Precision Optical Components for LiDAR Systems Developed for Autonomous Vehicles

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ABSTRACT

Recent developments in autonomous vehicle instrumentation have led to advancements in laser-based LiDAR sensors. For these type of systems, sensor performance is dependent on fast response time and good contrast (SNR) at long distances. Careful design for the optical transmitter assembly is paramount to achieving good device performance, and has become a primary differentiator between emerging LiDAR technologies. These systems rely heavily on both the source emitter quality as well as the conditioning and delivery of collimated beams using passive optical components. Most available sources, from semiconductor to fiber lasers, have the necessary spectral characteristics but lack the required beam quality for long distance propagation and detection. In order to overcome these limitations, LightPath leverages decades of experience in precision molded aspheres and fiber delivery systems to achieve quality collimation and astigmatic beam correction. These capabilities are applicable to a broad range of optical system configurations, and therefore transcend the differences in LiDAR system architecture. We will explore the basic optical requirements for emerging LiDAR transmitter systems and discuss their common reliance on precision optical components.

Keywords: LiDAR, optical components, Precision Glass Molding, PGM, asphere, collimator, lasers, transmitter.

1. INTRODUCTION

Autonomous vehicle instrumentation has been emerging within the last several years and continues to do so as the interest in self-driven vehicles increases. One of the most fundamental detection and ranging technologies that are currently being employed is Light Detection and Ranging (LiDAR) using a time-of-flight (ToF) methodology to generate 3D maps for navigation and distance measurements. These systems rely on reflectivity/intensity measurements to precisely determine the distance between nearby objects and potential hazards. For automotive applications, these systems need to react quickly in order to determine the types of objects encountered when traveling at high speeds.

Optics made using Precision Glass Molding (PGM) was pioneered in the nineteen seventies and is a well-established technology. PGM offers similar advantages as plastic molded optics but with the added benefits of glass as the raw material. Today, many different types of complex surfaces can be molded including aspheric, toric, diffractive, asymmetric cylindrical and freeform. Compared to other optical manufacturing technologies including traditional grind and polish, PGM is a high volume process that delivers high precision low-cost optics. PGM technology has been continuously evolving and continues to do so as the demands for more complex optics are made available.

2. BACKGROUND

Although LiDAR systems have been used for scientific and military applications for several decades they have only recently been employed for autonomous vehicles. Within the last couple of years, smarter vehicles have already incorporated advanced driver assistance systems (ADAS) such as adaptive cruise control, automatic braking and parking, blind spot and collision avoidance [1]. These “semi-autonomous” vehicles employ systems using several technologies such as radar, ultrasonic or camera-based sensors on the side, front and rear of the car. All these sensors must be synchronized to allow the monitoring of the surrounding environment and warn drivers of potential road hazards. Key to the operation of these systems is the ability to differentiate and recognize objects such as other vehicles, pedestrians, and obstacles while traveling at high speed. Although radar and camera-based systems are currently being used, experts agree that LiDAR will become a significant player in the detector market, first by being incorporated in ADAS and next in autonomous vehicles [2]. Compared with existing technologies, LiDAR provides greater range and accuracy and is a key sensing technology for partial to full autonomous driving [3].
Presently, one of the biggest obstacles to the widespread implementation of LiDAR systems is high cost. Current car manufacturers have set a threshold of around $250 per-unit, but expect the price to come down to around $150 per-unit within the foreseeable future [4]. Although several LiDAR manufacturers are able to meet the price requirement, production costs are threatened while trying to meet demand [5]. The demand for a low-cost LiDAR system requires inexpensive components including the optics. Presently, development efforts are focused on increasing the range of current LiDAR systems to 200m and as a result, this places a demand on laser sources having higher average powers.

Several key technologies have been evolving in recent years that have led to commercialization of various LiDAR systems. The high definition LiDAR (HDL) available from Velodyne resembles a “hockey puck” and employs a steering mirror that rotates to provide a 360-degree azimuth and 26.9-degree elevation field of view (FOV) [6]. A 64-channel version like the one seen on the Google car [7] generates a point cloud of up to 2.2 million points per second, has an accuracy of up to 2cm and range of 120m. Recently, Velodyne has developed a 128-channel version, called the VLS-128 that uses 128 laser beams [8]. Quanergy, a startup company based in California is pursuing a next-generation solid-state approach. These systems use solid-state technology which works by steering light using an optical phased array (OPA) [9]. The beam steering is accomplished by shifting the phase of the incoming light as it passes through the array. This type of beam steering has no moving parts and makes for a very compact design. In addition, the beam can be steered very rapidly to provide real-time 3D dynamic mapping. These types of systems form the core technology for Quanergy’s LiDAR systems. In April of 2017, Velodyne announced a solid state device of their own, the new Velarray LiDAR which uses Velodyne’s propriety application specific integrated circuits to achieve a 120-degree by 35-degree FOV [10].

Recently, Luminar Technologies announced a LiDAR capable of achieving a longer range than either Velodyne or Quanergy can achieve by employing a high power 1550nm laser. The extra power and longer wavelength (compared with Velodyne 903nm and Quanergy 905nm) extends the range by a factor of 10 and resolution by a factor of 50 [11].

Flash LiDAR based on pulsed vertical cavity surface emitting lasers (VCSEL) is being pursued by several companies including TriLumina and Continental as an inexpensive and more cost-effective solution for autonomous vehicles [12]. Conventional scanning LiDAR systems based on a rotating mirror and solid-state devices rely on multiple laser pulses to build a 3D picture of the surrounding area. Flash LiDAR relies on a single pulse from a wide angle source. In flash LiDAR each pixel is timed to the incoming pulses to create a ToF map. The FOV is determined by the wide-angle optics of the receiver. For flash LiDAR systems the pulse is much shorter than conventional LiDAR, typically on the order of a few nanoseconds to hundreds of picoseconds.

3. DESIGN ARCHITECTURE

The basic components of a LiDAR system are the transmitter, receiver, and electronics for signal analysis. The transmitter typically consists of the source and optics for producing a collimated beam. For coherent LiDAR systems, the source is typically a laser operating at a fixed frequency and wavelength. The transmitter optics are used to collimate the output beam so that it illuminates a target without too much loss of light. The receiver detects the backscattered light (which could be as low as 1%) and together with the electronics, a 3D map is generated of the surrounding area. The transmitter and receiver are housed and mounted at several locations. Early systems were mounted on the roof of vehicles for maximum visibility. However, these early systems were found to be large and cumbersome. Today, systems are more compact and are being placed in less conspicuous places such as in the vehicles bumper and body panels.

Figure 1: Several concepts for the transmitter optical assembly.
Figure 1 shows several concepts for the transmitter optical assembly. For sources that have a low divergence and a symmetric beam output, a single asphere could be used to collimate the light, (A). For sources that have an asymmetrical beam, the output is coupled into an optical fiber using an aspheric lens, (B). Coupling into the optical fiber may also be achieved using a fused fiber assembly (C) that would be described in section 6.2. The optical fiber provides homogenization and circularization for the incoming light. This is particularly important when dealing with sources that have large differences in the divergences along the X and Y axes, such as diodes. However, due to the fiber mode, there may be a significant tradeoff in efficiency and beam quality. In order to increase the transmitter power, several diodes may be stacked. The output for all the fibers is then collected by a larger lens and collimated.

LiDAR systems based on solid-state and micro-electro-mechanical systems (MEMS) steer a laser beam by deflecting it using electrical control. MEMS developed by the Dutch company Innoluce consists of a small oval mirror and uses electrical resonance to make it oscillate, thereby changing the direction of the laser [13]. Solid state devices or OPA’s provide beam steering using multiple optical antenna elements. Each antenna is separated on the order of the wavelength of light providing a $2\pi$ optical phase tunability for actively steering the beam [14,15].

Figure 2: (A) Beam steering accomplished using (A) MEMS and (B) Optical Phased Arrays (OPA’s).

4. LiDAR SOURCES REQUIRING PRECISION OPTICS

At the heart of all LiDAR systems is the source, which is typically a laser capable of generating infrared coherent radiation. The laser determines the overall system performance and its characteristics such as the beam divergence and laser beam quality determine the lateral resolution of mapping LiDAR’s [16]. Other characteristics, such as the pulse duration and timing jitter determine longitudinal accuracy. Pulse energy determines range. So, for a long range sensor, having high definition will require a high power laser with a short pulse and good timing jitter. However, increasing the power level to extend the range could easily lead to an excessively high power density that would exceed the limit for Class 1 laser safety. In such cases, the laser becomes an ocular hazard and the laser beam must be expanded to reduce the power density to an acceptable limit. LiDAR systems for autonomous vehicles operate in the near IR, away from the visible spectrum of the human eye. Current systems employ sources operating at a wavelength of 905nm, the peak responsivity of silicon detectors. Recently, due to concern for laser safety, more systems are transitioning towards 1550nm and employ InGaAs detectors.

LiDAR systems employing high power solid state lasers operating at 1064nm and its harmonics offered unparalleled performance in terms of beam quality and pulse characteristics. These systems have been traditionally used for agriculture and the military. For agriculture, LiDAR is used to map terrains and help guide farmers on the distribution of fertilizers and pesticides. For the military, uses include autonomous vehicles and drone guidance for target identification and tactical mapping. LiDAR systems employing diode pumped solid state (DPSS) Q-Switched lasers are high performance but tend to be very large and costly. Today, almost all commercial autonomous vehicles employ either fiber lasers or diode lasers, due to their small size and low cost.
Diode lasers operating near 905nm have found applications for solid state and scanning LiDAR systems. For these types of systems, there is either a single laser diode that is scanned across the FOV using a scanning mirror or multiple lasers (Multichannel) that illuminate the FOV simultaneously. Solid state systems based on OPA’s are advantageous over scanning systems because they have no moving parts, producing better reliability and ruggedness. Each laser is in the form of an epoxy encapsulated device or TO can. TO cans are hermetically sealed and advantageous over encapsulated devices. For multichannel systems, such as those having 16, 32, 64 and 128 channels, each laser forms a single channel and diodes are individually arranged to form a vertical stack, with each layer having a small heatsink.

Diode lasers are attractive because of their small size and efficiency but lack the beam quality necessary for the majority of precision systems. The beam exiting a laser diode is elliptical in shape and is more challenging compared with fiber and solid-state lasers. The beam from a laser diode is characterized using the full width half maximum (FWHM) and is described as having two different divergences, one along the emitter junction, labeled as $\theta_\parallel$, and the other perpendicular to the emitter junction labeled as $\theta_L$. Values for $\theta_\parallel$ and $\theta_L$ vary widely depending on the emitter design and wavelength, but commonly range from 25° to 40° for $\theta_\parallel$ and 6° to 16° for $\theta_L$. Due to the nature of the divergence, the beam has to be corrected separately for $\theta_\parallel$ and $\theta_L$ before being collimated. Additionally, differences for $\theta_\parallel$ and $\theta_L$ leads to astigmatism in the beam. If significant, astigmatism needs to be corrected before collimating the beam. Precision optical components can aid this correction, as described in the following sections.

![Figure 3: Single axis beam correction for laser diode using a cylindrical lens.](image)

Uncooled fiber lasers offer the best beam quality as the fiber operates in single mode. Fibers can be easily split and routed, thereby, allowing the distribution of a single output to several locations. Almost all fiber laser systems are based on a Master Oscillator Power Fiber Amplifier or MOPFA operating around 1550nm. In order to achieve a high peak power, the laser is Q-Switched at a rate of 5 to 250 kHz resulting in a peak power of 10 to 15kW. With the advent of femtosecond lasers becoming inexpensive and more readily available, these lasers offer unprecedented performance for high precision LiDAR applications. The output from a fiber laser is easily collimated using a single symmetric lens.

Regardless of the source type, precision optical components enable high-quality beam collimation and transmission systems with controlled divergence.

### 5. PRECISION GLASS MOLDING

Polymer or plastic optics are cheap, and could be produced in high volumes using injection molding processes, but lack the necessary properties for the demanding performance and reliability requirements of LiDAR systems. For automotive applications, plastic polycarbonate will develop “haze” over time and has been known to breakdown by 20% over 3-4 years, even without exposure to UV radiation [17]. When exposed to the environment, UV light, heat, and age cause plastics to suffer discoloration reducing transmission and increasing premature product failure. For applications requiring high precision and durability, glass has been and still remains the preferred material of choice.

Lenses made from glass have traditionally been spheres which are manufactured using conventional grind and polish techniques. This has been extended to include aspheres, Fresnel lenses, and micro-optics. Conventional grind and polish manufacturing is a well-established technology that produces precise components, but does not scale to high volume and cost competitiveness.
Precision glass molding overcomes the limitations of plastics and conventional grind and polished glass while still remaining cost competitive. High performance, low-cost aspheres can be molded using moldable glasses. The process of molding involves the compression of a ball preform into a lens shape using high temperature and pressure. The process has been described in a number of papers, but a brief description is presented below in Figure 4 [18,19].

Before a lens is pressed into shape, tooling is designed specifically for the product to be manufactured. The tooling stack consists of the top mold tooling, sleeve and bottom mold tooling. The tooling is made to the specific shape of the lens using precision diamond turning or grinding. The sleeve is precisely machined and determines the lens OD. A ball preform is inserted into the space between the top and bottom molds. The ball preform is the glass that would be “formed” into the lens and comes in a variety of sizes depending on the final lens volume. The system is evacuated to remove air and the preform is heated to its transition temperature, \( T_g \) after which it becomes a viscoelastic material [20]. At this point pressure or load is applied to form the lens shape. The load is then removed and the system is allowed to cool. Finally, the lens is removed. The whole process is used to make a variety of symmetric aspheres.

Figure 4: Precision Glass Molding Process Flow, [20].

In many instances, multiple elements may be required to correct a laser source. If the source characteristics differ in both the X and Y directions, a correction will need to be implemented accordingly. Two elements having crossed aspherical cylindrical surfaces have been produced. Such elements provide beam correction for both X and Y. Also in development is a single element capable of providing correction similar to a two-element device. The element is mounted externally to circularize an elliptical beam. Such elements called “CircuLight™” have been used for correcting the beam from red and blue diode lasers.

Figure 5: CircuLight™ element used for correcting beam from a laser diode.
6. FIBER COLLIMATORS

Fiber collimators come in a variety of types. LightPath manufacturers both air gap collimators and fused fiber collimators which collimate the light exiting from a divergent source, typically a fiber. With the advent of fiber based sources for LiDAR systems, both air gap and fused fiber collimators are becoming increasingly popular.

6.1 Air Gap Collimators

Air gap collimators come in two types, connectorized collimator assemblies (CCA’s) and sleeve mounted. CCA’s tend to be bulky compared to their fused counterparts and are seldom used for compact LiDAR systems. CCA’s generally consist of the cleaved fiber and a molded asphere. The asphere provides collimation for the light exiting the fiber. For high power applications, a “pellet” (or flat rod window made of fused silica) is laser fused to the fiber end to reduce the power density. CCA’s generally consist of the main housing that holds the asphere and a fiber connector. The fiber connector can be of several types such as SMA, FC/PC or FC/APC.

Figure 6: LightPath connectorized collimator assemblies (CCA) [21].

Sleeve mounted collimators tend to be more compact than CCA’s, but must be precisely aligned during manufacture. The fiber ferrule and collimating lens are precisely located within a housing that could either be metal or glass and bonded into place. Figure 7 shows a design based on a Quartz sleeve housing.

Figure 7: Sleeve Mounted Collimator.

6.2 Non-Air Gap Collimators

Non-air gap collimators generally consist of a fiber bonded to a plano-convex “C-lens” (or plano-convex rod lens). This type of structure produces a monolithic device that is a more robust assembly and has a reduced risk of damage to the fiber over traditional CCA’s or sleeve mounted collimators. The method of bonding the fiber to the lens is typically accomplished using an adhesive (where the fiber is “glued” to the lens using an optical epoxy) or laser fusion. Fused fiber collimators use a patented process pioneered by LightPath Technologies. Initially developed for the telecom industry several decades ago, this process has been applied to a number of products including LiDAR systems.

Figure 8: Fused fiber assembly.
The fusion process has been described elsewhere, so only a brief description is presented [22]. In order to achieve the best performance, the fiber and lens must be the same material, typically fused silica. The optical fiber is brought in close proximity to the C-Lens and a carbon dioxide laser creates a localized melt zone at the fiber/lens interface. Both materials reach melting point and are fused upon cooling. The result is a monolithic structure with no noticeable interface and no appreciable residual stress.

7. CONCLUSIONS

LiDAR systems require high precision optics. Manufacturers are turning away from plastic optics and looking towards precision optics made from glass. Glass has a higher laser damage threshold than plastics, is harder and is a more durable material. This is advantageous for environmental applications where optics may be exposed to the elements. PGM has a significant advantage over traditional grind and polish techniques as a high volume cost competitive process. Several geometry types have already been successfully molded using the PGM, including aspherical and diffractive optics. Recently, this technology has been extended to include cylindrical aspheric surfaces and free form optics. PGM is a mature technology that is well suited for low-cost LiDAR systems [23].

REFERENCES


