Liquid Crystals New Frontier; LiDAR Uses?

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Keyword: LiDAR, Phase modulation, Liquid Crystal, Wave front

ABSTRACT

A hard surface object detection LiDAR has been developed for military purpose, and this intensity only detection LiDAR is expected to be applied for autonomous driving device uses. This type of LiDAR requires beam steering capability and liquid crystal devices have some potential to be applied for this uses.

1 Scope of the investigation

In these four decades, liquid crystals have been showing their significant performance in display applications with large market endorsement. One of the critical performances of the successful penetration of liquid crystals is their amplitude modulation with decent level of drive voltages. Rapid large market creation by liquid crystal technologies is also in conjunction with thin film transistor (TFT) technology development. TFT technology has been effectively demonstrating good match with amplitude modulation capability of liquid crystals. In addition to the amplitude modulation function, liquid crystals have another useful function. Phase modulation capability is the other unique function of liquid crystals. Unlike amplitude modulation for display application which uses half-lambda condition to incident light wavelength, phase modulation capability is dependent on not only birefringence of liquid crystals, but also optical path length. One of the major factors to govern phase modulation capability is retardation amount of a liquid crystal device. Although optical response time may be of concern, with specific large optical path design, a phase modulation device with a liquid crystal is able to create huge retardation amount, which potentially covers not only visible wavelength range, but including much longer wavelength such as tera Hz, and giga Hz or microwave region. As discussing below, LiDAR devices have been used in relatively long wavelength region to penetrate atmospheric disturbance. As shown in Figure 1, most of telesthetic detection over outer space is used longer wave length such as microwave and/or radio wave. On the other hand, most of atmospheric circulation detection by LiDAR such as wind speed, weather detection is used visible to infrared region of wavelength. Current thermotropic liquid crystals would be applicable between peta Hz to tera Hz wavelength region or even in some giga Hz (microwave) region for phase delay uses.

This paper describes an overview of potential penetration of liquid crystals as a phase modulation device or pure-time-delay detection with longer wavelength region than visible wavelength region. LiDAR, or light detection and ranging device is one of the potentials uses of liquid crystal with longer wavelength than visible wavelength. Recent rapid development of autonomous car uses as a "LiDAR" is of our intention. However, actual "LiDAR" has much longer history than that of autonomous car development, which means "LiDAR" may have wider application expectation other than autonomous car driving uses. Regardless light beam intensity only detection, or time delay detection only uses, the primary function of liquid crystals for LiDAR device is very different from those for display devices. Therefore, with some introduction of LiDAR, this paper explores new device application opportunities of liquid crystals as a phase modulation device.

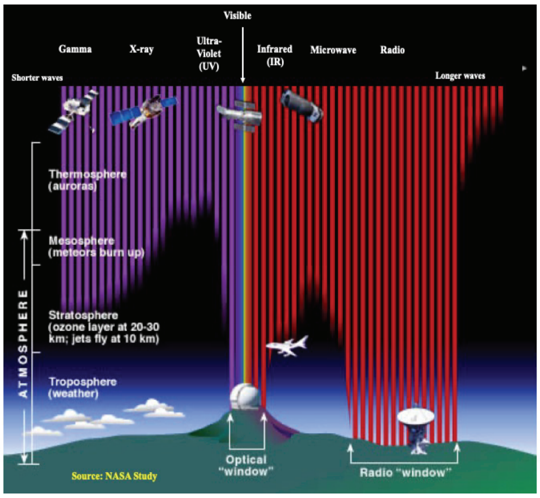

Figure 1. Electro-Magnetic waves windows by their vertical direction

2 Brief history of LiDAR

The most acceptable definition of LiDAR would be "it sends out an electromagnetic wave and receives the reflected signal back" [1]. Based on this definition of "LiDAR", a microwave radar has similar function. Unlike a radar, "LiDAR" can have increased angular resolution associated with the shorter wavelengths than that for radar, and still operate 24 hours per day. Compared to tera Hz region, or even peta Hz region of wavelength, giga Hz region of electromagnetic wave has significant angular coverage limitation. On the other hand, microwave has much longer penetration length depending on the initial power of the electromagnetic wave. Actual penetration is also dependent on environmental situation such as fog particles having 1 to 100 μm diameter size, rain drops having 0.5 to 5 mm diameter size in average, respectively as shown in Figure 1.

Every object has a finite number of observable features that can be exploited by a remote electro-optic sensing system. There are five types of features as following. (1) Geometry, (2) Surface character, (3) Plant noise, (4) Effluents, and (5) Gross motion. As described above, it is reasonably assumed "LiDAR" application to environmental observation including weather/climate detection, air pollution detection, and some natural disaster watching. Actually, "LiDAR" has been developed with atmospheric circulation watching including air pollution, and weather detection followed by military applications as shown in Figure 2. Figure 2 suggests some concept level of use amount of LiDAR system by major application field since 1960 to present. Figure 2 is just for conceptional increase in "LiDAR" by year for relative amount expectation only.

After lasers came out to be available in late 1960s, LiDARs have been developed mainly for military uses such as a laser beam-rider surface-to-air missile (SAM). In 1960s, LiDAR was also used to measure a range from the Earth to the Moon by MIT Lincoln Lab in 1962. Then, time-of-flight measurement was developed by NASA for the Lunar Orbiter Laser Altimeter (LOLA) project which specified the landing site of Apollo space crafts on the surface of the Moon [2]. LiDARs have been also used for detection of wind speed, hurricane movement as a volume-scattering, or soft targets [3].

3 Varieties of "LiDAR"

There are several ways to classify "LiDAR". In this discussion, the classification focuses on potential involvement of liquid crystal technologies. Table 1 summarizes categories of LiDAR. Three major categories based on major function are listed up in Table 1. The first category is direct detection LiDAR, which detects light beam intensity only.

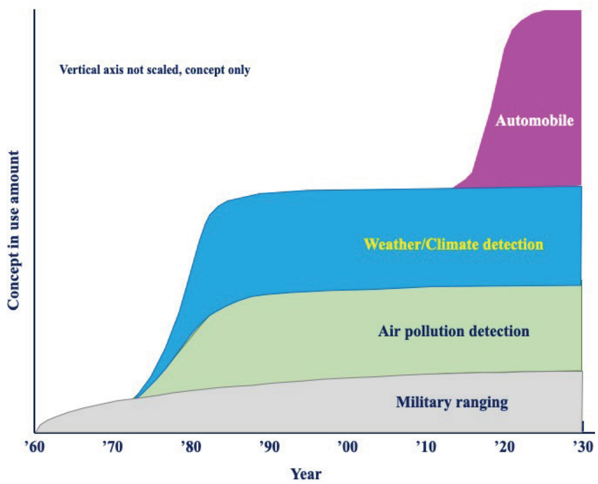

Figure 2. Concept level of LiDAR application amount by category in use.

Table 1. Type of LiDAR

- Direct Detection LiDAR ← Intensity only detection
  - 1D range only LiDAR
  - Tomographic imaging LiDAR
  - Range-gated active imaging (2D LiDAR)
  - 3D scanning LiDAR
  - 3D flash imaging
  - 3D mapping applications
  - Laser-induced breakdown spectroscopy
  - Laser-induced fluorescence
  - Active multispectral LiDAR
  - LiDAR using polarization as a discriminant
- Coherent LiDAR ← Both phase & intensity
  - Laser vibration detection
  - Range-Doppler imaging LiDAR
  - Speckle imaging LiDAR
  - Aperture-synthesis-based LiDAR
- Multiple-Input, Multiple-Output Active EO Sensing ← Multiple physical sub-apertures

The second category is coherent LiDAR, which detects both phase and intensity. The last category is multiple-input, multiple-output active EO (electro-Optic) sensing, which detects multiple physical sub-apertures. In principle, liquid crystal technologies are potentially applicable for all of the listed uses in Table 1, however, based on current some limited performance in liquid crystal devices, the first category: Direct Detection LiDAR, specifically 1D range only LiDAR, and LiDAR using polarization as a discriminant would be most practical. Therefore, following discussion will limit the function of LiDAR just for these two categorized functions.

4 Autonomous navigation uses

As shown in Figure 2, in these several years, automobile application of LiDAR is an emerging field of application. From application point of view, an autonomous car driving use is very different from atmospheric applications those led major applications of "LiDAR" till ten-years ago. It would be reasonably assumed that current emerging uses for autonomous car driving applications are originated from a military application. From 1979 to 1984, DARPA had a program called as the Autonomous Terminal Homing (ATH) project. This project successfully migrated to the Cruise Missile Advanced Guidance (CMAG) program, which resulted from the need for improved guidance and flight control of autonomous cruise missiles. This project purpose would be some sort of a direct predecessor of autonomous car driving uses in terms of hard surface objects detection.

5 How are Liquid Crystal technologies able to be involved in LiDAR?

Regardless function of a LiDAR for light beam intensity detection only, liquid crystal technology involvement on the LiDAR is its phase modulation capability unlike amplitude modulation function for display devices. Figure 3 illustrates expected basic functions of liquid crystals dependent on electromagnetic wavelengths.

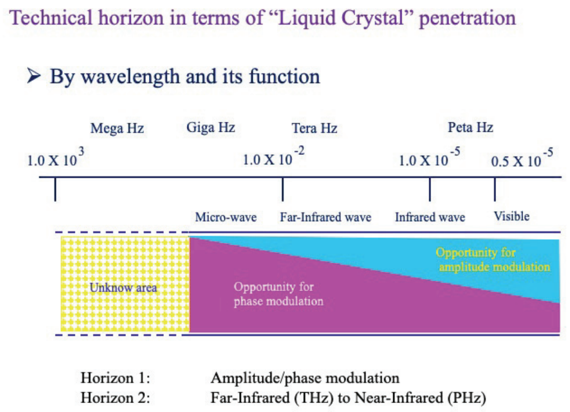

Figure 3. Expected core function of liquid crystals dependent on electromagnetic wavelength.

Typical visible wavelength is in peta Hz region and this region including near IR region mainly use amplitude modulation function of liquid crystals. Display devices are the most successful uses of amplitude modulation function of liquid crystals. Increasing wavelength and decreasing frequency

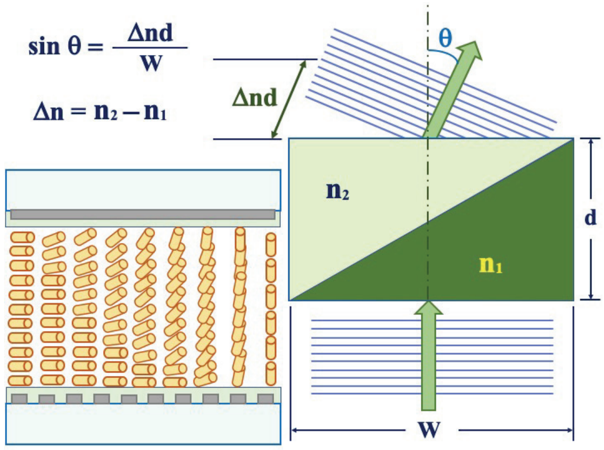

Figure 4. Principle of beam steering by a liquid crystal device.

from peta Hz to tera Hz, and giga Hz, an opportunity of liquid crystal technologies is leaning to phase modulation function from amplitude modulation. For the first category LiDAR application, it is assumed that the most practical approach is to use of beam steering capability of liquid crystal devices. For an autonomous car driving use LiDAR requires large beam steering angle such as the minimum several degrees. In general, to obtain large beam steering angle, significantly larger retardation switching than those for display uses is necessary. There are two primary means to have larger retardation in a liquid crystal device. One is to use of higher birefringence of liquid crystal material, the other is to have longer optical path.

Figure 4 illustrates principle of beam steering by a liquid crystal device. A continuous refractive index change throughout the span of incident wave-front "W" gives spatial continuous change in retardation though the optical path "d", resulting in beam steering angle θ. The expected steering angle is given by $\sin\theta = \Delta nd/W$. As discussed above, to obtain larger steering angle θ, larger birefringence (Δn) and optical path (d), and smaller wave-front width (W) are required. In principle, birefringence (Δn) is a liquid crystal material parameter, and optical path (d) is a liquid crystal device configuration matter, and wave-front width (W) is a relative factor between incident light beam size and a device configuration.

As illustrated in Figure 4, both the larger birefringence and the larger optical path are, however, giving longer electro-optic switching time. In particular, autonomous car driving application requires much wider operational temperature range than those for display devices in general such as – 40C to + 125C as the Grade 1 on AEC-Q100 criteria in European Automobile Association. In general, larger retardation switching requires larger phase modulation, and larger phase modulation takes longer optical switching time. Therefore, larger beam steering angle and fast enough optical switching time are inconsistent characters each other in general. In this particular point, it is highly required to introduce new concept device configuration which enables maximizing phase modulation capability of liquid crystals without sacrificing their optical response time. Since larger birefringence in liquid crystal material is limited up to 0.45 in practical manner, it may not be realistic simply relay on larger birefringence of liquid crystal materials to obtain large enough steering angle specifically from compatibility with optical response time.

In order to overcome the inconsistency, some well-considered device configuration is most required. One remarkable example of the unique approach to overcome the inconsistency is shown in Figure 5.

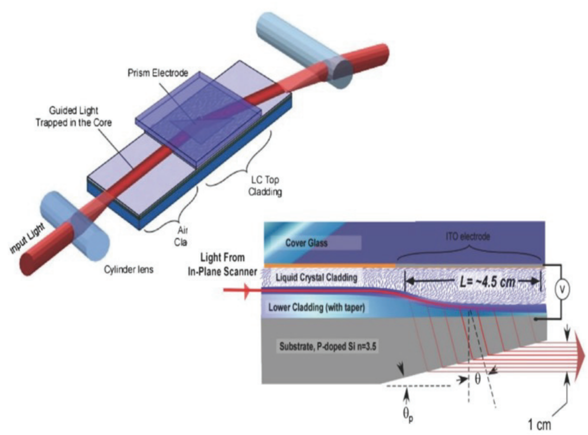

Figure 5. A steerable electro-evanescent optical refractor (SEEOR) from Reference 4.

Figure 5 configuration controls evanescent light intensity and it enables very long optical path such as several centimeters without sacrificing optical switching time. This configuration enables large beam steering angle without sacrificing optical response time. One limitation of this approach is its limited beam aperture size; however, this configuration is assumed to be a good candidate for autonomous car driving uses.

6 Concluding remarks

LiDAR has over 60 years long history of its practical uses. Until 10 years ago, most of uses of LiDAR was both military applications and atmospheric circulation detection uses. Most of military applications are targeting a hard surface object, and atmospheric circulation detection is targeting soft and somewhat vague objects. Large amount phase delay capability of liquid crystal devices has potential applications in wide range of wavelength, or frequency from visible wavelength to microwave region. Although liquid crystal technologies have such potential capability, a practical use in tera Hz region would be intensity only detection type of LiDAR. This specific use is based on beam steering capability of liquid crystal devices. Large enough steering angle and fast enough optical switching time are inconsistent characteristic properties each other. For larger steering angle, both larger birefringence and larger optical path are required, however both these requirements make longer optical switching time. An optical path is adjustable by specific device configuration keeping substantial liquid crystal layer thickness which is the direct factor to decide optical response time small enough. It is the most important factor to have large enough optical path keeping actual liquid crystal layer thickness small enough to obtain practical beam steering device for autonomous car driving application LiDAR. In addition to the device configuration, wide enough operational temperature range for automobile use is also of important requirement. Although above technical challenges are not easy, liquid crystal

based LiDAR for autonomous car driving application has some distinguished advantages compared to other mechanical based LiDAR including a compact and light weight system, low power consumption, non-mechanical based vibration durable device, and relatively inexpensive expectation.

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