WG51S2 Infrared Sensor

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There are two methods for online film thickness measurement, the contact type and the non-contact type. Most measurement systems use the non-contact type to avoid damaging the product. The non-contact type includes the radiation type such as β-ray or X-ray, and the infrared type. Use of the infrared type has increased in recent years to prevent radiation exposure, and in line with this market trend Yokogawa has developed a non-contact-type film thickness sensor using infrared radiation.

Utilizing recent progress in thin films, Yokogawa has achieved high measurement accuracy and robustness equivalent to radiation-level quality based on Yokogawa's specific optical system. This paper describes the new product and its technology which can handle various sheet materials such as paper, film, composite materials, and other materials.

INTRODUCTION

Driven by the increased demand for electric vehicles (EVs), the functionality of films and sheets used for the separator sheets of secondary batteries is being upgraded, and their thickness is becoming thinner. Meanwhile, instrumentation systems must avoid using radioactivity to help protect people's lives, in line with the sustainable development goals (SDGs).

Since 1962, Yokogawa has been offering thickness gauge systems that accurately measure the thickness of films and sheets online in coating equipment, display thickness distribution graphs (profiles), and automatically control coating systems to achieve good coating uniformity. Yokogawa has the largest share of this market in Japan. In 2015, Yokogawa released the latest model, the WEBFREX NV online thickness gauge.

As a solution in the OpreX™ Quality Control System family, the newly developed WG51S2 online infrared sensor is used with the WEBFREX NV to measure the thickness of films and sheets. With the WG51S2 and its proprietary optical system, Yokogawa has achieved high measurement accuracy and robustness that are equivalent to the performance of models using radioactive rays.

Figure 1 shows the external view of the WG51S2, and Table 1 shows its major specifications. In Table 1, "previous model" refers to the WG31S1. This paper introduces the technologies developed and used for the WG51S2, in comparison with those used for Yokogawa's previous model.

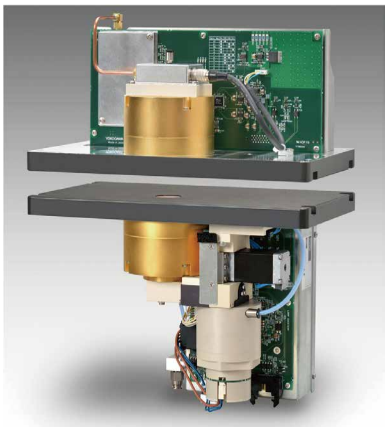

Figure 1 External view of the WG51S2 infrared sensor

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Table 1 Major specifications

Item	Previous model (S1)	WG51S2 (S2)
Light source	Electrically heated wire	Halogen lamp
Photodetector	PbS	InGaAs PIN-PD
Wavelength discrimination method	Rotating turret –	Frequency modulation Lock-in amplifier
Thickness measurement range	(10) to 2,000 μm Haze film: Not measurable Multilayer: Not measurable	10 to 2,000 μm Haze film: Measurable Multilayer: Partly measurable
Average value repeatability	Within ± 0.2 μm or ± 0.2%, whichever is larger –	Within ± 0.2 μm or ± 0.2%, whichever is larger Max. accuracy: ± 0.1 μm*1
Sampling	About 13 ms –	0.25 ms Simultaneous measurement of different frequencies at the same area
Measurement light	Parallel light	Diffused light
Method of preventing thin film interference	–	Angle averaging method
Elimination of disturbance light and thermal radiation	–	Lock-in amplifier
Allowable pass-line fluctuation	± 2 mm	± 10 mm

*1 Polypropylene (PP) film of 20 μm thickness

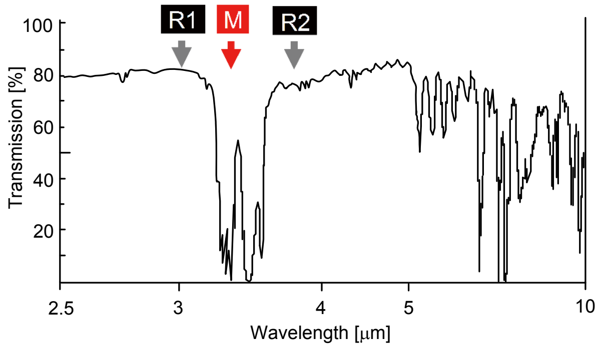

Figure 2 Infrared absorption spectrum of polystyrene film

PREVIOUS INFRARED THICKNESS SENSORS

Measurement Principle

Measurement objects have characteristic absorption spectra depending on their materials and components. Infrared thickness sensors calculate the thickness of objects based on the dependence of infrared radiation intensity absorbed (decayed) by the object on the thickness of the object that the infrared radiation passes through.

Absorption of infrared radiation due to vibration-rotation of CH groups in polymer molecules is used for measuring the thickness of polymer films.

Figure 2 shows an infrared absorption spectrum of polystyrene film. Yokogawa uses the absorption at the wavelength, M, after being corrected by using the light intensity at the reference wavelengths, R1 and R2, to eliminate the effect of haze of materials and variation in the relative position of the sample sheet with respect to the sensors (pass-line fluctuation), for measuring the film thickness accurately and stably.

Structure of Previous Thickness Sensors

Figure 3 shows the structure of previous thickness sensors. Three optical filters mounted on a disc selectively transmit light of specific wavelengths, M, R1, and R2, respectively. The disc is rotated by a motor (at several thousand rpm), and transmits light rays of three wavelengths sequentially. The light rays illuminate the object, after being reflected by a mirror, and are detected by a photodetector placed on the opposite side of the object.

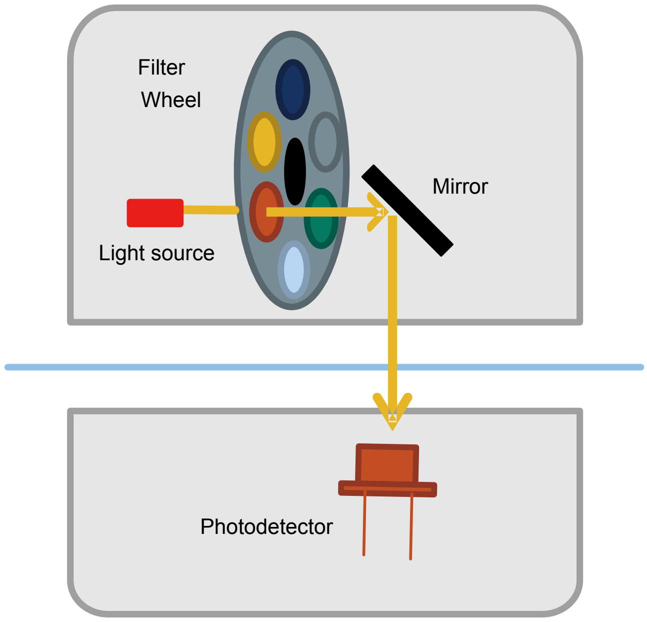

Figure 3 Structure of previous thickness gauges

Problems

In the previous sensors, the light rays of three wavelengths, R1, M, and R2, illuminated a traveling film sequentially. Since the film is traveling, the spots illuminated by the light rays of three wavelengths are not exactly the same, as shown in Figure 4. Thus, the correction is calculated using the results from different spots, and cannot eliminate the effect of haze film and pass-line fluctuation completely. This limits the accuracy of measurements using the previous sensors.

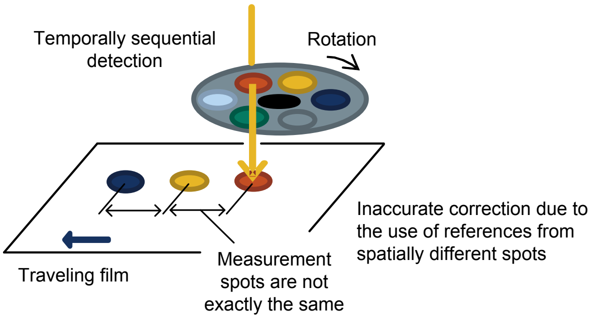

Figure 4 Problem of measuring different spots

Another factor for the limited measurement accuracy is the pass-line fluctuation during measurement, which means the temporal fluctuation in the position of the traveling film between the light source and the detector heads, in the measurement configuration in which a film travels through the gap between the two heads. The measurement value of film thickness depends on the position of the traveling film between the heads. The allowable pass-line fluctuation is within ± a few mm for most thickness sensors, including those of Yokogawa and its competitors, although the exact figure depends on the measurement method and correction method. Rollers and film guides may be used for reducing the pass-line fluctuation, but may cause scratches on the film.

Another problem, which is not directly related to the structure of thickness sensors, is the thin film interference, which is a periodic variation in the intensity of transmitted light, caused by the interference of light reflected by the front and the rear surfaces of a thin film. Figure 5 shows the variation in the intensity of reference light due to thin film interference. The effect of interference is more noticeable for thinner films, making the reference light intensity unstable and hence the calculation of absorbed light intensity inaccurate.

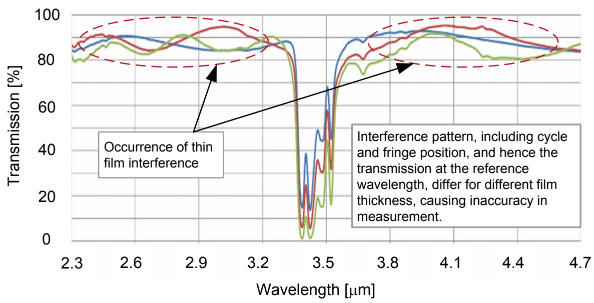

Figure 5 Disturbance in reference light intensity due to thin film interference

Manufacturers of thickness sensors take various countermeasures in their optical systems to suppress the effect of thin film interference. A typical countermeasure is the method of "p-polarized light incident at Brewster's angle." This method aims to suppress thin film interference by minimizing light reflection at film surfaces, making p-polarized light incident on the film surface at Brewster's angle. However, the effect of this method is limited especially on biaxially stretched films, which are the most commonly used today, due to the bowing phenomenon.

The bowing phenomenon is the inconsistency of film characteristics of the center and the edge of the film, caused by the non-uniformity in the stretching force both in magnitude and direction, during biaxial stretching processes. Optically, the result of bowing is non-uniform in-plane distribution of birefringence and the angle of maximum refractive index (molecular orientation angle) (Figure 6).

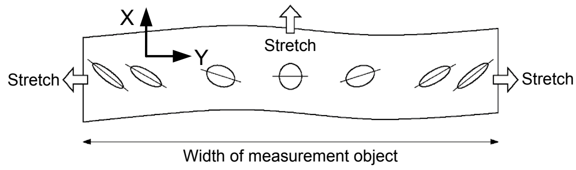

Figure 6 Bowing phenomenon and rotating molecular orientation

Figure 7 shows the results of measuring transmission at two different molecular orientations using a Fourier-transform infrared spectrophotometer (FTIR). Although the spectra were measured at the condition of Brewster's angle of incidence of p-polarized light, the transmission varies with rotation of the sample. Thus, the method of p-polarized light incident at Brewster's angle is not sufficient for effectively suppressing the effect of thin film interference, because the bowing phenomenon cannot be eliminated completely in the film production process.

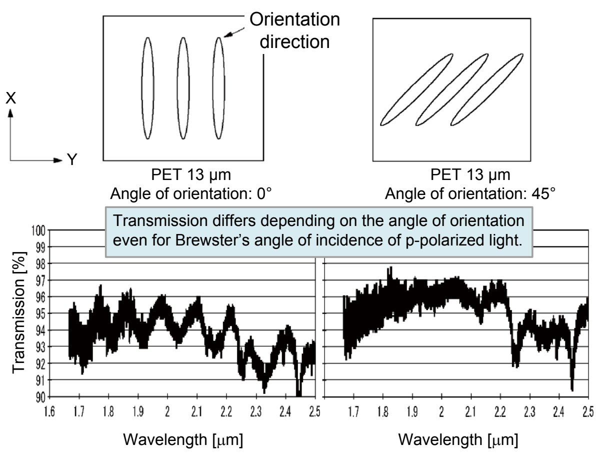

Figure 7 Relation of transmission characteristics and molecular orientation measured by FTIR

NEW INFRARED THICKNESS SENSOR

The newly developed WG51S2 infrared sensor has the following features.

1. High accuracy of up to ±0.1 µm
2. Designed for easy maintenance and good compatibility with the previous models

The technologies that have enabled the first feature are described below; details of the second feature will be described later.

High accuracy of up to ±0.1 µm

The WG51S2 offers significantly improved accuracy and measurement stability owing to its unique optical system consisting of a frequency-modulated light source and dual-integrating spheres combined with a digital lock-in amplifier circuit for weak-signal detection. The WG51S2 enables stable and high accuracy (within ±0.2 µm or ±0.2%, whichever is larger) measurements of film thickness for a wide range of samples, from thin films (10 µm thick) to thick films (2,000 µm thick). The maximum accuracy achieved in measuring polypropylene film of 20 µm thickness is within ±0.1 µm. The WG51S2 is also applicable to a wide variety of measurement objects, including transparent, opaque, and foamed films. The new measurement method minimizes the effect of pass-line fluctuation of film samples and external thermal disturbances on measured values, and enables highly reliable measurement of fast-traveling films.

Frequency-modulated Light Source

The newly developed light source modulates the light from the source by a different method from that used in the previous model, the filter turret method. The measurement light is modulated at three different frequencies, and light rays of three different wavelengths are selectively transmitted through three bandpass filters and illuminate a spot on the sample film after being color-mixed in integrating spheres. Figure 8 shows the configuration of the frequency-modulated light source. The new light source solves the problem of measuring different spots in the conventional thickness sensors.

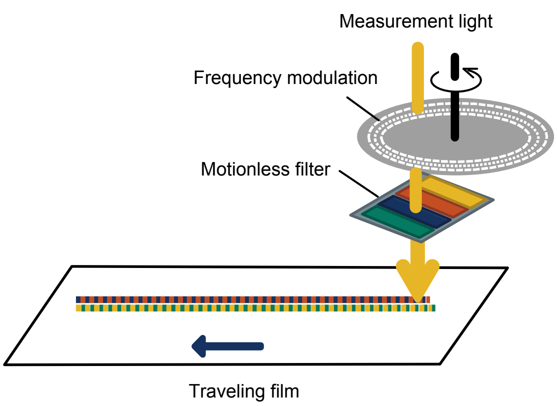

Figure 8 Configuration of frequency-modulated light source

Dual-integrating Spheres

The WG51S2 features two integrating spheres, one on the light source side and the other on the detector side. The infrared radiation from the source passes through the sample film from the first integrating sphere into the second integrating sphere. Then, the second integrating sphere, while sending part of the light to the detector, serves as the secondary light source and sends the light back to the first integrating sphere through the film. The light that comes back to the first integrating sphere is again reflected by the inner wall and passes through the film for the third time. Thus, the incident light passes through the film multiple times, enabling a high S/N ratio when measuring thin films. Figure 9 shows the configuration of the dual-integrating spheres.

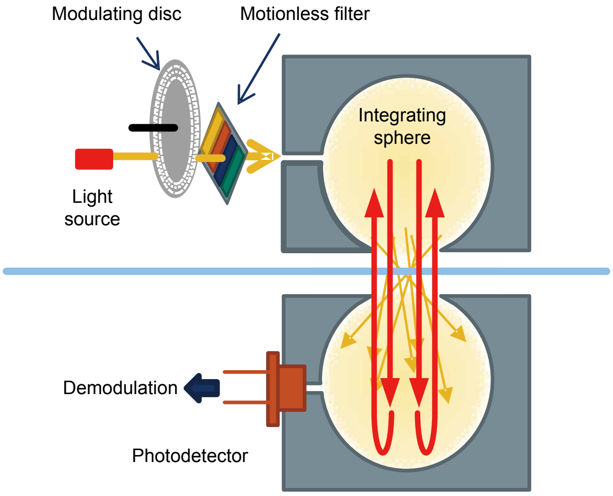

Figure 9 Configuration and principle of dual-integrating spheres

A remarkable advantage of the dual-integrating spheres is that the wide-angle, omnidirectional illumination of films by diffused light averages out the effect of thin film interference. This is called the angle averaging method, which is achieved by the use of the dual-integrating spheres. The wide-angle, omnidirectional infrared radiation of 0 to 45° angle of incidence from the integrating spheres is ideal for achieving the angle averaging method and suppressing thin film interference stably and reliably. The use of diffused light also makes the system tolerant to optical misalignment, and hence can reduce measurement errors significantly in online measurements involving moving heads.

Yokogawa has patented this unique optical system with dual-integrating spheres in Japan (Patent number P6394825).

Digital Lock-in Amplifier

The WG51S2 uses a high-performance digital lock-in amplifier to extract the signal of a particular frequency from the measured signal including noises. The signal received by the detector is discriminated by multiple demodulators for analyzing multiple signals at different frequencies simultaneously. Although integrating spheres lose much light intensity, the optical system of dual-integrating spheres has been achieved by the use of a digital lock-in amplifier that compensates for the loss in light intensity by its high sensitivity.

Pass-line Fluctuation

The optical system with dual-integrating spheres cancels out the effect of fluctuation in the position of the film, because the light goes through the film from the light source side to the detector side and in the reverse direction repeatedly. Thus, the system is highly tolerant to pass-line fluctuation, allowing a maximum pass-line fluctuation of ±10 mm, compared with ± several mm for conventional thickness sensors. Measurements with the WG51S2 are hardly affected by the shaking of film movement, wrinkles, and curling at the film edge. The WG51S2 outperforms the thickness sensors of competitors in terms of the allowable pass-line fluctuation.

Disturbing infrared radiation

One cause of measurement errors is thermal emission from the film itself, which is produced at high temperature, and ambient infrared radiation in the environment coming into the infrared detector of the sensor. To protect measurements from such external disturbances, the frequency limit function of the lock-in amplifier eliminates the effect of thermal fluctuation of up to approx. 15 Hz.

Easy Maintenance and Good Compatibility with Previous Models

The use of a frequency-modulated light source has eliminated the use of mechanical parts whose lifetimes are limited. The only maintenance part is the light source block, which customers can replace easily without the need for adjustment. Compatibility with the previous model of infrared thickness gauges is maintained, and users of the WEBFREX NV can attach the WG51S2 sensor on the existing frame.

MEASUREMENT EXAMPLE

Figure 10 shows an example of measuring the thickness of a polyethylene sheet of about 550 mm width and 30 µm thickness.

The upper half of the figure (cyan line on black background) shows an overlay of 10 raw data without averaging procedure obtained by the WEBFREX NV thickness gauge equipped with the WG51S2 infrared sensor. The results show excellent repeatability. The data contain less noise than from thickness gauges using β- or X-ray. Therefore, the temporal averaging procedure is not required, which enables measurements with a fast response. Thus, the WG51S2 can meet future requests for higher speeds of sheet traveling and scanning.

The lower half of Figure 10 compares the results of thickness measurement by the WG51S2 (average of 10 measurements) and an X-ray sensor that has a solid track record. Profiles of both data show excellent agreement.

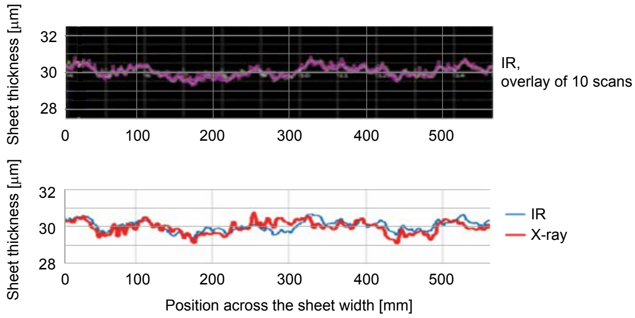

Figure 10 Measurement results of a polyethylene sheet (sample test)

CONCLUSION

With Yokogawa's proprietary dual-integrating spheres, the newly developed WG51S2 infrared sensor has achieved high measurement accuracy and robustness. Yokogawa will continue to expand the range of its applications, as the core component sensor for avoiding the use of radioactivity, aiming to achieve the SDGs. Yokogawa will continue to respond quickly to customers' transformations in management and operation, and to offer outstanding reliability to support their efficient, high-quality, safe, and stable operation bases.