Research Article

Simulation and System Design of a 3D Metrology Optical System Based on a Bidirectional OLED Microdisplay

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Innovative display technologies enable a wide range of different system applications, specifically, in metrology, medical, and automotive applications. In the last decades, OLED microdisplays were in the focus of display development. A new class of OLED microdisplays with an integrated photodiode array is the latest development. The so-called bi-directional OLED microdisplays combine light-emitting devices (AM-OLED microdisplay) and photodiode detectors (photodiode matrix) on one single chip based on OLED-on-CMOS-technology. Currently, this kind of display is still a prototype. Based on such a novel bidirectional OLED microdisplay, we present for the first time a system simulation and design of a 3D optical surface metrology system. The first step is the full characterization of the microdisplay. Depending on the characterization results, the future system parameters are determined. Based on the characterization results and the application parameters, the system design parameters are defined. The functionality of the system is simulated, and a theoretical proof of concept is presented. An example for our application on 3D optical surface metrology system is evaluated.

1. Introduction

Expanding requirements on manufacturing technology increase the demands on noncontact metrology systems. Typical optical metrology systems are based on a separated light-emitting unit (e.g., projection unit) and detection unit (e.g., camera unit) [1, 2]. This fact limits the miniaturization of the sensor system. Furthermore, the use of two optoelectronic devices complicates the integration and the alignment, which leads to higher production costs.

Typically, a projection unit includes a light source with a collecting optics, illuminating a light modulator (such as DMD (digital micromirror device) or LCoS (liquid crystal on silicon) displays) and a projection lens, imaging the generated pattern into the measurement plane. A first step towards the miniaturization of such an unit is the application of a self-emitting microdisplay (as active matrix OLED microdisplay) for pattern generation [3]. OLED microdisplays are state-of-the-art microdisplays, and they are used in a wide range of applications (e.g., multimedia, medical, and metrology applications [2–7]). Such devices comprise light source and light modulator in one element, minimizing the number of components in a system. In contrast to conventional projection systems, OLED microdisplays allow a simple and small system integration [6].

A further miniaturization can be realized by applying a microdisplay combining OLED microdisplay and sensor unit (i.e., photodiode matrix) on one single element. Such a bidirectional OLED microdisplay (BiMiD) was realized using OLED-on-CMOS-technology by Fraunhofer IPMS [8–10]. That means that the light source/image device is placed in the same plane as the detector. The bi-directional display used in this investigation consists of an AM-OLED microdisplay with an integrated photodiode matrix. That implies that each display pixel contains an emitting OLED pixel and a photodiode. Both functions work simultaneously and in the same wavelength range. First applications that are based on a similarly working BiMiD are flow, color, and reflex...
sensors, which are presented in Reckziegel et al. [8]. Another
application based on a BiMiD that works in different wave-
length ranges for the OLED imaging and photodiode detec-
tion is an HMD and a distance sensor, which are mentioned
in Richter et al. [9, 11].

In this paper we present a 3D surface optical metrology
system based on phase-shifting fringe projection [1, 12–17]
with BiMiDs. Fringes are projected onto the surface of
measuring object. As they are observed via a different angle
(triangulation angle), the fringes appear deformed accord-
ing to the surface deformation of the measuring object.
This deformation of the fringes allows calculating the 3D
coordinates of all visible points. Up to now such systems are
divided in a projection and an imaging unit increasing the
size of the system.

We will demonstrate that the application of a bi-direc-
tional OLED microdisplay enables the realization of a highly
integrated compact surface metrology sensor.

2. Fringe Projection Principle

A simple fringe projection 3D measurement system consists
of an image acquisition sensor and a digital pattern (e.g.,
fringe) projector (see Figure 1(a)) [1]. The pattern/fringes
are generated by a digital projection unit based on LCD,
LCOS, DMD, or OLED microdisplay technology [2]. The
image acquisition sensor can be applied as a conventional
CCD. The 3D metrology system is based on fringe projection
onto the surface of the measurement object. The fringes
appear deformed when observed from a different angle
(triangulation angle). The triangulation angle is the angle
between the optical axis of the projection lens and the
imaging lens. From the deformation of the fringes the 3D
coordinates of all visible points can be calculated and thus
the object shape can be determined.

In Figure 1(b) a prototype of a 3D surface metrology
system is shown. This system is based on an OLED projec-
tion unit and an imaging system. The triangulation angle is 18°.
The OLED microdisplay generates the fringe patterns that
are projected via the projection lens onto the measuring
object. The imaging lens displayed the object during the
pattern sequence on the detector. Based on the variety of
fringe images the 3D shape of the measuring object can be
calculated. On the right side of Figure 1(b) the result of the
measurement of a calibrated target is shown. A well-done
conformity of the measured and target shape is presented.

A structured light approach combining the projection of
a sequence of phase-shifted sinusoidal fringe patterns in
combination with a sequence of Gray code patterns was
used [18]. Due to the fact that phase-shifted sinusoidal
fringe patterns produce $2\pi$ periodic phase values, additional
phase unwrapping is necessary to solve these ambiguities,
which is possible through the use of a Gray code sequence
giving each sinus period a unique identifier [12, 17]. To
be able to calculate 3D points on the objects surface using
triangulation methods, at least 2 phase values for each 3D
point are necessary in this setup along with a fully calibrated
sensor arrangement (e.g., orientation parameters for the
measurement camera and the fringe projector). This can be
achieved using two projected pattern sequences rotated 90°
to each other. As a result each pixel in the measurement
camera has a pair of phase values assigned to it. This pair of
phase values describes exactly one position in the projector
matrix (e.g., interpolated projector pixel). Using the orienta-
tion parameters of both sensor units, a simple triangula-
tion can be used to calculate the 3D point on the surface
[15]. Using this approach, the accuracy of the 3D coordinate
measurement depends directly of the accuracy of the phase
measurement (proportional).

3. Bidirectional OLED Microdisplay

OLED microdisplays are widely used in the commercial
applications like displays, which are directly observed by the
user (mobile phone screens, head-mounted displays) [7, 9].
This display technology benefits from small geometrical size,
low weight, low power consumption, and potentially high
resolution [19]. High-brightness OLED microdisplays can
also be applied as image generating devices in picoprojectors
(e.g., for mobile phones) [2, 6]. However, those systems are
unidirectional [9].

The development of light-emitting-polymer-(LEP-) on-
CMOS-technology [19] opens the possibility to combine
light emission and detection on one single chip. The so-
called bi-directional OLED microdisplay (BiMiD), based on
the OLED-on-CMOS-technology, has been developed by
the Fraunhofer Institute for Photonic Microsystems (IPMS,
Dresden)[8–10]. Such a display offers a new flexibility to
optical metrology systems, because projection and imaging
units can be combined in one optical path.

The CMOS-technology enables a simple electronics inte-
gration of OLED [19]. Figure 2 shows the cross-section of the
design of the BiMiD. The CMOS top metal represents simul-
taneously the OLED bottom electrode (OLED cathode). A
semitransparent thin metal layer is used as OLED electrode.
The OLED layer is directly deposited onto the CMOS
substrate. A detailed OLED layer structure is described in
Reckziegel et al. [8]. The photodiodes (PDs) are embedded
in the CMOS substrate. That means in each BiMiD pixel
one OLED emitting pixel and one photodiode are integrated.
Due to CMOS-technology (embedded photodiodes) a high
fill factor of 90% comprising OLED pixel and photodiode
can be realized.

The emitting unit is an active-matrix-(AM-) OLED
microdisplay. Photodiodes with diameter of around 8 μm are
integrated in each OLED pixel (34 μm²). The photodiodes
are positioned about 7 μm below the OLED layer. Figure 3(a)
shows the BiMiD displaying an image, and Figure 3(b) shows
a detailed view of the pixel structure.

Due to processing reasons, the first prototype of a BiMiD
for our application has a limited photodiode resolution.
Even though photodiodes are placed in each OLED pixel,
only one photodiode out of four is integrated in the
electronic control and therefore active. Accordingly, the
photodiode resolution is reduced by four in comparison to
the OLED resolution. The resulting resolution for the OLED
microdisplay is QVGA (240 × 320), and the photodiode
resolution is QQVGA (120 × 160). With this device, either
simultaneous or sequential emission (OLED projection) and detection (photodiode) can be realized [20]. In the sequential mode of operation, the OLED projection and photodiode detection are wavelength independent ($\lambda_{\text{OLED}} \neq \lambda_{\text{photodiode}}$). In the simultaneous mode of operation, as we use it in our BiMiD prototype, OLEDs and photodiodes work in the same wavelength range ($\lambda_{\text{OLED}} = \lambda_{\text{photodiode}}$). In this case, however, direct crosstalk effects between OLEDs and photodiodes can disturb the functionality.

We classify two different types of crosstalk: local and global crosstalk. Local crosstalk occurs directly between an OLED pixel and its neighbouring photodiodes, caused, for example, by internal reflection at CMOS layers (i.e., optical waveguide effect). In contrast to local crosstalk, global
crosstalk indicates the influence of an emitting OLED pixel onto the photodiodes being spread over the whole display device. Global crosstalk can, for example, be caused by (e.g., multiple) reflections at the display cover glass and can therefore be detected by photodiodes being positioned not in the direct neighbourhood of the emitting OLED pixel. Local and global crosstalk have a strong impact onto the characteristics of the detected signal [11].

To limit the local crosstalk, we can take advantage of the limited resolution of photodiodes. As in a $2 \times 2$ pixel matrix only one photodiode is able to detect light, the OLED pixel surrounding the active photodiode is not used for light emission. Therefore, all images which are used are masked, that means that the OLED pixel including active photodiodes is inactive (e.g., black pixel projection). In this way, local crosstalk between the photodiode and its surrounding OLED can be prevented.

The current BiMiD prototype that we used for our prototype emits in the orange visible range ($\lambda_{\text{cd}} = 622 \text{ nm}$) with a bandwidth of 48 nm (FWHM). The luminance of the OLED display at different voltage adjustments lies between 260 cd/m$^2$ and 7.8 kcd/m$^2$, which is suitable for high brightness projection applications. The radiation angle is around $\pm 45^\circ$ for each luminance level. The uniformity over the display is around 90%. The contrast ratio of the OLED display is around $30000 : 1$ (ratio of full screen bright to full screen dark image). This impressive contrast ratio is a big advantage of OLED microdisplays compared to conventional microdisplays for projection purposes. The photodiodes exhibit a exposure time between 0.1434 ms and 1.174 s. The uniformity lies around 83% at the highest exposure times.

More details about the technology of the bi-directional OLED-on-CMOS-microdisplay are presented in Richter et al. [9].

### 4. Conceptual Design

The central element of our 3D sensor is the bi-directional OLED microdisplay (BiMiD). To prove the principle of the sensor the BiMiD was characterized. The measured parameters were used for the system simulation with the optical design program ZEMAX. In addition, a software for the generation of a 3D model was used.

First the BiMiD was characterized (see Section 3). The OLED microdisplay, the photodiode matrix (PD), and the crosstalk between OLED and photodiodes were evaluated. To measure the crosstalk of the BiMiD a paraxial lens design was used (see Figure 5). The BiMiD emits and detects light in the same plane and in the same spectral range. Figure 4(a) shows the projected test image (white square with a diagonal of 3 mm), and Figure 4(b) shows the detected image without additional optical elements (e.g., lens and mirror). A direct crosstalk between OLED pixel and photodiodes is detectable. The desired detection signal is lower than the crosstalk signal ($I_{\text{Detection}} < I_{\text{Crosstalk}}$). Due to the direct crosstalk the BiMiD active area was divided in two different fields: an object field and a detection field. In Figure 5 the paraxial lens design setup and the simplified laboratory setup that contains the separation of the projection and detection fields are shown. In the paraxial lens setup the blue path describes the projection path, and the green one describes the imaging path. Both object and image fields are placed next to each other. Fold mirrors are integrated in the projection path. The position of the fold mirrors and the dimension of the optical system configuration determine a triangulation angle ($\alpha_T$). The imaging path is unfolded. In both optical paths two paraxial lenses are integrated (Figure 5(a)). The realized setup including off-the-shelf optics is shown in Figure 5(b).

Figure 4(c) shows the detected image of the object. On the left-hand side the direct crosstalk image of the projection field and on the right hand side the object image are shown. Due to the internal display effect the active OLED pixel is imaged onto the photodiodes that are placed next to each other. Therefore, the projection object field and the detection field have to be separated via ray path folding. As described before the detection signal is not measureable in the area of the crosstalk. The distance (gap) between the projection and detection fields has to be larger than the crosstalk range radius. The dimension of the gap is depending on the OLED luminance and the photodiode sensitivity. For the following paraxial simulation the crosstalk around the projection field is neglected (gap $= 0$). But for further development of an optical prototype a gap $> 0$ between object field and detection field has to be considered.

As discussed before, the detection field has to be separated from the projection field on the display. Thereby, the detection field (diagonal 4.46 mm) is two times larger than the projection field (diagonal 8.92 mm) to realize a higher resolution ($592 \times 592$ Pixel) for the imaging path. Figure 6 shows the compact paraxial optical system design for the 3D sensor: on the left side the BiMiD and on the right side the MO.

The object (e.g., fringe pattern, see Figure 7) is imaged by a paraxial lens into the focal plane of the sensor. In the focal plane a MO is placed. Via a second paraxial lens the MO is observed during the fringe projection sequence and the image is detected by the PD. The system parameters are shown in Table 1. The OLED (object field) emits with
(a) Bi-directional OLED microdisplay showing an image.

(b) Detailed view of the pixel matrix. The green pixel represents the OLED pixel and the circular mark highlights the active integrated photodiodes.

Figure 3: Bidirectional OLED-on-CMOS-microdisplay (at Fraunhofer IPMS).

(a) Test image of the object field (projection path, diagonal 3 mm).

(b) Detected test image via the integrated photodiode matrix (PD) without optical elements (e.g., lens, mirror).

(c) Image of the detected test image in the labor setup (see Figure 5(b)) (detection path).

Figure 4: Image of test image and the detected photodiode image applying the 3D sensor system application (triangulation angle). The red square highlighted the object projection field. Due to the crosstalk effect the projection and detection fields have to be separated.
Table 1: System parameters of the paraxial lens design of the 3D sensor system (see Figure 6).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range projection-imaging</td>
<td>Visible</td>
</tr>
<tr>
<td>NAProjection</td>
<td>0.019</td>
</tr>
<tr>
<td>NAImaging</td>
<td>0.13</td>
</tr>
<tr>
<td>Lens diameter projection</td>
<td>5 mm</td>
</tr>
<tr>
<td>Lens diameter imaging</td>
<td>6 mm</td>
</tr>
<tr>
<td>Magnification projection $\beta'$</td>
<td>0.224</td>
</tr>
<tr>
<td>Magnification imaging $\beta''$</td>
<td>11.15</td>
</tr>
<tr>
<td>Object field diagonal (projection)</td>
<td>3.564 mm</td>
</tr>
<tr>
<td>Measurement field diagonal</td>
<td>0.85 mm</td>
</tr>
<tr>
<td>Detection field diagonal (imaging)</td>
<td>8.92 mm</td>
</tr>
<tr>
<td>Trinagulation angle</td>
<td>$\pm 9^\circ$</td>
</tr>
<tr>
<td>Distance BiMiD-MO (projection path)</td>
<td>$\approx 160$ mm</td>
</tr>
<tr>
<td>Detector resolution (imaging)</td>
<td>592 × 592 Pixel</td>
</tr>
<tr>
<td>Active area BiMiD</td>
<td>12.8 mm × 9.6 mm</td>
</tr>
</tbody>
</table>

The complete system principle is shown simplified in Figure 8. The first simulation part is to simulate the projection path of the OLED image. The OLED acts as an image/light source with lambertian radiation characteristics. The fringe pattern image is projected on the MO. In the first simulation step, the MO is used as a detector. The images are saved and used for the second simulation step, the imaging/detection path. The detected image, MO with fringes, acts as an image/light source for the imaging of the MO into the real detector plane, the BiMiD. The radiation characteristic of the MO-fringe image is uniform. Figure 8(a) shows one of the fringe pattern images that is displayed in the measurement plane on the MO. The MO is a sinusoidal ideal object which is shown in Figure 8(b) and Figure 9(a). Figure 8(c) depicts the detected image of the MO during one fringe projection sequence. For the second part of simulation this image acts as an image/light source. The image is projected into the BiMiD detection field as shown in Figure 8(d). 46 fringe pattern images and 2 reference images were imaged onto the MO. Therefore, 48 images of the MO with fringe pattern were imaged into the BiMiD detection field (23 pattern images for each orientation, horizontal or vertical, and 2 reference images) (see Figure 7). Based on these detection images (BiMiD) the simulated measurement object could be recalculated to a 3D model. The result is shown in Figure 8(c) and Figure 9(b).

For the 3D calculation we decided to use a 16-step phase shift of the fringe pattern. Each pattern consists of a series of fringes next to each other with a width of 16 pixels each. During the sequence each pattern is shifted by 1 pixel between two adjacent steps. The basic pattern size is 1024 × 1024 consisting of 64 periods of fringes (independent of the projector resolution, only the centered area is projected onto the object). This implies a gray code sequence of 7 images resulting in 23 images projected in one direction. As reference a black image and a bright image are also recorded. Therefore, we use 48 images for the complete measurement. In Figure 7 some test images are shown. During measurement each pixel records a series of intensity values. The periodic phase value is calculated from the intensity values of the 16 fringe patterns normalized with the dark and the bright image for reference using interpolation. Phase unwrapping is done using the Gray code images in the sequence. The intensity values of the Gray code sequence for each pixel are translated into a binary sequence representing the period number. Now a multiple of $2\pi$ is added to each periodic phase value depending on its period number to unwrap the phase values. After this calculation the sinusoidal MO, which is simulated in ZEMAX, is recalculated to a 3D model.
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Figure 6: Paraxial optical system setup of the 3D sensor. On the left-hand side a top view of the BiMiD is shown and on the right-hand side the paraxial lens setup is shown. The projection and detection fields are oriented to reach the best fill factor for the microdisplay. Due to this effect the display is rotated for the paraxial system simulation. Projection and detection fields are orientated perpendicular. At the paraxial lens setup the bi-directional OLED microdisplay is positioned on the left side and on the right side the measurement object (e.g., sinusoidal mirror element) is placed. The blue ray path describes the projection and the green one describes the imaging path.

(a) Reference images: dark and bright full-screen image.
(b) Exemplary fringe pattern images, in horizontal and vertical orientation.

Figure 7: Simulated test images, which are used as source images for the projection path.

The recalculated and, for comparison, the simulated object is shown in Figure 9. The calculated 3D model shows well conformity to the simulated MO.

5. Conclusion

The monolithic design of OLED-on-CMOS backplane with photodiodes combines emitting and detecting units on one single chip. That offers a new flexibility for applications in optical metrology for surface and shape characterization and allows for compact optical systems, especially in the field of optical metrology.

In this paper we presented a compact, highly integrated 3D metrology system based on a fringe projection principle using a bi-directional OLED microdisplay developed by Fraunhofer IPMS. This microdisplay combines light emitting pixels called OLED microdisplay (projection unit) and light detecting pixels called photodiodes (camera unit) on one single device. This technology provides the opportunity for miniaturization of optical metrology systems.

In contrast to conventional 3D sensor systems (that are based on projection and imaging unit) the presented setup based on BiMiD is compact. The presented 3D metrology system is based on fringe projection onto the surface of the measurement object. The fringes appear deformed when being observed via a different angle (triangulation angle). Based on the deformation of the fringes the 3D coordinates of all visible points can be calculated and, thus, the object shape can be determined.

Due to the internal crosstalk effect two separate lenses for projection and imaging are necessary. The system lens design is based on the BiMiD and two paraxial lenses, which are orientated via a triangulation angle of 18°. Both apertures are smaller than 6 mm. The measurement field has a diagonal of 0.85 mm. For the recalculation of the measurement object different reference and fringe pattern images are necessary. 23 fringe pattern images and 2 reference images are simulated through the optical system in both directions, projection and imaging, and both orientations, horizontal and vertical. Based on the detected images (images of the measuring object during fringe projection sequence), fringes are deformed due to the irregular measurement surface. The simulated measurement object can be recalculated to a 3D object model. Well conformity of the simulated and
calculated measurement object could be shown. This system simulation shows the proof of concept of a 3D surface sensor based on bi-directional sensor device.

Due to the application of the bi-directional OLED micro-display the fringe generating elements and the detectors are combined into one single device. Therefore, an ultracompact and solid system concept for 3D surface metrology has been realized. Such a compact sensor is very suitable for applications like inline quality control in manufacturing processes. In case of elimination of the crosstalk, it would be possible to realize a sensor with only one optics whereas in a next step, different optical system configurations, the application of microoptics, hybrid optics, and freeform optical elements will be considered to design and construct a full working 3D surface sensor.

Figure 8: Principle of the 3D sensor system. The pattern images (OLED-BiMiD/(a)) are projected via a projection lens onto the measurement object (e.g., sinusoidal MO) (b). Then the detector (PD-BiMiD/(d)) detects the image of the measurement object during fringe projection (c). For this part the detected image of (c) is used as image/light source and is imaged into the BiMiD detector plane that is shown in (e). The 3D model is calculated with an internal Fraunhofer IOF software. (a) OLED generated fringe pattern image, (b) 3D measurement object, (c) fringe projection on the measurement object, (d) detected image of the measurement object during fringe projection, and (e) reconstructed 3D object.

Figure 9: Simulated and reconstructed sinusoidal measuring object.

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