Metasurface Optics Applications in Automotive LiDAR and DMS

Introduction

Optical sensors are rapidly becoming standard equipment on many vehicles. Sensors on the outside of the vehicle, such as light detection and ranging (LiDAR), play a critical role for self-driving cars and driver assisted safety features. Optical sensors on the inside of the vehicle are being used to monitor the driver to determine attentiveness and to interpret gestures. Metalenz is commercializing metasurfaces – a new optical element that allows complete control over all aspects of light (phase, wavelength, intensity, and polarization) with a single, planar semiconductor layer. Comprised of subwavelength nanostructures, a single metasurface can carry out optical functions typically requiring four or more conventional refractive and/or diffractive optics. This document will explore the different scenarios in automotive sensing systems – both external LiDAR and in-cabin driver monitoring – where a solution with Metalenz's innovative optical metasurfaces (meta-optics) can provide cost and performance improvements over traditional optics and whole new insights into the environment that current cameras and machine vision systems cannot capture.

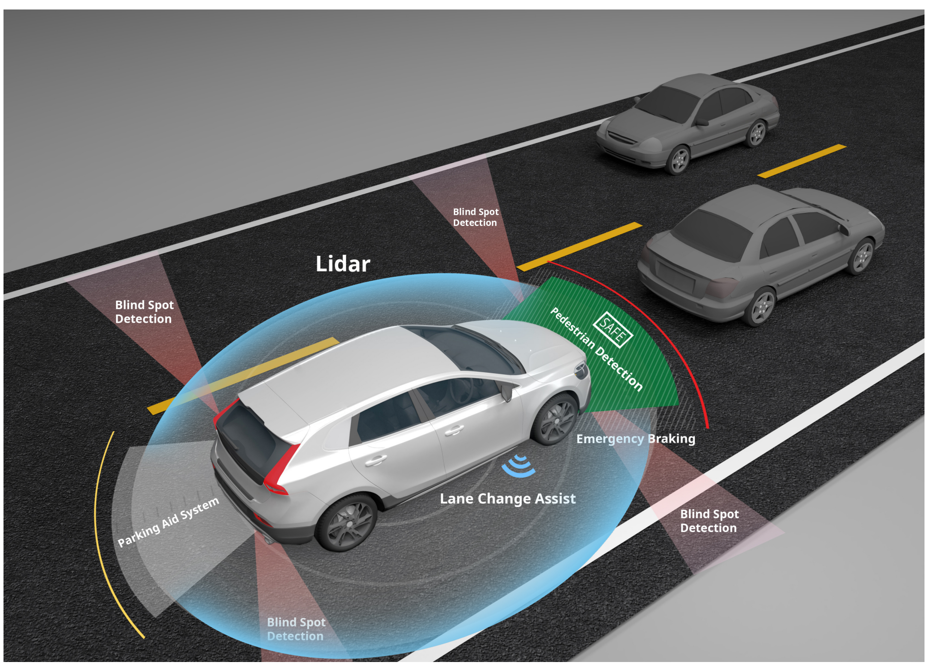

Figure 1: LiDAR and other external sensors on vehicles.

External Automotive Sensing

In current and future iterations of cars, both traditional and self-driving/autonomous, external sensing plays a critical role in the safety and operation of the vehicle. A variety of sensors provide the vehicle with a trove of real-time data about the surrounding environment, enabling the driver and the vehicle itself to make better decisions on the road. Different sensing modalities are used for specific applications and purposes. For example, ultrasonic sensors are typically used for parking assistance, visible light cameras are used for hazard identification, lane assistance, and parking assistance, radio detection and ranging (RADAR) is used for collision avoidance and emergency braking, and LiDAR is used for blind spot detection, object detection, collision avoidance, emergency braking, and autonomous piloting.

Each of these sensing approaches have advantages and disadvantages, making them well-suited for particular use cases. It is well documented that RADAR systems suffer from limited angular resolution, making them less desirable for the long-range measurements needed for reliable & safe autonomous piloting. Additionally, visual camera systems suffer from limited performance in dark (e.g., night) or direct illumination (e.g., oncoming headlights) conditions. LiDAR systems are of particular interest for their high-resolution and active illumination capabilities, which overcome some of the drawbacks of other sensing approaches. These systems typically operate using near-infrared (NIR) or short-wave infrared (SWIR) light and have uses for both short and long range external automotive sensing. As a result of these advantages, LiDAR is seen as an enabling technology for highly autonomous vehicles.

Approaches to LiDAR

There are a variety of approaches to automotive LiDAR which are dependent upon desired system-level characteristics, including but not limited to: light source, range, illumination method, ranging method, and operating wavelength.

Range & Illumination Considerations for LiDAR: "Flash" vs. Scanning

Most LiDAR systems use vertical-cavity surface-emitting lasers (VCSELs) as light sources due to their high optical power output, array-enabling architecture, narrow bandwidth, and cost-effectiveness. Edge emitting lasers (EELs) are also used in LiDAR systems, typically for high-power and long-range applications. These sources are built into LiDAR systems which tend to operate in specific range regimes:

Short-range/Mid-range (“Flash”) LiDAR: These systems tend to operate by spreading laser light (usually from VCSELs) into a particular pattern or into a diffuse field (also known as “flood” illumination). They are often known as “Flash” systems, since they usually image the entire scene with one laser pulse, like the flash of a traditional camera. The return signal is collected by a high-resolution image sensor and converted to a 3D point cloud, which contains the relevant position and depth information. Flash systems tend to have higher data rates than other systems but suffer from high power requirements and low dynamic range due to the collection of all incoming light.

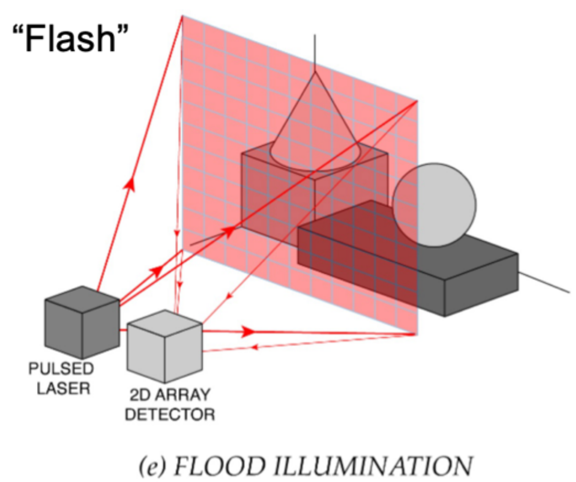

Figure 2: An example of "Flash" LiDAR using flood illumination. Image adapted from Villa et. Al., Sensors **2021**, 21, 3839

Long-range (Scanning) LiDAR: These systems typically operate by collimating a single high-power laser or an array of multiple high-power lasers to create an intense spot or line that is scanned throughout the scene. There are a large variety of methods of scanning the output beam, from mechanical assemblies of spinning mirrors to countless solid-state approaches, which are too numerous to cover in detail here. The return signal is then collected by a single-photon detector or an array of single-photon detectors to achieve a high-resolution 3D point cloud containing the relevant position and depth information. Larger optics are desired for these systems, where maximizing the return signal from objects at long distances (>200 m) is critical. By limiting the area of illumination, scanning systems are more robust to high ambient light conditions, though they suffer from a dependence on the method of scanning the beam.

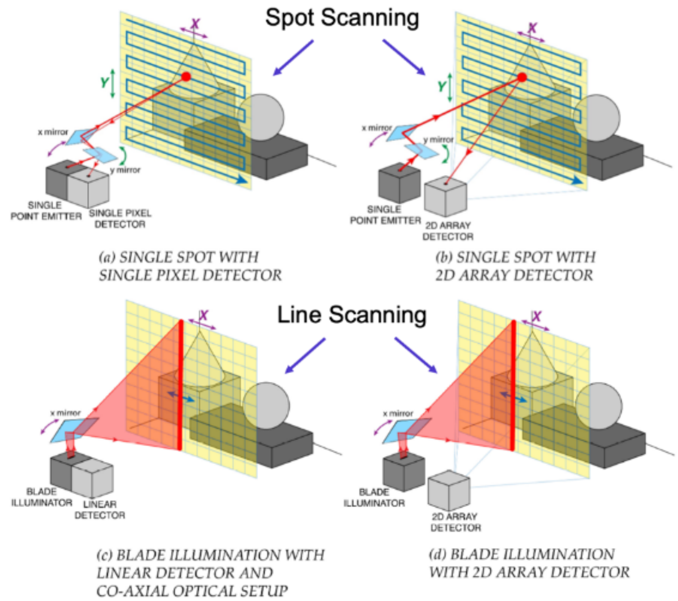

Figure 3: Examples of spot scanning and line scanning LiDAR. Image adapted from Villa et. Al., Sensors **2021**, 21, 3839

Additional System Level Options

As with any laser-based optical source, eye safety comes into play in the design of LiDAR systems. Systems operating at NIR wavelengths (905 nm, 940 nm) are more power-limited while SWIR-based systems (1550 nm) can operate at much higher optical power levels, due primarily to eye safety considerations. Wavelength selection also plays a role in overall system design and cost, as NIR wavelengths enable the use of cheap and effective Si-based detectors while SWIR wavelengths require more expensive InGaAs-based detectors. Mechanical, thermal, and reliability concerns are also high priorities of automotive original equipment manufacturers (OEMs). The automotive environment requires adherence to strict reliability standards (such as IATF 16949, AEC-Q100 and AEC-Q200), large temperature ranges (for example from -45°C to 150°C), and large vibrational forces. Any component which desires to be included in the vehicle must adhere to these standards, which has a significant effect on the final design of a LiDAR system, for example.

Two main ranging methodologies are used in LiDAR systems – time-of-flight (ToF) based systems and frequency-modulated continuous wave (FMCW, also known as "coherent") systems. ToF systems operate by directly or indirectly measuring the time it takes for light to travel from its source to a detector, which can be converted to a distance using the speed of light. These systems tend to be cheaper to implement than alternatives and can be used for both short-range and long-range systems. FMCW systems operate by changing the frequency (and therefore wavelength) of the laser source, interfering the outgoing signal with the return signal, and measuring the frequency change of the combined signal. The measured change in frequency is proportional to the travel time, which can again be converted to a distance using the speed of light. These systems tend to have high performance but at the expense of increased cost and complexity and are practically limited to longer-range systems where the higher performance is a more desirable benefit.

Why use Meta-optics for LiDAR?

While LiDAR systems contain various high-level tradeoffs, certain component-level choices can provide distinct advantages. The optics of many LiDAR systems use a combination of traditional refractive lenses and a diffractive optical element (DOE) for the transmitting (Tx) optics and refractive lenses for receiving (Rx) optics. As mentioned previously, automotive requirements dictate that optical systems operate across a very large temperature range and collect as much light as possible. Since the optical properties of traditional lenses vary with temperature, a complex optical assembly requiring many elements is typically required to athermalize the system. These additional system complexities and added costs can be overcome by using metasurface optics to replace refractive lenses and DOEs on the Tx and Rx sides of an automotive LiDAR system. Meta-optics can combine the optical functions typically found in multiple refractive or diffractive optics into a single planar optical element. For example, a single Tx metasurface optic can simultaneously perform the collimating functions of a refractive lens stack and the pattern generation function of a DOE and achieve similar or better optical performance. Alternatively, a single Rx metasurface optic can simultaneously perform the collimating and focusing functions of a refractive lens stack, again with similar performance. These meta-optics can improve optical performance by improving light collection and contrast, reducing noise, and allowing wider field of illumination (FOI) and field of view (FOV) using single optical elements. In addition to their multifunctional design and performance enhancing capabilities, meta-optics have higher thermal stability than conventional optics, enabling them to maintain performance in the demanding automotive environment. Meta-optics also benefit from the proven semiconductor industry processes which are used to fabricate them, ensuring high part-to-part repeatability and reasonable scale-up to automotive quantities. These advantages make metasurface optics an attractive solution for automotive OEMs and Tier 1 suppliers.

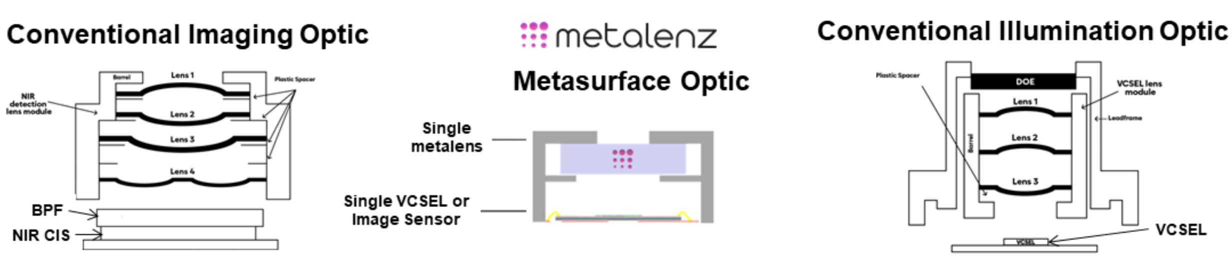

Figure 4: Comparison between conventional imaging and illumination optics stacks and a metasurface optic solution. The imaging stack contains refractive lenses, a bandpass filter (BPF), and a NIR CMOS image sensor (CIS). The illumination stack contains a DOE, refractive lenses, and a VCSEL as the optical source. The meta-optic stack consists of a single metasurface lens (metalens) and a single optical source or image sensor. Note that in an imaging application the BPF will also be included above the image sensor.

Metalenz Tx LiDAR Modules: Simpler & Better

There are additional benefits to using a metasurface optic in an automotive LiDAR system, particularly on the Tx side. For line scanning applications, a single meta-optic can generate many (greater than one hundred) lines without a complex optical system and with a wide FOI (>150°). For diffuse patterns where a metasurface optic would replace a DOE and a refractive stack, precise control over the intensity throughout the FOI is possible in a single optic. In dot pattern applications for direct time-of-flight LiDAR systems, a meta-optic from Metalenz can generate highly uniform spots with high contrast ratio throughout the relevant FOI. As demonstrated by these examples, a key advantage of metasurface optics is their design flexibility due to their precise control over the characteristics and properties of the incoming light.

Meta-optics from Metalenz have a particular design advantage for short-to-mid range LiDAR systems for autonomous vehicles. Wide FOI optics are particularly desirable for peripheral sensing applications such as blind spot detection or lane assist, where shorter range LiDAR systems excel. Additionally, transmitting patterns rather than flood illumination can improve signal-to-noise ratio for these short-range applications. Metasurface optics from Metalenz can combine these desirable functions in a single optical element, saving cost while not compromising on performance.

Metalenz's optics are fabricated in state-of-the-art semiconductor foundries using well-established production techniques perfected over decades. The unparalleled precision achievable in semiconductor foundries enables the highest levels of part-to-part repeatability, which allows rapid scaling into mass production quantities, well-suited for automotive applications. In addition, being able to produce metasurface optics in the semiconductor foundry leverages tremendous economies of scale in the supply chain, allowing metasurface optics to provide performance advantages at very competitive price-points. Automotive LiDAR systems are in a prime position to reap the benefits of metasurface optics.

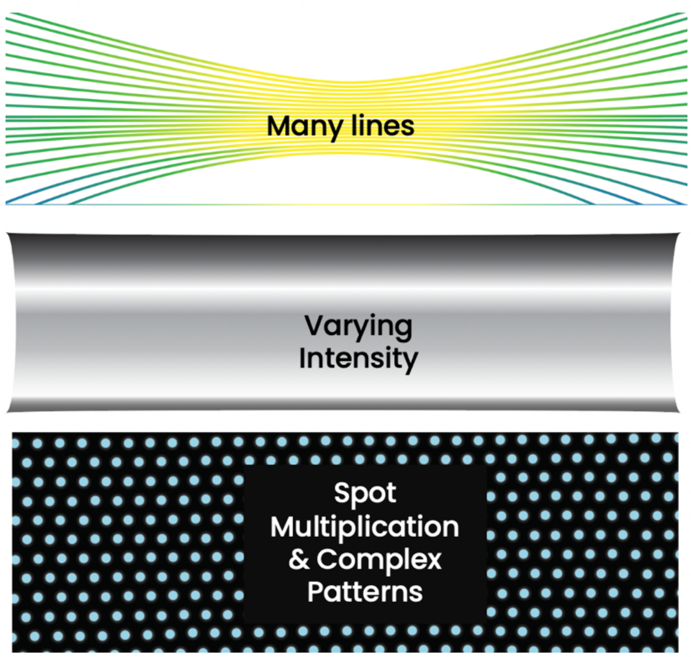

Figure 5: Potential advantages of using metasurface optics on the Tx side of an automotive LiDAR system.

Scanning LiDAR in a Single Meta-optic

Much of the development of long-range scanning automotive LiDAR has been focused on achieving "fully solid-state" LiDAR – a solution or approach which does not require any physical moving parts for scanning. Approaches like this decrease system costs and improve reliability by not relying on bulky spinning mechanical components, but there are again a large variety of ways to accomplish this solid-state scanning. One method of solid-state scanning involves an array of switchable optical emitters behind a lens, known in the literature as lens-assisted beam steering (LABS). An example of this is an addressable VCSEL array, where each section of the VCSEL array illuminates a different portion of the optic. Based on which portion of the optic is illuminated, light is directed at different angles into the external scene, to effectively scan an area as the entire array is switched on and off in sequence. A system like this is particularly well-suited for a metasurface optic, where the optic can be optimally designed to match the layout of the switchable VCSEL array. The optic can even be designed to project unique patterns at these different angles, so they do not overlap and can still scan the full FOI of the meta-optic. This enables solid-state scanning in a single module with a small form factor, greatly simplifying the cost and complexity of a scanning LiDAR system. Such a system could be used for driver assistance/monitoring functions or as part of an autonomous driving system.

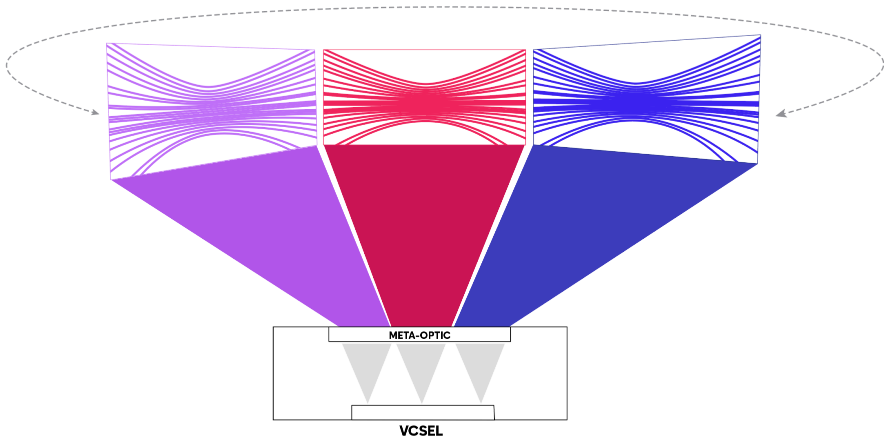

Figure 6: Depiction of a scanning LiDAR system using a meta-optic and an addressable VCSEL array. This method of lens-assisted beam steering provides a unique approach to solid-state scanning and can simplify the cost and complexity of such systems.

In-Cabin Automotive Sensing: Driver Monitoring Systems (DMS)

Sensing systems have not only permeated the external environment of the car but have moved into the cabin as well. The field of in-cabin automotive sensing has taken off in recent years, as higher levels of automated driving require monitoring and engagement of the driver while the vehicle is moving. Such systems are known as driver monitoring systems (DMS). DMS and the sensors which constitute them tend to focus on monitoring driver alertness, making sure they are awake, attentive, and not distracted. DMS may also incorporate a form of driver facial identification to turn on the vehicle instead of a push-to-start button, providing an extra layer of security. Some of the sensors in these systems do not exclusively focus on the driver, but monitor the status of the entire cabin, including if children or pets are present in the rear seats. They may also check for distracting objects such as cell phones or other electronic devices, as well as monitoring body orientation for optimal air bag deployment in the event of an accident. These sensors need to operate effectively in a variety of lighting conditions, including at night. This is really only possible with infrared cameras that use illumination of the car interior that remains invisible to the human eye. The advantages of DMS solutions along with the requirement of such solutions for higher levels of autonomous driving have led the European Union to require some levels of DMS in Europe as early as new models sold in 2024, with the United States and others expected to follow.

Meta-optic Advantages for DMS

The emerging DMS market requires wide FOV, small form factor, automotive-grade optical solutions for these systems, which tend to go into the steering wheel or the rear-view mirror of the vehicle. IR solutions are particularly advantageous compared to visible light cameras due to their performance in high ambient light conditions and their invisible illumination of the cabin for sensing. These requirements all point towards metasurface optics as a potential solution. Metalenz's meta-optics can effectively cover a wide field of view, providing a simpler optical system with a single optical element. The form factor reduction and temperature stability of meta-optics can decrease system costs and increase system reliability, of paramount importance to automotive OEMs and Tier 1 suppliers. Additionally, Metalenz's meta-optics operate in the near-IR, enabling better performance in a variety of lighting conditions compared to approaches using visible cameras.

If you have any questions regarding meta-optics and automotive applications, we would be happy to discuss this with you in more detail. Please reach out to us at sales@metalenz.com.