REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
27-02-2017	Final Report	1-Sep-2014 - 31-Aug-2015

4. TITLE AND SUBTITLE
Final Report: K-SPACE IMAGING AND EXCITATION USING FOURIER MICROSCOPY

5a. CONTRACT NUMBER
W911NF-14-1-0585

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
Vinod Menon

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
CUNY - City College of New York
160 Convent Avenue

New York, NY 10031 -9101

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
66444-EL-RI.3

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
This instrumentation grant helped develop a Fourier space (k-space) imaging and spectroscopy facility in the PIs laboratory at CCNY. The k-space imaging system consists of an Olympus inverted microscope with the back Fourier plane of the objective focused into the slit of a Princeton Instruments monochromator and detected by an EMCCD camera. The input to the inverted microscope is either a laser for photoluminescence or a white light source for reflection and absorption measurements. Using this experimental system we have carried out dispersion measurements on microcavities under the strong coupling, band structure of photonic hypercrystal, directional light

15. SUBJECT TERMS
Fourier space imaging

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Vinod Menon
					19b. TELEPHONE NUMBER
					212-650-7443

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Final Report: K-SPACE IMAGING AND EXCITATION USING FOURIER MICROSCOPY

ABSTRACT

This instrumentation grant helped develop a Fourier space (k-space) imaging and spectroscopy facility in the PIs laboratory at CCNY. The k-space imaging system consists of an Olympus inverted microscope with the back Fourier plane of the objective focused into the slit of a Princeton Instruments monochromator and detected by an EMCCD camera. The input to the inverted microscope is either a laser for photoluminescence or a white light source for reflection and absorption measurements. Using this experimental system we have carried out dispersion measurements on microcavities under the strong coupling, band structure of photonic hypercrystal, directional light emission from active hyperbolic metamaterials and dipole orientation of molecules and 2D semiconductors.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
02/23/2017	1	Tal Galfsky, Zheng Sun, Christopher R. Considine, Cheng-Tse Chou, Wei-Chun Ko, Yi-Hsien Lee, Evgenii E. Narimanov, Vinod M. Menon. Broadband Enhancement of Spontaneous Emission in Two-Dimensional Semiconductors Using Photonic Hypercrystals, Nano Letters, ( ): 4940. doi:
02/23/2017	2	Tal Galfsky, Jie Gu, Evgenii Narimanov, and Vinod Menon. Photonic Hypercrystals: new media for control of lightmatter interaction, Under Review, ( ): . doi:

TOTAL: **2**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

MRS Fall Meeting 2016: NM2.14.09
Dipole Aligned Energy Transfer Between Excitons in 2D Semiconductors and Organic Materials
Jie Gu 1 2 , Xiao Liu 3 , Yi-Hsien Lee 4 , Stephen Forrest 3 , Vinod Menon 1 2

1 Physics City University of New York New York United States, 2 Physics Graduate Center City University of New York New York United States, 3 Electrical Engineering and Computer Science and Physics University of Michigan Ann Arbor United States, 4 Department of Materials Science and Engineering National Tsing Hua University Hsinchu Taiwan

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

None to report

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME | PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Under Graduate students supported

NAME | PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME | PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

"See attachment"

Technology Transfer

None to report on this grant

Report Type:	Final Report
Proposal Number:	66444ELRI
Agreement Number:	W911NF1410585
Proposal Title:	K-SPACE IMAGING AND EXCITATION USING FOURIER MICROSCOPY
Report Period Begin Date:	09/01/2014
Report Period End Date:	08/31/2015

Abstract: This instrumentation grant helped develop a Fourier space (k-space) imaging and spectroscopy facility in the PIs laboratory at CCNY. The k-space imaging system consists of an Olympus inverted microscope with the back Fourier plane of the objective focused into the slit of a Princeton Instruments monochromator and detected by an EMCCD camera. The input to the inverted microscope is either a laser for photoluminescence or a white light source for reflection and absorption measurements. Using this experimental system we have carried out dispersion measurements on microcavities under the strong coupling, band structure of photonic hypercrystal, directional light emission from active hyperbolic metamaterials and dipole orientation of molecules and 2D semiconductors.

Introduction: Fourier microscopy, wherein one images the back focal plane of a microscope objective to characterize the directionality of light emission/scattering has been used recently to characterize dipole orientation, emission pattern of nanowires coupled to plasmonic antenna, dispersion of microcavity polaritons and surface plasmon polaritons, light propagation and Bloch

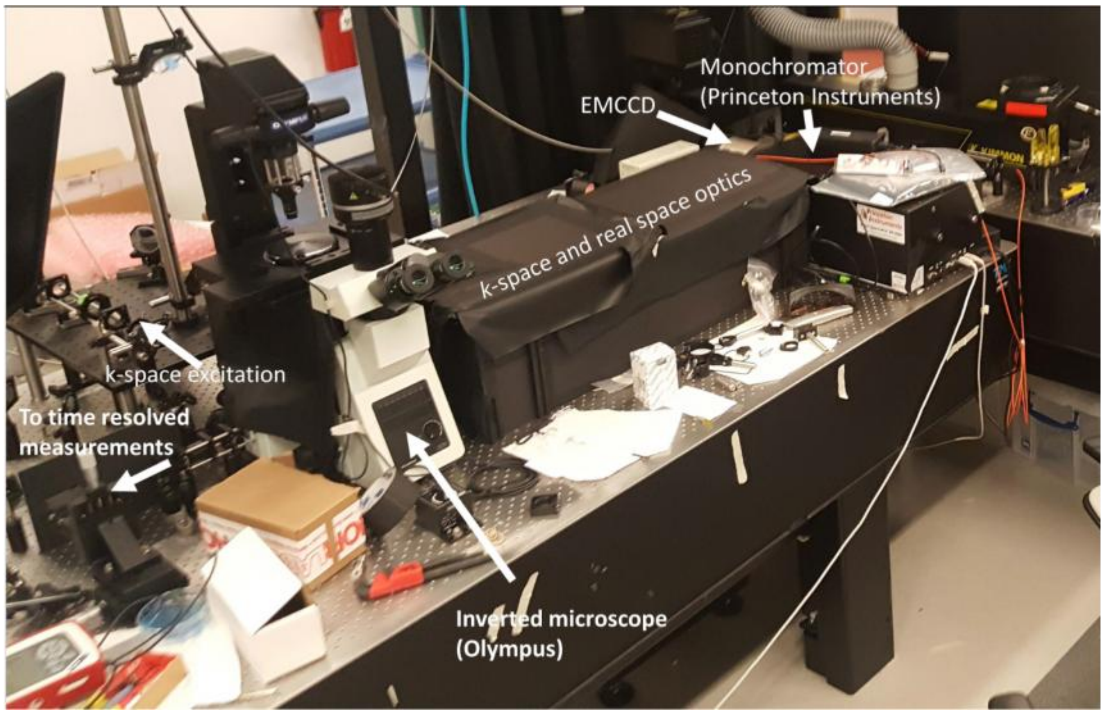

Fig. 1. Photograph of the k-space imaging and excitation set up in the PIs lab.

modes in photonic crystals, and structure of self-assembled nanostructures[1]–[6]. While most of these demonstrations were carried out for imaging, one could also conceive reversing the strategy and carrying out excitation experiments in the *k*-space. Here, one can pick and choose the *k*-vectors for illumination. This can be implemented using an optical fiber with X/Y translation positioned at the Fourier plane and thereby control the exact k-value of excitation.

Under this instrumentation grant we developed a k-space imaging and excitation set up. Shown in in Fig. 1 is the photograph of the set up in the PIs lab. The system consists of:

- A modified Olympus inverted microscope which allows for both upright and inverted illumination,
- The k-space imaging optics that is a 4f system that images the back plane of the microscope objective onto the monochromator slit.
- Princeton instruments half meter monochromator (SP2500) with one entrance and two exit slits
- Pro EM (electron multiplying) CCD camera with 1024 x 1024 array.
- The k-space excitation optics at the back entrance of the Olympus microscope to allow for k-specific excitation. This consist of an optical fiber tip on an x-y translation stage placed at the Fourier plane of the objective lens. The optical fiber at the other end is coupled to the laser source.
- The second exit port of the microscope takes the signal to a time resolved luminescence and photon correlation measurement set up from Picoquant.
- There is also a low resolution camera on the microscope for imaging.

The set up was built during summer 2015 and was fully operational by fall 2015. Schematic of the setup is shown in Fig. 2 below.

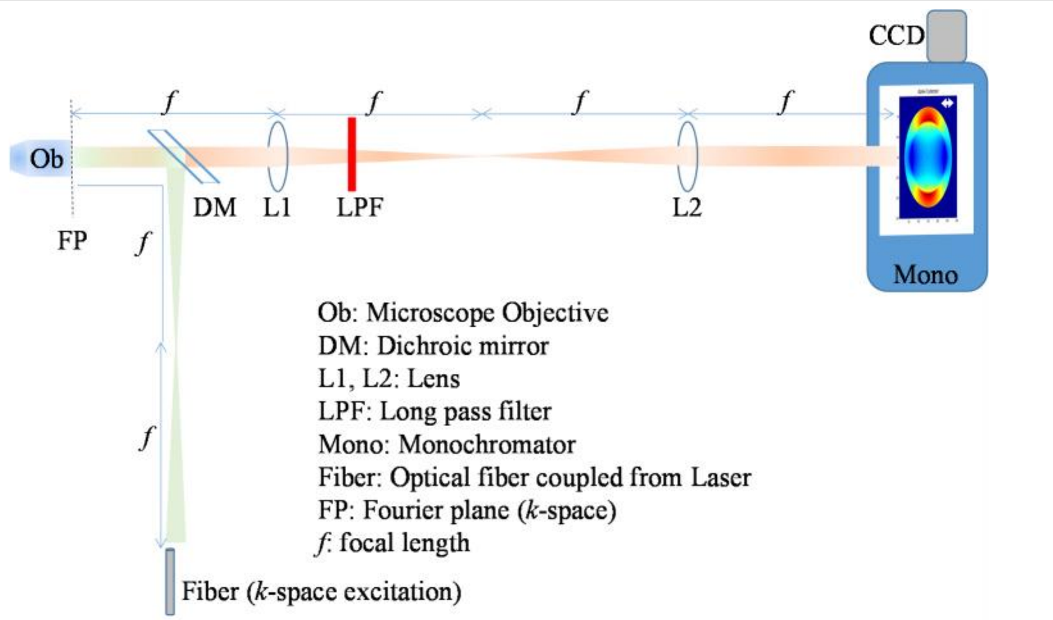

Fig. 2. Schematic of the k-space imaging and excitation set up. The optical fiber is used for the excitation.

A variety of measurements have been carried out using the set up and have now become one of the most widely used set up in the lab and even by collaborators. Below we discuss some of the key results obtained using the set up.

Exciton-Polariton dispersion

Through a prior ARO research grant PIs group demonstrated the strong coupling of excitons in 2D semiconductors of MoS_2 to cavity photons [7]. More recently we have demonstrated strong coupling in an all-metal microcavity and also demonstrated the valley polarization property of the polaritons. This work is currently under review. Shown in Fig. 3 is the dispersion of three different microcavities with different detuning (Δ = Eex – Eph), where Eex and Eph are the exciton and cavity photon energies, respectively at k=0. The left panel shows angle resolved (k-resolved) white light reflectivity and the right panel shows the angle dependent photoluminescence (PL) obtained using the k-space set up. Clear anticrossing is seen at different angle values for the different detuning. Using the k-space excitation we were able to further excite with specific k-value and energy and there by resonantly pump the polariton states. This was important to demonstrate the valley polarization property o the polaritons. This work is currently under review.

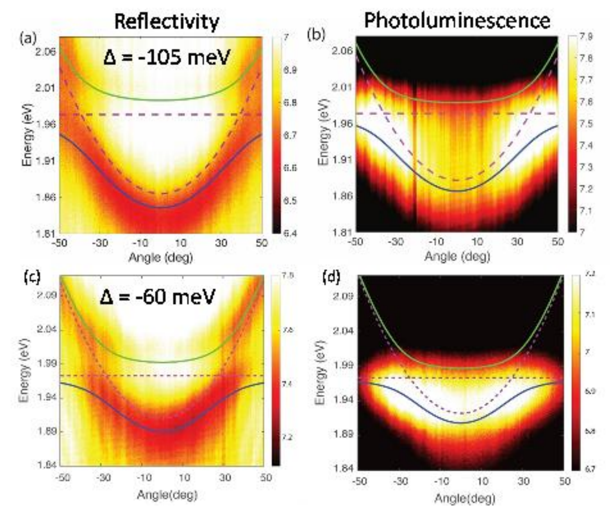

Fig. 3. Dispersion of exciton –polaritons in 2D MoS_2 based microcavities with different detuning, Δ. Reflectivity measurements with white light are shown in the left panel and the photoluminescence in the right panel.

Dipole orientation in monolayer semiconductors

In another project where we were studying the energy transfer between 2D monolayers of various transition metal dichalcogenides (TMDs) and organic thin films, we needed to establish the dipole orientation in these layers. Shown in Fig. 4 is the simulation of expected dipole radiation for in-plane dipoles along with the experimentally obtained k-space image using the experimental set up discussed above. This was important to establish the dipole orientations for studying energy transfer between dissimilar excitonic systems. Manuscript based on this work is currently being prepared for submission.

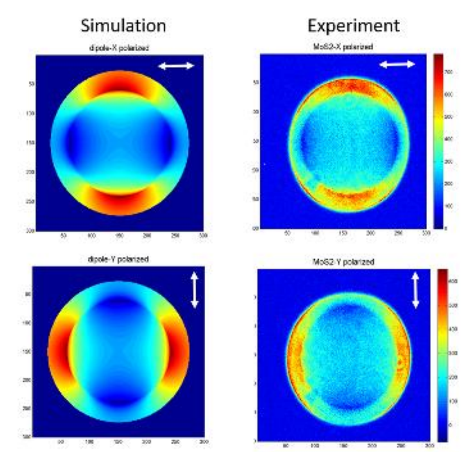

Fig. 4. Radiation pattern due to in-plane dipole orientation in 2D monolayer semiconductors. Left panel shows simulation and right panel shows experimental results.

Radiation pattern of photonic hypercrystal

Through a previous and current ARO research grant we have developed the photonic hypercrystal, a new artificial photonic media that combines the large density of photonic states arising from the hyperbolic dispersion of the metamaterial constituent and the enhanced light out-coupling from the photonic crystal band structure which translates all the dark states that lie below the light line into radiative states. The k-space image shown in Fig. 5 shows the directional emission over a wide spectral range from the photonic hypercrystal and hence better detection of emitted radiation from embedded quantum dots. The hypercrystal consists of CdSe quantum dots embedded inside the hyperbolic metamaterial with a 2D lattice playing the photonic crystal part (inset of Fig. 5). The *k*-space image shown in Fig. 5 was obtained using white light reflectivity. Using the hypercrystal, we were able to show 100x enhancement in light out-coupling compared to purely hyperbolic metamaterial and also 20x enhancement in the radiative rate (Purcell enhancement). This work is currently under review.

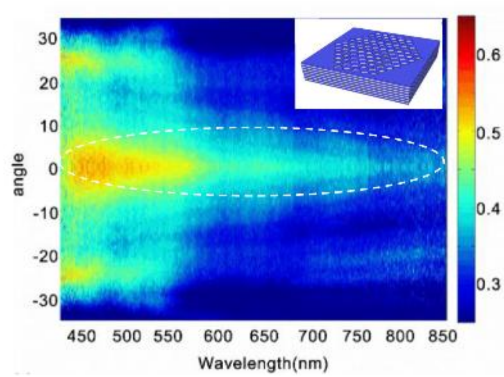

Fig. 5. *k*-space image of reflectivity from the photonic hypercrystal showing narrow angular dispersion in scattering over a wide spectral range (white dashed ellipse). The inset shows the schematic of a hypercrystal.

Dispersion of all-dielectric metasurface

Under the current ARO research grant we are investigating all-dielectric metasurfaces to enhance the luminescence of 2D TMDs. As a first step in this direction, we have fabricated all-silicon dielectric metasurface and investigated the *k*-space scattering to obtain the band structure. Shown in Fig. 6 is the obtained *k*-space image from an all-dielectric metasurface. This is work being carried out in collaboration with the group of prof. Alex Khanikaev at CCNY.

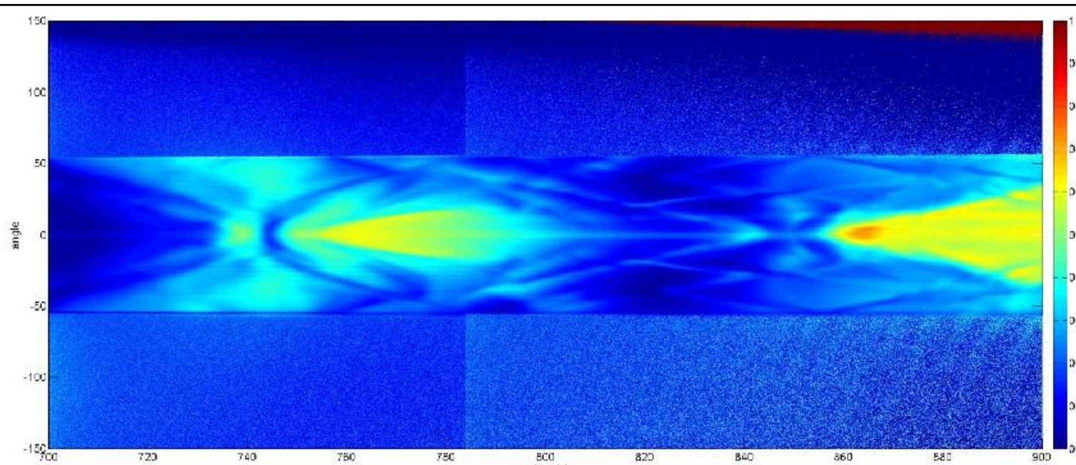

Fig. 6. *k*-space image of scattering from all-dielectric metasurface showing the dispersion and the bandgaps.

Currently we are investigating structures that can simultaneously enhance luminescence as well as have polarization selection to exploit the valley polarization in 2D TMDs, specifically WSe_2 and $MoSe_2$.

Summary: Through this instrumentation grant we have successfully built a Fourier space imaging and excitation set up that has now been utilized to study dispersion and angular emission patterns of a variety of low-dimensional materials embedded in artificial media such as metamaterials as well as in microcavities. This system has become one of the most utilized tools in the lab currently with over 15 students already trained to use it. This includes 3 undergraduate, 9 graduate and 3 post-doctoral researchers.

In the future we will be carrying out *k*-space excitation experiments to study nonlinear optical properties of the strongly-coupled polariton states.

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