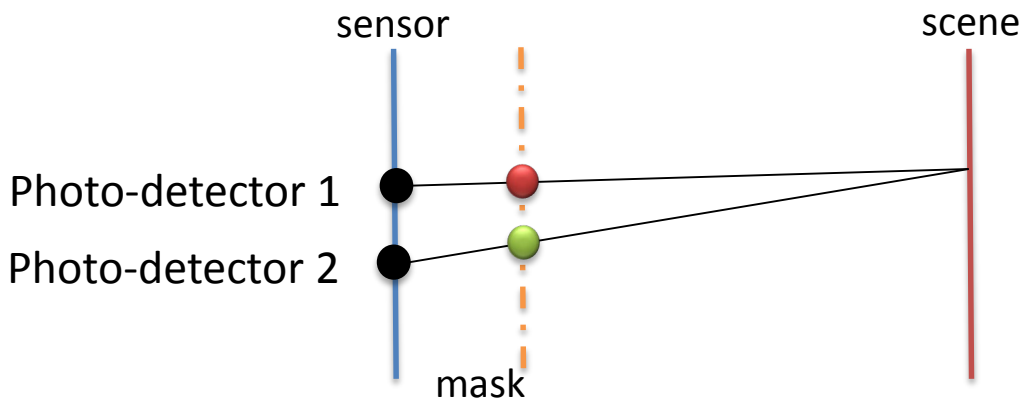
- **Approach: Lensless imaging**
  - nontrivial for incoherent light
  - leverage recent progress in coded aperture and **compressive sensing**
  - exciting opportunities for **flat** and **flexible cameras**

RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Lensless Imaging

- Joint work with John Rogers, UIUC
- Use a **mask** to code light rays from different angles
- Apply **compressive sensing** (sparsity-based) recovery algorithm to recover image of scene





RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Conclusions: Accomplishments

1. Spectrally selective nanodetectors established in multiple materials systems
2. Responsive plasmonic materials in well-established (noble metals) and new materials systems (graphene)
3. Design, fabrication and successful demonstration of platform for responsive materials
4. Identification of opsin in cephalopod dermal regions that may serve in functional photodetection
5. Identification of distinct neuronal pathways in cephalopod dermis related to specific color-functional structures
6. Mapping specific neuronal control of color elements in cephalopods, implying some peripheral integration
7. Demonstration of lensless imaging with distributed light collectors

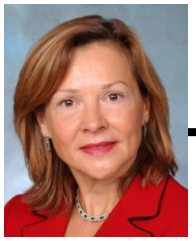
RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Next steps: big picture

- Integration of selected responsive components with platform architecture
- Investigate distinct neural pathways identified in cephalopods relative to remote optical detection capabilities
- Relate behavioral assays to optical response of cephalopods
- Demonstrate image acquisition experimentally with incoherent detector network

RICE MBL Biological Discovery in Woods Hole ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN UMBC AN HONORS UNIVERSITY IN MARYLAND ONR Revolutionary Research . . . Relevant Results

Biologically-inspired routes to sense-and-response in adaptive, intelligent metamaterials



Naomi Halas, Rice U.

Peter Nordlander, Rice U.

Stephan Link, Rice U.

Rich Baraniuk, Rice U.

John Rogers, UIUC

Roger Hanlon, Woods Hole MBL

Tom Cronin, UMBC

ONR Basic Research Challenges, 2013 Review Teleconference

RICE

MBL Biological Discovery in Woods Hole

ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

UMBC AN HONORS UNIVERSITY IN MARYLAND

ONR Revolutionary Research . . . Relevant Results