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Summer Undergraduate Research Proposal:

Programming optical antenna arrays for next generation machine vision

Abstract

The proposed research experiment aims to complete one step in developing non-mechanically implemented LiDAR, by dynamically steering a laser beam using an electronically controlled nano-optical device known as a metasurface. The Lawrence Lab has proposed a new beam-steering concept involving the use of highly sensitive resonant pixels whose light scattering properties can be tuned by applying small electric currents. My project will entail developing the control electronics for delivering the correct electrical bias signals to the nanofabricated metasurface structure to facilitate steering to a desired angle. To apply voltages to the metasurfaces' gold terminals, I will design a printed circuit board (PCB) to distribute power from a power supply to the nanoscale components. This circuit will also incorporate a microcontroller that can reconfigure the circuit based on instructions from the end user. Finally, I will program the microcontroller so that a specific steering angle can be chosen. To test the performance of the system, I will assist in carrying out optical experiments where the metasurface is illuminated with an infrared laser and the reflection is captured by an imaging spectrometer. Recording and analyzing the Fourier image of the light diffraction will then determine if the metasurface was programmed correctly.

Introduction:

As a member of the Electronic and Data Acquisition Department at WashU Racing, I am excited by the Lawrence Lab's research on optics at the nanoscale level, particularly Professor Lawrence's investigations into controlling and studying the diffraction of light from nanoantenna arrays, targeting next-generation LiDAR systems. LiDAR, also known as light detection and ranging, is a methodology that employs the time taken for light to travel from and return to a source in order to measure distances. Steering the direction of the light pulse to create a 3-dimensional map of the environment is the most challenging aspect of LiDAR development and it is this problem the Lawrence Lab is addressing. LiDAR's versatility, with applications ranging from oceanography to astronomy, serves as a connection between my engineering research interests and the Lawrence Lab's work.

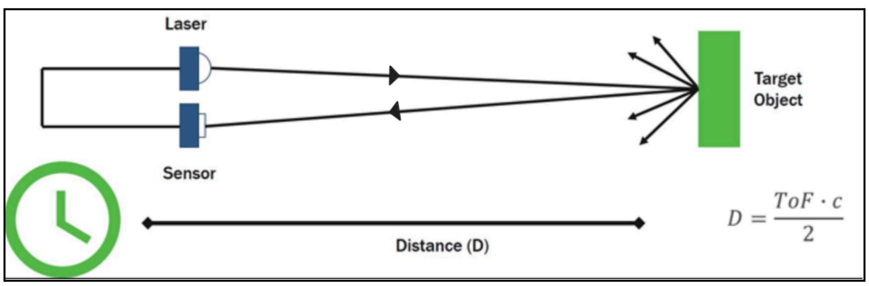

Figure 1a: Lidar Diagram[1]

The objective of the proposed research experiment is to develop efficient and non-mechanically implemented beam-steering for LiDAR. Many existing LiDAR sensors rely on mechanical mechanisms to steer light, including the basketball-sized sensors used in self-driving cars in my hometown San Francisco which rely on spinning lasers to point at every location in the environment. However, this approach leads to large, heavy, expensive, and slow sensors. Fortunately, there are other methodologies that can circumvent mechanical problems by bending light via diffraction rather than mechanical motion.

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[1] Lidar News. "Lidar Technology Explained at the Electronics Level." *Lidar News*, 19 Sept. 2021, https://blog.lidarnews.com/lidar-technology-explained-at-the-electronics-level/.

One approach to bending light is through the use of spatial light modulators (SLMs), which are arrays of pixels that can electronically refract light. SLMs are composed of liquid crystals, which constrain the maximum frequency of each pixel. Commonly used SLMs include ferroelectric liquid crystals (FC-LC), digital-micro-mirror-devices (DMD), and galvanic-light-valves (GLV). However, these systems require high voltages that can mechanically move the mirrors within the SLM. Therefore, the Lawrence Lab is exploring ideas to overcome this issue.

The Lawrence Lab has proposed another concept involving the use of highly sensitive resonant pixels to steer light. Lin Lin, a Ph.D. student working in the lab, is currently focused on the nanofabrication of arrays of these pixels, known as metasurfaces. Metasurface fabrication begins with etching nanostructures into a thin silicon film sitting on a sapphire wafer using electron beam lithography (EBL) and reactive-ion-etching. Subsequently, the nanostructures are coated with silica before depositing nickel wires on top via a second EBL step. Being highly resistive, nickel converts electricity to heat very effectively, which allows electric currents in the nickel to heat up the silicon. While the previous stages will be performed by others, I will assist with the final fabrication step, involving photolithography to extend the nickel nanowires off the metasurface via gold microwires, eventually serving as terminals for the control circuit.

As mentioned above, applying an electric current to the nickel wires increases the temperature of the silicon nanoblocks. Increasing the temperature of silicon causes its refractive index to increase very slightly. Typically this small change, corresponding to a roughly 1% increase for a 190°C rise in temperature, has next to no effect on light scattering. Crucially, the nanostructure shapes are chosen to trap light in standing wave resonances, much like the acoustic resonances of a guitar string. As shown in Fig.2a, Just like a guitar string of a certain length amplifies sound of a specific pitch, light is amplified inside the silicon antennas at a specific color, or wavelength. However, when the temperature and therefore refractive index increase the effective resonant wavelength also increases. The resonance of light within the cavity can be described using the following equation, where "d" represents the distance that light travels in the cavity, "m" is a positive integer, "λ_0" represents the wavelength of the light, "o" is the wavelength of the light in the effective cavity, and "n" represents the index of refraction.

$$d = m\lambda = m\frac{\lambda_0}{n}$$

In other words, the light inside the metasurfaces can exhibit resonance, which forms the basis of Lin's experiment. As seen in the equation above, resonance occurs in the metasurface cavity when light travels a distance that is an integer multiple of the wavelength. The index of refraction can be changed by temperature, so the effective wavelength must increase to stay at a resonant frequency. The largest decrease in phase occurs when the wavelength is at resonant frequency. When the resonant frequency increases, the reflectance shifts toward the right of the graph with it. More importantly, as the resonant frequency increases, the phase decreases. In summary, as the temperature increases due to currents flowing in the nickel nanowires, the reflected phase decreases. When the bandwidth of the resonator is small, the metasurface reflection phase will be highly sensitive to tiny electric currents.

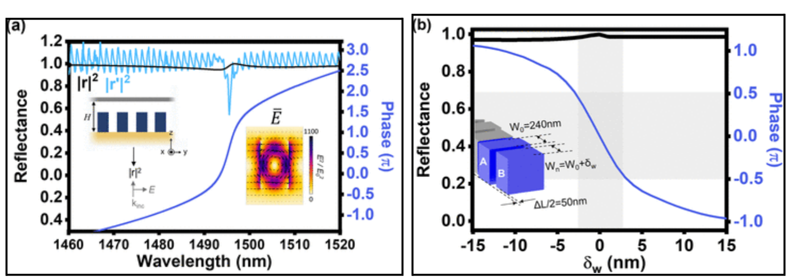

Figure 2a: Reflectance as a Function of Wavelength and Metasurface Width[2]

[2] Lin Lin, Jack Hu, Sahil Dagli, Jennifer A. Dionne, and Mark Lawrence
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Methods:

My research project will involve facilitating small voltage application to Lin's metasurfaces. As previously stated, the goal is to modify the temperature of the cavity by applying various voltages to the gold terminals of the metasurfaces. Overall, the plan is for the raspberry pi to supply voltages to a circuit board whose terminals can be connected to the metasurfaces. After supplying the voltages, the amplitude of the light will be measured by analyzing the Fourier image received by the lens. Eventually, various voltages corresponding to 100 microamps to 1 milliamp will be supplied to various terminals and the Fourier image.

To achieve this objective, a microcontroller can be utilized, such as Raspberry Pi or Arduino, which supports programming languages such as Python and C++. Raspberry Pi devices specifically can import libraries that can supply different voltages on the Pi's pins, specifically the general-purpose input output (GPIO) library. Additionally, the argparse library may be employed to specify voltages between trials or add a time delay with the time library. My proficiency in microcontroller programming comes from the electrical engineering course, Introduction to Engineering Design (ESE 205), where I automated a small toy car using a Raspberry Pi. My proposed research has some similarities to one of my most recent labs, where my group coded the Raspberry Pi to take an image with a camera, calculate the angle between the center of the image and the center of mass of blue objects, and adjust the duty cycle of the servo to point the camera toward the object.

Furthermore, a hardware component must be created to distribute voltage to various terminals. To create a circuit board, the industry-standard software Altium may be used to generate a circuit schematic illustrating the component's connections and layout showing the component's physical placement. A company such as JCLPCB can print the circuit board. Voltages from the Raspberry Pi can be distributed throughout the board using layers, polygons, and vias to ensure maximum heat distribution throughout the board during testing. My prior experience with PCB manufacturing originates from WashU Racing, where I created the power distribution module in Altium to distribute the battery's 12-volt power supply to various sensors. Potential components that may be used include Deutsch connectors capable of accommodating up to 36 pins or more, as well as other through-hole components to facilitate soldering.

Implications and Importance to the Field of Study:

Though mechanical LiDAR is the precedent for many self-driving car companies such as Waymo and Cruise, nonmechanical LiDAR has the potential to be 100s or 1000s of times smaller, lighter, and cheaper, by bending light with diffraction. Consequently, the coverage and durability of sensors on self-driving cars could be greatly enhanced. Beyond miniaturization, nonmechanical LiDAR promises improved performance, with the potential to operate much faster while consuming far less power than conventional devices. The versatility of LiDAR also extends to climate change research as well. Scientists Aljosja Hoojier and Ronald Vernimmen wrote the article Global LiDAR land elevation data reveal greatest sea-level rise vulnerability in the tropics in the journal Nature Communications.[3] They used satellite data to determine the countries most vulnerable to ocean rising. Another application is aerospace research where LiDAR sensors can be used to keep track of the chlorine and alumina byproduct from when rockets are launched and their impact on the ozone layer.[4] Therefore, smaller and cheaper LiDAR sensors that are much more easily deployed, could greatly improve the quality of climate data and help humanity deal with its greatest threat.

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[3] Hooijer, A., Vernimmen, R. Global LiDAR land elevation data reveal greatest sea-level rise vulnerability in the tropics. *Nat Commun* 12, 3592 (2021). https://doi.org/10.1038/s41467-021-23810-9

[4] S. M. Beck, J. A. Gelbwachs, D. A. Hinkley, D. W. Warren and J. E. Wessel, "Aerospace applications of optical sensing with lidar," 1996 IEEE Aerospace Applications Conference. Proceedings, Aspen, CO, USA, 1996, pp. 91-96 vol.2, doi: 10.1109/AERO.1996.495968.

Covid Protocol Information

I can also perform the majority of my research if my access to the Lawrence Lab is restricted due to COVID-19 restrictions. To begin, the hardware portion of my research can be completed without having to come to campus because it would entail component research and software design. In that case, Professor Lawrence, Lin, and I would meet virtually and often to discuss circuit design. All of the parts may be sent to the lab for Lin or Professor Lawrence to solder together. I also have soldering supplies that I can use to create the board if the components are shipped to my apartment, which I could mail to the lab for future use. Writing the code for the raspberry pi could also be completed virtually, as I have two Raspberry Pis and a GitHub account to share code. If socially distanced lab work is required, I will undergo virtual training of the optical equipment before tag teaming measurements while maintaining a safe distance from my lab partner. At the same time, I will follow all COVID protocols, such as regularly disinfecting work surfaces and logging my attendance.