A Novel Frequency-Shift Moiré Fringe Method for 3D Inspection of BGA Packaging*

Mingtao ZHAO**, Ningqun GUO** and Wenyi CHEN**

BGA (ball-grid array) is an advanced electronic packaging technology that has increasingly become more important and demanding in microelectronic industry. However, no effective technique is available to inspect the performances of the welding points and its co-planarity. The moiré fringe method is often employed to measure the three-dimensional (3D) shape of the welding spot on BGA, and a high-resolution CCD camera is utilised to capture the deformation stripe image. In order to gain high measuring accuracy, a frequency-shift moiré fringe technique is proposed in this paper, in which three light-sources are deployed to create the fringe. The system parameters are designed to ensure the BGA ball height within exactly one grade moiré fringe. By using zero-maximum equation transformation, the measuring range can be segregated into eight subsets. Equal-step interpolation and indexed table approaches are also introduced to greatly improve the measurement speed, so it may be useful for industrial on-line application. Finally, the predicted results based on the simulated images are presented, demonstrating that its measuring accuracy can be achieved to 5 micron.

**Key Words:** Moiré Fringe Technique, BGA Packaging

1. Introduction

Ball grid array (BGA) package technology is making progress along with the development of semiconductor industry. Its principle is to connect the silicon chip to a printed circuit board through a bottom side array of solder balls or columns. Now, BGA increasingly becomes a preferable surface mount technology in semiconductor industry. There are two main key factors to push the extensive application of BGA.

The first factor is that the solder ball pitch is very small. According to the standard, BGA packages are with 1.0, 1.27 or 1.5 millimetre pitch, and its body sizes are from 7 to 50 millimetres. Hence, it is extendible to very high input/output and can be either single chip or in multiple chip module (MCM). There is a minimum investment in development and capital[1]. BGA has higher yield than the conventional package quad flip packaging (QFP). The second advantage is that the solder balls of BGA can be easily removable, rechangeable, especially that can be reworked. BGA surface mount technology has been reputed as an effective tool to dwindles the scale of electronic products.

However, BGA has also its limitations. For example, its solder balls and their geometry are difficult to inspect and to measure accurately. In order to verify the performance of BGA, many researchers are engaging on the non-destructive characterisation of its dimension and defects. Till now, X-ray technique is one important means to detect opens and bad points, but it is hard to interpret the X-ray signatures correctly in such case. Structured light technology as illustrated in Fig. 1 is also employed to measure the 3D shape of the solder ball[2]. It has the full field measurement advantage, based on its triangular measurement principle, and its measuring accuracy can be up to 10 μm.

In this paper, a novel frequency-shift moiré fringe method is proposed for the three dimensional inspection of BGA. A shadow of the reference grating is cast onto the surface of BGA to create moiré fringes and three deformed images are obtained to retrieve the 3D property of the BGA solder ball. Figure 2 illustrates the principle of the measurement. It is a derivative method from the phase-shift technology[3], however it avoids the phase unwrapping[4] and phase
shifting problems, which are intrinsic problems associated with the phase-shift techniques. Hence, it could be a useful means to control the yield and prevent bad parts to enter the next processing stage.

2. Principle of the Frequency-Shift Moiré Method

Shadow moiré fringe measurement is a well-known technique. When an illuminated grating is closed to an object, its shadow can be seen on the object through the grating as shown in Fig. 2. Two superimposed gratings can produce a moiré fringe pattern with respect to the contour lines of the 3D surface of the measured object. Its fringe intensity can be expressed as follows,

\[ I(x, y) = A(x, y) + B(x, y) \cos \frac{2 \pi b_z}{p_b} Z \]  

(1)

where \( A(x, y) \) is the fringe intensity of the background or DC light level, and \( B(x, y) \) is the fringe contrast. Other parameters are defined as follows, \( p_b \) is the grating pitch, \( h \) is the distance with respect to observer-grating, \( b_z \) is the distance between the CCD camera and each light source, and \( Z \) is the surface height of the measured object.

From above equation, it can be found that changing parameters of \( p_b, h, \) and \( b_z \) could retrieve the value of \( Z \), i.e., the surface height of the measured object. In actual measurement set up shown in Fig. 2, the parameter \( b_z \) will be changed three times to simplify the system complexity. The relation between \( Z \) and the varying camera-light source distance \( b_z \) is given as follows,

\[ I(x, y) = A(x, y) + B(x, y) \cos \frac{2 \pi b_z}{p_b} Z \]  

(2)

\[ I(x, y) = A(x, y) + B(x, y) \cos \frac{2 \pi b_z}{p_b} Z \]  

(3)

\[ I(x, y) = A(x, y) + B(x, y) \cos \frac{2 \pi b_z}{p_b} Z \]  

(4)

For simplicity, it is assumed that the distances between the two light sources are equal, i.e.,

\[ b_2 - b_1 = b - b_2 = \Delta b \]  

(5)

Substituting above in Eq. (2) to Eq. (4) it can be shown that,

\[ I_b(x, y) = A(x, y) + B(x, y) \cos \frac{(w + \Delta w)Z}{p_b} \]  

(6)

\[ I_b(x, y) = A(x, y) + B(x, y) \cos \frac{wZ}{p_b} \]  

(7)

\[ I_b(x, y) = A(x, y) + B(x, y) \cos \frac{(w + \Delta w)Z}{p_b} \]  

(8)

where \( w = \frac{2 \pi b_2}{p_b} \) and \( \Delta w = \frac{2 \pi \Delta b}{p_b} \).

It can be seen that Eqs. (6) and (8) are now expressed similar to Eq. (7) but with a change of the frequency of the moiré fringe, hence the name of the frequency-shift technique. It is different from the phase-shift technique. By incorporating the above three equations of fringe intensity, one can define a normalised rate function \( F(Z) \) as,

\[ F(Z) = \frac{b_2 - b_1}{b_1 - b_2} \frac{\cos \omega x - \cos \omega Z}{\cos \omega Z - \cos \omega Z} \]

\[ = \frac{\sin((w + \Delta w)Z)}{\sin((w + \Delta w)Z)} \sin \Delta w Z \]  

(9)

i.e.,

\[ F(Z) = \frac{\sin((w + \Delta w)Z)}{\sin((w + \Delta w)Z)} \frac{f(Z)}{g(Z)} \]

or \( G(Z) = \frac{1}{F(Z)} \)

where \( f(Z) \) and \( g(Z) \) are the numerator and denominator of function \( F(Z) \) respectively. A mapping relationship between \( Z \) and \( F(Z) \) is therefore established.

3. Indexed-Table Technology

It can be seen that the measurement of parameter \( Z \) can easily be obtained once the function \( F(Z) \) is known from the three measurements. However, for online inspection the measurement speed is a very critical factor, and the indexed-table technology is introduced for this purpose.

To speed up the on-line real time calculation, a fixed \( Z \) vs. \( F(Z) \) table can be made in advance. By utilising this table, the values \( Z \) can be rapidly searched out according to the measured values of \( F(Z) \) and there is no need to calculate the values \( Z \) in real time. This will save considerable computing time. Zero-maximum transformation is employed to make the indexed-table and to simplify the measurement range.

From Eq. (9) it can be seen that the function
\( F(Z) \) has many zero points and many maximums. The zero and maximum points of the function \( F(Z) \) can be found by letting its numerator and denominator functions to be zero as shown in Eq. 3. The combination of those points is used to divide the range of \( Z \) into 8 subsets according to the signs of the functions. All the maximum points can be changed into zero points for easy processing purpose by defining function \( G(Z) = 1/F(Z) \). The zero points of \( F(Z) \), as shown in Fig. 3(a), can be found as follows,

\[
\sin [(\omega + \Delta \omega)/2] = 0
\]

i.e.

\[
Z_{\text{zero}} = f_k = \frac{k \pi}{\omega + \Delta \omega/2} = \frac{k}{5.625} = \frac{1}{6.875} = 0.145, 0.291, 0.436,
\]

where \( k = 1, 2, 3, \ldots \) integer. (10)

The maximum points of \( F(Z) \), as shown in Fig. 3(b), can be found as,

\[
\sin [(\omega - \Delta \omega)/2] = 0
\]

\[
Z_{\text{max}} = g_k = \frac{k \pi}{\omega - \Delta \omega/2} = \frac{k}{5.625} = 0.178, 0.356, 0.533;
\]

where \( k = 1, 2, 3, \ldots \) integer. (11)

If \( p = 0.05 \text{ mm}, \omega = 6.25 \pi, \Delta \omega = 1.25 \pi, f_k \) and \( g_k \) denote the zero points and maximum points respectively. The normalisation rate function \( F(Z) \) is shown in Fig. 4. Comparing Fig. 3(a) and Fig. 3(b), the measurement range of \( Z \) can be segmented into the eight subsets within a cycle of function according to varying signs of both numerator and denominator in functions \( F(Z) \) and \( G(Z) \).

For example, if both the numerator and denominator are positive in a subset, the subset will be represented as \( F(+/+) \). The other seven subsets can thus be denoted as, \( F(+/-) \), \( F(-/+)) \), \( F(-/-) \), and \( G(+/+) \), \( G(-/+)) \), \( G(-/-) \), \( G(-/-) \). The term \( \sin (\Delta \omega/2) \), which is reduced in Eq. (9), is a low frequency modulating item, and its invariant sign ensures that the \( F(Z) \) sign will not be affected by the sign of the modulating term. The eight segregated subsets are displayed in Fig. 5 with their respective shades. It can be seen that in every subset range the value \( Z \) maps a functional value of \( F(Z) \) or \( G(Z) \). Hence an indexed-table for \( Z \) vs. \( F(Z) \) or \( Z \) vs. \( G(Z) \) can be constructed. The breakpoints of different subsets are where \( F(Z) = 1 \) as shown in Fig. 5.

In the range covering these eight subsets, the equal-step interpolation approach is used to gain an indexed-table. The interpolation step is dependent upon the resolution of the CCD camera and digital accuracy of image grabber (ADC). The following rules are applied for practical procedure.

For 8 bits AD converter which has 256 grey grades, the step is,

\[
\Delta Z \approx \frac{L(x, y)_{\text{max}}}{256} \text{ per pixel for 8 bits ADC (12)}
\]

Similarly,

\[
\Delta Z \approx \frac{L(x, y)_{\text{max}}}{4096} \text{ per pixel for 12 bits ADC (13)}
\]

\[
\Delta Z \approx \frac{L(x, y)_{\text{max}}}{64000} \text{ per pixel for 16 bits ADC (14)}
\]

where \( I(x, y)_{\text{max}} \) is the maximum fringe intensity. An example of the indexed-table is illustrated in Table 1 for \( Z \Rightarrow F(Z) \) with an interpolation step of 0.5 \( \mu \)m. A similar table can be used for \( F(Z) \Rightarrow Z \).

The general flow procedures can be summarised as follows,

1. Customise an indexed-table with respect to the parameter \( p, h \), and \( b \).

![Fig. 4](image-url)  
**Fig. 4** The normalisation rate function of \( F(Z) \) solid line for \( F(Z) \) and circle line for \( \sin (\Delta \omega/2) \)

![Fig. 5](image-url)  
**Fig. 5** Eight segregated subsets in \( Z \) dimension (Circle line for numerator and asterisk line for denominator of \( F(Z) \), each 4 breakpoints of 8 subsets are where \( F(Z) = 1 \) )
Table 1 The index table with the specified function $F(Z)$ vs. value $Z$

<table>
<thead>
<tr>
<th>$Z$ (mm)</th>
<th>$F(Z)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.0061</td>
</tr>
<tr>
<td>1.00</td>
<td>0.0326</td>
</tr>
<tr>
<td>1.50</td>
<td>0.0578</td>
</tr>
<tr>
<td>2.00</td>
<td>0.0819</td>
</tr>
<tr>
<td>2.50</td>
<td>0.1015</td>
</tr>
<tr>
<td>3.00</td>
<td>0.1271</td>
</tr>
<tr>
<td>3.50</td>
<td>0.1484</td>
</tr>
<tr>
<td>4.00</td>
<td>0.1688</td>
</tr>
<tr>
<td>4.50</td>
<td>0.1885</td>
</tr>
<tr>
<td>5.00</td>
<td>0.2076</td>
</tr>
</tbody>
</table>

(2) Grab three different moiré fringe images $I_1$, $I_2$ and $I_3$.

(3) Compute the function $F(Z)$ or $G(Z)$ from the measurements.

(4) Obtain the $Z$ values of the solder balls by searching the indexed-table.

The three dimensional shapes of solder balls can be reconstructed using the values of $Z$. The image processing technologies such as edge detection, segmentation, etc. can also be used to retrieve more useful information of BGA, such as,

- Geometry properties of solder balls (hitch, diameter, volume, and position).
- Presence/absence of solder balls.
- Co-planarity.

An example will be illustrated using the simulated data. However, the range and accuracy are discussed first.

4. Analysing of Measurement Range, Accuracy, Speed and Digital Simulation

From Eqs. (10) and (11), it can be seen that the system measurement range is subjected to $\omega = 2\pi b/(ph)$. As shown in Fig. 3 the parameters ($p$, $h$ and $b$) determine the positions of zero points and maximum points, and confine the system measurement range. In order to take an integer cycle, the measurement range can be either $(f_i - f)$ or $(g_n - g_0)$, and the latter is the actual selected measurement range, and it is 0.355 mm. Exceeding $(g_n - g_0)$ range will be another measurement cycle, and it means $F(Z)$ will repeat a new 8 subsets. So we must design the system parameters to ensure the BGA ball height within exactly one grade moiré fringe. This is the key property of the frequency-shift technique, and these parameters can be configured to fit a special need of BGA measurement.

In an actual measurement, the values $p$ and $h$ can remain as constants, just changing the value $b$. In this system, the value $b$ is designed to meet 0.355 mm measurement range. Pertaining to the accuracy, it is also restricted by following three factors: (a) the bits of image grabber; (b) the pitch of the moiré fringe ($p$); (c) the indexed table making method. The more the bits of the image grabber, the more precious pixel resolution, which can also be explained by Eqs. (12), (13) and (14). As to the grating pitch $p$, in theory, the lower $p$ corresponds to higher accuracy. However if the value $p$ is too low, it will reduce the brightness and contrast of the moiré fringe hence reduces the accuracy correspondingly. In average, the value $p$ is selected as 0.05 mm.

The last factor is related to establishment of an indexed-table. In practice an equal-step interpolation rule along the $Z$ dimension can be used to make the indexed-table. It means following equation,

$$k^e \Delta Z = f(k^e \Delta Z), \quad k = 1, 2, 3, \ldots \text{integer} \quad (15)$$

In ideal situation, we hope $df/(Z_i + \Delta Z) = df/(Z_i + \Delta Z)$, where $Z_i \neq Z_n$. However, Eq. (15) shows $F(Z)$ is a non-linear function, so Eq. (15) is impossible to fit well everywhere, only linear approximation. This case can be shown in Fig. 6, and it has the same vertical range, 0 – 1 with respect to 8 nonlinear horizontal measurement range, $\Delta \theta_1 + \Delta \theta_2 + \ldots + \Delta \theta_8$. That means varying measurement accuracy with different measurement subsets. In practice, in order to fulfill measurement accuracy, eight subsets can be divided by step of confining the following condition,

$$\Delta Z = \text{accuracy} / x$$

where $x = \max(\Delta \theta_1, \Delta \theta_2, \ldots, \Delta \theta_8)$.

In this system, let $x = 2$ for easy processing. Figure 6 demonstrates that the resolution of function $F(Z)$ varies with different subsets. It can be shown that a high speed measurement can be achieved by using the indexed-table method, for example, 200 balls can be easily inspected within a second.

Following is an example that illustrates the application of the method and algorithm based on the computer simulation. Figure 7 shows the original BGA image, and its three different moiré fringe images obtained with three different lights generated by the computer. Figure 8 shows the simulated image.
the reconstructed value $Z$. It can be seen that the error in the height reconstruction is less than 2 μm, and an accuracy up to 5 μm can be expected in actual applications.

5. Conclusions

The conventional methods are difficult to be applied for applications in the BGA soldering ball measurement. In this paper, a moiré fringe technology to evaluate the 3D geometric properties of the solder balls has been studied, and a frequency-shift technique is developed to assure the measurement accuracy. The indexed-table method is also adopted for high-speed measurement that is required in production. It shows that the frequency-shift moiré fringe technology has higher measurement accuracy. Since it is field measurement, there is no need for scanning system any more, and it can be a very useful means for real-time inspection of BGA packaging such as geometry measurement and co-planarity.

References