Development of High Performance LED Light Source Unit, and Its Applications

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This article presents the development of an LED light source unit for rotary encoder and its applications. Using the developed light source, optical characteristics of rotary encoders have been much improved. Besides, temperature characteristics and durability to humidity have been improved. This high-performance optical unit has realized high-resolution, compact, adjustment-free, high reliability, and other various advantages to encoders without increasing the cost.

Key Words: rotary encoder, LED, interference, diffraction, luminous flux

1. Introduction

Koyo previously made an attempt to improve resolution of rotary encoders by narrowing the light beam using FZP (Fresnel Zone Plate)\(^1\).

The result showed that a wavefront-reconstruction type optical element, wherein the pitch of the index scale coincides with that of the main scale, can outperform the light-concentration type optical element not only in practical application and manufacturing facility, but in terms of the light utilization efficiency and the interphase accuracy of an encoder signal.

This time, therefore, a project has been set out to develop a new rotary encoder light source utilizing the phenomenon that the slit image is reproduced at positions determined by the wavelength of the illuminant and the slit pitch. While the development was aimed at improvement in resolution of rotary encoders, it was also expected to allow the use of film slits for low resolution encoders on which control of the distance between the main slit plate and the index slit plate (hereinafter called slit plates’ distance) is relaxed. Thus, the newly developed light source has been designed to be widely applicable for a broad range of rotary encoders.

2. Optical Design

Conventionally, as far as a slit shutter type is concerned, it has been established that the smaller is the slit plates’ distance, the better is its performance. However, in a system that proactively utilizes the interference due to diffracted light, the slit plates’ distance is designed at the distance\(^2\) \(Z_0 = n \cdot \frac{p^2}{\lambda}\) where the image of the index scale is formed, as expressed below.

\[ Z_0 = n \cdot \frac{p^2}{\lambda} \]  \hspace{1cm} (1)

\((n: \text{a positive integral number}, p: \text{slit pitch}, \lambda: \text{wavelength of light source})\)

In order to form a diffracted image, it is imperative that the light passing through the slit should be a plane wave. To this end, the luminous flux emitted from the lens must not only be parallel, but also be appropriate in terms of its phases. Then, an aspherical lens was newly developed by resin molding process.

As the material for the lens, a cycloolefin type resin, ZEONEX, was applied, which excels in reliability and optical properties at high temperature and in high humidity. Its typical properties are shown in Table 1 compared with commonly used PMMA (polymethylmethacrylate) and PC (polycarbonate).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>PMMA</th>
<th>PC</th>
<th>ZEONEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmissivity, %</td>
<td>92</td>
<td>87~90</td>
<td>92</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.492</td>
<td>1.567</td>
<td>1.525</td>
</tr>
<tr>
<td>Index of birefringence</td>
<td>10~20</td>
<td>40~80</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Thermal distortion temperature, °C</td>
<td>100</td>
<td>138</td>
<td>123</td>
</tr>
<tr>
<td>Glass transition temperature, °C</td>
<td>105</td>
<td>140</td>
<td>138</td>
</tr>
<tr>
<td>Water absorption (saturated), %</td>
<td>2.0</td>
<td>0.4</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

To positively utilize the diffraction, the lens was carefully designed to provide high luminance of emitted luminous flux, as well as to improve uniformity of the quantity of light within the effective illuminating area diameter. In fabrication, special attention was paid to minimize RMS wave aberration, setting the target at RMS 0.2 \(\lambda\) maximum.

In order to evaluate the errors of shot in the plastic molding process, sampling inspection was conducted for sampled lenses during 200 to 10 000 pieces molding. The error was evaluated in terms of magnitude of RMS wave aberration. Figure 1 shows the result of this inspection, which is a satisfactory level of wave aberration.
3. Prototyping of Light Source Unit

3.1 Target of Development

It was found that conventional light emitting units could not provide adequate optical properties required to attain such targets as; productivity improvement by expansion of slit plates’ distance, and moderation of its accuracy requirement; preparation of film as high resolution slit plate; and availability for diffraction element. Therefore, Koyo decided to develop a high performance light emitting unit which could assure both high parallelism of luminous flux and uniform distribution of luminous intensity, as shown in Table 2.

### Table 2: Target specification of LED assembly to develop

<table>
<thead>
<tr>
<th>Classification</th>
<th>Comparison</th>
<th>Optical property</th>
<th>High output</th>
<th>Long life</th>
<th>Environmental durability</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>Long (infrared)</td>
<td>( \triangle ) (coherence: less)</td>
<td>–</td>
<td>( \triangle ) (activation energy high)</td>
<td>( \triangle ) (Al corrosion)</td>
<td>( \triangle ) (less available in market)</td>
</tr>
<tr>
<td>Size of luminant</td>
<td>Large</td>
<td>( \triangle ) (parallelism less, coherence less)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>( \triangle ) (less available in market)</td>
</tr>
<tr>
<td>Shape of luminant</td>
<td>Rectangular</td>
<td>( \times ) (uneven)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Structure</td>
<td>Standard (center electrode)</td>
<td>( \times ) (shadow of wire)</td>
<td>( \triangle )</td>
<td>( \triangle )</td>
<td>( \triangle ) (current density high)</td>
<td>( \triangle ) (less available in market)</td>
</tr>
</tbody>
</table>

3.2 Selection of LED Chip

In order to select an LED chip best suited for the development, various types of red ~ infrared LED chips commonly used as light sources on optical sensors were classified in terms of (1) wavelength, (2) size of light emitting area, (3) shape of light emitting area and (4) structure. These were carefully studied in preliminary tests with respect to several characteristics related to the purpose of this development (Table 3).

Concerning the wavelength of the emitted light ray, an infrared LED of three-element type (AlGaAs) was compared with a red LED of four-element type (InAlGaP). Although the half-value width of the red LED spectrum is approximately half as small as that of infrared LED and is better suited in optical properties including higher coherence, it has various problems in such aspects as compatibility with spectral sensitivity of a light detecting element (photodiode), service life, environmental durability and actual usage. Finally, an AlGaAs infrared chip with a luminous peak at the wavelength of 860 nm was selected.

Although a smaller diameter of the light emitting area is preferred for parallelism of the luminous flux, the difference in performance between two available diameters, \( \phi \) 0.05mm and \( \phi \) 0.15mm, is insignificant except for applications utilizing diffraction positively. Therefore, a chip with light emitting area diameter of \( \phi \) 0.15mm is considered more suited because of its luminous output and life.

Concerning the shape and structure of the light emitting device, conventional rectangular design with wire bonded electrode at its center is considered inappropriate for applications requiring high optical performance, because shadows of the wire causes irregularity of luminous intensity. Instead, an LED chip with circular light emitting point incorporating current constriction structure was adopted (Fig. 2).
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3.3 Optical Evaluation of Light Source Unit

First, the prototype light source unit (Fig. 3), fabricated by mounting the LED chip on a stem and attaching to the newly developed resin molded cap lens, was evaluated with respect to optical properties of the unit itself.

3.3.1 Parallelism of Luminous Flux

Parallelism of luminous flux was evaluated based on the definition of "light divergence angle (θ)" as illustrated in Fig. 4. The test on the final LED illuminant prototype resulted in the divergence angle as small as 0.3~0 deg., which proved the high parallelism of the luminous flux as compared to that of 2.4 degree with the conventional unit.

3.3.2 Effective Illuminated Area Diameter and Uniformity of Luminous Intensity Distribution

Both the effective illuminated area and the uniformity were evaluated by way of profiling the luminous intensity distribution as shown in Fig. 5. The final developed illuminant prototype achieved an effective illuminated area of 4.50~4.60mm and variation of luminous intensity as small as 10% p-p or less, both of which satisfied the targets.

3.3.3 Influence of Assembled Lens Height Variation

In order to determine how accurately the molded resin cap lens should be mounted on the stem, the relationship between the assembled lens height and the light divergence angle was investigated. As a result, it was found that the light divergence angle changed with the assembled height of the lens at a rate of -9.13 deg./mm and the assembled height need to be held within ±0.055mm to control the light divergence angle within the target range of ±0.5 deg (Fig. 6).

As far as the prototype sample (n = 30) used for this investigation are concerned, the 3σ variation of the assembled height was approx. 0.014mm which corresponds to variation of the light divergence angle ±0.12 deg. at ±3σ.

3.3.4 Optical Performance of Illuminant Unit

A typical example of a slit image and its luminous profile are shown in Fig. 7.

Figure 8 shows how the optical contrast changes depending on the distance from the slip plate, wherein the optical contrast is defined by the following equation based on the peak and bottom luminosity values, \( I_{\text{max}} \) and \( I_{\text{min}} \), respectively.

\[
C = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}
\]
With conventional illuminants, optical contrast diminished monotonously with the increase of distance from a slit plate. With the newly-developed prototype illuminant, on the other hand, the optical contrast produced by 20 𝜇 m slits started to rebound at the distance of 250 𝜇 m and peaked around 450 𝜇 m where the diffraction image was formed, though it diminished straight with 40 𝜇 m slits.

On the contrary, an increase of slit pitch \( p \) causes the slit plates' distance \( Z_n \) to increase in proportion to \( p^2 \). A too large slit pitch hence is impractical.

Supposing that usable range of diffraction image is to be held within 300 𝜇 m from the slit plate, the threshold slit pitch to use diffraction positively is \( p = 16 \) 𝜇 m. If a slit pitch is larger than that is used, the conventional approach of narrowing the distance is more desirable.

### 4. Evaluation as Mounted on Rotary Encoders

The developed prototype illuminant unit was mounted on a conventional rotary encoder replacing the existing illuminant unit therein and its electrical performance was comparatively evaluated.

#### 4.1 Influence of Distance between Main Slit Plate and Index Slit Plate (Slit Plates' Distance)

To evaluate the electric output from the photodiode which receives the optical signals, an oscilloscope was used to measure the voltage waveform of the analog output as shown in Fig. 11, on which the ratio of the wave amplitude, \( a - b \), to the background, \( b \), was defined as the S/N ratio \( [(a - b)/b] \). In this way, the relation between the distance between the main and index slit plates and signal S/N was evaluated. This measurement was conducted on both the conventional and the developed prototype illuminant units with varied slit plates' distance.

![Waveform of PD analog output](image)

The resultant S/N ratios are plotted on Fig. 12. Although the signal amplitude was about the same, the S/N ratios produced with the developed illuminant unit stayed at a high level. It is especially noticeable that while the conventional illuminant unit produced S/N ratio of 3 at the design slit plates' distance of 0.3mm, the developed illuminant unit provided an equal or better S/N ratio at the slit plates' distance of 0.8mm.

Consequently, it was found that the development would be significantly effective in expansion of slit plates' distance, as well as in moderation of its accuracy requirement.
4. 2 Temperature Characteristics

The rotary encoders were tested at different ambient temperatures from 0°C to 80°C, while measuring the analog output from the PD. As a result, the developed unit showed extremely small reduction of output compared to that of the conventional illuminant unit (Fig. 13).

4. 3 LED Deterioration Simulation Test

In order to evaluate the effect of LED deterioration, a test was conducted with the LED luminous output reduced down to 15% of its original. The result was extremely favorable showing no influence on A – B phase difference, or on A – B phase pulse duty (Fig. 14).

4. 4 Application to High Resolution Slits

In order to apply the developed LED unit to a high resolution slit, it was combined with a film slit plate of 2 048 pulses. The attained S/N ratios at various slit plates’ distances are as plotted in Fig. 15, based on which it is expected to produce an S/N ratio close to 3 at the slit plates’ distance of 0.2 mm, whereas the conventional LED produced almost zero S/N ratio. This S/N ratio of 3 was equivalent to that obtained by the conventional LED assembly combined with a 512 pulse slit plate, implying that almost four times as high resolution as the conventional illuminant unit is attainable with a film made slit plate.

Furthermore, an additional test to apply the developed illuminant unit to 4 096 pulses (p = 20 µm) and 8 192 pulses (p = 10 µm) was conducted together with a conventional illuminant unit for comparison. The S/N ratios obtained in these tests are shown in Fig. 16.

Note that the slit plates’ distance for the 10 µm slit pitch was 120 µm in accordance with the equation (1), whereas for p = 20 µm unit, the same 60 µm spacing as for the conventional unit was used.

From these findings, it was confirmed that the developed illuminant unit with 4 times as high resolution slit as that on conventional unit could produce an equivalent S/N ratio. On top of that, the slit plates’ distance can be twice as large allowing significant moderation of control for the spacing in the assembly process. In the case of 20 µm slit pitch, or doubled resolution slit, substantial improvement in S/N ratio was confirmed, even though diffraction image was not available.
5. Application Examples to Products

A couple of examples where the developed high performance LED are incorporated in mass-production rotary encoders are introduced below:

5.1 Encoder for Integration in Thin Electric Motor

Boundary dimensions: 44 × 36mm (Fig. 17)
Resolution: 8,192 ppr (optical 4,096 ppr)
- Size down of the encoder to 1/2 OD compared with conventional type with the same resolution
- Improvement of optical resolution by 1.6 times compared with conventional type with same OD (conventional illuminant unit failed to produce normal output)
- Elimination of LED position adjustment structure allowed reduction of thickness by 11mm
- Expansion of the slit plates’ distance and moderation of accuracy improved productivity

5.2 High Resolution Encoder for Servo Motors

Boundary dimensions: 36.5 × 26mm
Resolution: 2,048 ppr (optical)
- Four times increase of the slit plates’ distance and replacement of glass-made rotating slit plate with film slit plate helps cost reduction.
- Requirement for adjustment of pulse duty on A – B phase is eliminated (on the conventional units, the signal variation due to light ray inclination and un-uniformity of light intensity were so large that duty adjustment by variable resistor was required.).
- Adjustment of print board position not required

6. Conclusions

Development of a high precision illuminant unit has succeeded in improving the optical properties of rotary encoders.

This improvement has not only enabled rotary encoders to be designed compactly and with higher resolution, but to produce stabilized output of pulses even when the illuminant is deteriorated.

Moreover, moderation of the slit plates' distance accuracy has made film slit available, which would lead to further reduction of inertia. In manufacturing, too, it provides such significant benefit as elimination of matching in assembly and doing away with optical as well as electrical adjustment due to uniform illumination.

Throughout the development, close attention was paid to improvement of general reliability of the products, as exemplified by careful selection of lens material and LED chip to improve their high temperature performance as well as resistance to heat and humidity.

In the future, Koyo will continue the research into visible light LED's that will be beneficial in handling and optical properties, together with development of photodiodes for visible light. Hopefully, Koyo will keep supplying reliable encoders that are the key device for motion control.

References