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Final Report: Ultra-Slim Device for Focus Scanning in Optical Neural Implant

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6. AUTHORS
Andrei Faraon, Amir Arbabi, Yu Horie

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
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14. ABSTRACT
We developed the technology that will enable a fast and slim device capable of focusing light at arbitrary points in a volume on the same order of magnitude as a cortical column in the brain. The slim and lightweight characteristics will enable implantation on rodent skulls. The enabling technology is the recent invention of dielectric meta-surfaces, structures thinner than a wavelength that allow for unprecedented control of free-space propagating light. The optical system is composed of two lenses where the focus is scanned by moving the plates with respect to each

15. SUBJECT TERMS
Microscopy, Metasurface, Neural Implant, Optics

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Andrei Faraon
UU	UU	UU	UU		19b. TELEPHONE NUMBER 626-395-3086

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Report Title

Final Report: Ultra-Slim Device for Focus Scanning in Optical Neural Implant

ABSTRACT

We developed the technology that will enable a fast and slim device capable of focusing light at arbitrary points in a volume on the same order of magnitude as a cortical column in the brain. The slim and lightweight characteristics will enable implantation on rodent skulls. The enabling technology is the recent invention of dielectric meta-surfaces, structures thinner than a wavelength that allow for unprecedented control of free-space propagating light. The optical system is composed of two lenses where the focus is scanned by moving the plates with respect to each other like in a telescopic system. The uniqueness of our technology stems from the capability to lithographically place the phase plates in very close proximity (tens of microns) and to actuate them at high speeds using electrostatic forces like in micro electro-mechanical devices (MEMS). This is a versatile platform that can be applied to various types of microscopy, including two-photon neural microscopy.

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
08/27/2015	1	Amir Arbabi, Yu Horie, Mahmood Bagheri, Andrei Faraon. Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission, Nature Nanotechnology, (08 2015): 0. doi: 10.1038/nnano.2015.186 365,081.00
08/27/2015	2	Amir Arbabi, Yu Horie, Alexander J. Ball, Mahmood Bagheri, Andrei Faraon. Subwavelength-thick lenses with high numerical apertures and large efficiency based on high-contrast transmitarrays, Nature Communications, (05 2015): 7069. doi: 10.1038/ncomms8069 365,082.00
09/30/2016	3	Amir Arbabi, Ryan M. Briggs, Yu Horie, Mahmood Bagheri, Andrei Faraon. Efficient Dielectric Metasurface Collimating Lenses for Mid-Infrared Quantum Cascade Lasers, Optics Express, (08 2015): 0. doi: 365,096.00
09/30/2016	16	Yu Horie, Amir Arbabi, Seunghoon Han, Andrei Faraon. High resolution on-chip optical filter array based on double subwavelength grating reflectors, Optics Express, ( ): 29848. doi: 1,018,550.00
09/30/2016	17	Yu Horie, Amir Arbabi, Ehsan Arbabi, Seyedeh Mahsa Kamali, Andrei Faraon. Wide bandwidth and high resolution planar filter array based on DBR-metasurface-DBR structures, Optics Express, ( ): 11677. doi: 1,018,551.00
09/30/2016	18	Seyedeh Mahsa Kamali, Amir Arbabi, Ehsan Arbabi, Yu Horie, Andrei Faraon. Decoupling optical function and geometrical form using conformal flexible dielectric metasurfaces, Nature Communications, ( ): 11618. doi: 1,018,552.00
09/30/2016	19	Mikael P. Backlund, Amir Arbabi, Petar N. Petrov, Ehsan Arbabi, Saumya Saurabh, Andrei Faraon, W. E. Moerner. Removing orientation-induced localization biases in single-molecule microscopy using a broadband metasurface mask, Nature Photonics, ( ): 459. doi: 1,018,553.00
09/30/2016	20	Ehsan Arbabi, Amir Arbabi, Seyedeh Mahsa Kamali, Yu Horie, Andrei Faraon. Multiwavelength polarization-insensitive lenses based on dielectric metasurfaces with meta-molecules, Optica, ( ): 628. doi: 1,018,554.00

TOTAL: **8**

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

1. Y. Horie, A. Arbabi, and A. Faraon, "Reflective Optical Phase Modulator Based on High-Contrast Grating Mirrors," in CLEO: 2014, OSA Technical Digest (online) (Optical Society of America, 2014), paper STh4M.8.
2. Y. Horie, A. Arbabi, A. Faraon, "On-chip broadband spectral filtering using planar double high-contrast grating reflectors," Proc. SPIE 9372, High Contrast Metastructures IV, 93720O (February 27, 2015); doi:10.1117/12.2080451.
3. Y. Horie, A. Arbabi, A. Faraon, "Guided resonance reflective phase shifters," Proc. SPIE 9372, High Contrast Metastructures IV, 93720W (February 27, 2015); doi:10.1117/12.2077744.
4. Y. Horie, A. Arbabi, E. Arbabi, S. M. Kamali, and A. Faraon, "Active dielectric antenna for phase only spatial light modulation," in Conference on Lasers and Electro-Optics, OSA Technical Digest (2016) (Optical Society of America, 2016), paper STh1E.2.
5. Y. Horie, A. Arbabi, E. Arbabi, S. M. Kamali, and A. Faraon, "Dielectric metasurface narrowband filter array," in Conference on Lasers and Electro-Optics, OSA Technical Digest (2016) (Optical Society of America, 2016), paper STh1E.7.
6. A. Arbabi, Y. Horie, A. J. Ball, M. Bagheri, and A. Faraon, "Efficient high NA flat micro-lenses realized using high contrast transmitarrays," SPIE Photonics West, 2015.
7. A. Arbabi, Y. Horie, M. Bagheri, and A. Faraon, "Highly efficient polarization control using subwavelength high contrast transmitarrays," SPIE Photonics West, 2015.
8. A. Arbabi, Y. Horie, M. Bagheri, and A. Faraon, "Simultaneous and complete control of light polarization and phase using high contrast transmitarrays," Conference on Lasers and Electro-Optics (CLEO), 2015.
9. A. Arbabi, Y. Horie, and A. Faraon, "Planar retroreflector," Conference on Lasers and Electro-Optics (CLEO), 2014.
10. A. Arbabi, M. Bagheri, A. J. Ball, Y. Horie, D. Fattal, and A. Faraon, "Controlling the phase front of optical fiber beams using high contrast metastructures," Conference on Lasers and Electro-Optics (CLEO), 2014

Number of Presentations: 10.00

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

Simultaneous Polarization and Wavefront Control Using a Planar Device
Serial Number: 14/852,450   Filed: 9/11/2015
CIT File Number: 6991
Inventor: Amir Arbabi; Andrei Faraon

EIR: 1073501-14-0084

Image Sensor Including Nanostructure Color Filter
Serial Number: 14/953,569   Filed: 11/30/2015
CIT File Number: 7055
Inventor: Seunghoon Han; Yu Horie; Andrei Faraon; Sungwoo Hwang

EIR: 1073501-14-0097

Aplanatic Metasurface Flat Lens
Serial Number: 62/144,750   Filed: 4/8/2015
CIT File Number: 7156-P
Inventor: Amir Arbabi; Andrei Faraon; Seunghoon Han

EIR: 1073501-15-0029

Multi-Wavelength Optical Dielectric Metasurfaces
Serial Number: 62/147,392   Filed: 4/14/2015
CIT File Number: 7159-P
Inventor: Ehsan Arbabi; Amir Arbabi; Andrei Faraon

EIR: 1073501-15-0030

Conformal Optical Metasurfaces
Serial Number: 62/151,531   Filed: 4/23/2015
CIT File Number: 7167-P
Inventor: Seyedeh Mahsa Kamali; Ehsan Arbabi; Amir Arbabi; Andrei Faraon

EIR: 1073501-15-0034

Thin-Imaging Optics using Nanostructured Thin-Lenses for Optical & Image Sensor Applications
Serial Number: 62/151,108   Filed: 4/22/2015
CIT File Number: 7211-P
Inventor: Seunghoon Han; Amir Arbabi; Sungwoo Hwang; Andrei Faraon; Byoung Lyong Choi; Jang-Woo You

EIR: 1073501-15-0051

Planar Diffractive Device with Diffraction Spectrum Matched to a Specific Target Spectrum
Serial Number: 62/208,447   Filed: 8/21/2015
CIT File Number: 7272-P
Inventor: Andrei Faraon; Amir Arbabi; Yu Horie

EIR: 1073501-15-0095

High Resolution On-Chip Optical Filter Array Based On Double Sub-Wavelength Grating Reflectors
Serial Number: 62/211,535   Filed: 8/28/2015
CIT File Number: 7273-P
Inventor: Yu Horie; Amir Arbabi; Seunghoon Han; Andrei Faraon

EIR: 1073501-16-0008

Compact Planar Metasurface Spectrometer
CIT File Number: CIT 15-193
Inventor: Yu Horie; Amir Arbabi; Seunghoon Han; Andrei Faraon

EIR: 1073501-15-0094

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	DISCIPLINE
Yu Horie	83	
FTE Equivalent:	**0.83**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Amir Arbabi	0.14
FTE Equivalent:	**0.14**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Dr. Andrei Faraon	0.05	
FTE Equivalent:	**0.05**	
Total Number:	**1**	

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
Amir Arbabi	0.23
FTE Equivalent:	**0.23**
Total Number:	**1**

Sub Contractors (DD882)

Inventions (DD882)

5 **Aplanatic Metasurface Flat Lens**

Patent Filed in US? (5d-1) Y
Patent Filed in Foreign Countries? (5d-2) N
Was the assignment forwarded to the contracting officer? (5e) N
Foreign Countries of application (5g-2):

5a: Seunghoon Han

5f-1a:

5f-c:

5a: Andrei Faraon

5f-1a:

5f-c:

5a: Amir Arbabi

5f-1a: California Institute of Technology

5f-c: 1200 East California Blvd

Pasadena CA 91125

5 **Compact Planar Metasurface Spectrometer**

Patent Filed in US? (5d-1) N
Patent Filed in Foreign Countries? (5d-2) N
Was the assignment forwarded to the contracting officer? (5e) N
Foreign Countries of application (5g-2):

5a: Yu Horie

5f-1a:

5f-c:

5a: Andrei Faraon

5f-1a:

5f-c:

5a: Amir Arbabi

5f-1a:

5f-c:

5a: Seunghoon Han

5f-1a:

5f-c:

5 **Conformal Optical Metasurfaces**

Patent Filed in US? (5d-1) N

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Seyedeh Mahsa Kamali

5f-1a: California Institute of Technology

5f-c:

5a: Andrei Faraon

5f-1a:

5f-c:

5a: Amir Arbabi

5f-1a:

5f-c:

5a: Ehsan Arbabi

5f-1a:

5f-c:

5 **High Resolution On-Chip Optical Filter Array Based On Double Sub-Wavelength Grating Reflectors**

Patent Filed in US? (5d-1) N

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Seunghoon Han

5f-1a:

5f-c:

5a: Andrei Faraon

5f-1a:

5f-c:

5a: Amir Arbabi

5f-1a:

5f-c:

5a: Yu Horie

5f-1a:

5f-c:

5 **Image Sensor Including Nanostructure Color Filter**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Seunghoon Han

5f-1a: California Institute of Technology

5f-c: 1200 East California Blvd.

Pasadena CA 91125

5a: Andrei Faraon

5f-1a: California Institute of Technology

5f-c: 1200 East California Blve

Pasadena CA 91125

5a: Sungwoo Hwang

5f-1a:

5f-c:

5a: Yu Horie

5f-1a: California Institute of Technology

5f-c: 1200 East California Blvd

Pasadena CA 91125

5 **Multi-Wavelength Optical Dielectric Metasurfaces**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Andrei Faraon

5f-1a:

5f-c:

5a: Ehsan Arbabi

5f-1a: California Institute of Technology

5f-c: 1200 East California Blvd

Pasadena CA 91125

5a: Amir Arbabi

5f-1a:

5f-c:

5 Planar Diffractive Device with Diffraction Spectrum Matched to a Specific Target Spectrum

Patent Filed in US? (5d-1) N

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Yu Horie

5f-1a:

5f-c:

5a: Andrei Faraon

5f-1a:

5f-c:

5a: Amir Arbabi

5f-1a:

5f-c:

5 Simultaneous Polarization and Wavefront Control Using a Planar Device

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Amir Arbabi

5f-1a: California Institute of Technology

5f-c: 1200 East California Blvd.

Pasadena CA 91125

5a: Andrei Faraon

5f-1a: California Institute of Technology

5f-c: 1200 East California Blvd

Pasadena CA 91125

5 **Thin-Imaging Optics using Nanostructured Thin-Lenses for Optical & Image Sensor Applications**

Patent Filed in US? (5d-1) Y
Patent Filed in Foreign Countries? (5d-2) N
Was the assignment forwarded to the contracting officer? (5e) N
Foreign Countries of application (5g-2):

5a: Byoung Lyong Choi
5f-1a:
5f-c:

5a: Andrei Faraon
5f-1a:
5f-c:

5a: Sunwoo Hwang
5f-1a:
5f-c:

5a: Amir Arbabi
5f-1a: California Institute of Technology
5f-c: 1200 East California Blvd.
Pasadana CA 91125

5a: Seunghoon Han
5f-1a:
5f-c:

5a: Jang-Woo You
5f-1a:
5f-c:

Scientific Progress

See attachement

Technology Transfer

Two inventions were acquired by Samsung Electronics

Final report for proposal W911NF1410345/ARO 66084PHDRP, "Ultra-Slim Device for Focus Scanning in Optical Neural Implant"

A. ABSTRACT

This proposal aims to develop a fast and slim device with the capability to focus light at arbitrary points in a volume on the same order of magnitude as a cortical column, with spatiotemporal resolution that will enable optical addressing in 1ms of all neuronal cell bodies in the volume. Because of the slim form factor, we envision that these devices will be implanted on/under the skull. The main innovation that enables this technology is the recent development of dielectric meta-surfaces (also known as high contrast gratings (HCGs)) that allow for unprecedented control of free-space propagating light. Using this technology, our group has demonstrated micron-thick phase plates (lenses) that can be assembled in sub-millimeter thick optical systems with fast tunable focus. Our group has also demonstrated HCG micron-thick reflectors that can be used in fast tunable phase arrays. We will use this technology to investigate two methods for fast focus scanning in brain tissue.

End project goal/objectives:

- Development and characterization of a planar device based on two HCG phase plates for 3D optical scanning.
- Demonstrate few pixels of a SLPM for arbitrary control of optical phase fronts at ultra fast speeds.

B. RETURN ON INVESTMENT

Number of newly trained scientists in this area: 2
Number of PhD theses initiated based on this work: [1, to be completed in 2017]
Discoveries utilized on other efforts: none
Patents filed: 9
Papers published: 7 (*Nature Nanotechnology, Nature Photonics, Nature Communications, Optica, Optics Express)*
Presentations given: 10
Technology licenses: two of our patents related this seedling were acquired by Samsung Electronics
New companies formed: none
Venture capital: none
Follow-on funding: Part of this technology will be used in a project funded by Samsung. The focus scanning device for brain implants will be funded by NSF.

C. PROGRESS ON THE STATEMENT OF WORK

In this document we report the progress on each task of the statement of work. For clarity, the original tasks proposed in the statement of work are written in blue font and underlined.

Task 1: Development and characterization of a planar device based on two HCG phase plates for 3D optical scanning.

The device will have the following properties:

i. Thickness smaller than 100μm (this is the thickness of the space occupied by the lenses and the distance in between them, and does not include other volume required for packaging, electronics, etc)

ii. The device will be able to focus the light at a depth of ~1mm with a focus spot size on the order of ~10μm×10μm×10μm over a volume greater than 100μm×100μm×100μm at a depth of ~1mm.

iii. Focus scanning will be achieved by moving the two lenses with respect to each other along at least one axis using MEMS, and/or by changing the angle of the incident beam.

iv. The wavelength of operation will be 930nm, which is suitable for two-photon fluorescence imaging of brain tissue using elements labeled with GFP-like markers [1]. Two-photon excitation will be demonstrated in a solution containing GFP.

Approach (Subtasks)

1.1 (months 0-3) *Design the two-lens 3D focus-scanning device.*

Our initial simulations show that by using two phase plates (500 microns in diameter, 10 microns apart) it is possible to scan the focus over a volume of ~$(100\mu m)^3$ while keeping the size of the focal spot at ~$(10\mu m)^3$. The on-axis scanning is achieved by moving one lens by ~±2μm. The in-plane scanning is achieved by laterally displacing the same lens by ~±10μm or by steering the angle of the input beam. These simulations assume ideal phase plates. We will perform simulations to optimize the design so the desired performance is achieved taking into consideration all the parameters for the real device.

Subtask 1.1 has been accomplished. We perfected our design procedure that now uses the Zemax Optic Studio design package. The phase profile of the two optical phase plates has been optimized to ensure that the focal point has a minimal size when the two lenses are displaced with respect to each other. The scanning rate has been increased. While the preliminary demonstrations where we wrote the proposal indicated a scanning range of 100microns around a focal length of 1000microns, new designs allow for 300microns along the z-axis (Figure 1).

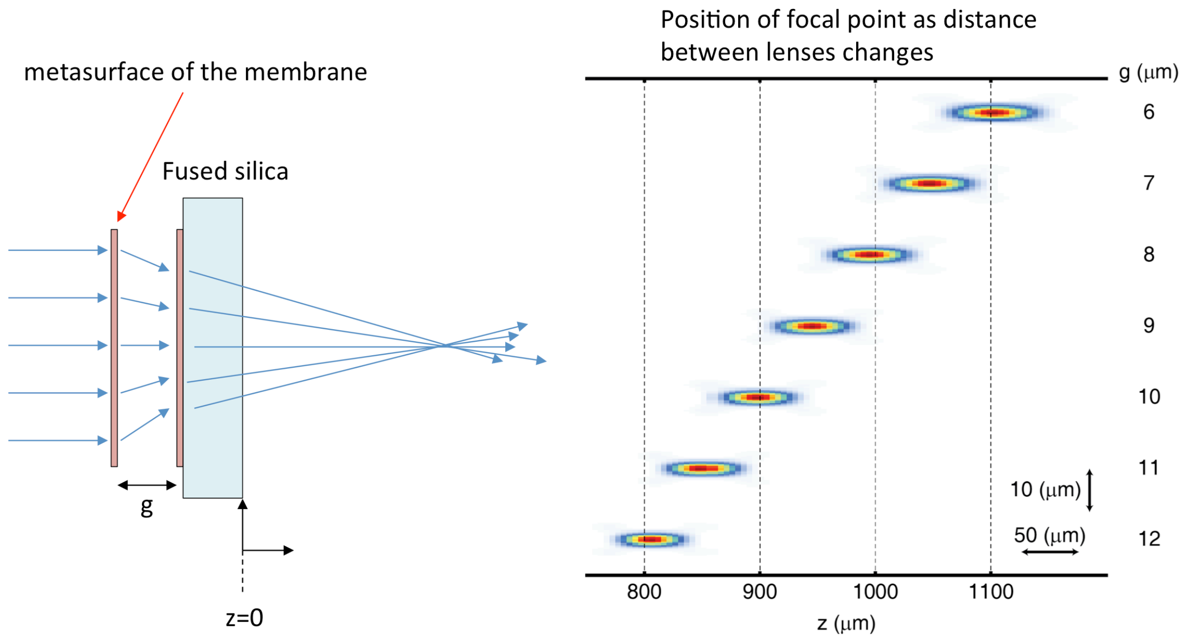

Figure 1 (left) Schematic of the proposed device composed of two metasurface lenses spaced by ~10microns. Changing the distance between the lenses modifies the focal distance of the lens system that allows for scanning of the focal length. (right) simulation with Zemax showing that optimized phase plates allow for changing of the focal length by 300microns.

1.2 (months 3-9) *HCG lens fabrication and optical characterization*

The two lenses will be fabricated separately in amorphous silicon and their optical properties will be characterized and compared to simulations. Each lens will be mounted on a xyz stage with piezoelectric actuation, and scanning of the focal point over the proposed volume will be demonstrated (no speed specification).

Subtask 1.2 has mostly been accomplished. We demonstrated diffraction limited lenses operating at 915nm (Figure 2). Various types of lenses and other phase masks are discussed in our manuscripts published in *Nature Nanotechnology[2]* and *Nature Communications[3]* (Figure 3). We decided not to do anymore the scanning of the focal point with piezoelectric actuation because of the tedious alignment procedure of the two lenses using the x-y-z stage. Instead we decided to move to the next task where the lenses are integrated in a focus-scanning device and thus are very well aligned using cleanroom fabrication techniques.

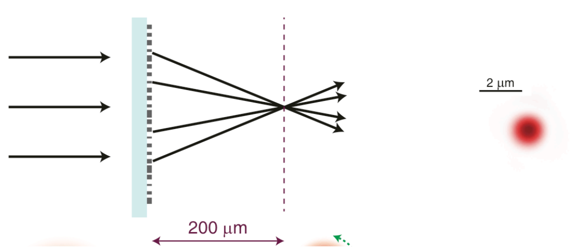

Figure 2 (left) Schematic of a metasurface lens focusing at a focal length of 200 microns. (b) Measured diffraction limited focusing of 915nm light.

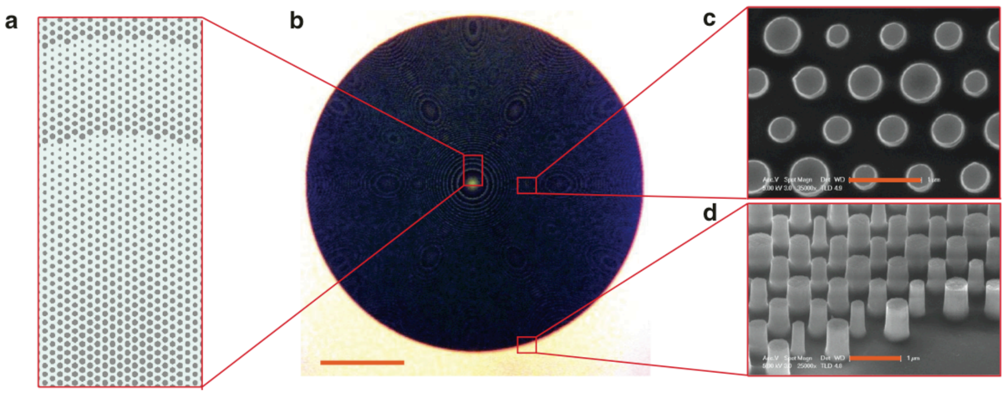

Figure 3 (a) Schematic of the lattice of silicon posts forming the lens (b) Optical microscope image of the lens. (c,d) Scanning electron microscope images of the silicon nanoposts.

1.3 (months 9-18) *Integration of the two lenses in a MEMS device*

The two lenses will be integrated in a MEMS device so the distance between them can be modified using an applied voltage. The device will have the capability to scan over the proposed volume. We expect a scan speed of at least 1kHz in each direction (axial and in-plane). State of the art MEMS devices based on dielectric meta-surfaces have achieved MHz speed so a similar frequency response is expected from more advanced versions of this two-lens device [4].

We demonstrated bonding of the substrates that hold the lenses. As described in our proposal, one lens will be located on a glass substrate while the other lens will be located on a suspended silicon nitride membrane that can be actuated. In Figure 4 we show pictures of the silicon nitride (squares with sides of 400 microns).

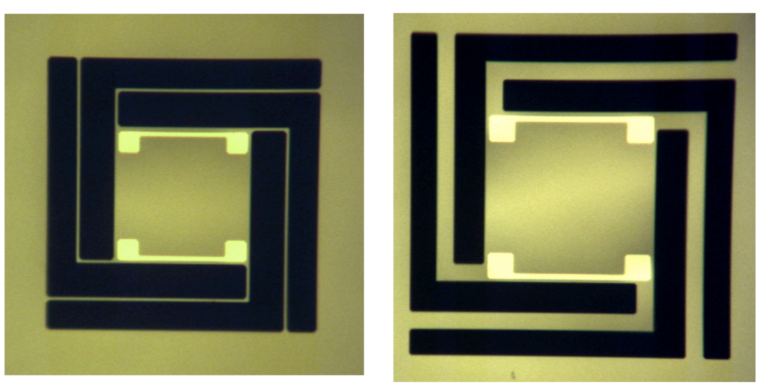

Figure 4 Pictures of the Silicon Nitride membranes that will hold the metasurface lenses. The membranes are equipped with electrodes used to actuate the membranes.

We demonstrated electric actuation of the membrane that will hold the movable lens.

The project encountered difficulties at the step where we had to create movable membranes holding metasurface lenses. The main problem relates to cracking and buckling of the membranes.

1.4 (months 6-18) *Demonstrate two-photon excitation.*

In this subtask we verify that HCG lenses can be used to focus near-infrared light for two-photon microscopy. We will build a microscope setup for two-photon imaging in a liquid solution containing GFP. For this experiment, only the illumination will be done via the HCG lens while the fluorescence will be collected using a conventional lens.

We tested single metasurface lenses inside a fluorescent solution and we already demonstrated that they can be used for two photon excitation. This is shown in Figure 5, where a fluorescent solution has been used to demonstrate two-photon excitation.

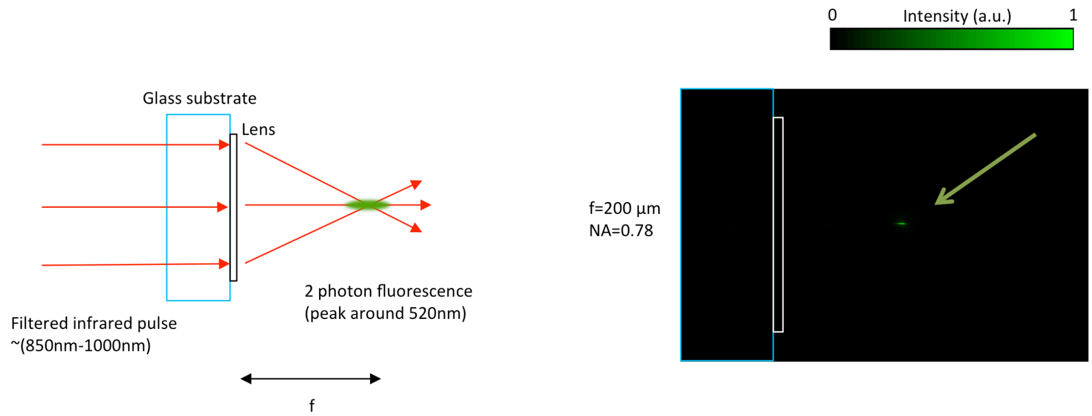

Figure 5 (left) Schematic of the lens that focuses infrared pulses and excites two photon fluorescence in the focal spot (right) Experimental data showing two photon signal at the focal point of the lens (green dot pointed by the arrow). The data was taken by exciting with a Ti:Sapphire laser and focusing in a fluorescent solution.

Task 2: Demonstrate few pixels of a SLPM for arbitrary control of optical phase-fronts at ultra-fast speeds.

We will fabricate and then demonstrate control of at least four SLPM pixels. Each pixel of the SLPM is a reflective Gires-Turneau interferometer (GTI) composed of a HCG mirror located on top of a DBR mirror. We will fabricate devices out of Si and GaAs/AlAs with operation at ~1550nm. The performance of the device will be quantified by analyzing the interference pattern from the four pixels. We expect modulation speeds of at least 100MHz.

Approach (Subtasks)

2.1 (months 0-3) *Device design for all optoelectronic SLPM*

In this subtask we will design the structure consisting of a DBR stack and a top HCG mirror. The DBR will be a GaAs/AlAs stack grown via molecular beam epitaxy. The HCG mirror will be made out of silicon because the fabrication procedure is well established and its index of refraction can be tuned easily using carrier injection.

Subtask 2.1 has been accomplished. Instead of a GaAs/AlAs DBR stack we chose an all-dielectric (SiO_2/TiO_2) DBR stack that we bought directly from Advanced Thin Films Inc. (Figure 6). These are the DBR mirrors with the highest reflectivity available and this is why we decided to go on this route. The HCG is designed to be fabricated out of crystalline silicon.

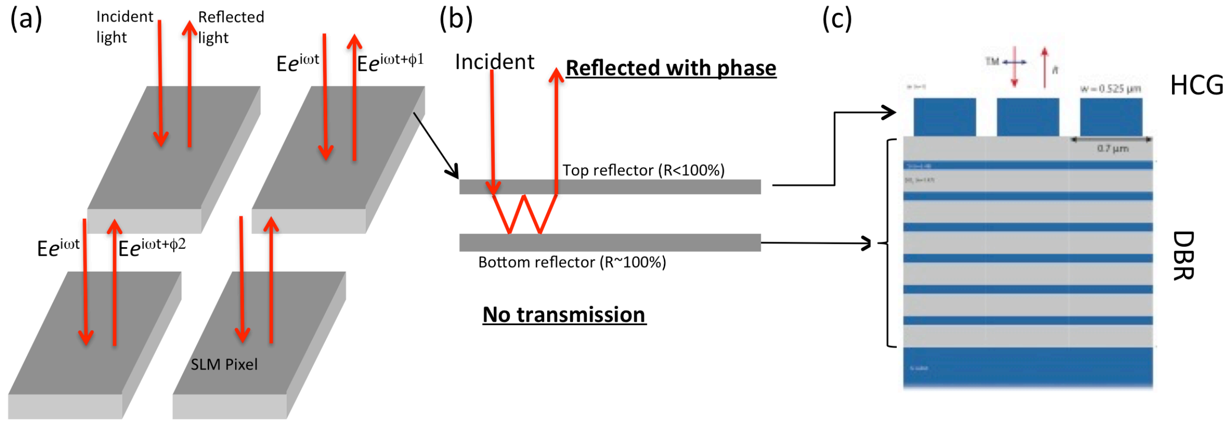

Figure 6 (a) Schematic of GTI spatial light phase modulator (SLPM) composed of one-sided resonators. (b) Due to the assymetric design of the resonaotor light just gets reflected with the acquired phase. (c) GTI design with a high reflectivity DBR and a high contrast grating reflector on top.

2.2 (months 3-6) *Fabrication of HCG with high reflectivity*

In this subtask we will develop the fabrication procedure for high contrast gratings with high reflectivity. Our target reflectivity is 99.9%. The reflectivity will be measured by integrating the HCG mirrors into a Fabry-Perot cavity and measuring the finesse.

Subtask 2.2 has been accomplished. We fabricated Fabry-Perot resonators composed of two high contrast grating reflectors separated by a distance less than a micron Figure 7. We measured quality factors as high as Q~3000, which correspond to mirror reflectivities of ~99.9. The transmission of a set of such filters is shown in Figure 7(d)

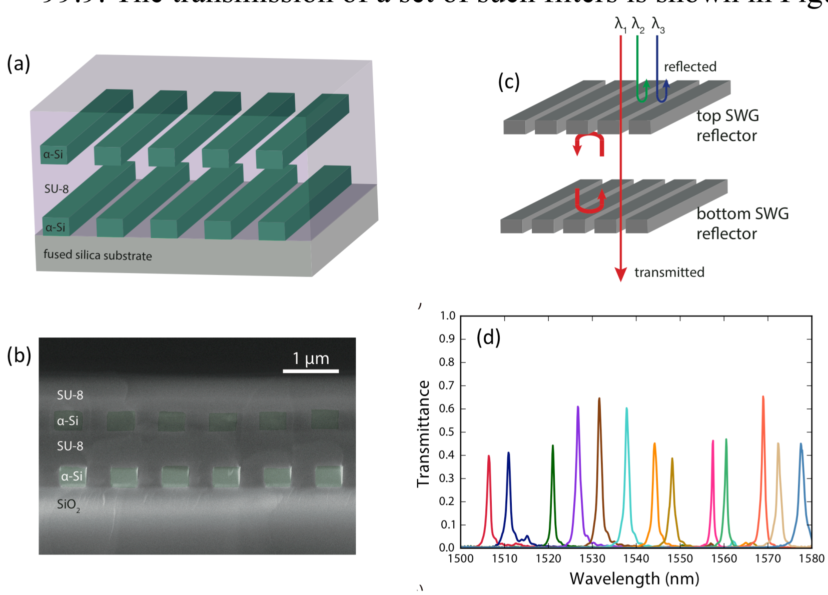

Figure 7 (a) Fabry-Perot resonator composed of two amorphous silicon high contrast gratings embedded in SU-8 polymer. (b) Cross section of the fabricated structure. (c) Schematic of the measurement. Only one wavelength (λ_1) that corresponds to the Fabry-Perot resonance is transmitted by the resonator. (d) Measurement results showing resonances with quality factor ranging from 1000 to 3000.

2.3 (months 6-15) *GTI fabrication and measurement.*

In this subtask we will fabricate a high Q (1000-10000) GTI resonator integrating a HCG mirror on top of a DBR stack. The HCG will be integrated with p-i-n junctions and electrodes. The GTI resonance will be tuned using carrier injection. This will enable full 2π phase modulation that is electrically controlled. We expect speeds exceeding 100MHz with prospects of achieving 1GHz.

We demonstrated high Q GTI devices that provide a full 2π phase shift across a resonance with a quality factor Q~1000 while maintaining a reflectivity larger than 75% (Figure 8). The device is formed from a high contrast grating located on top of the high reflectivity DBR stack from Advanced Thin Films.

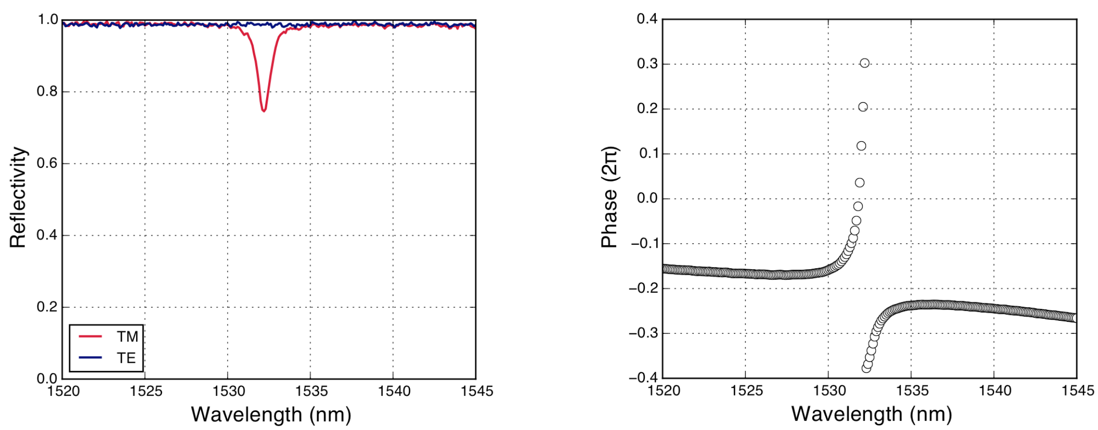

Figure 8 (left) Reflectivity spectrum showing that the reflected light is higher than 75% across the GTI resonance for the TM mode. The TE mode exhibits flat unity reflectivity. (right) Phase approaching a full 2pi across the GTI resonance.

Using thermal modulation, we were able to modulate the phase of light reflected from single pixel devices. The a scanning electron microscope image of the device is shown in Figure 9 (a). The heater is made of Ni/Cr and the contacts are made of gold. The shift of the resonance as a function of the applied power is shown in Figure 9 (b,c). The change in phase from the device was measured using a cross-polarized setup, and the results are shown in Figure 10 (left). A change in phase of 1.2pi is schieved.

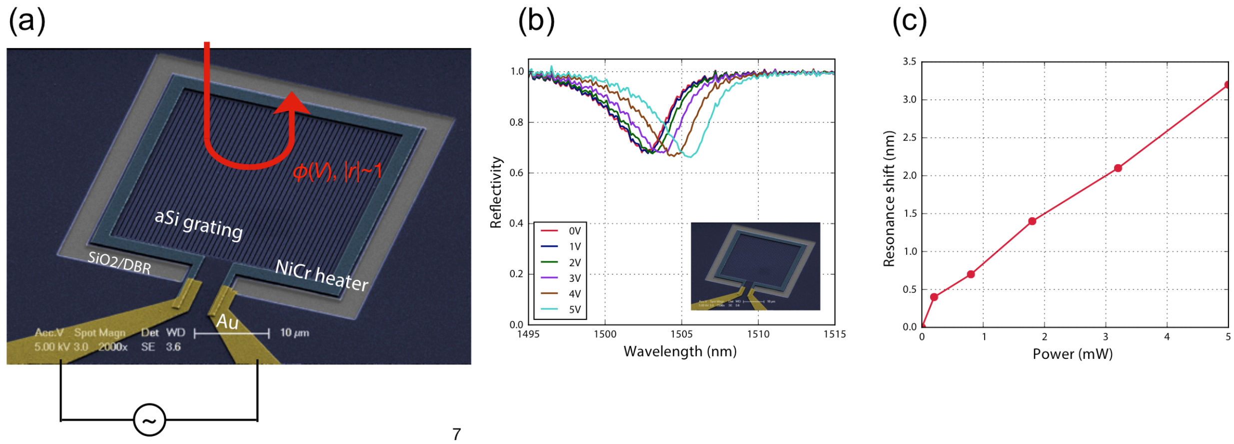

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Figure 9 (a) Image of a single pixel device with thermal heater. (b) Reflectivity of a single pixel device, showing how the resonance shifts with applied voltage across the heater. (c) Resonance shift versus heating power.

The temporal response of the device is shown in in Figure 10 (right). The temporal response varies from 5ms for devices with dimension of 60x60microns to 20ms for devices with dimensions of 120x120microns. As expected, the temporal response scales with the device area.

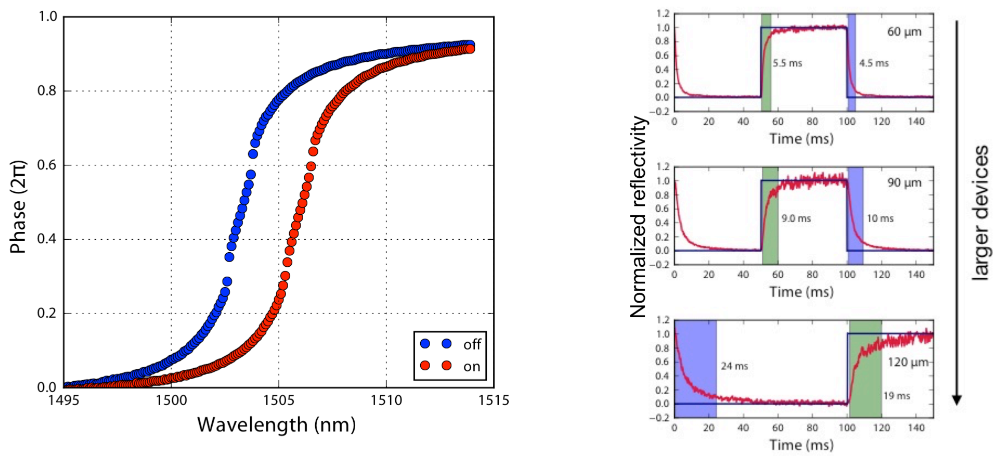

Figure 10 (left) Change in the phase of the reflected light by applying a bias voltage on the device. (right) Temporal response of the device as a function of the device size. The thermal response time changes from ~5ms for devices with 60 microns in lateral dimension to ~20ms for devices with 120um in lateral dimensions.

2.4 (months 12-18) *Demonstration and testing of a four-pixel device*

In this subtask we will demonstrate at least a four-pixel device where the pixels are controlled electronically by biasing p-i-n junctions at a speed exceeding 100MHz. As a proof of concept demonstration, the device will be used for beam steering.

This aim was not completed as the funding ended before we could start working on it.

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