Detection and analysis of diamond fingerprinting feature and its application

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Abstract. Before becoming a jewelry diamonds need to be carved artistically with some special geometric features as the structure of the polyhedron. There are subtle differences in the structure of this polyhedron in each diamond. With the spatial frequency spectrum analysis of diamond surface structure, we can obtain the diamond fingerprint information which represents the “Diamond ID” and has good specificity. Based on the optical Fourier Transform spatial spectrum analysis, the fingerprinting identification of surface structure of diamond in spatial frequency domain was studied in this paper. We constructed both the completely coherent diamond fingerprinting detection system illuminated by laser and the partially coherent diamond fingerprinting detection system illuminated by led, and analyzed the effect of the coherence of light source to the diamond fingerprinting feature. We studied rotation invariance and translation invariance of the diamond fingerprinting and verified the feasibility of real-time and accurate identification of diamond fingerprint. With the profit of this work, we can provide customs, jewelers and consumers with a real-time and reliable diamonds identification instrument, which will curb diamond smuggling, theft and other crimes, and ensure the healthy development of the diamond industry.

1. Introduction

Diamond is one of the world’s most precious jewels. The production of diamond is rare and not well-distributed in nature so that diamond industries in many countries rely on import which create a capacious market for diamond smuggling. High worth, small size and easy carry make people take risks for diamond smuggling. How to curb these crimes has become an onerous but urgent problem.
At present, researches of diamond identification technology at home and abroad can be divided into three levels. The first level is the most primitive way which is relatively simple, including thermal conductivity tests, rigidity verification, growing point examination, reflected light observation, similar chemical composition tests etc. The second level is the common methods which are relatively reliable, including birefringence character, refractive index measurement, characteristic spectrum etc. The third level is more advanced which includes cathode luminescence technology, Raman spectrum technology, neutron activation analysis technology and X-Ray diffraction technology\textsuperscript{[1]}.

Indeed, there have been numerous reports on diamond identification technologies. Most of these works focus on the diamond material characters. However, researches on diamond fingerprint still remain deficient. The only literature report about space frequency is delivered by Weizmann Institute of Sciences in Israel. Technologies in this report have been patented and the “Gemstone Registration System”\textsuperscript{[2]} has been applied into real life. In this system, tilt collection of fingerprint will cause image distortion and affect the accuracy of fingerprint analysis.

In this study, parallel light beam irradiates the diamond table board vertically and excites surface reflected light, which can produce a space spectrum as Fingerprinting Map, and has good specificity and space-invariance. Recording diamond fingerprint and binding to other information (origin, production date, trading resume, present owner, carat weight etc.) as a “Diamond File” can improve management of diamond imports and exports for customs and effectively strike diamond smuggling crimes.

2. Theoretical analysis of diamond fingerprinting map

2.1. Optical Fourier Transform Implementation

In order to obtain the space spectrum of diamond surface reflected light, we need to process Fourier Transform. The mathematical expression is demonstrated as follows.

\[
F \{E(x, y)\} = \int \int E(x, y) \exp[-i2\pi(f_x x + f_y y)]dxdy
\]  

(1)

In the optical field, Fourier Transform can be implemented by Fourier lens which has incomparable parallel processing speed comparing with computer. The lens plays an important role in the process of 2D Fourier Transform, the lens could produce a space frequency spectrum on the behind focal plane, which is related to the space frequency of the diamond table board reflected light wave.

Analysis is executed in the case of plane illumination light wave as shown in figure 1. Diffraction plane is located in the distance of \(L_0\) from the lens and is illuminated by monochromatic plane wave. In this case, the relationship between the complex amplitude in back focus plane \(\tilde{E}_i(x_i, y_i)\) and the complex amplitude in diffraction plane \(\tilde{E}(x, y)\) is demonstrated as follows\textsuperscript{[3]}.
Where \( k \) represents wave number, \( \lambda \) is wave length, \( f \) represents focal length, \( L_0 \) corresponds to the distance from the diffraction plane to the lens. The relationship between spatial frequency coordinate \((x, y)\) and back focus plane coordinate \((x', y')\) is shown as follows.

\[
x' = \lambda f x, \quad y' = \lambda f y
\]

Formula (2) indicates that the complex amplitude distribution on back focus plane consists of the product of the Fourier transform of the complex amplitude distribution on diffraction plane \(F\{E(x, y)\}\) and a phase factor

\[
\exp \left[ \frac{ik}{2f} \left( 1 - \frac{L_0}{f} \right) \left( x_1^2 + y_1^2 \right) \right].
\]

\[2\]

**Figure 1.** Optical Fourier Transform setup of lens.

### 2.2. Theoretical Analysis of Diamond Fingerprinting Map

In this study, parallel light beam irradiates the diamond surface vertically and excites surface reflected light beams which have discrete spatial frequencies. The superposition of light beams produce specific complex amplitude distribution in space domain which is processed by 2D Fourier transform by the lens. The space spectrum is displayed in the form of complex amplitude distribution in the back focus plane. In fact, the CCD can only detect light intensity instead of complex amplitude distribution. Therefore it’s necessary to calculate the light intensity distribution \(|\tilde{E}'(x', y')|^2\) in frequency domain. The light intensity distribution is demonstrated as follows.
\[
|\hat{E}'(x', y')|^2 = \sum_{i=1}^{n} A_i^2 \left[ \delta\left(\frac{x_i'}{\lambda f} - f_i\right) \delta\left(\frac{y_i'}{\lambda f} - f_{y_i}\right) \right]^2
\]  

(4)

In the Formula (4), \(A_i\) represents amplitude of reflected light beams, \(\lambda\) represents wave length of light source, \(f\) represents lens’ focal length, \((f_{x_i}, f_{y_i})\) represents spatial frequency coordinate of different light beams, \((x', y')\) is the screen coordinate.

Formula (4) is the mathematic model of the diamond fingerprinting map, which indicates that the light intensity distribution in the receiving screen is comprised of a series of the square of discrete impact functions which are visually a set of bright spots. The number of the spots \(n\) is equal to the number of diamond surfaces. Besides, the position of the spots corresponds to the spatial frequency value. The relationship has been shown as Formula (3). Consequently, if the coordinate \((x', y')\) of the spot is given, we could calculate the spatial frequency \((f_{x_i}, f_{y_i})\) of diamond surface geometry structure character. On the contrary, if the geometry structure of diamond is given, we can calculate the position of the corresponding spatial frequency spot as well.

3. Construction of diamond fingerprint detecting platform

In order to realize the detection of diamond fingerprint and the related researches, the diamond fingerprinting map detecting system is constructed. For the first time, a coaxial symmetry light path is adopted in figure 2.
The focal length of lens will affect the distances from beam splitter to the pin hole and to the screen. If we use lens of short focal length to decrease the volume, some mechanical components which help to connect or fasten and some optical components such as the splitter, would prevent the light beams and lead to deficiency of space spectrum map. Conversely, if we choose the long one, the area of the spectrum would be very large and a tremendous receiving screen would be needed, will result in unexpected big system structure in volume. In order to gain the best focal length, we did experiments in several different focal lengths of 33mm, 50mm, 100mm, 150mm. Experimental results show that the focal length of 50 mm has the best effect.

The concave-convex type of lens affects the imaging performance as well. Based on the experiments using double-convex and concave-convex lens, the results indicate that in the condition of lens at 25mm in diameter, concave-convex lens achieve better convergence of the high spatial frequency beams.

In the system, VC2003 (Visual Studio 2003) linking to the OpenCV library is used as the software development environment. Coding is completed with functions of background-noise-removed real-time image collection, image preview, saving and analysis. Due to factors such as coherence of the light source and reflected light of components, there is heavy background noise in experiment. Background-noise-removed real-time image collection can help users observe more clear and legible fingerprint. The software interface of diamond fingerprinting spectrum analysis is shown in figure 3.

Diamond fingerprinting map is analyzed accurately by “Radius Comparison Method”, the main process is shown as follows.
(1) Detect and calculate the center pixel coordinate of each spot in the fingerprinting spectrum image.

(2) Compare the amount of spots in each spectrum images. Analysis ends if the amount is not equal.

(3) Calculate the distances from the point of zero spectrum to all other spectrum spots (referred to as radius below) and sort them in a sequence.

(4) Compare the two sequences and calculate the mean square error and the maximum error.

**Figure 3.** Diamond fingerprinting map detecting system.

### 4. Results and discussion

#### 4.1. The light coherence impact to the system.

In this paper, Image Signal to Noise Ratio (ISNR) is used to analyze the light coherence impact to the system. ISNR formula is shown as follows \(^4\).
\[ R_{\text{SNR}} = 10 \log \frac{I_{\text{max}} - B}{\sigma} \]  

In the formula, \( R_{\text{SNR}} \) represents ISNR. \( I_{\text{max}} \) is the maximum gray value of the spectrum spot signal. \( B \) represents the gray value of the background, which can be estimated from the average value of the image background of all pixels. \( \sigma \) represents the noise standard deviation.

In the condition of the same mechanical structure and light path, we respectively did experiments based on LED (partial coherent source) and laser (complete coherent source). Firstly we turned off the light source and collected a background image, the average gray value \( B \) was obtained. Secondly we turned on the light source and collected a background image to calculate the noise standard deviation \( \sigma \). Finally we placed the diamond into the system and collected the diamond fingerprinting spectrum images and estimated the maximum gray value \( I_{\text{max}} \). The experimental data is shown in table 1.

|       | \( I_{\text{max}} \) | \( B \) | \( \sigma \) | \( R_{\text{SNR}} \) (dB) |
|-------|-------------------|------|--------|-----------------|
| LED   | 176               | 16   | 9.81   | 12.12           |
| Laser | 254               | 16   | 11.85  | 13.03           |

Data in the table 1 illustrates that coherence source can enhance the Signal Noise Ratio of diamond fingerprinting image.

4.2. Feasibility analysis of real-time accurate identification

In fact, when the same diamond was repeatedly detected, we can’t guarantee that the position of diamond is completely the same. Therefore, it is prerequisite that fingerprinting radius information is invariable under center translation and axis rotation. We call them translation invariance and rotation invariance.

In this article, the two parameters “Mean Square Error” (MSE) and “Maximum Error” (ME) are used to estimate the difference between two fingerprint images. When the precondition of the same spots amount is met, the distances from zero-point to all the spots are sorted, MSE the mean square deviation of the radius in the same sequence number indicates the similarity of fingerprint images. The less the mean square deviation of the radius is, the higher the similarity of fingerprint images is. ME is the maximum value of all the subtractions of the radius in the same sequence number. Theoretically, both of the MSE and ME are translation invariance and rotation invariance. However, error exists in the actual system and these two parameters can be used to evaluate the accuracy of the diamond fingerprinting map detecting system.

In the illumination of laser, we did experiment for center translation invariance and axis rotation invariance, recorded and analyzed five groups of fingerprinting maps. The analysis results are shown
in table 2 and table 3. Furthermore, we did experiments for another sample and analyzed its fingerprints as well. The analysis results are shown in table 4. The MSE and ME in these tables are presented in the form of percentage, which is ratio of the real MSE or ME to the maximum radius in the maps.

Table 2. Center translation error analysis of fingerprint

|    | 1    | 2    | 3    | 4    | 5    | Average |
|----|------|------|------|------|------|---------|
| MSE| 0.76%| 0.72%| 0.98%| 1.16%| 0.70%| 0.86%   |
| ME | 1.55%| 1.63%| 1.30%| 2.89%| 1.02%| 1.67%   |

Table 3. Axis rotation error analysis of fingerprint

|    | 1    | 2    | 3    | 4    | 5    | Average |
|----|------|------|------|------|------|---------|
| MSE| 0.72%| 0.89%| 0.82%| 1.55%| 1.88%| 1.17%   |
| ME | 1.12%| 1.97%| 2.58%| 3.42%| 3.62%| 2.54%   |

Table 4. Fingerprinting map error analysis of different samples

|     | MSE | ME  |
|-----|-----|-----|
|     | 3.27%| 9.18% |

The comparison of the three tables demonstrates that there is identifiable difference in different samples. Both the MSE and ME of the fingerprint of the same sample are small compared to that of different samples, which certifies the feasibility of real-time accurate identification.

Error produced by center translation is due to large distortion when high spatial frequency beams pass through lens. The essence of axis rotation is the movement of each diamond surface. Therefore one of the error sources of axis rotation is the same as the center translation. Besides, it’s obvious that the error of axis rotation is a little larger than that of center translation, the reason is that lens, receiving screen and CCD are not completely coaxial. In a word, the error of axis rotation can be regarded as the superposition of the error of center translation and incomplete co-axis.

5. Conclusions

In summary, we have constructed the theoretical model of diamond fingerprint and developed a
diamond fingerprint detecting system, the fingerprinting maps of diamond are collected and the validity of theoretical model is proved. Based on our method and system, the coherence impact of light source to the system is analyzed and the feasibility of real-time accurate identification of diamond fingerprinting maps is verified.

There are two innovations in this paper. Firstly, co-axial symmetry light path detecting structure is adopted in our diamond fingerprinting map detecting system, which overcomes the existed disadvantage in reference 2 where CCD tilt imaging leads to distortion of collecting image and improves the accuracy of fingerprint analysis. Secondly, the software system realizes fingerprinting map preview, saving, analysis as well as real-time background-noise-removed collection, which is more simple and efficient than the mechanical and optical methods.

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