Spectral matching imager using amplitude-modulation-coded multispectral light-emitting diode illumination

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Abstract. We propose a spectral matching imager using light-emitting diodes (LEDs) of narrowband spectral power distributions. Each spectral channel of the LED illumination undergoes amplitude modulation (AM) with one of an orthonormal set of carrier signals. This imager, which employs the correlation image sensor (CIS) as its imaging device, performs spectral correlation pixelwise between a reference spectrum and that of the object in every frame by demodulating the orthonormal AM carriers via temporal correlation. This sensing principle enables a higher efficiency in the use of illumination power than the spectral matching imager we originally proposed. A twelve-channel AM-coded multispectral light source is developed by assembling commercial LEDs. Under this LED light source, experiments were carried out on pairs of glass pieces of a similar color, but with different spectral transmittance functions. The results confirmed that the proposed imager successfully performed spectral matching on each pair of glass pieces in real time. © 2004 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1666679]

Subject terms: correlation image sensor; spectral matching; spectral imaging; colorimetry; material identification; inspection; counterfeit detection; watermarking.

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1 Introduction

Spectral properties of materials, which usually originate from distinct chemical composition or geometrical micro- or nano-structures, allow the materials to be identified easily. The most exact identification is done by spectral matching, i.e., correlation matching of the spectral reflectance or transmittance of the object material \( R(\lambda) \) to a reference spectrum \( R_0(\lambda) \), based on the matched filtering principle:

\[
\int_{\lambda} R(\lambda)R_0(\lambda)d\lambda \leq \left[ \int_{\lambda} |R(\lambda)|^2d\lambda \right]^{1/2} \left[ \int_{\lambda} |R_0(\lambda)|^2d\lambda \right]^{1/2}.
\]

where \( \lambda \) denotes the wavelength range of interest. We can hence identify a particular material by examining whether the correlation reaches the maximum to satisfy the equality in Eq. (1), which holds when \( R(\lambda) = K \cdot R_0(\lambda) \) (\( K: \) constant), i.e., when the spectrum of the object exactly matches the reference spectrum except scale.

For the purpose of realizing spectral matching with high spectral resolution in real time, we proposed the spectral matching imager,\(^{14,15} \) which can perform spectral matching pixelwise under a conventional frame rate. This imager consists of the time-domain correlation image sensor (CIS),\(^{16–19} \) which produces the temporal correlation between the incident light intensity \( f_{ij}(t) \) and the global reference signal \( g(t) \) over a frame interval \( T \) at each pixel \((i,j)\):
Using this device, the spectral matching imager performs correlation matching pixelwise between the spectral reflectances or transmittances in the scene and a reference spectrum in the time domain.

The key consideration about the spectral matching imager consists in active illumination to convert the spectral information into the time domain. In the originally proposed imager, we introduced variable wavelength monochromatic illumination, which sweeps its peak wavelength along with time by mechanically scanning a light flux diffracted from a white light. A problem with this illumination is poor efficiency in the use of illuminant power, since only a small portion of the whole illuminant spectrum is used at a time as the effective illumination.

To increase the power efficiency, we propose amplitude modulation (AM)-coded multispectral illumination, which modulates each spectral component with one of an orthonormal set of AM carriers. This allows all the spectral components to be used as illumination at the same time, because each spectral component can be demodulated independently by the CIS. We develop AM-coded multispectral illumination using commercially available light-emitting diodes (LEDs). Modulated LED illumination was originally introduced to color imaging by Xiao et al. for RGB color imaging with a monochrome image sensor and separation of ambient illumination. Here we multiplex twelve spectral channels with narrowband LEDs for real-time spectral matching on the CIS using much higher AM frequencies than those used in Ref. 22.

In the following, we first present the theory of AM-coded spectral matching. Next, we describe the experimental system we fabricated, with emphasis on a twelve-channel AM-coded multispectral LED light source. We then demonstrate and discuss experimental results of real-time spectral matching of colored glass pieces obtained with the fabricated system, and finally give conclusions.

2 AM-Coded Spectral Matching

2.1 Spectral Matching via AM Demodulation

Consider the imaging system in Fig. 1. The AM-coded multispectral illumination consists of \( N \) channels of spectral bands, each of which is assumed to be narrow enough to be characterized by its peak wavelength \( \lambda_k \) \((k=1, \ldots, N)\). Moreover, each channel is amplitude modulated with a carrier signal \( a_k(t) \) that constitutes an orthonormal set:

\[
\langle a_k(t) a_l(t) \rangle = \delta_{kl}, \quad \langle a_k(t) \rangle = 0, \quad (k, l=1, \ldots, N),
\]

where \( \langle \cdot \rangle \) denotes time averaging or frame integration, and \( \delta_{kl} \) the Kronecker’s delta. The spectral power distribution of the illumination is then expressed as

\[
E(\lambda, t) = \sum_{k=1}^{N} \left[ a_k(t) + b_k \right] E_0(\lambda_k) \delta(\lambda - \lambda_k),
\]

where \( E_0(\lambda_k) \) denotes the illuminant intensity at the \( k \)’th channel and \( b_k \) a dc bias term. This illumination gives rise to a photocurrent at a pixel \((i, j)\) of the correlation image sensor (CIS) as

\[
f_{ij}(t) = \int_{0}^{\infty} \int_{0}^{\infty} E(\lambda, t) R_{ij}(\lambda) S(\lambda) d\lambda
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where $R_{ij}(\lambda)$ denotes the spectral reflectance (or transmittance) of the illuminated object observed at $(i,j)$, and $S(\lambda)$ the spectral sensitivity of the CIS. Equation (5) implies that the input pattern to the CIS, $f_{ij}(t)$, is composed of the sum of spectral images $E_0(\lambda_i)R_{ij}(\lambda_k)S(\lambda_k)$, each modulated with the AM carrier $a_k(t)+b_k$ at the corresponding channel. The spectral image at a particular channel $E_0(\lambda_k)R_{ij}(\lambda_k)S(\lambda_k)$ can then be demodulated by supplying the CIS with a reference signal $g(t)=a_k(t)$, i.e., the AM carrier at that channel. In fact, recalling the orthonormality in Eq. (3), we find for the output image of the CIS that

$$
\phi_{ij} = (f_{ij}(t)g(t)) = \sum_{k=1}^{N} (\{a_k(t)+b_k\}a_k(t))E_0(\lambda_i)R_{ij}(\lambda_k)S(\lambda_k) = E_0(\lambda_k)R_{ij}(\lambda_k)S(\lambda_k).
$$

(6)

Based on the formula in Eq. (6), we can perform real-time spectral matching pixelwise with respect to a reference spectrum $R_0(\lambda)$ using a reference signal consisting of a weighted sum of the AM carriers $a_k(t)$:

$$
g(t) = \sum_{k=1}^{N} g_k a_k(t),
$$

(7)

$$
g_k = \frac{1}{E_0(\lambda_k)S(\lambda_k)} \frac{R_0(\lambda_k) - m_0}{\sigma_0}.
$$

(8)

where $m_0$, $\sigma_0^2$ denote the mean and variance of the spectrum samples $R_0(\lambda_k)$, respectively:

$$
m_0 = \frac{1}{N} \sum_{k=1}^{N} R_0(\lambda_k),
$$

(9)

$$
\sigma_0^2 = \sum_{k=1}^{N} [R_0(\lambda_k) - m_0]^2.
$$

(10)

[$\sigma_0^2$ in Eq. (10) is actually defined as the theoretical variance times the number of samples $N$ to normalize $R_0(\lambda_k) - m_0$. The same applies to $\sigma_{ij}^2$ in Eq. (14).]

Then the CIS output becomes

$$
\phi_{ij} = \sum_{k=1}^{N} g_k E_0(\lambda_k)R_{ij}(\lambda_k)S(\lambda_k) = \sum_{k=1}^{N} R_{ij}(\lambda_k) \frac{R_0(\lambda_k) - m_0}{\sigma_0}.
$$

(11)

Substituting into Eq. (11)

$$
R_{ij}(\lambda_k) = \sigma_{ij} \frac{R_0(\lambda_k) - m_{ij}}{\sigma_{ij}} + m_{ij},
$$

(12)

where $m_{ij}$, $\sigma_{ij}^2$ denote the mean and variance of $R_{ij}(\lambda_k)$, respectively [see Eqs. (9) and (10)], and noting that

$$
\sum_{k=1}^{N} \frac{R_0(\lambda_k) - m_0}{\sigma_0} = 0
$$

(13)

by Eq. (9), we can rewrite Eq. (11) as

$$
\phi_{ij} = \sigma_{ij} \sum_{k=1}^{N} \frac{R_{ij}(\lambda_k) - m_{ij}}{\sigma_{ij}} + m_{ij} \sigma_{ij} \sum_{k=1}^{N} \frac{R_0(\lambda_k) - m_0}{\sigma_0}.
$$

(14)

The product-summation term in Eq. (14) represents the cross-correlation coefficient between the spectrum of the object $R_{ij}(\lambda)$ and the reference spectrum $R_0(\lambda)$ over the samples at $\lambda_k$, satisfying

$$
\phi_{ij} = \sigma_{ij} \sum_{k=1}^{N} \left[ \frac{R_0(\lambda_k) - m_0}{\sigma_0} \right]^2 = \sigma_{ij}.
$$

(15)

Equations (14) and (15) imply that in every frame, the spectral matching imager detects with maximum output values the region in which the spectrum of the object $R_{ij}(\lambda)$ exactly matches the reference spectrum $R_0(\lambda)$ in the sense that

$$
R_{ij}(\lambda_k) = K_1 R_0(\lambda_k) + K_2 \quad (k=1,\ldots,N),
$$

(16)

where $K_1$ and $K_2$ are constants.

We consider the following remarks noteworthy.

1. The contribution from background illumination, which can be assumed to be uncorrelated with $a_k(t)$, is eliminated through the temporal correlation.

2. The normalization of $R_0(\lambda_k)$ in Eqs. (7) and (8) makes the spectral matching imager insensitive to the condition $R_{ij}(\lambda) = \text{const.}$, which implies a perfectly white diffuse object or a specular reflection component.

3. The multiplying term $\sigma_{ij}$ to the correlation coefficient in Eq. (14), meaning the deviation of $R_{ij}(\lambda_k)$, scales the output value, depending on the spectral waveform of the object.

4. The spectral power distributions at the channels of the AM-coded multispectral illumination may not be ideally sharp, as with the case of using LEDs as adopted in this work, for example. In this case, spectral matching should be performed on the spectrum samples, which are the output of smoothing filters characterized by the illuminant spectra at each channel, with the original spectral reflectance or transmittance being the inputs. See the Appendix in Sec. 6 for derivation.
2.2 Differential Spectral Matching

As a special case, we consider discriminating a pair of objects with different spectral properties, as seen later in the experiment. Let \( R_1(\lambda) \) and \( R_2(\lambda) \) denote the spectral reflectance functions of the two objects. Also let

\[
\mathbf{r}_1 = [r_{11}, \cdots, r_{1N}]^T, \quad \mathbf{r}_{1k} = \frac{R_1(\lambda_k) - m_1}{\sigma_1},
\]

\[
\mathbf{r}_2 = [r_{21}, \cdots, r_{2N}]^T, \quad \mathbf{r}_{2k} = \frac{R_2(\lambda_k) - m_2}{\sigma_2},
\]

where \( m_n, \sigma_n^2 \) denote the mean and variance of \( R_n(\lambda_k) (n = 1, 2) \). Noting the property \( \| \mathbf{r}_1 \| = \| \mathbf{r}_2 \| = 1 \), we find that the common- and differential-mode vectors of \( \mathbf{r}_1, \mathbf{r}_2 \)

\[
\mathbf{r}_+ = \mathbf{r}_1 + \mathbf{r}_2, \quad \mathbf{r}_- = \mathbf{r}_1 - \mathbf{r}_2
\]

become orthogonal to each other, since their inner product satisfies \( \langle \mathbf{r}_+, \mathbf{r}_- \rangle = \| \mathbf{r}_1 \|^2 - \| \mathbf{r}_2 \|^2 = 0 \). It then follows that

\[
\langle \mathbf{r}_1, \mathbf{r}_\pm \rangle = \frac{1}{2} \langle \mathbf{r}_+ + \mathbf{r}_-, \mathbf{r}_\pm \rangle = \frac{1}{2} \| \mathbf{r}_\pm \|^2,
\]

\[
\langle \mathbf{r}_2, \mathbf{r}_\pm \rangle = \frac{1}{2} \langle \mathbf{r}_+ - \mathbf{r}_-, \mathbf{r}_\pm \rangle = \pm \frac{1}{2} \| \mathbf{r}_\pm \|^2
\]

(double signs in the same order). In comparison to Eq. (14), Eqs. (20) and (21) imply that, with a reference signal \( g(t) \) synthesized from \( \mathbf{r}_+ \) or \( \mathbf{r}_- \) instead of \( \{R_0(\lambda_k) - m_0(\lambda_k)/\sigma_0 \} (k = 1, \cdots, N) \) in Eq. (8), the spectral matching imager detects the regions of the two objects with the same polarity for the common-mode spectrum samples \( \mathbf{r}_+ \), and with opposite polarities for the differential-mode spectrum samples \( \mathbf{r}_- \). This further means that the differential-mode reference signal helps discriminate two objects distinctively, even if they have quite similar spectra.

3 Implementation

3.1 Correlation Image Sensor

Figure 2(a) shows the 32×32-pixel CIS used in this work. It belongs to the three-phase type with three reference inputs, which can simultaneously demodulate the amplitude and phase of a sinusoidally modulated incident light pattern within a single frame, as well as yield a conventional average intensity image, although we used it in a cross-correlation mode in this work. Major specifications of the sensor chip, fabricated through VLSI Design and Education Center (VDEC) at the University of Tokyo, Japan, are listed in Table 1. The frame rate was set to 30 Hz. The spectral sensitivity \( S(\lambda) \) of the sensor was measured as shown in Fig. 2(b).

3.2 Twelve-Channel AM-Coded Multispectral LED Light Source

We fabricated an AM-coded multispectral light source using commercially available LEDs. We set the number of spectral channels to \( N = 12 \), expecting a bandwidth of 25 nm throughout the visible region of 400 to 700 nm. For orthonormal AM, we adopted sinusoidal carriers of frequencies listed in Table 2, which were determined by a twelve-channel oscillator circuit we also fabricated. Figure 3(a) shows the fabricated light source, each channel of which consists of eight line segments made of twelve 5-mm LEDs, placed at spacings of 45 deg. The LED line segments are positioned so that the emitted lights converge at a distance of about 25 cm from the light source. Figure 3(b) plots the spectral power distributions of the twelve types of LEDs used in Fig. 3(a), measured as spectral irradiance at the same distance of 13 cm under an LED driving current of 20 mA. The peak wavelengths and full widths at half maximum (FWHM) of the distributions are also specified in Table 2.

<table>
<thead>
<tr>
<th>Table 1 Specifications of the three-phase CIS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication process</td>
</tr>
<tr>
<td>Image resolution</td>
</tr>
<tr>
<td>Pixel size [( \mu )m(^2)]</td>
</tr>
<tr>
<td>Die dimension [mm(^2)]</td>
</tr>
<tr>
<td>Correlation SNR [dB]</td>
</tr>
<tr>
<td>Cutoff frequency</td>
</tr>
</tbody>
</table>

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**Fig. 2** 32×32-pixel three-phase CIS. (a) Camera package. The CIS chip is fixed at the center of the printed circuit board. (b) Measured spectral sensitivity \( S(\lambda) \).
Unfortunately, the results in Fig. 3 and Table 2 indicate that: 1. some of the channels, especially of shorter wavelengths, have bandwidths broader than 25 nm; and 2. the spacings between adjacent channels are not uniform. We can still perform spectral matching, however, in terms of samples of smoothed spectra, by taking into account the spectral power distributions of the LEDs as formulated in the Appendix in Sec. 6.

Another problem we found is that the light source in Fig. 3 does not produce spectral irradiance of uniform spatial distribution. Figure 4 shows the irradiance pattern produced on a diffuse white screen at about 25 cm from the light source by only the LEDs at each single channel. They were captured by the CIS through demodulation with the AM carriers $a_k(t)$. Spatial nonuniformity of the LED illumination can be observed.

Table 2 Measured spectral properties and AM frequencies of the twelve-channel AM-coded multispectral LED light source.

<table>
<thead>
<tr>
<th>Channel number $k$</th>
<th>Peak wavelength $\lambda_k$ [nm]</th>
<th>FWHM [nm]</th>
<th>AM frequency [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>426</td>
<td>62</td>
<td>0.861</td>
</tr>
<tr>
<td>2</td>
<td>467</td>
<td>29</td>
<td>1.06</td>
</tr>
<tr>
<td>3</td>
<td>492</td>
<td>32</td>
<td>1.25</td>
</tr>
<tr>
<td>4</td>
<td>518</td>
<td>37</td>
<td>1.59</td>
</tr>
<tr>
<td>5</td>
<td>559</td>
<td>16</td>
<td>1.96</td>
</tr>
<tr>
<td>6</td>
<td>570</td>
<td>16</td>
<td>2.31</td>
</tr>
<tr>
<td>7</td>
<td>586</td>
<td>17</td>
<td>2.96</td>
</tr>
<tr>
<td>8</td>
<td>608</td>
<td>19</td>
<td>3.54</td>
</tr>
<tr>
<td>9</td>
<td>619</td>
<td>17</td>
<td>4.48</td>
</tr>
<tr>
<td>10</td>
<td>635</td>
<td>17</td>
<td>5.22</td>
</tr>
<tr>
<td>11</td>
<td>641</td>
<td>18</td>
<td>7.09</td>
</tr>
<tr>
<td>12</td>
<td>657</td>
<td>23</td>
<td>7.53</td>
</tr>
</tbody>
</table>

Unfortunately, the results in Fig. 3(b) and Table 2 indicate that: 1. some of the channels, especially of shorter wavelengths, have bandwidths broader than 25 nm; and 2. the spacings between adjacent channels are not uniform. We can still perform spectral matching, however, in terms of samples of smoothed spectra, by taking into account the spectral power distributions of the LEDs as formulated in the Appendix in Sec. 6.

Another problem we found is that the light source in Fig. 3(a) does not produce spectral irradiance of uniform spatial distribution. Figure 4 shows the irradiance pattern produced on a diffuse white screen at about 25 cm from the light source by only the LEDs at each single channel, imaged by the CIS through demodulation, with the AM carriers $a_k(t)$. This is critical to spectral matching, because it introduces a spatially nonuniform multiplicative factor to the object spectrum $R_{ij}(\lambda_k)$. In the experiment described later, we compensate for this factor by off-line normalization with the LED irradiance images in Fig. 4 channel by channel.

4 Experimental Results

4.1 Colored Glass Pieces

For test objects, we employed three pairs of glass pieces of a similar apparent color (green, pink, or purple), but with different spectral transmittances. Each pair of glass pieces is pigmented with $\text{Pr}_6\text{O}_{11}$ or $\text{Cr}_2\text{O}_3$ for green, $\text{Er}_2\text{O}_3$ for pink, and $\text{Nd}_2\text{O}_3$ or $\text{MnO}_2$ for purple, giving rise to spectral transmittances as plotted in Figs. 5(a) through 5(c). [The full names of the oxide materials mentioned are: $\text{Pr}_6\text{O}_{11}$: praseodymium (III,IV) oxide; $\text{Cr}_2\text{O}_3$: chromium (III) oxide; $\text{Er}_2\text{O}_3$: erbium (III) oxide; $\text{SeO}_2$: selenium (IV) oxide; $\text{Nd}_2\text{O}_3$: neodymium (III) oxide; and $\text{MnO}_2$: manganese (IV) oxide.] Note that the glass pieces doped with oxides of rare-earth elements ($\text{Pr}_6\text{O}_{11}$, $\text{Er}_2\text{O}_3$, and $\text{Nd}_2\text{O}_3$) exhibit characteristic fine-structured spectra compared to those doped with conventional pigments ($\text{Cr}_2\text{O}_3$, $\text{SeO}_2$, and $\text{MnO}_2$). Using the spectra in Figs. 5(a) through
5(c), as well as the LED spectra $E_k(\lambda)$ in Fig. 3(b) and the CIS spectral sensitivity $S(\lambda)$ in Fig. 2(b), we computed the samples of smoothed spectra $\hat{R}_{0k}$ for each channel $k$ following Eqs. (28), (25), and (26) in the Appendix in Sec. 6. Figures 5(d) through 5(f) plot the computed $\hat{R}_{0k}$ for each pair of glass pieces, which also means expected outputs of the CIS for the glass pieces, denoted by $R_{ij,k}$ in Eq. (24), obtained when we demodulate only the single spectral image $A_k \hat{R}_{ij,k}$ at each channel $k$, and then normalize it by $A_k$ defined in Eq. (25). In Figs. 5(d) through 5(f) we observe some loss of spectral resolution introduced by the LED spectra $E_k(\lambda)$. The computed spectrum samples in Figs. 5(d) through 5(f) are used as the weights $g_k$ of the AM carriers $a_k(t)$ in the reference signal to the CIS.

For convenience, we hereafter refer to each of the glass pieces, and also the reference signal associated with the spectral transmittance of it, with an acronym of the pigment doped in the glass, as PR (Pr$_6$O$_{11}$), CR (Cr$_2$O$_3$), ER (Er$_2$O$_3$), SE (SeO$_2$), ND (Nd$_2$O$_3$), and MN (MnO$_2$). We also denote the reference signals weighted with common- and differential-mode samples of a reference spectrum defined by Eqs. (17), (18), and (19) as, respectively, PR+CR and PR−CR (or CR−PR for its inverted form), for example. Moreover, for notational simplicity, we use $R_0(\lambda_k)$ and $R_{ij}(\lambda_k)$ to denote the spectrum samples and the original notations derived in Sec. 2.1, even if we actually have to use $\hat{R}_{0k}$ and $\hat{R}_{ij,k}$, taking into account the smoothing effect by LED spectra $E_k(\lambda)$ as derived in the Appendix in Sec. 6.

---

**Fig. 5** (a), (b), and (c) Spectral transmittance functions of the colored glass pieces doped with pigment oxides. (d), (e), and (f) Computed samples of the spectra after smoothing the spectral transmittances in (a), (b), and (c) by the LED spectra in Fig. 3(b). The plots are normalized over the channels. Some of the fine structure in the original spectra of the rare-earth-doped glass pieces in (a), (b), and (c) is lost due to the smoothing effect.

**Fig. 6** Output images of spectral matching from the CIS for each glass pair, obtained by projecting the light through the glass onto a diffuse white screen. The acronyms right below the images denote the type of reference signal applied to the CIS. While the results in (a) show a correct output pattern in accordance with the type of reference signal, those in (b) and (c) do not.
4.2 Real-Time Spectral Matching

We first performed real-time spectral matching on each pair of the colored glass pieces using the reference signal \( g(t) \) given by Eqs. (7) and (8). Figure 6 shows output images of the CIS for reference signals associated with the samples of each spectral reflectance in Figs. 5(d) through 5(f), or with the common- or differential-mode component of the spectrum sample sets for each pair of glass pieces of similar color. We obtained the images by projecting the light through the glass onto the same diffuse white screen used in obtaining the images in Fig. 4. In Fig. 6(a), the PR–CR pair appear to give good results as expected—either the glass PR or CR is highlighted exclusively with reference signal PR or CR, respectively, while both are highlighted with the same or opposite polarities with reference signal PR+CR or PR–CR, respectively. In Figs. 6(b) and 6(c), however, we cannot observe clear enough results to convince us that the imager worked properly. We consider that these undesirable results were caused by the spatial nonuniformity of the LED illumination shown in Fig. 4.

4.3 Compensation for Spatial Nonuniformity of LED Irradiance

To examine whether the spectral matching imager works correctly, we compensated for the spatial nonuniformity of the LED illumination in the following manner.

1. Obtain 12 spectral images \( e_{ij,k}E_0(\lambda_k)R_{ij}(\lambda_k)S(\lambda_k) \) of an object with the CIS through demodulation with the AM carriers \( a_k(t) \), as described in Eq. (6), where \( e_{ij,k} \) denotes a position-dependent factor representing spatial nonuniformity of the LED illumination.

2. Divide each spectral image pixelwise with the irradiance image \( e_{ij,k}E_0(\lambda_k)S(\lambda_k) \) shown in Fig. 4 at the corresponding channel, to obtain images of \( R_{ij}(\lambda_k) \) only.

Fig. 7 Spectral images of the PR-CR pair, captured by the CIS through demodulation with each of the AM carriers \( a_k(t) \). The images exhibit the influence of spectral nonuniformity of the LED illumination.

Fig. 8 Pixel values of the spectral images (a) before and (b) after compensating for spatial nonuniformity of the LED illumination channel by channel, averaged over 8×8 pixels within the region of each glass piece. The pixel values were brought much closer to the expected responses in Figs. 5(d), 5(e), and 5(f) after compensation.
3. Do off-line computation by applying Eq. (14) to the images $R_{ij}(\lambda_k)$.

Figure 7 shows the original spectral images for the PR-CR pair, for example, exhibiting the effect of spatially nonuniform irradiance. From the original spectral images, we plotted the pixel value averaged over an 8×8 area in the region of each glass piece, as shown in Fig. 8(a). After compensation by dividing the spectral images in Fig. 7 by the irradiance images in Fig. 4 channel by channel, we obtained the plots of the average pixel value, supposedly equal to $R_{ij}(\lambda_k)$, as shown in Fig. 8(b). In comparison to Fig. 8(a), we can see good agreement of the plots in Fig. 8(b) with those of the computed spectrum samples in Figs. 5(d) through 5(f). These results suggest that the compensation has worked well, and therefore that the spectral matching imager can capture each spectral component of an input pattern correctly if the AM-coded multispectral illumination gives spatially uniform spectral irradiance.

### 4.4 Off-Line Spectral Matching After Compensation

We carried out spectral matching for the compensated spectral images by off-line computation. Figure 9 shows synthesized output images of spectral matching, indicating that the spatial nonuniformity observed in Fig. 6 has significantly been removed. We also clearly see that the images for the PR-CR and ND-MN pairs now give correct output patterns according to the type of the reference signal applied.

We further compared the pixel value in each region of the glass piece with that estimated from the computed spectrum samples $R_{ij}(\lambda_k)$ in Figs. 5(d) through 5(f). Figure 10 plots the experimental pixel values of the spectral matching output images averaged over an 8×8 area within the region of each object, along with the estimated ones. The plots for the PR-CR and ND-MN pairs show good agreement between the experimental and estimated pixel values. These results imply that spectral matching can be performed correctly if the AM-coded multispectral illumination gives spatially uniform spectral irradiance.

In contrast, the plot for the ER-SE pair in Fig. 10(b) shows larger discrepancy than those for the PR-CR and ND-MN pairs in Figs. 10(a) and 10(c). We consider that the rather poor response for the ER-SE pair is attributable to the small variance $\sigma_{ij}^2$ of the spectral transmittance of the ER glass, as observed in Fig. 5(b), which suppresses the output of the CIS to lower the signal-to-noise ratio (SNR) as commented before in Sec. 2.1.

### 4.5 Verification of Off-Line Analysis

In Sec. 4.4, we have only verified the off-line spectral matching from compensated spectral images. To examine
how close the synthesized images in Fig. 9 are to those that would be obtained by direct imaging under AM-coded multispectral illumination of spatially uniform spectral irradiance using the reference signal given by Eqs. (7) and (8), we compared the direct imaging results in Fig. 6, which should be denoted by $\sum_{l=1}^{N} e_{ijl} E_0(\lambda_k) R_{ij}(\lambda_k) S(\lambda_k)$, with images obtained by computing a weighted sum of uncompensated spectral images $e_{ijl} E_0(\lambda_k) R_{ij}(\lambda_k) S(\lambda_k)$. Figure 11 shows computed images for each glass pair and reference signal. It is difficult to see discrepancies between the direct output images in Fig. 6 and the synthesized output images in Fig. 11. We computed the SNR of the synthesized images with respect to the direct images as listed in Table 3, regarding the former and latter as signals with and without noise, respectively, and scaling each synthesized image properly, according to the corresponding direct image. We consider that the smaller values for the ER-SE and ND-MN pairs were caused by small variances of the spectrum samples $\sigma_{ij}^2$ for the SE and MN glass pieces, as seen in Figs. 5(e) and 5(f). Apart from this point, we observe that reasonable SNR has been achieved, considering that the SNR of the CIS is about 30 dB, and that it becomes high especially for objects with considerably winding spectra. These results confirm that we will certainly obtain correct spectral matching results as well by direct imaging under AM-coded multispectral illumination of spatially uniform spectral irradiance.

5 Conclusions and Discussion

We propose a spectral matching imager using AM-coded multispectral LED illumination, which modulates each spectral component of the object with one of an orthonormal set of AM carriers. Under this illumination, the imager performs real-time spectral matching by demodulating spectral images channel by channel and producing a

![Fig. 10](image1.png)

**Fig. 10** Average output values in the $8 \times 8$-pixel regions of each glass piece for different types of reference signals, in comparison with expected values. The plots are normalized to unity for the ideal cases of matched detection. The expected and actual output values agree well for most of the colored glass pieces.

![Fig. 11](image2.png)

**Fig. 11** Synthesized output images obtained by computing a weighted sum of uncompensated spectral images. The synthesized images are close in appearance to those obtained by direct imaging, as shown in Fig. 6.

| Table 3 | SNR of the synthesized output images in Fig. 11 with respect to the direct output images in Fig. 6. High SNR values imply good agreement between synthesized and direct output images. |
|---------|---------------------------------|----------------|
| Object type | Reference type | SNR [dB] |
| PR-CR | PR | 15.7 |
| | CR | 27.3 |
| | PR+CR | 16.8 |
| | PR–CR | 13.7 |
| ER-SE | ER | 14.3 |
| | SE | 4.5 |
| | ER+SE | 10.2 |
| | ER–SE | 11.1 |
| ND-MN | ND | 20.3 |
| | MN | 8.1 |
| | ND+MN | 17.5 |
| | ND–MN | 13.6 |
weighted sum of them in the focal plane of the CIS. We fabricate a twelve-channel light source using commercially available LEDs. In spite of nonideal spectral properties of the LED illumination, the experimental results on colored glass pieces confirm that the imager can perform real-time spectral matching under ideal illumination.

To realize ideal AM-coded multispectral illumination, it is necessary 1. to improve on spatial uniformity of spectral irradiance, and 2. to use LEDs of narrowband spectral power distributions densely at channels of shorter wavelengths to increase spectral resolution or accuracy of spectral matching. Regarding the first issue, spatial uniformity can be improved by properly designing the arrangement of LEDs, for example. The second issue might force us to turn to light sources other than LEDs, since availability of commercial LEDs is very thin in blue-green channels at present.

Another aspect important in practical applications is the distance over which the proposed imaging system works. The working range of the current system is fixed to about 25 cm, at which the fabricated LED light source in Fig. 3(a) is designed to make the lights emitted from the LEDs converge together. Outside of that range, the light flux diverges away to produce weaker and less uniform spectral irradiance. To extend the working range while maintaining irradiance intensity and uniformity of the AM-coded multispectral illumination, one possible approach may be to assemble the LEDs within a housing and project the light from the LEDs with lenses. We expect that the working range can be extended to one to two meters by elaborately arranging the LEDs and properly designing lens optics as employed in slide or liquid crystal display (LCD) projectors. Although this range may be somewhat shorter than that of the projectors, which is mainly because LEDs are not as strong a light source as filament or discharge lamps, it will still be sufficient for applications that observe objects in detail from a relatively short distance, such as product inspection or counterfeit detection.

6 Appendix: Spectral Matching Under Broad Illuminant Spectra

Consider AM-coded multispectral illumination with a spectral power distribution $E_k(\lambda)$ at each channel. The total spectral power distribution of the illumination is then given by

$$E(\lambda, t) = \sum_{k=1}^{N} [a_k(t) + b_k]E_k(\lambda).$$

(22)

This gives rise to an input pattern to the CIS as

$$f_{ij}(t) = \sum_{k=1}^{N} [a_k(t) + b_k] \int_{0}^{\infty} E_k(\lambda)R_{ij}(\lambda)S(\lambda) d\lambda$$

$$= \sum_{k=1}^{N} A_k \hat{R}_{ij,k} [a_k(t) + b_k],$$

(23)

where

$$\hat{R}_{ij,k} = \int_{0}^{\infty} h_k(\lambda)R_{ij}(\lambda) d\lambda,$$

(24)

$$A_k = \int_{0}^{\infty} E_k(\lambda)S(\lambda) d\lambda,$$

(25)

$$h_k = \frac{E_k(\lambda)S(\lambda)}{A_k} \left[ \int_{0}^{\infty} h_k(\lambda) d\lambda = 1 \right].$$

(26)

Equation (23) implies that $f_{ij}(t)$ consists of the sum of spectral images $A_k \hat{R}_{ij,k}$, in which $\hat{R}_{ij,k}$ means the output of a smoothing filter $h_k(\lambda)$, with $R_{ij}(\lambda)$ being its input. We supply the CIS with a reference signal $g(t)$ as defined in Eq. (7), with its weights $g_k$ now given by

$$g_k = \frac{1}{A_k} \hat{R}_{ok} - \hat{m}_0,$$

(27)

$$\hat{R}_{ok} = \int_{0}^{\infty} h_k(\lambda)R_0(\lambda) d\lambda,$$

(28)

where $\hat{m}_0$, $\hat{\sigma}_0^2$ are the mean and variance of the spectrum samples $\hat{R}_{ok}$, i.e., the output of the smoothing filter $h_k(\lambda)$ with a reference spectrum $R_0(\lambda)$ being its input:

$$\hat{m}_0 = \frac{1}{N} \sum_{k=1}^{N} \hat{R}_{ok},$$

(29)

$$\hat{\sigma}_0^2 = \frac{1}{N} \sum_{k=1}^{N} (\hat{R}_{ok} - \hat{m}_0)^2.$$  

(30)

Using this reference signal, we obtain a temporal correlation image as

$$\phi_{ij} = \sum_{k=1}^{N} g_k \cdot A_k \hat{R}_{ij,k} = \sum_{k=1}^{N} \hat{R}_{ij,k} - \hat{m}_0 \frac{\hat{R}_{ok} - \hat{m}_0}{\hat{\sigma}_0}.$$  

(31)

Substituting into Eq. (31)

$$\hat{R}_{ij,k} = \hat{\sigma}_{ij} \frac{\hat{R}_{ij,k} - \hat{m}_{ij}}{\hat{\sigma}_{ij}} + \hat{m}_{ij},$$

(32)

where $\hat{m}_{ij}$, $\hat{\sigma}_{ij}^2$ denote the mean and variance of the filtered spectrum samples $\hat{R}_{ij,k}$, respectively, [see Eqs. (29) and (30)], and noting that

$$\sum_{k=1}^{N} \hat{R}_{ok} - \hat{m}_0 = 0$$

(33)

by Eq. (29), we can rewrite Eq. (31) as

$$\phi_{ij} = \hat{\sigma}_{ij} \sum_{k=1}^{N} \frac{\hat{R}_{ij,k} - \hat{m}_{ij}}{\hat{\sigma}_{ij}} + \frac{\hat{m}_{ij}}{\hat{\sigma}_{ij}} \sum_{k=1}^{N} \hat{R}_{ok} - \hat{m}_0$$

$$= \hat{\sigma}_{ij} \sum_{k=1}^{N} \frac{\hat{R}_{ij,k} - \hat{m}_{ij}}{\hat{\sigma}_{ij}} \frac{\hat{R}_{ok} - \hat{m}_0}{\hat{\sigma}_0}.$$

(34)

984 Optical Engineering, Vol. 43 No. 4, April 2004
We see that Eq. (34) can be obtained by replacing the spectrum samples $R_i(\lambda_k)$ and $R_0(\lambda_k)$ in Eq. (14) with the samples of smoothed spectra $\hat{R}_{i,k}$ and $\hat{R}_{0,k}$, respectively. Consequently, even under AM-coded multispectral illumination with broad illuminant spectra $E_k(\lambda)$, spectral matching can be performed on the samples of spectra smoothed by the filter functions $h_k(\lambda)$ derived from $E_k(\lambda)$ by Eqs. (25) and (26).

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References


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