June 2020

Utilization of shortwave infrared (SWIR) light cameras for industrial inspections

1. Introduction

Infrared light, which are the electromagnetic waves with wavelengths longer than visible light, were discovered by Hershel in the United Kingdom more than 200 years ago in 1800. He was studying how the temperature rise of the thermometer changes due to the color of sunlight. The sunlight was diffracted by the prism and turned to the color from red to purple. He accidentally discovered that there was radiation of a different quality from visible light. It was because the temperature rose even if there was no light cast on the thermometer. He called the radiation with the different characteristics from visible light as a heat beam. Subsequent studies have shown that this heat beam is an invisible light of longer wavelengths than visible light and have been termed “infra-red” which means “beyond the red” in Latin. Infrared light are now widely used to measure heat (temperatures) [*1)].

The infrared light used to measure temperature are called far-infrared light with wavelengths between 4000 nm and 1 mm. In this article, on the other hand, we introduce imaging and inspection technologies using SWIR light (wavelengths between 780 nm and 2500 nm), which are located between visible light (wavelengths between 380 nm and 780 nm) and far-infrared light. Inspections utilizing SWIR light have become particularly active in recent years. Whereas far-infrared radiation has been used for temperature measurement since ancient times, SWIR radiation has become widely used for testing in the past 50 years. Research and development of semiconductors, such as silicon and InGaAs (indium gallium arsenide), which can measure the intensity of light electrically by converting visible light and SWIR light to electricity, has progressed. Electronic devices such as sensors using these semiconductors and electronic equipment incorporating semiconductor devices have become less expensive. The most commonly used electronic device in which SWIR light is used is a remote control. The remote control typically uses SWIR light with wavelengths from 940 nm to 950 nm.

SWIR radiation is also used for venous authentication, which has recently become widely used. This mechanism takes advantage of the ability of hemoglobin in the blood to absorb SWIR light. It is possible to identify the person by imaging the shape of veins projected in black. Besides, SWIR light of certain wavelengths are absorbed by materials such as water and oils. The absorbance (the rate of light which is absorbed by the material) at each wavelength differs depending on the materials. The difference depending on the wavelength and the materials make it possible to utilize SWIR light for quality testing and foreign matter detection for industrial products, food, and agricultural products in recent decades.

This article describes the technologies used for the inspection utilizing SWIR light, especially the inspection utilizing the image taken by cameras. We hope that this white paper will help you gain a better understanding of the inspection using SWIR spectroscopy, for which further development is expected.

2. SWIR inspection

As briefly described in the Introduction, SWIR radiation refers to electromagnetic waves with wavelengths ranging from 780 nm to 2500 nm. Utilizing the property of SWIR light that the absorbance changes depending on the substances and the wavelength, SWIR light are used for the inspections for various test objects.

A basic procedure is to use a lighting instrument to irradiate a test object with SWIR light and use the resulting image to perform the inspection. As shown in Figure 1, there are two ways to capture images, one using transmitted light and the other using reflected light.

2.1 Inspection by transmitted light

Testing with transmitted light is used primarily to inspect semiconductor devices. As shown in Figure 2[*2)], visible light is not transmitted through silicon, whereas SWIR light with wavelengths of 1200 nm (1.2 μm) or more are transmitted.

Therefore SWIR radiation is used to inspect the interior of silicon wafers and devices. However, the following tests utilizing reflected light are more commonly performed because of the limited substances such as silicon with high transmittance in the broadband of SWIR wavelengths.

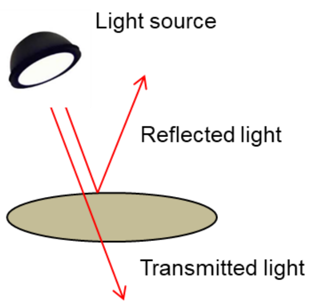

Figure 1 Transmitted light and reflected light

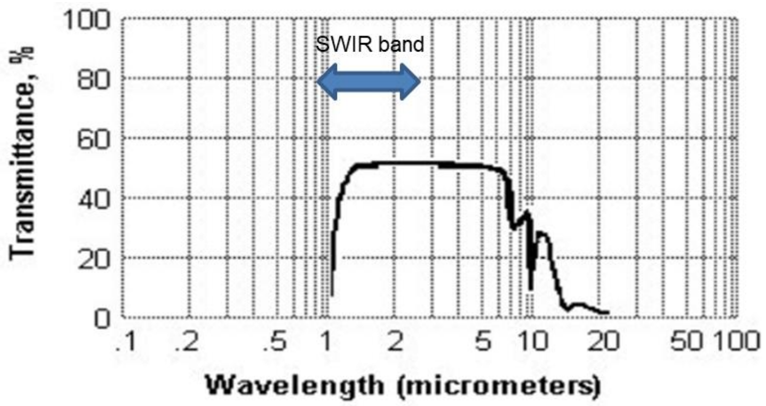

Fig. 2 Transmission of silicon

2.2 Inspection with reflected light

Because many substances have different absorption rates for SWIR wavelengths, reflective light is widely used for the inspection by measuring the absorbance. Exposure to SWIR light causes the intensity of the reflected light at the wavelength absorbed by the test objects to weaken, resulting in the darkening of the image. This property makes it possible to use SWIR light for food and pharmaceutical inspections.

For example, water absorbs infrared light near 1450 nm and 1950 nm, and sugar has a high absorbance for wavelengths above 1400 nm. Fig. 3a shows the wavelength-absorbance characteristics of water and Fig. 3b shows the wavelength-absorbance characteristics of sugar.*1)

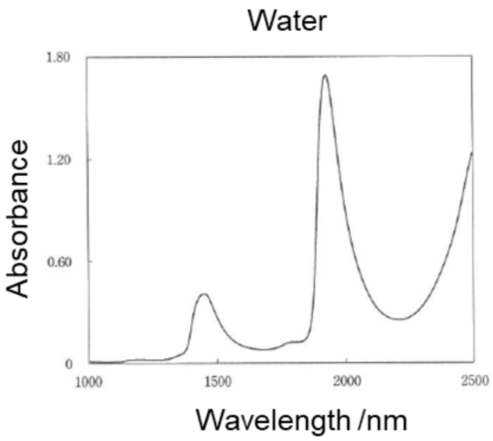

Fig. 3a Absorption of water in the SWIR region

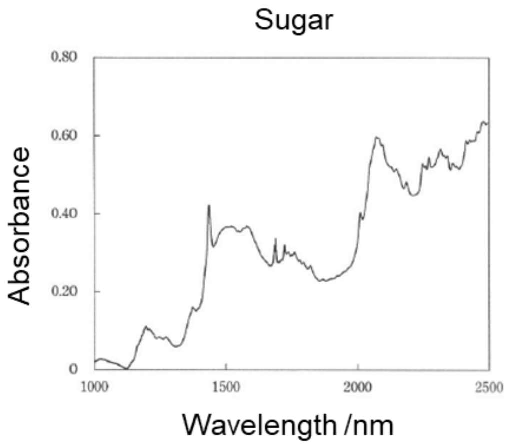

Fig. 3b Absorption of sugar in the SWIR region

On the other hand, salt does not absorb light at SWIR wavelengths. Therefore, when salt, sugar, and water are imaged in SWIR, the image in SWIR (Fig. 4b) is quite different from that seen in visible light (Fig. 4a). (Shot with SWIR light from 950 nm to 1700 nm)

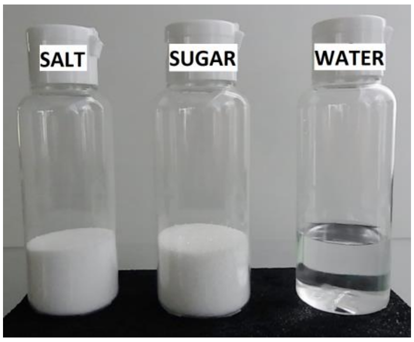

Figure 4a Shooting with visible light

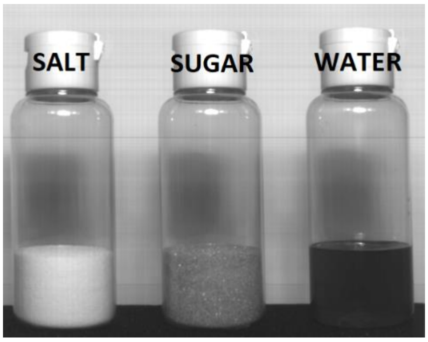

Figure 4b Shooting with SWIR light

In this way, the inspection, which was impossible with visible light, has become possible by utilizing SWIR light. Until a few years ago, SWIR cameras were not widely used because of the following reasons: the price of the sensors was prohibitive, or the size of cameras became large because the cooling mechanism to cool down the heat generated by sensors needed to be embedded. Recently, however, since infrared sensors have become less expensive and pixel-intensive, the introduction of SWIR cameras has progressed for inspection at production sites such as factory lines. The next chapter describes inspection technologies utilizing the imaging with SWIR light.

3. Imaging with SWIR light

This chapter describes sensors for detecting SWIR light, cameras incorporating sensors, lenses mounted on cameras, and lighting equipment required for imaging, which are used for inspection of industrial products and foodstuffs.

3.1 SWIR sensor

Digitization of ordinary visible light cameras has progressed over the past 30 years. It is well known that as the light detection element, CCD sensors using silicon were firstly introduced, followed by CMOS sensors, which are now widely used.

Sensors using silicon are sensitive not only in visible light but also in the infrared range from 780 nm to around 950 nm. Recently, technology has been introduced to increase the sensitivity in the infrared region, and sensors using silicon are widely used to detect infrared light at wavelengths up to around 950 nm.

On the other hand, since silicon is not sensitive at wavelengths greater than 1000 nm, compound semiconductors are instead used as materials for sensors. InGaAs (indium gallium arsenide), PbS (lead sulfide), PbSe (lead selenide), InAs (indium arsenide), InSb (indium antimonide), and etc. are currently used. Semiconductors other than InGaAs require a cooling system that increases the package size of the sensor and are still expensive. On the other hand, InGaAs has a stable manufacturing process. Sensors with low noise and multiple pixels that can operate without cooling if the wavelength is below 1700nm have been put into practical use. In addition, when the cooling system is installed, sensors that can detect the wavelength range up to around 2550 nm have been put into practical use.

3.2 SWIR Camera

In the industrial inspection field, in addition to area cameras with rectangular captured images as consumer cameras, line scan cameras (or line sensor cameras) that capture test objects on very long screens are widely used. For further information regarding line scan cameras, please refer to the whitepaper "IIoT and Industrial Line Scan Cameras" [*3)]. The following descriptions include both area cameras and line scan cameras.

Cameras for inspection using SWIR light can be classified into the following cameras depending on the number of wavelengths that the camera utilizes.

Single-wavelength (monochrome) camera: Cameras which correspond to only one wavelength band

Multi-Spectral Camera: Cameras which correspond to approximately up to 10 different wavelength bands

Hyper-spectral camera: Cameras which correspond to several hundred wavelength bands. It is viewed as an inspection for pseudo-continuous wavelength.

The following explains each type of camera.

3.2.1. Single wavelength (monochrome) camera

Monochrome cameras are cameras equipped with a single sensor that output images captured at all wavelengths detected by this sensor. As shown in Figure 2, silicon has a SWIR transmittance of nearly uniform over a wavelength band of 1,200 nm or longer. Therefore, this monochrome camera can be used for the inspection of silicon wafers and devices.

On the other hand, for many substances, absorption rates vary significantly with SWIR wavelengths, as we saw in water and sugar. In this case, to identify the test objects, it is necessary to use the specific wavelengths characteristic of the test objects from within the wavelength band covered by the sensor. There are two ways to use a specific wavelength: attaching a band-pass filter to the camera that transmits only the necessary wavelength or utilizing the illumination which emits only the wavelength of light required for inspection.

It is easy to use a filter because the wavelength can be selected simply by attaching a filter to the camera. However, the wavelength that can be used is limited to one single wavelength band. On the other hand, in the latter method, low-cost LED lighting with various wavelengths and high brightness, have become widely available. By switching the emission of LEDs with different wavelengths in time division, it becomes possible to use a single sensor to correspond to multiple wavelengths.

3.2.2. Multispectral camera

The following describes a typical multi-spectral camera structure: using prism spectroscopy and multiple filters.

a) Prism spectroscopy method

The first method is to handle multiple bands by splitting the bands with the prism, which can accommodate SWIR light. The configuration of the prism makes it possible to divide the input light into up to four wavelengths. Figure 5 shows an example of a line scan camera that splits the input light into A and B wavelength bands with a prism.

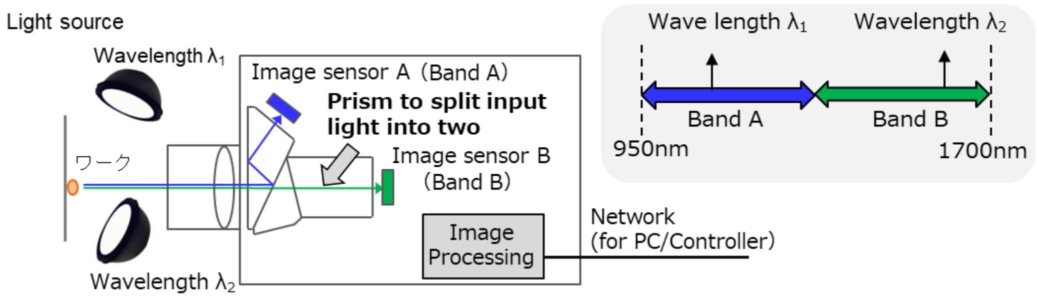

Figure 5 Configuration of spectroscopic prism camera

In this camera example, the incoming SWIR light are split with a prism into two wavelength bands A and B. By illuminating the LED that emits light at wavelengths of λ_1 and λ_2, the sensor A capture images at λ_1 wavelength, and the sensor B can capture images at λ_2 wavelengths. In chapter 4, a line scan camera equipped with two InGaAs sensors with 1024 pixels that split input SWIR light into two is introduced as an example of a spectroscopic prism camera.

b) Method using multiple filters

Multi-spectral cameras with multiple band-pass filters are used when more wavelengths that cannot be supported by prism spectroscopy need to be utilized. By changing the band-pass filter before the sensor that transmits only a specific wavelength in a time-division manner, SWIR light of various wavelengths can be detected. Figure 6 shows an example of a filter that realizes the time-division switching for filters. By rotating such filters at high speeds, images can be obtained for eight wavelengths from λ_1 to λ_8.

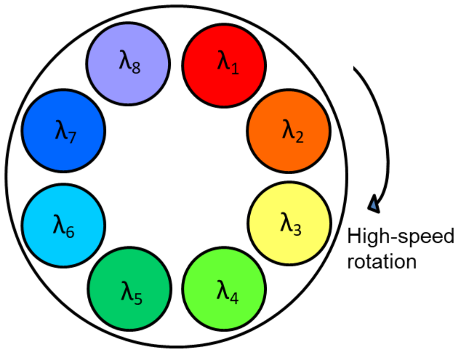

Figure 6 An example of band pass filter

3.2.3. Hyperspectral camera

Whereas the number of wavelengths that can be distinguished by a multispectral camera is around 10, the number of wavelengths that can be distinguished by a hyperspectral camera is several hundreds, which is said to correspond to pseudo-continuous wavelengths. Figure 7 shows the configuration of a general hyperspectral camera.

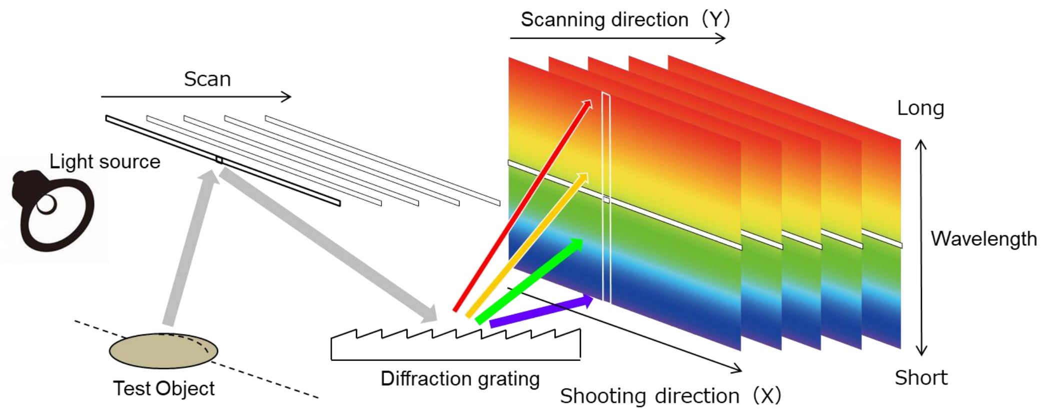

Figure 7 Example of hyperspectral camera configuration

The hyperspectral camera takes pictures of the test objects on a line-by-line basis over time. The SWIR radiation at each point on the line that captures the reflected light from the test objects is decomposed into wavelength information by devices such as a diffraction grating. The diffraction grating is a device which has a spectroscopic function. It uses the property of light that the refractive index varies depending on the wavelength and decomposes light into wavelength components. In the figure, the light of a long wavelength is shown in red, and the light of a short wavelength is shown in blue-purple. The SWIR light of one input line is expanded in a two-dimensional plane with the horizontal axis as the captured line and the vertical axis as the wavelength information. This two-dimensional information is obtained using an area sensor with sensitivity to SWIR bands such as InGaAs sensor. Further, by scanning the lines (moving the line to be captured temporally), three-dimensional information, the X plane and the Y plane in the drawing and the wavelength can be obtained.

3.3 Lens

Light has a different refractive index depending on the wavelength, as shown in the configuration example of a hyperspectral camera. Although a hyperspectral camera has been realized using this property, in the case of a lens that collects light in one location, the refractive index differs significantly between SWIR and visible light. Therefore, if the lens for visible light is used directly in SWIR light, it cannot be focused, and the performance required for inspection cannot be achieved. For this reason, a lens designed to be explicitly accommodated to SWIR or to both SWIR and visible light is needed. Furthermore, for the case of far-infrared light, the far-infrared light does not transmit materials used for visible and SWIR lenses such as N-BK7. It is necessary to change the material of the lens itself to materials that transmit far-infrared light such as germanium or silicon.

3.4 Lighting equipment

The light used in the inspection should deliver SWIR radiation at the required wavelength at the required brightness. The type of illumination required varies depending on the type of cameras. The illumination which can radiate SWIR light of only specific wavelengths is required when the SWIR wavelengths needed is already determined, such as the case of monochrome or multispectral cameras (Case A). In contrast, the illumination which can radiate SWIR light of continuous wavelengths is required when test objects need to be irradiated by SWIR light of continuous wavelengths in a band measured, such as the case of hyperspectral cameras (Case B).

Firstly, in case B, incandescent lamps or halogen lamps that can radiate the SWIR light with continuous wavelengths in a band measured are commonly used. Both lamps are capable of continuously irradiating a wide range of wavelengths from visible light to SWIR light. Halogen lamps are mainly used for industrial inspections that require long periods of operation. As for halogen lamps, a trace amount of halogen gas such as iodine and bromine is introduced into the inert gas encapsulated in the lamp, thereby extending the lamp's life and providing a higher brightness than incandescent lamps.

Even when the wavelength to be measured is predetermined as in monochrome and

multispectral cameras in case A, it has been prevalent in the past to use a halogen lamp for illumination and use a band-pass filter to transmit only the light of wavelengths to be measured.
However, in recent years, the brightness of the infrared LEDs has significantly improved: the number of available wavelengths has been increasing, the lifetime has been increasing, and the cost has been lowered. Therefore, the use of LEDs that emit SWIR light has increased for the illumination for imaging by monochrome cameras and multispectral cameras.

4. SWIR line scan camera from CMICRO Corporation

CMICRO Corporation, a major Japanese company in the industry of line scan cameras, commercializes NHB050H equipped with one InGaAs line sensor with 512 pixels and NDB100H equipped with two InGaAs line sensors with 1024 pixels. In this chapter, we introduce NDB100H, which was put on the market in June 2020. The camera split input SWIR light into two using a prism.


NDB100H

The main specifications are as follows.

Physical Characteristics/Operating Range	Unit	
Sensor type	-	Single line InGaAs sensor × 2
Resolutions	pixels	1024
Spectral wavelengths	nm	Sensor (S): 900～1400 Sensor (L): 1400～1700
Pixel size	μm	25 x 25
Lens mount	-	F mount / M52 mount
Size (without lens mount or connector)	mm	90×90×88(WxHxD) (Camera Link) 90×90×121.6(WxHxD)(GigE Vision)
Weight (excluding lens)	g	1000 (TBD)
Data output format	-	Camera Link (Base Configuration) / GigE Vision
Data rate (Camera Link output clock)	MHz	60 / 40 (Camera Link)
Line rate	kHz	Max: 40
Data format	bit	8/10/12
Operating temperature	deg C	Min:0 Max:45
Input voltage	DC V	Typ. 12 ～ 24

NDB100H splits input SWIR light into two bandwidths at 1400nm wavelength. The camera can run at up to 40KHz line scan rate. Two models, one with Camera Link interface and one with GigE Vision interface, are provided.

It is more than happy if you can consult with CMICRO Corporation if you have a test object which you could not inspect it well using visible light, but which you think that you might be able to inspect it well using SWIR light after you read this paper.

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