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Chestnut Hill, MA 02467

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Forward deployed military units have a critical need for a robust, low cost, easy to use diagnostic system providing real-time, quantitative, and multiplex capability of identifying biomarkers for infectious disease, including tuberculosis. This is a project to develop a new diagnostic device for detection of the tuberculosis biomarker lipoarabinomannan based on a novel "plasmonic halo" effect. In the initial stage, various halo nanodevices using a set of chosen metals and dielectrics were fabricated, and their plasmonic-optical response / sensitivity characterized. A major finding was that bulls-eye halos are significantly more responsive than standard devices, with sensitivities above 100 nm/RIU (refractive index unit). Moreover, incorporation of inorganic quantum dots has shown promise for enhancing sensitivity further.

15. SUBJECT TERMS
Plasmonics, Biomarker, Quantum Dot, Biosensor, Finite Element Modeling, Bioassay, Index of Refraction

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1. INTRODUCTION

There is an acute, unmet need for low cost, rapid detection of tuberculosis, as well as biomarkers of other diseases and pathogens, in a broad range of health care applications, including routine point of care (PoC) clinical evaluation, real time diagnosis and detection of infectious disease in military personnel. A critical aspect of recognizing and controlling tuberculosis in military personnel, and in future epidemics, relies on the development of such diagnostics that can be quickly deployed at multiple sites. The current project aims to develop a diagnostic device for active tuberculosis via detection of TB-specific biomarkers, such as lipoarabinomannan (LAM). In the short term, the technology will provide a rapid assay for PoC detection of tuberculosis in urine, with future goals of detecting biomarkers in blood and breath. In the long term, the developed assay will be applied to a range of infectious and noninfectious human diseases, potentially including cancer.

2. KEYWORDS

Plasmonics; Biomarker; Lipoarabinomannan; Quantum Dot; Biosensor; Sensitivity; Functionalize; Spectroscopy; Nanofabrication; Metal Nanoparticle; Plasmon-enhanced; Materials optimization; Photolithography; Electron microscopy; Finite Element Modeling; Bioassay; Index of Refraction

3. ACCOMPLISHMENTS

Major goals of the project:

The main goal of the project is to develop a device that can quantitatively and with high sensitivity detect the presence of TB-specific biomarkers in solution (*i.e.,* urine) in a compact, plasmonic halo device. The specific concept is that the optical (UV-Vis) responses of these specific biomarkers will be characterized in advance, and then plasmonic halo drumhead devices will be custom designed and fabricated based on those response characteristics. Upon narrow-band illumination at or near an absorption peak of the target molecule or tethered light absorber/emitter, with that molecule resident in the near electromagnetic field of the drumhead surface, a readily detectable change in the transmission intensity arises. This change, corresponding to the presence of the target biomarker, is detected via a change in photocurrent in a proximate photodiode. The general concept is that this scheme can be applied to a wide range of disease biomarkers, in addition to tuberculosis. High specificity for such a device is provided by matching the drumhead halo structure's resonant mode(s) with the target biomarker's absorption peak(s), while high sensitivity is aided by the extreme sensitivity of photodiode detectors. As individual drumhead devices are only a few micrometers in size, the scheme is readily amenable to multiplexing, such that combinatorial analysis (multiple absorption peaks toward fingerprinting an individual target simultaneous to multiple molecular targets) is straightforward.

Specific Aims:

Aim 1: Select molecular targets
– Milestone 1a: Identify candidate biomarkers from a pool of emerging TB antigens, including LAM, ESAT6 and CFP10. LAM antigen has been chosen. (month 3; 100% complete)
– Milestone 1b: Identify at least two anti-LAM antibodies from a pool of commercially-available monoclonal- and polyclonal- specific LAM antibodies. We have identified NR-13811 and NR-13812 monoclonal anti-mycobacterium tuberculosis LAM, Clone CS-35 (produced *in vitro*). (month 5; 100% complete)
– Milestone 1c. Confirm sensitivity and specificity of anti-LAM antibodies on metal-attached surfaces via conventional SPR. (month 8, 25% complete)
Aim 2: Simulate/model response of plasmonic halos
– Milestone 2a. Complete 2nd generation halo computer models. (month 12, 100% complete)
– Milestone 2b. Complete prototype portable light source & light detector that could be used for halo measurements. (month 15, 25% complete)
Aim 3: Fabricate plasmonic halo structures
– Milestone 3. Demonstrate proof-of-concept of halo-based detection of TB antigen above antigen-free control sufficient to warrant further development. (month 17; 0% complete)

Major Activities and Significant Results

In this reporting period, the project team modeled, made and measured a series of plasmonic halo devices in terms of their optical response in the presence of proxy biological targets. That is, we ventured to optimize the halo structures by characterizing their performance when biofunctionalized with known analytes and antigens, with the anticipation of transferring to TB-LAM as the molecular target once the detection scheme has been finalized.

In terms of modeling, we used the Finite Element Method COMSOL to model/simulate the response of a halo structure to incident light without and with a biological target attached to the halo structure metal surface. To this end, we experimented with the 'standard' drumhead halo, and a modified 'bulls-eye' structure that simulations suggest can be significantly more responsive (sensitive) to small changes in dielectric environment caused by specific binding of target molecules. This bulls-eye structure was then fabricated, characterized and tested.

An example of a particular bulls-eye plasmonic halo structure is shown below in Figure 1, in four different views: an electron microscope image (SEM), a COMSOL simulation of the electric field due to plasmonic interactions along with metal surfaces, and atomic force microscope (AFM) image of the structure, and an optical microscopic image.

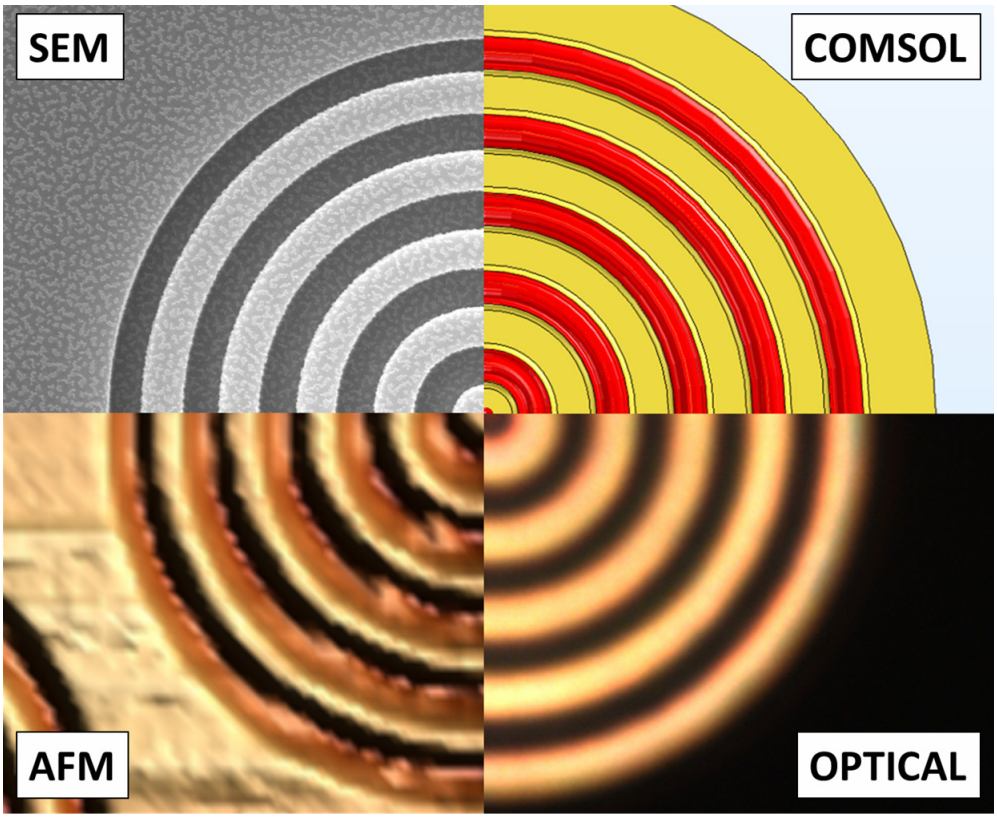


Figure 1. 'Bulls-eye' plasmonic halo structure displayed four ways. The overall diameter is approximately 10 μm.

Figures 2 and 3 below show views of COMSOL results that both depict the 3-D structure of the bulls-eye architecture and the presence of surface plasmons along the metal surfaces (plotted as power loss density), when illuminated from below with light.

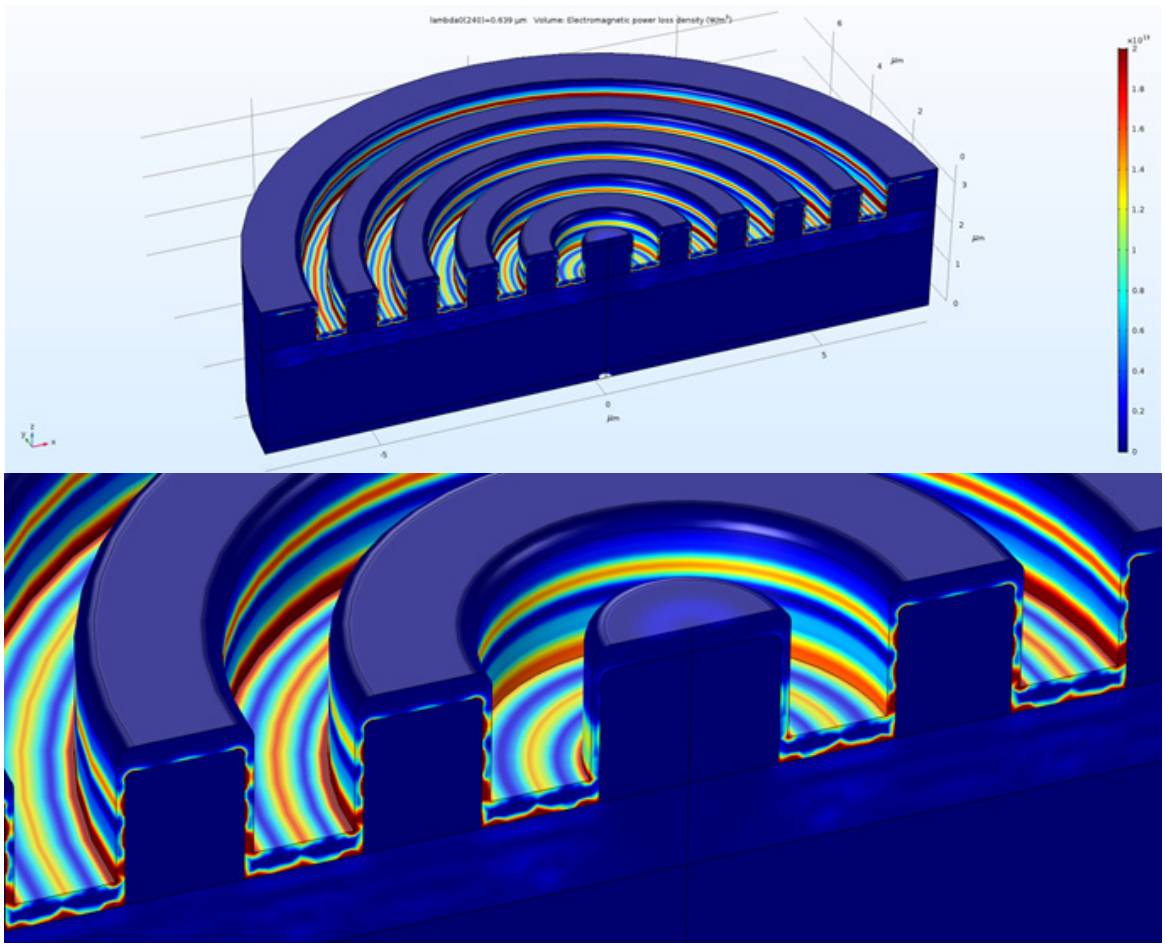


Figure 2. Computer simulation (COMSOL) of power loss density (transmitted electric field) in a 'bulls-eye' plasmonic halo structure. Both the width of each bulls-eye ring and the separation gap between neighboring rings is set to 650 nm. Surface plasmon resonances can be seen as standing waves along the metal (Au) surfaces.

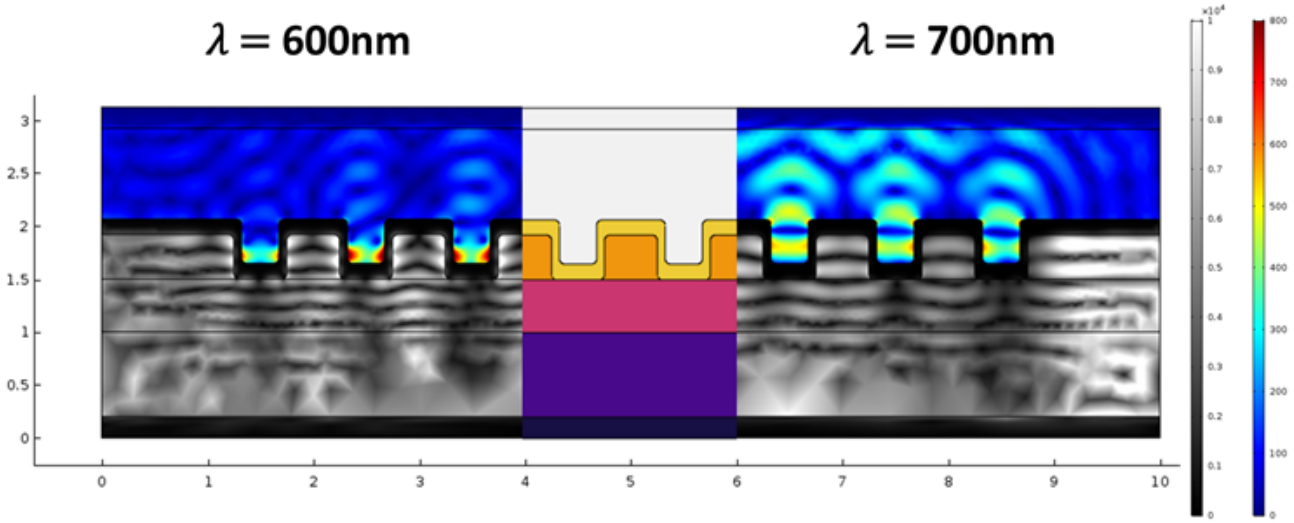


Figure 3. COMSOL images that provide additional insight into the workings of the bulls-eye halo. Cross-sectional plot showing normalized *E*-field for 600 nm (left) and 700 nm (right) incident light, and material domain (middle).

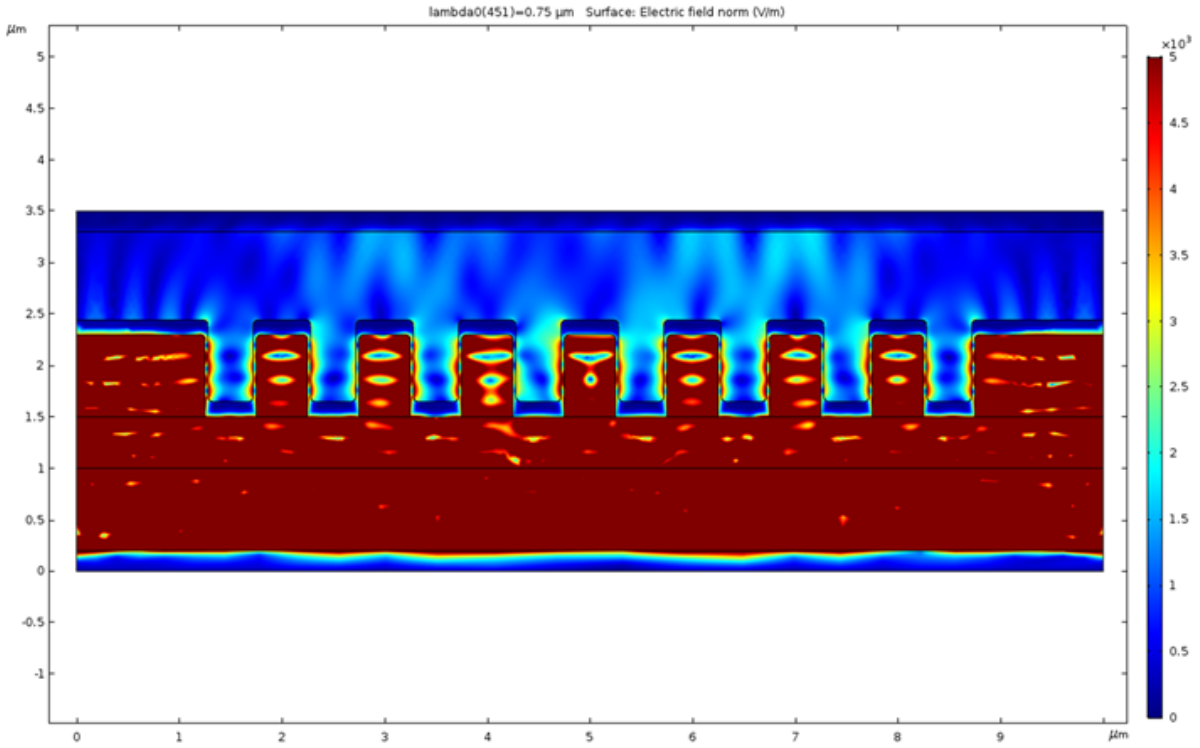


Figure 4. COMSOL image of a bulls-eye structure showing far field transmittance through the concentric rings, where the metal film thickness on the (vertical) walls is 20% that of the (horizontal) rinds bases. This sidewall thickness is an important design parameter in the development of the device as a sensor.

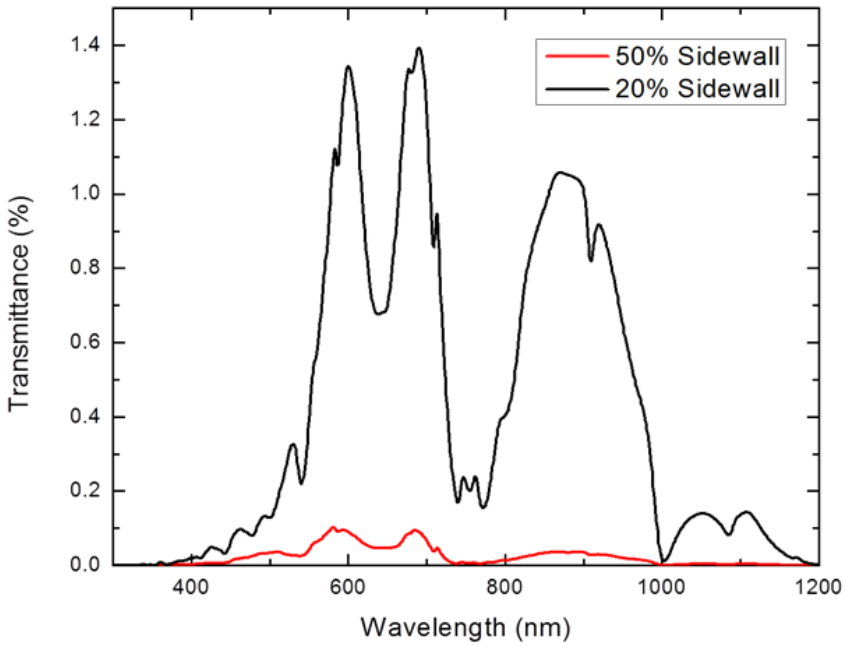


Figure 5. COMSOL results of transmittance through the structure in Figure 4, for two difference sidewall-to-base thickness ratios, showing the aforementioned role of that wall thickness in facilitating light leakage and subsequent plasmonic resonance activity.

Figure 6 below shows a schematic of the architecture of the bulls-eye device, along with an SEM and two optical images of fabricated devices, the latter under the conduction of backside illumination with white light. The colors seen transmitting through as concentric "halos" are due to plasmonic interactions on the bulls-eye metal surfaces, the core physics of the intended biosensing action.

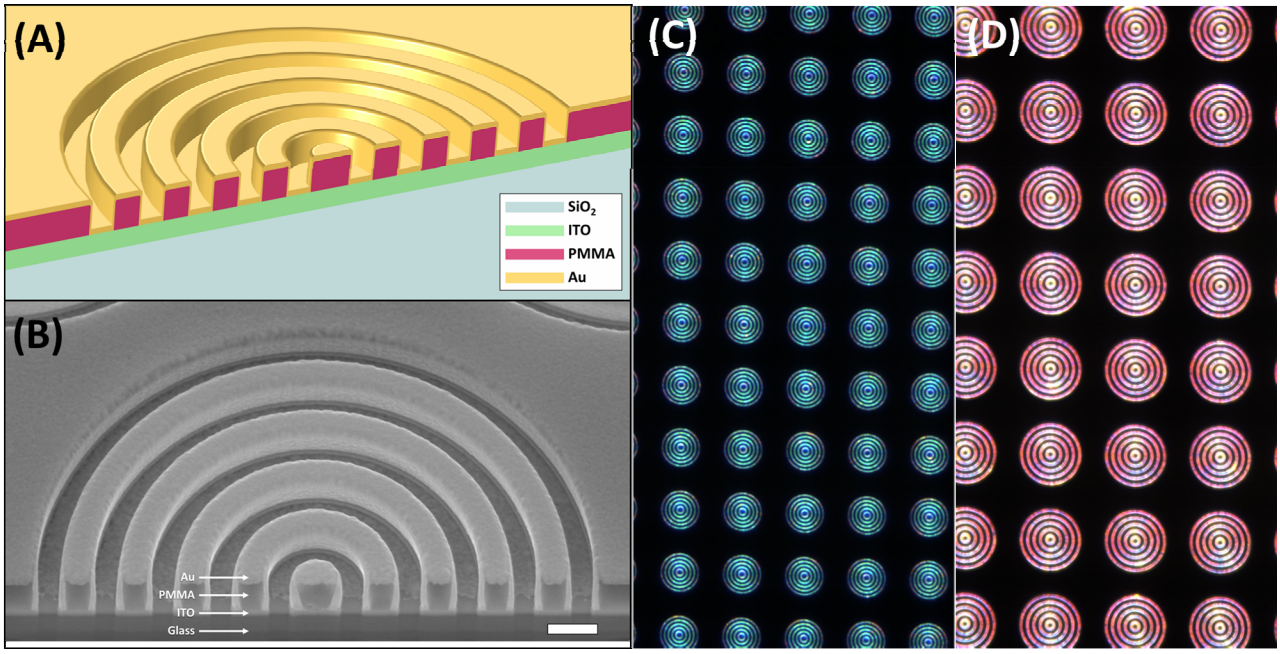


Figure 6. 'Bulls-eye' plasmonic halo structure. (A) Cut-out schematic showing both the structure and the material composition. (B) Tilted view SEM image of a focused ion beam (FIB)-cut bulls-eye, showing actual structure and materials. Scale bar: 1 μm. (C) and (D) Optical micrographs of light transmitted through two bulls-eye halo arrays, each having different ring pitch and width (*i.e.* 400 nm for C and 675 nm for D).

After using modeling to predict and optimize the halo device structure and performance, we fabricated and tested devices under dry and biologically-relevant conditions. Figure 7 shows representative data for a series of devices, where the bulls-eye gap size was systematically varied, and the resulting optical transmittance recorded. The purpose of this study was to identify the dominant/characteristic absorbance and transmittance features resulting from plasmonic interactions, toward identification of size structures that optimize sensitivity.

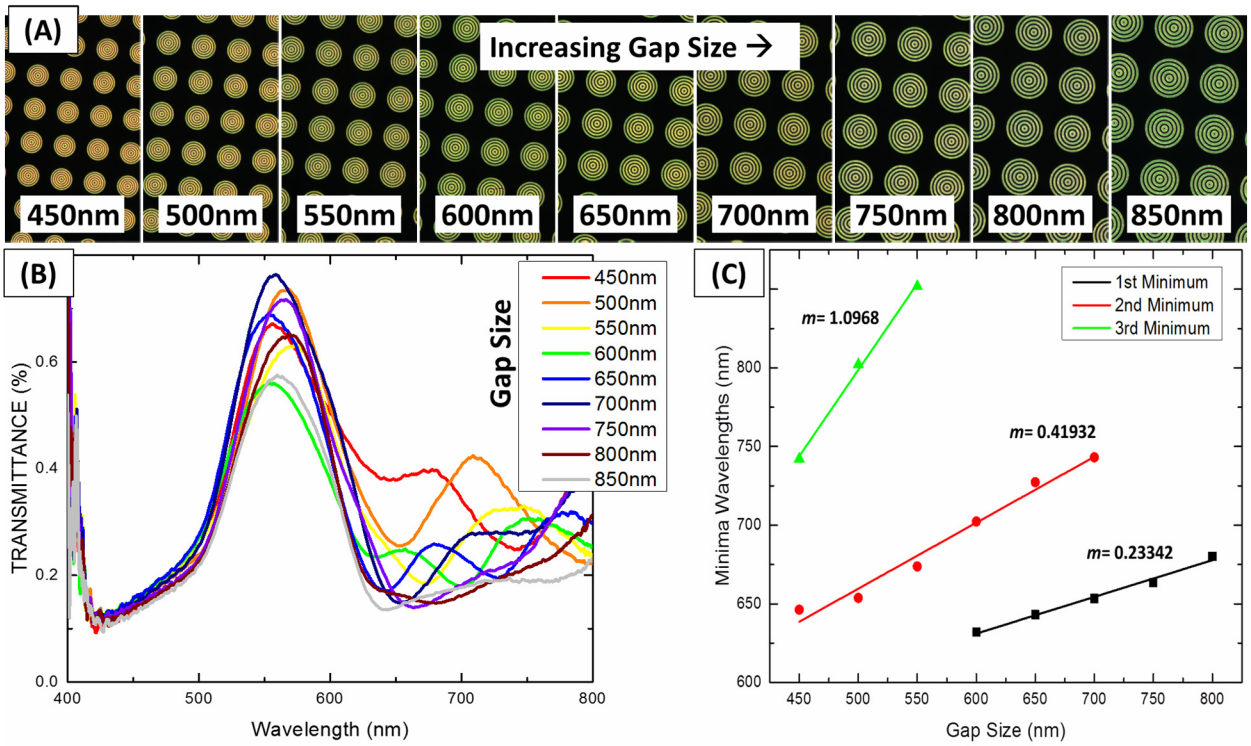


Figure 7. Varying feature size of bulls-eye plasmonic halo structure. (A) Measured transmitted light through bulls-eye arrays with varying gap sizes indicated. (B) Transmittance spectra of samples in A. (C) Wavelengths of sequential minima in transmittances showing systematic characteristics.

For further characterization of sensitivity with respect to changes in index of refraction of the medium along the plasmonically-active surfaces (i.e. the base and side-walls as shown in several figures above), the structure in Figure 7 with the 650 nm gap size was selected. Then, a particular transmittance feature (a local maximum) was monitored as the liquid medium was systematically varied. This variation led to a systematic variation of the refraction index. As such, a sensitivity in units of peak wavelength change per refractive index unit (RIU) could be calculated. Figure 8 below shows a representative plot.

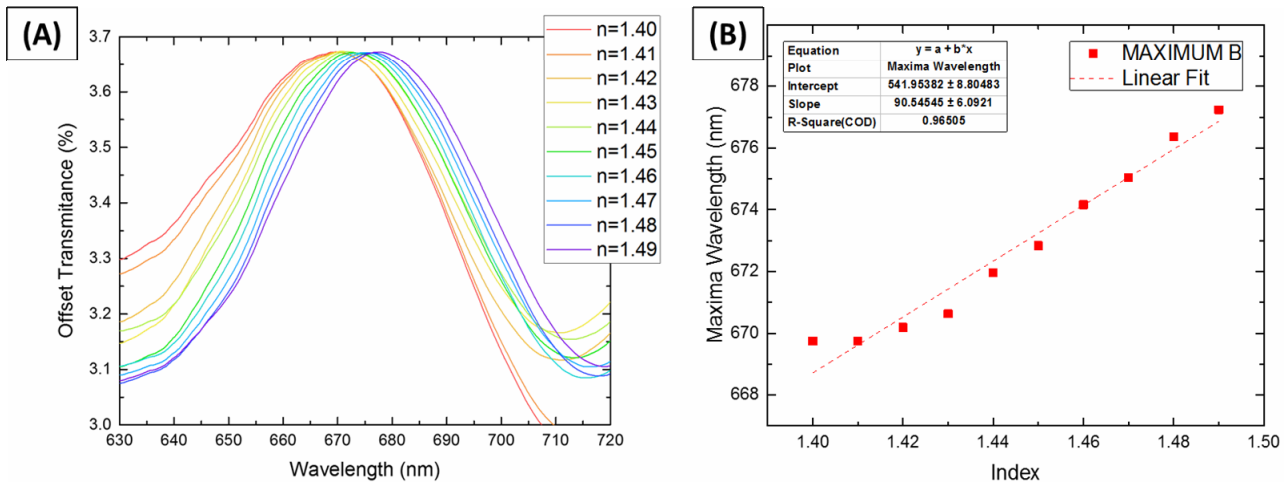


Figure 8. Y-axis shifted transmittance maxima of 650 nm gap bulls-eye sample for different refractive index immersions. (B) Plot of maximum wavelength vs RIU. The slope is a common value of sensitivity used in literature, here ~100 nm/RIU.

Our ability to scale the bulls-eye plasmonic halo device is demonstrated below. Wafer-scale arrays have been fabricated using readily-available lithographic tools. The performance of one array (change in transmitted light dry versus immersed in water) is also shown.

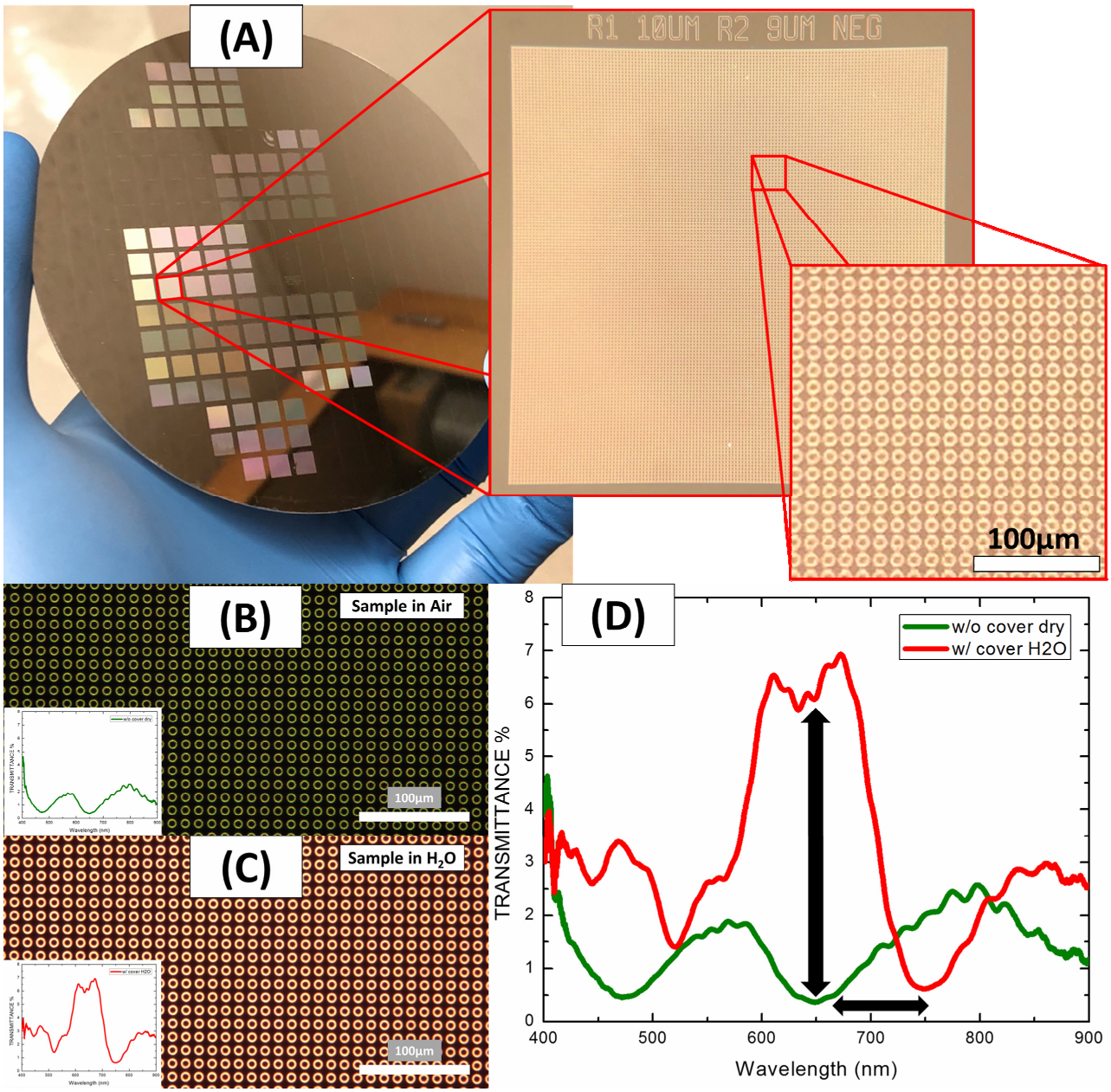


Figure 9. (A) Optical images of illuminated light with insets of higher magnifications. Devices fabricated via photolithography. (B) Transmitted light image of region in air with inset spectrum. (C) Transmitted light image of region in DI-H2O with inset spectrum. (D) Comparison of transmission spectra, showing sensitivity of the architecture.

Preliminary Conclusions

While we feel we have our modeling, device fabrication, bioconjugation chemistry, and biological and optical measurement capabilities well under control, we are not yet fully satisfied with the performance of our devices. We have identified two main issues with which we intend to contend and improve upon. One is in regard to absolute optical transmittance. On the one hand, we desire strong transmission of "leaked" light - that is, the light that passes into the far field, through the vertical walls of the halo structure, after being modified by the excitation of surface plasmons. On the other, we desire strong interaction of incident light with the plasmonically-active metal surfaces within the drumhead / bulls-eye structures, which naturally reduces the intensity of the leaked light. This is one reason we conceived of and introduced the bulls-eye architecture: to simultaneously increase both surface interaction and transmitted light. As such, we are concentrating on this modified architecture for the remaining project period. The second issue has to do with the proportional change in transmitted light resulting from the change in surface plasmonic absorbance due to the presence of target biomolecules. This, in part, boils down to how large a change in refractive index is generated by the presence of captured target molecules.

To remind, the core idea is that (resonant) standing waves of plasmons are wavelength-shifted when target molecules (e.g. TB-LAM) are captured onto the halo structure surface in such a way as to be resident in the significantly enhanced electric field provided by the localized plasmon. Thus, even though the dielectric constant of the captured entity may differ only slightly from its ambient medium, the difference is amplified. This indeed occurs, and is measurable, but we believe we can do significantly better than current performance results. To this end, we have introduced a modified "sandwich" capture method, using the same device structure and same detection method (*i.e.*, using a primary "capturing" target antibody), but now with the addition of a quantum dot (QD) that is tethered to a secondary "detecting" antibody. With this configuration, we may be able to excite the structure (i.e. the plasmon) with monochromatic light (from e.g. a laser or LED), with its wavelength chosen to match the QD absorption spectrum. With the tethered QD well within the near electromagnetic field of the plasmon, which will only occur when a target antigen is captured, its emission intensity will be amplified, and readily detected. A schematic of this scheme is shown below. Notably, we will pursue this approach in parallel with our standard approach, within the time and funds aspects of the project.

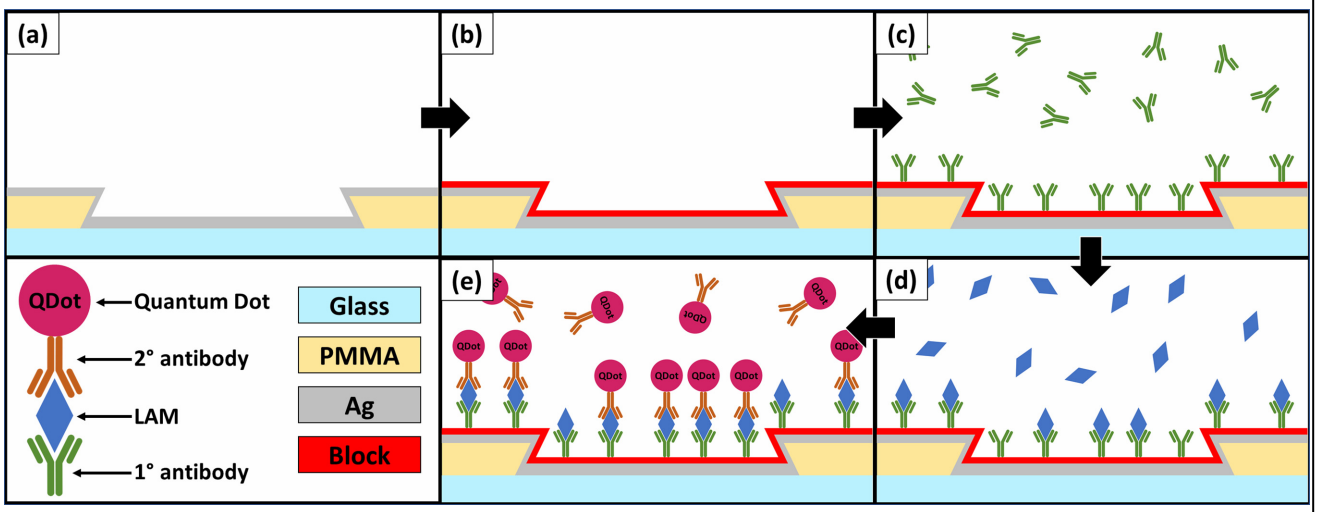


Figure 10. (a) Halo cross-section schematic. (b) Application of blocking layer for chemical protection of the Ag surface from physiological liquids. (c) Functionalize surface with conjugated primary antibody to target antigen. (d) Flow antigen-containing fluid. (e) Flow secondary antibody conjugate with a QD that will interact with plasmon for achieving sensitivities not possible with antigen alone.

Toward this modified capture scheme, we tested the ability to bind biofunctionalized nanoparticles (NPs) to our bulls-eye structures. We used Au NPs as a first step, which was successful, as shown below, where we back-illuminated (as per usual) with broadband (white) light, and recorded the transmittance spectrum. A particular absorbance peak (transmittance dip) was identified to gauge the effect of the NPs in the plasmon field.

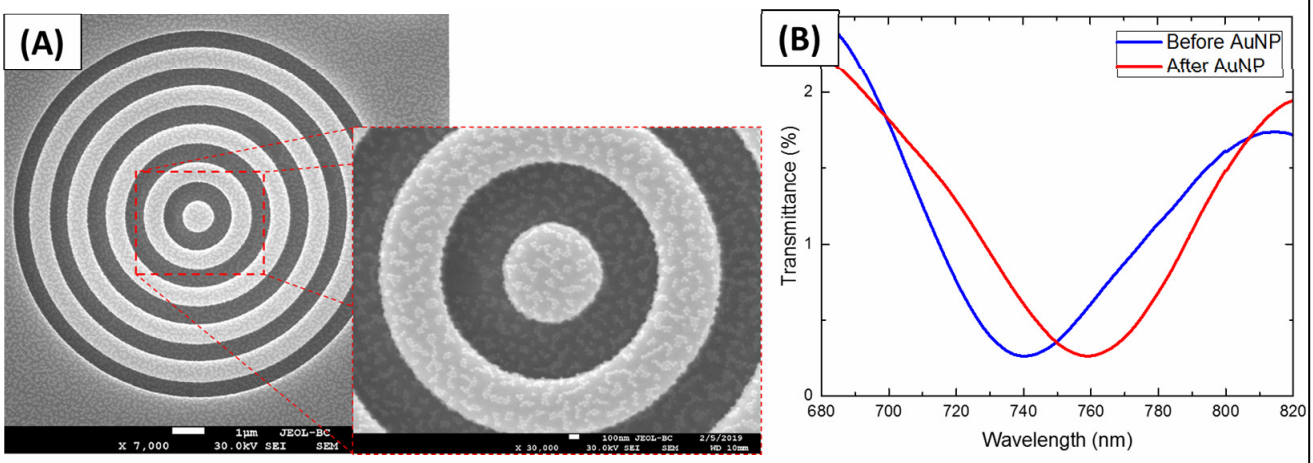


Figure 11. (A) Top-down SEM (1 μm scale bar) with inset showing thiolated-Au NPs (bright dots, some in small clusters) bound to bulls-eye surface. (B) Before and after transmittance near a 750 nm minimum, with shift observed due to addition of AuNPs.

We followed this test with one incorporating biofunctionalized QDs, in this case ~ 20 nm diameter CdSe@ZnS core-shell dots (ThermoFisher) that emit near 625 nm. We excited the bulls-eye with a 405 nm LED, and recorded the resulting emission. The data shown below suggest this is a promising route to plasmonic halo biosensing.

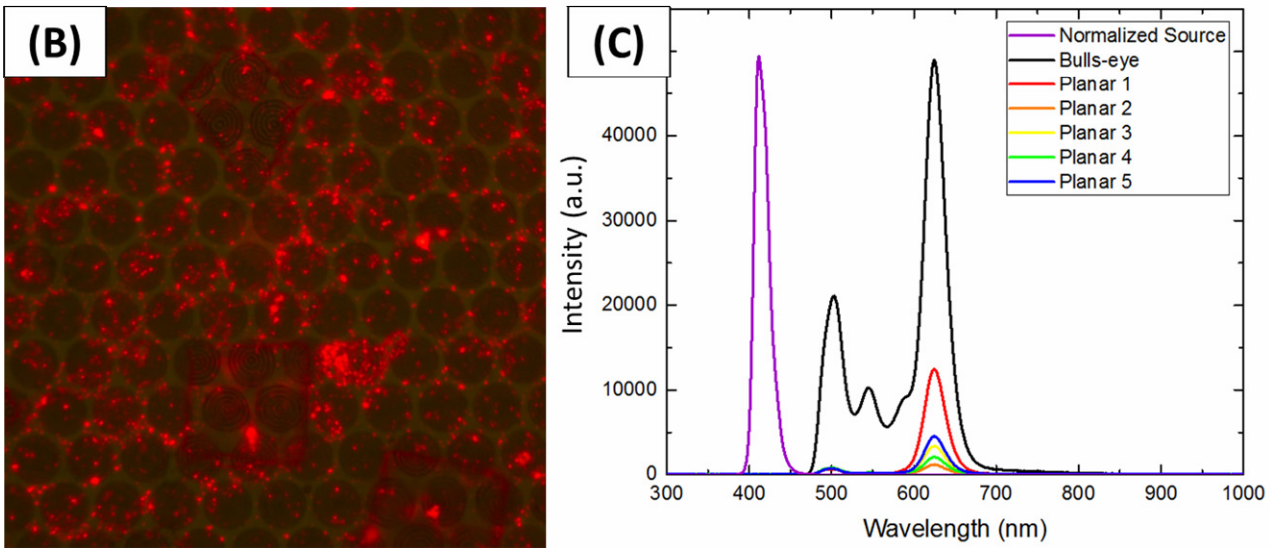


Figure 12. (B) Top-side optical image showing the presence and distribution of QDs on top of (faintly visible) bulls-eye array. (C) Intensity of transmitted light through this bulls-eye array and comparison to 5 planar regions containing no bulls-eyes.

Opportunities for training and professional development the project has provided

An undergraduate student had the opportunity to develop extensive experience through involvement in this research, including training on scientific equipment (BioNavis SPR system), conducting experiments, preparing and presenting experimental results, and studying related materials in both physics and biology. The training and professional development for graduate students involved was also extensive. These opportunities included the advising of undergraduate research activities, advancing software skills in data analysis and computer modeling, proposing and presenting design of experiments, directing and executing of experiments, designing and producing samples using an array of state-of-art cleanroom technologies, disseminating research at national scientific conferences, and preparing results to publish to the broader scientific community.

How results were disseminated to communities of interest

– Contributed talk by Boston College graduate student Luke D'Imperio at the APS (American Physical Society) March meeting in Boston, March 5, 2019 "Plasmonic Halos Towards Molecular Sensing of Disease Biomarkers" in *Session H23: Physics in Medicine: Imaging, Therapy, and Disruptions on the Horizon*, coauthors Juan M. Merlo, Chaobin Yang, Yitzi M. Calm, Megi Maci, Michael J. Burns, Timothy Connolly, Thomas C. Chiles, Michael J. Naughton. *https://meetings.aps.org/Meeting/MAR19/Session/H23.5*
– Laboratory visit to Naughton Lab by 20 (nonscience major) undergraduate students in Boston College core curriculum course *Inspiration in Imagination*, to hear and see details of the project; February 19, 2019.

Plans during the next reporting period to accomplish project goals

For the next reporting period, which will in fact extend to the duration of the project, we will exploit the opportunities for enhanced halo device sensitivity presented by the aforementioned bulls-eye structure and the incorporation of conjugated quantum dots. Moreover, we will transition from proxy antigen-antibody molecular targets to the detection of TB-LAM. To this end, we will revisit the establishment of a collaboration US Navy, via the Biological Defense Research Directorate and the Navy Drug Screening Laboratory, who will provide de-identified human urine samples for the proof-of-concept studies. We also plan to obtain donor human urine from commercial sources, such as Innovative Research (Novi, MI).

4. IMPACT

Impact on the development of the principal discipline(s) of the project

The diagnostic nanodevice being developed, which relies on detection of specific human disease biomarkers, will address an unmet need for low cost, rapid detection of active tuberculosis. In the short term, the technology will provide a rapid assay for PoC detection of tuberculosis in urine; however the technology can be scaled to detect tuberculosis biomarkers in serum and breath. In the long term, the developed assay can be applied to a range of infectious and noninfectious human diseases. If successful, the research can become a foundation for future effort aimed at emerging infectious diseases to protect our military, with eventual benefit to those in low-resource areas where access to clinical infrastructure and technology is limited, such that accurate, PoC detection is highly desired.

Impact on other disciplines

Integrating the nanofabrication techniques and materials with the biological schemes and assays necessary to achieve our targeted novel detection mechanisms and sensitivities can have a significant impact on the interdisciplinary fields of global public health, biomedicine and nanotechnology. Our research solutions to the problems of developing an impactful biosensing device can be an important to others in this growing field of interdisciplinary science.

Impact on technology transfer

An invention disclosure is in preparation on a modification to the core plasmonic halo concept, wherein quantum dot nanoparticles are integrated into the plasmonic drumhead structure to enhance optical output when tethered to target biomolecules. A subsequent provisional and/or utility patent application will include full attribution of the current funding.

Impact on society beyond science and technology

If successful, the research can become a foundation for future effort aimed at emerging infectious diseases to protect not only US military personnel and those in low-resource areas where access to major infrastructure and technology is limited, but to conventional clinical settings in hospitals and doctors' offices, thus providing large public health benefit.

5. CHANGES/PROBLEMS

Changes in approach and reasons for change

As discussed above, our computer simulations suggested that multiply-nested plasmonic halos, otherwise describable as bulls-eye structures, can be significantly (>40) more sensitive as plasmonic biosensors than the original single-drumhead design. As such, we have decided to focus on this structure. This decision does not impact in any way the overall approach of objectives of the project.

As also discussed above, we plan to investigate, in parallel with the original biofunctionalization scheme, the incorporation of quantum dots conjugated to secondary antibodies that themselves conjugate with the target antigen, as a means to both amplify the plasmonic halo transmittance and localized the spectral width to that of the QD emitter. These changes are expected to significantly enhance the detection capabilities of the device, in terms of both sensitivity and selectivity.

Actual or anticipated problems or delays and actions or plans to resolve them

As discussed above, the absolute intensity of light transmitted through the drumhead plasmonic halos has been less effective than anticipated. Our plan to resolve this unforeseen difficulty is to incorporate the bulls-eye structure, which facilitates both enhanced optical throughput and enhanced plasmonic interaction, but significantly increased the active surface that will be available to the target antigen to bind.

Changes that had a significant impact on expenditures

Nothing to Report

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Nothing to Report

Significant changes in use or care of human subjects

Nothing to Report

Significant changes in use or care of vertebrate animals

Nothing to Report

Significant changes in use of biohazards and/or select agents

Nothing to Report

6. PRODUCTS

- **Publications, conference papers, and presentations**

– Contributed talk by Boston College graduate student Luke D'Imperio at the APS (American Physical Society) March meeting in Boston, March 5, 2019 "Plasmonic Halos Towards Molecular Sensing of Disease Biomarkers" in *Session H23: Physics in Medicine: Imaging, Therapy, and Disruptions on the Horizon*, coauthors Juan M. Merlo, Chaobin Yang, Yitzi M. Calm, Megi Maci, Michael J. Burns, Timothy Connolly, Thomas C. Chiles, Michael J. Naughton. *https://meetings.aps.org/Meeting/MAR19/Session/H23.5*

- **Other publications, conference papers and presentations**

Nothing to Report

- **Website(s) or other Internet site(s)**

Nothing to Report

- **Technologies or techniques**

Nothing to Report

- **Inventions, patent applications, and/or licenses**

Nothing to Report

- **Other Products**

Nothing to Report

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Name:	**Michael J. Naughton, Ph.D.**
Project Role:	PI
ORCID ID:	0000-0002-6733-2398
Nearest person month worked:	1
Contribution to Project:	Prof. Naughton has supervised all aspect of the work.
Funding Support:	This award
Name:	**Thomas C. Chiles, Ph.D.**
Project Role:	Co-PI
Nearest person month worked:	1
Contribution to Project:	Prof. Chiles has co-supervised the biological and biochemical aspects of the work.
Funding Support:	This award
Name:	**Timothy Connolly, Ph.D.**
Project Role:	Co-PI
Nearest person month worked:	1
Contribution to Project:	Dr. Connolly has contributed to the SPR experiments, bioassay development and co-supervised the bio/chemical aspects of the work.
Funding Support:	This award
Name:	**Michael J. Burns, Ph.D.**
Project Role:	Consultant**
ORCID ID:	0000-0001-9804-405X
Nearest person month worked:	1
Contribution to Project:	Dr. Burns has contributed to the SPR experiments and co-supervised the modeling aspect. He is currently a consultant on the project.
Funding Support:	This award **Dr. Burns' role for the remainder of the project will be Consultant. His role will change from co-PI to Consultant, and will advise on array fabrication and assist in the device development experimental plan. There will be no project impact and no budget impact.
Name:	**Luke D'Imperio**
Project Role:	Graduate Student
ORCID ID:	0000-0001-8281-2552
Nearest person month worked:	12
Contribution to Project:	Mr. D'Imperio is a graduate student on the project involved with most aspects of the research, including nanofabrication of plasmonic halo devices, FEM modeling, and SPR measurements.
Funding Support:	This award
Name:	**Chaobin Yang**
Project Role:	Graduate Student
ORCID ID:	0000-0002-7550-8154
Nearest person month worked:	6
Contribution to Project:	Mr. Yang is a graduate student that has worked on the project, primarily assisting Mr. D'Imperio with photolithography and nanofabrication of plasmonic halo devices
Funding Support:	This award

Name:	**Megi Maci**
Project Role:	undergraduate Student
Nearest person month worked:	3
Contribution to Project:	Ms. Maci is a biology undergraduate student invovled with the project. She has been involved with the surface plasmon resonance experiments and the biological and biochemical aspects of the work.
Funding Support:	Boston College Undergraduate Research Fellowship award

Change(s) in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period

Nothing to Report.

Other organizations were involved as partners

Nothing to Report.

8. SPECIAL REPORTING REQUIREMENTS

COLLABORATIVE AWARDS: *N/A*

QUAD CHART: *attached*

9. APPENDICES:

Curriculum vitae of M. J. Naughton

Emerging Infectious Disease Diagnostic via Novel Optoelectronic Halo Effect

Log Number PR172111, FY17 Peer Reviewed Medical Research Program, Discovery Award
W81XWH-1810102

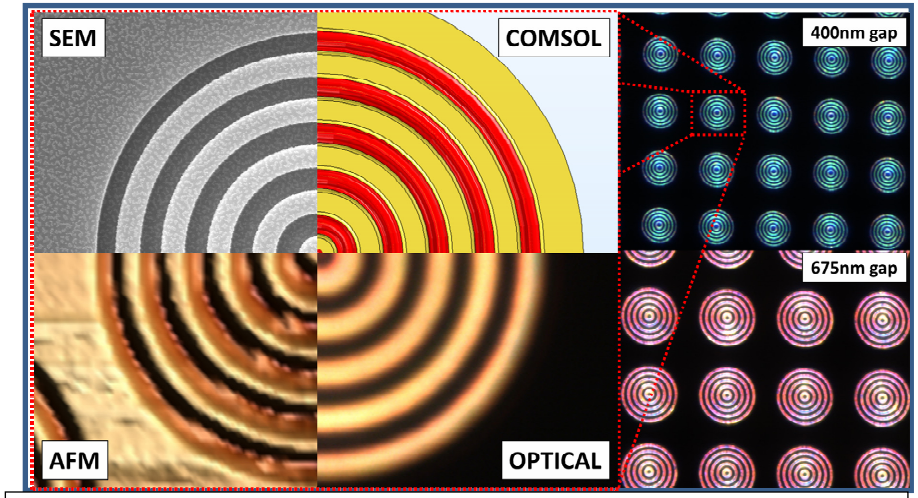
PI: Michael J. Naughton, Ph.D. **Org:** Boston College **Award Amount:** 313,000

Study Aim

• Exploit the plasmonic halo effect to develop a high sensitivity, high selectivity molecular biosensor targeting biomarker of emerging infectious diseases, such as that for tuberculosis, lipoarabinomannan (LAM).

Approach

- Model, Make and Measure plasmonic halos as sensitive biosensors.
- Simulate, using the finite element method, the interaction of light with the plasmonic halo, as a prediction tool toward optimization of the architecture as a biosensor.
- Fabricate and test devices for sensitivity and selectivity.



Left: Simulated, fabricated and characterized plasmonic halo structures for optimized design. Right: Measured the response of chemical and biological plasmonic halo assays.

Timeline and Cost

Activities CY	19	20
Identify candidate biomarkers		
Simulate plasmonic response		
Fabricate & characterize devices		
Demonstrate proof-of-concept		
Estimated Budget ($K)	**$180,000**	**$133,000**

Updated: 13 May 2019

Goals/Milestones

CY19 Goal – Optimize structure via simulation and fabrication
☐Validate design architecture for enhanced sensitivity

CY20 Goal – Demonstrate proof-of-concept of halo-based detection of TB antigen above antigen-free control sufficient to warrant further development

Comments/Challenges/Issues/Concerns

- Advanced architecture introduced (bulls-eye)
- Advanced optical interaction scheme introduced (quantum dots)

Budget Expenditure to Date

Projected Expenditure: $200,000
Actual Expenditure: $185,026

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Education

Boston University, Ph.D. Physics 1986
St. John Fisher College, B.S. Physics 1979

Professional

Ferris Professor	Boston College	2008--
Chairman	Department of Physics, Boston College	2006-2018
CTO	Solasta Inc., Newton, MA	2006-2010
Assoc. VP Research	Boston College, interim	2005-2006
Professor	Department of Physics, Boston College	1998--
Professor	Department of Physics, State University of New York at Buffalo	1998
Visiting Scientist	National High Magnetic Field Laboratory, Tallahassee, Florida	1996
Visiting Scientist	Service National de Champs Magnetique Pulses, Toulouse, France	1995
Associate Professor	Department of Chemistry, State University of New York at Buffalo	1993-1998
Associate Professor	Department of Physics, State University of New York at Buffalo	1993-1998
Assistant Professor	Department of Physics, State University of New York at Buffalo	1988-1993
Post-Doc	Department of Physics, University of Pennsylvania	1986-1988

Thesis and Post-Doc Advisors

James S. Brooks (Ph.D.) and Paul M. Chaikin (post-doc)

Honors & Awards

Young Investigator Award, National Science Foundation, 1992
Fellow, American Physical Society, 2003
Distinguished Research Award, Boston College, 2005
Nano^{50}, Nanotech Briefs, 2006
Ignite Clean Energy, MIT Enterprise Forum (2nd place), 2006
Karl Herzfeld Memorial Lecturer, Catholic University, 2011

Professional Activities

Member, American Physical Society, Materials Research Society, American Chemical Society, Society for Neuroscience
Co-Founder, Solasta Inc.
Founder, Tau Sensors LLC
Executive Committee, American Physical Society, Division of Condensed Matter Physics, 1998-2002
Chairman, inaugural National High Magnetic Field Laboratory Users' Committee, 1995-1998
Organizer, American Physical Society New England Section Annual Meeting, *Energy Matters*, 2014
Organizer, Near-Field Nanophotonics Workshop, Boston College, 2014
Member, External Academic Review Committee, University of Vermont Department of Physics, 2014
Member, Review Committee, Research Core in Interdisciplinary Science, Okayama University, 2012-2014
Participant, Ignatian Colleagues Program, 2012-2015
Proposal Reviewer, National Science Foundation, Department of Energy, National Institutes of Health
Member, Scientific Advisory Board, NBD Nanotechnologies, Boston, MA

Publications

updated February, 2019
(*H*-Index: 48, i10-index: 111, citations: ~7,300, 204 publications plus 24 issued patents)

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