Optical Design of LIDAR System for Spectroscopic Measurement in Deep Ultraviolet Wavelength Region

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Abstract: The optical system that can measure spectra in the deep UV wavelength range with high sensitivity and focus laser beams was designed using ray tracing to develop a LIDAR system for resonance Raman spectroscopy for remote detection of trace amounts of hazardous substances. The single Cassegrain-type telescope for focusing the laser beam and scattered light was used to achieve a high overlap between the fields of view of the laser beam and the optics receiving the scattered light. The simulation results showed that the laser beam and scattered light could be imaged with small aberrations.

1. Introduction

Several techniques have been developed for remotely measuring substances that are difficult for humans to approach, such as flammable or toxic substances. Optical methods, such as infrared and Raman spectroscopy, are often used.

Raman spectroscopy requires a high detection sensitivity and the ability to identify a wide variety of substances. In general, Raman-scattered light is very weak; however, its intensity can be significantly increased in the deep ultraviolet (DUV) wavelength region owing to resonance effects [1]. Optical systems with high throughput in the DUV wavelength region have been developed to measure Raman-scattered light. Additionally, it has been experimentally demonstrated that localized SO_2 gas can be measured remotely [2]. In this experiment, the optical system for focusing the laser beam and the optical system for collecting the Raman scattered light were prepared separately. The overlap between the fields of view of the laser beam and the optics receiving the scattered light can be increased if a single optical system can focus the laser beam and collect the Raman scattered light, and the Raman spectra can be measured with higher sensitivity.

Herein, we present the design results of an optical system that can focus a laser beam to an arbitrary position and collect light in the DUV wavelength range.

2. Instrument Overview

Figure 1 shows the configuration of the LIDAR measurement system. The optical filter is a long-wave pass filter that separates the laser beams and scattered light. The filter was assumed to reflect light in the DUV-to-ultraviolet wavelength range and pass light in the visible-to-near-infrared wavelength range. The wavelength of the laser beam was assumed to be in the visible-to-near-infrared range. The laser beam passed through the optical filter and entered the Cassegrain-type telescope, whose primary mirror had an effective aperture of 300 mm and was focused at a distance L > 10 m from the telescope.

Many glass materials used for lenses have low transmittance in the DUV wavelength range, which reduces the throughput of the optical system in refraction-type optical systems. In addition, the shorter the wavelength, the greater the chromatic aberration. Thus, an optical system using lenses limits the wavelength of light that can pass through the entrance slit of the spectrometer. Therefore, we designed an optical system using only mirrors.

The telescope is used not only to focus the laser beam but also to collect scattered light. The scattered light in the DUV-to-ultraviolet wavelength range collected by the telescope is reflected by an optical filter and a mirror with holes and then focused by a concave mirror. The focused light passes through the hole in the mirror and is focused onto the entrance slit of the spectrometer. Generally, a telescope collects light emitted from a single point and focuses it at another point. On the contrary, the telescope shown in the figure is a one-sided telecentric optical system that collects light emitted from one point and converts it to collimated light. This optical system enables the telescope to focus on a collimated laser beam and is used for remote measurements via laser-induced breakdown spectroscopy [3].

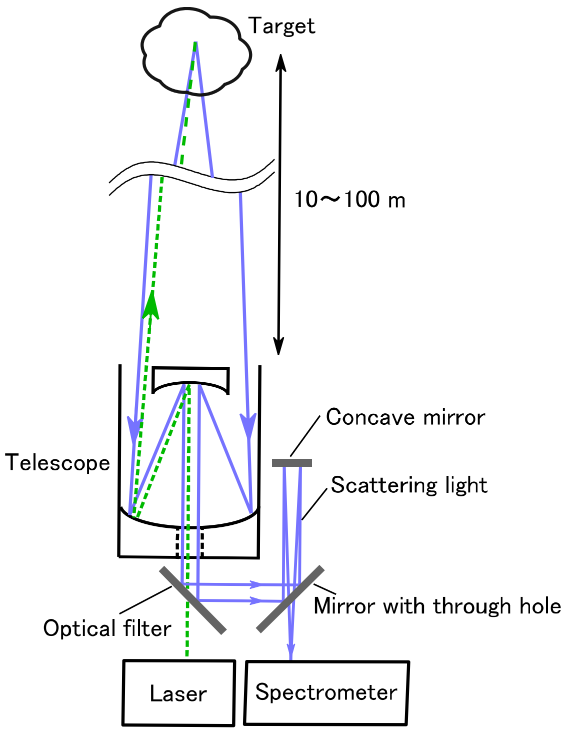

Figure 1. Schematic of LIDAR system. Solid and dashed lines show the paths of laser beam and scattered light, respectively.

3. Light collection

An optical design software (Optic Studio v.18.9, Zemax Inc.) was used to investigate the imaging performance of the optical system. Figure 2 shows the optical layout used to collect the scattered light and light ray propagation near the mirror with holes. The diameters of the primary and secondary mirrors were set to 300 and 80 mm, respectively, and the curvature of the primary and secondary mirrors and the spacing between them were optimized by sequential analysis. The results show that in the range L = 10–100 m, the ratio of rays reaching the edge of the entrance slit of the spectrometer to the ray's incident on the primary mirror was 91.3–92.7%, which increased monotonically with L. The percentage of light rays is not 100% because a part of the scattered light is shielded by the secondary mirror of the Cassegrain-type telescope. Consequently, the cross section of the scattered light after it passes through the telescope has the shape of a doughnut. To make the diameter of the mirror with holes smaller than the diameter of the donut holes, all scattered light that passes through the telescope can reach the entrance slit of the spectrometer without being shielded by the mirrors with holes.

The advantage of an optical system is that it focuses light without coma or astigmatism at low cost. In astronomical telescopes, light enters the telescope at an angle to the axis of the lens or mirror to eliminate vignetting. In this study, multiple aspherical lenses and mirrors were used to reduce the coma aberration and astigmatism. Aspherical optics must be custom-made, which results in high costs. On the contrary, optical systems use spherical mirrors with commercially available specifications to focus the scattered light that has been collimated; therefore, these optical systems incur a low cost.

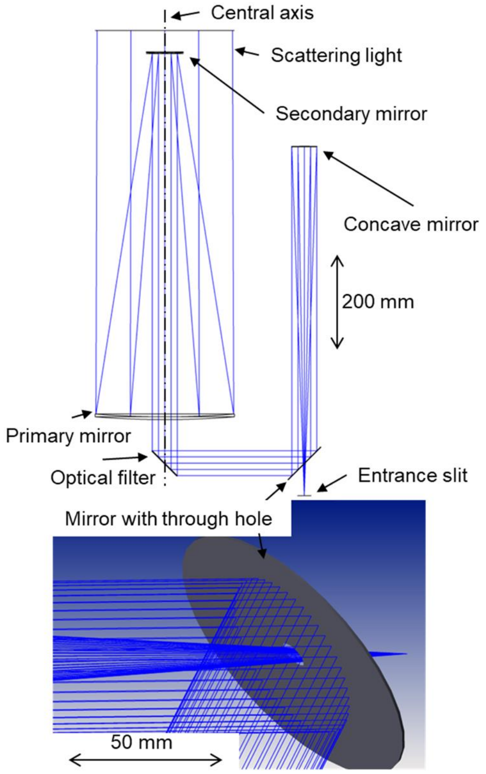

Figure 2. Optical schematic of scattered light in the LIDAR system. The scattered light enters from the left side of the primary mirror. The exit is at the entrance slit of the spectrometer.

Figure 3 shows the magnification of the optical system used to receive light. A smaller value on the vertical axis indicates that the image can be further reduced. The solid line in the figure shows the result of the least squares regression of the magnification obtained by sequential analysis as a function of $a + bL^c$, using the constants a, b, and c. Owing to the approximation, $a = 4.71\times10^{-3}$, $b = 4.79$, $c = -1.06$, and the magnification is proportional to $1/L$. For example, if scattered light were emitted from an area 1 mm in diameter, as viewed from the telescope at $L = 50$ m, the diameter of the image focused on the entrance slit would be 80 μm. A part of the scattered light can pass through the entrance slit of the spectrometer because the spectrograph is expected to have an entrance slit width of 10–50 μm. Increasing the width of the entrance slit improves the throughput of the optical system but decreases the wavelength resolution of the spectrum. Selecting an appropriate slit width for remote material detection is a future task.

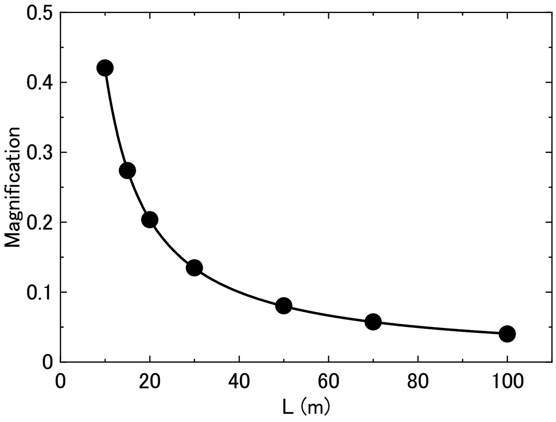

Figure 3. Dependence of magnification of the optical system dependence on the distance from the second mirror of the telescope. Solid line shows the fitting results by the inverse function.

4. Laser focusing

The laser beam is usually passed along the optical axis of a telescope to reduce the laser beam diameter at the focal point when the telescope is used to focus the laser beam. In this case, the component of the center part of the laser beam is reflected by the secondary mirror and returns to the laser device without being reflected by the primary mirror, resulting in shielding of some of the laser beam. Therefore, the optical axes of the telescope and laser beam are shifted parallel to each other, as shown in Figure 4. This allows the laser beam to be reflected and focused entirely by part of the primary mirror and is not shielded by the telescope.

In practice, an optical system is required between the laser device and the optical system, as shown in Figure 4, to align the laser beam precisely into the telescope. The optical system for the alignment consists of plane mirrors and is not shown here because it does not affect the ray-tracing results.

A ray with a diameter of 15 mm and a beam spread of 10 mrad was set up using a part of light emitted isotropically on a sphere from a point source and entered the optical system for ray tracing. The beam passes through an optical filter and enters the telescope. The laser beam can be focused on any position by adjusting the distance between the primary and secondary mirrors.

The diffraction effects were significant at the focal point of the laser beam. Physical optics propagation analysis was used in the ray tracing because sequential analysis cannot consider diffraction effects.

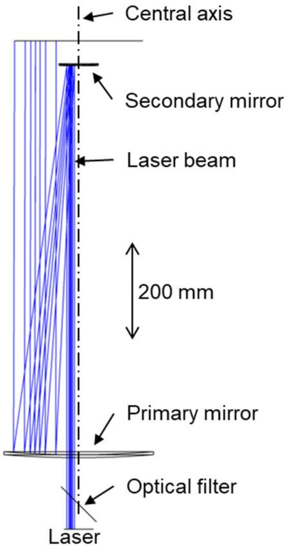

Figure 4. Optical schematic of the laser beam in the LIDAR system. The entrance is on the laser side, exit is at the secondary mirror of the telescope.

Figure 5 shows an image of the focused laser beam at $L = 50$ m. The energy density profile of the beam cross section along the x-axis was a Gaussian profile with a full width at half maximum of approximately 0.15 mm. The results indicated that the laser beam could be focused using a telescope.

However, the actual laser beam is emitted from the space inside the resonator, whereas ray tracing uses light emitted from a point source to set the laser beam spread and beam diameter; thus, the width of the beam profile is expected to be larger than the result of ray tracing in the actual case.

The primary and secondary mirrors were coated with optical thin films with high reflectivity in the DUV wavelength region. Confirming the tolerance of optical thin films to laser beams is the next step.

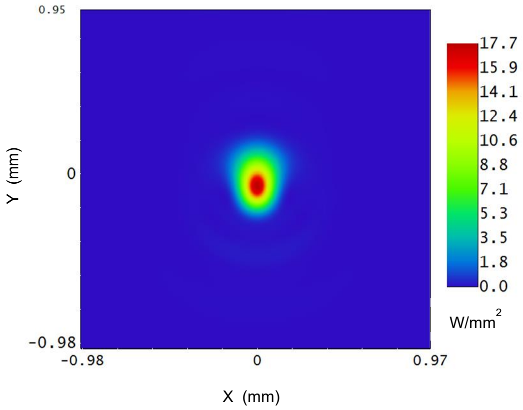

Figure 5. Beam image focused at L = 50 m. Color shows the density of the beam power at the focal point when the laser beam of 1 W passes through the optical system.

5. Conclusions

We designed an optical system to focus laser beams and scatter light for the remote measurement of trace amounts of hazardous substances. The LIDAR system can be constructed by combining the designed optical system, a spectrometer, and a laser.

The optical system for collecting scattered light consisted of a Cassegrain-type telescope and a mirror with a hole. High throughput is achieved because the scattered light is not shielded, except by a secondary mirror. In addition, there is no chromatic aberration because no lenses are used, and spectral measurements can be performed simultaneously in the DUV to near-infrared wavelength range.

The laser beam can be focused to any position between L = 10 and 100 m using a telescope, which is part of the optical system that collects scattered light. The laser beam was not shielded by the telescope by shifting the optical axis of the telescope parallel to that of the laser beam. In the future, an optical system will be fabricated based on the results of this optical design.

Acknowledgment

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