The influence of light path length on the color of synthetic ruby

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The corrected ultraviolet–visible light spectrum was used to calculate the color of synthetic rubies with different light path lengths, and the influence of light path length and standard light source on the color of synthetic ruby was studied. The results show that the difference in colour between the o light direction and the e light direction of the synthetic ruby decreases as the length of the light path increases. At the same time, as the length of the light path increases, the lightness L* decreases, and the hue angle h° increases. The chroma C* first increases as the length of the light path increases, and then begins to decrease under the influence of the continuous decrease in lightness. The color difference ΔE*ab reaches the maximum when the light path length is around 10 mm, and the standard light source has the greatest influence on the color difference ΔE*ab. As the length of the light path continues to increase, the influence of the standard light source on the color difference ΔE*ab decreases. In the ultraviolet–visible light spectrum, the strong absorption band of Cr³⁺ at 545 nm is the main cause of the color of the ruby. The larger the area of the band at 545 nm, the lower the lightness and the higher the hue angle, which means the ruby colour is redder.

Ruby is a kind of corundum with a beautiful bright red color. It is widely distributed all over the world, such as Myanmar, Thailand, Sri Lanka, Tanzania, etc. When Al in corundum is replaced by various elements such as Cr, Fe, Ti, and V, the corundum will show various colors. The color of ruby is related to Cr³⁺. And as the replacement of Al³⁺ by Cr³⁺ increases, the color will change from light pink to red₁,² flame-fusion synthetic ruby is the most common type of synthetic ruby. Compared with natural ruby, it has a pure texture and is more suitable for chromaticity research.

There are many ways to evaluate the color of gems. The most common is the Cape series diamond color grading. The grader compares the diamond to be graded with a standard colorimetric stone to determine the color grade of the diamond³–⁵. However, in addition to diamonds, it is difficult to determine the color grade of other gemstones in this way, and because it is artificially graded, there may be large errors. The CIE standard colorimetric system can effectively solve this problem, of which the CIE1931-XYZ system and the CIE1976L*a*b uniform color space are the most widely used. Stockton⁶ first used the Gem ColorMaster instrument to quantify the color of peridot in the CIE1931 color space. But the CIE1931-XYZ system is a non-uniform color space and cannot describe the color of gems well. The CIE1976L*a*b uniform color space is modified based on the CIE1964 uniform color space, and it is widely used in gem color evaluation⁷–¹².

The main instrument currently used to measure the color of gemstones is a spectrophotometer. The portable spectrophotometer is used to measure the color of peridot¹³–¹⁵, amethyst¹⁶, turquoise¹⁷, rubellite¹⁸, and green chrysoprase¹⁹,²⁰. Color i5 and GemDialogue color cards are used to quantitatively describe the color of jadeite²¹. In addition, computer vision systems can also be used to measure the color of jadeite²². Because the portable spectrophotometer is a closed system, it cannot effectively reflect the pleochroism of some gemstones. The use of ultraviolet–visible spectrophotometer can effectively solve this problem²³. Compared with the portable spectrophotometer, the UV–Vis spectrophotometer measures color more objectively and accurately. The UV–Vis spectrophotometer calculates the colors of leaves²⁴ and flowers²⁵, garnets²⁶,²⁷, synthetic alexandrite²⁸, dyed purple opal²⁹, etc. by using CIE1931RGB and CIEXYZ color matching functions.

The human retina has three kinds of color photoreceptor cells, namely cone cells, that are sensitive to red, green, and blue light. S cones detect short wavelength (blue), M cones detect medium wavelength (green), L cones detect long-wavelength (red). When exposed to radiation, the spectral stimulus energy is absorbed by photoreceptors of the three cones. The cone cells produce different degrees of neurophysiological reactions. The International Commission on Illumination (CIE) has established a series of color matching functions through visual experiments. As a proxy for the cone response function, the CIE color-matching functions are used to express the linear combination of the average visual response³⁰. The matching function can be used to calculate the energy of light that enters the human eye and produces the color perception. Sun³¹ discussed the influence...
of different path lengths on the color of synthetic Cr-bearing chrysoberyl by calculating the color matching function. In addition, pleochroism is also a factor that needs to be considered when studying the color of gems31.

Two fully polished synthetic ruby cuboids R and Ru which have been oriented by an X-ray crystal orientation instrument are selected. Size is 5.89 mm × 5.97 mm × 9.29 mm and 5.46 mm × 5.41 mm × 8.9 mm. The sample is shown in Fig. 1. The height is the c-axis, and the surface is perpendicular to the optical axis. The length and width of the gemstone are selected as the a-axis and b-axis. The a, b, and c axes of the two samples are numbered respectively Ra, Rb, Rc, Rua, Rub, Rue. This paper mainly uses the color matching function to quantitatively characterize the color, and studies the influence of the light path length and the light source on the color of the ruby.

Results and discussion

UV–Vis spectral analysis. The UV–Vis spectrum of synthetic ruby is shown in Fig. 2. The top right-hand corner of Fig. 2 shows the ED-XRF data for synthetic ruby. ED-XRF is a semi-quantitative chemical composition test that can be used to quickly detect the content of most elements in synthetic ruby. It can be seen that there are obvious absorption peaks at 693.50 nm, 669 nm, and 659 nm, as well as broad absorption bands centered at 545 nm and 416 nm. The absorption peak at 693.50 nm is the fluorescence emission peak caused by Cr3+, which is caused by 2E → 4A2 of Cr3+, which is the reason for the strong fluorescence of synthetic ruby. The two weak absorption peaks at 669 nm and 659 nm are the 4A2 → 2T1 transition caused by Cr3+. The absorption peak near 581 nm is related to the charge transfer of Fe2+–Ti4+. The absorption peak at 528 nm is related to the 2D splitting of the Ti3+ spectrum item32,33. The absorption peaks at 545 nm and 416 nm are the 4A2 → 4T2 transition caused by Cr3+, which absorb yellow-green light, allowing red light and a small amount of blue-violet light to pass through, forming the color of synthetic ruby. As can be seen from the ED-XRF data in Fig. 2, the main chemical composition of the synthetic ruby is Al2O3, which accounts for 97.186%. The colour-causing elements Cr2O3 and Fe2O3 account for 0.998% and 0.008% respectively. This coincides with the absorption peaks in the UV–Vis spectrum of Fig. 2.

Correcting the UV–Vis spectra. When light passes through the sample, energy is lost in three ways. A is the total absorbance of the sample measured directly from the spectrophotometer, including Ac (absorbance contribution of the absorber), Ar (absorbance caused by light reflection at the boundary), Aisl (absorbance caused by scattering of internal inclusions)26,28.

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A = A_c + A_r + A_{isl}
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There are many different methods to correct the baseline. For example, Sun36 subtracted the absorption spectrum at 800 nm to obtain a corrected spectrum. In this study, the Sellmeier equation is used to eliminate Arl and to correct the baseline of the ultraviolet-visible spectrum. At the same time because the sample is synthetic ruby with pure texture and no inclusions, Aisl does not affect the UV–Vis spectrum. Thus, the corrected UV–Vis spectrum is obtained.
The absorption ($A_{\text{R}}$) of light reflected at the boundary is related to the refractive index ($n$) of the sample. The Sellmeier equation is an empirical formula that describes the refractive index and wavelength in a specific transparent medium and is used to determine the dispersion of light in the medium. Different materials have different Sellmeier coefficients. According to the research of Malitson34, we get the following Sellmeier formula:

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}$$

(2)

where $n$ is the refractive index, $\lambda$ is the wavelength, and $B_{1,2,3}$ and $C_{1,2,3}$ are different Sellmeier coefficients. For corundum, there are the following Sellmeier equations in the direction of the corundum $o$ light and the direction of the $e$ light respectively:

$$n^2(\lambda) = 1 + \frac{1.4313493\lambda^2}{\lambda^2 - 0.0726631} + \frac{0.65054713\lambda^2}{\lambda^2 - 0.1193242} + \frac{5.3414021\lambda^2}{\lambda^2 - 18.028251}$$

(3)

$$n^2(\lambda) = 1 + \frac{1.5039759\lambda^2}{\lambda^2 - 0.0740298} + \frac{0.55069141\lambda^2}{\lambda^2 - 0.1216529} + \frac{6.5927379\lambda^2}{\lambda^2 - 20.072248}$$

(4)

It is assumed that in the ideal state when unpolarized light is incident perpendicularly to the surface of the gemstone, a certain length of optical path will not be generated inside. In this case, the light absorption inside the gem can be ignored. Therefore, the transmittance through the surface of the gemstone can be expressed as:

$$T = 1 - R$$

(5)

According to Lambert Beer's law, transmittance can be converted to absorbance:

$$A = \lg \frac{1}{T} = kbc$$

(6)

where $A$ is the absorbance, $T$ is the transmittance, $k$ is the molar absorbance coefficient, $c$ is the concentration of the absorbing substance, and $b$ is the optical path of the light.

$$T = 10^{-A} = 1 - R$$

(7)

$$A = -\lg T = -\lg(1 - R)$$

(8)
R is the reflectivity, \( n_0 = 1 \) is the refractive index of light in the air, \( n_1 \) is the refractive index of light in corundum, \( T \) is the transmittance, and \( A \) is the absorbance produced by single boundary reflection. \( Arl \) is the absorbance produced by the reflection of the two boundaries.

Accurate visible spectroscopic measurements rely on correct calibration of the spectral baseline. Figure 3 shows the spectrum of baseline correction performed by the Sellmeier equation. The spectra of the synthetic ruby were converted to transmission spectra with light path lengths from 1 to 25 mm by multiplying the spectra by an appropriate value. That is I/I₀, where “I” is the desired light path length and “I₀” is the light path length of the reflection-corrected spectrum. By following the steps above, the ultraviolet–visible light spectrums corresponding to the light path length of 1 to 25 mm are obtained. The color matching function can be used to calculate the tristimulus value XYZ, and color space conversion can be used to obtain the color parameters L*, a* and b* in the CIE 1976 L*a*b* uniform color space. The detailed conversion steps are detailed in the method. The synthetic ruby color parameters of the light path length from 1 to 10 mm are shown in Table 1.

**Color calculation and colorimetric parameter maps analysis.** The color of transparent gems can be calculated based on the spectrum of the light source and the transmission spectrum of the gem. The integral of the spectral response curve corresponds to the signal emitted by the cone cells of the human eye. The reaction spectrum of the cone, the light source and the transmission spectrum of the sample are combined to determine the tristimulus value XYZ of the spectrum. The spectra of D65 light source and A light source used in this paper and the corresponding \( x(\lambda) \), \( y(\lambda) \), \( z(\lambda) \) color matching function spectra are shown in Fig. 4. The light source is represented by a colorimeter through a standardized spectrum. CIE D65 light source represents the average daylight with a correlated color temperature of about 6504 K, and CIE A light source represents an incandescent lamp with a correlated color temperature of about 2856 K (D65:X = 95.04, Y = 100, Z = 108.87; A:X = 109.85, Y = 100, Z = 35.58).

The CIE XYZ color space is based on the uniform distribution of color perception, and colors will not be scattered in the Cartesian coordinate space. The calculated Euclidean distances between various color coordinates cannot be reasonably compared with each other. In the CIE 1976 L*a*b* color space, a* and b* represent horizontal and vertical Cartesian coordinate axes, L* represents the displacement perpendicular to the circular a*-b* grid. Different combinations of a* and b* can reproduce different tones, and the position of the color coordinate along L* indicates the brightness of the color. In the CIE 1976 L*a*b* color space, the tristimulus value XYZ is non-linearly converted into color parameters. And calculate the chromaticity value C* and hue angle h° under
| Light path length | L* for daylight D65 | a* for daylight D65 | b* for daylight D65 | L* for incandescent light A | a* for incandescent light A | b* for incandescent light A |
|------------------|-------------------|-------------------|-------------------|--------------------------|--------------------------|--------------------------|
| 1 mm             | 81.72             | 25.72             | -5.4              | 85.02                    | 29.91                    | -3.3                     |
|                  | 81.86             | 25.14             | -2.4              | 85.12                    | 29.36                    | -3.06                    |
|                  | 83.79             | 12.85             | -3.62             | 85.65                    | 15.95                    | -2.37                    |
|                  | 80.7              | 24.49             | -1.94             | 84.16                    | 28.98                    | 0.65                     |
|                  | 78.07             | 22.82             | -2.09             | 81.29                    | 27.63                    | -2.58                    |
|                  | 83.71             | 9.58              | 3.02              | 85.51                    | 12.82                    | 1.51                     |
| 2 mm             | 69.35             | 43.56             | -7.82             | 74.79                    | 48.75                    | -3.9                     |
|                  | 69.5              | 42.81             | -5.2              | 74.9                     | 48.1                     | -3.09                    |
|                  | 71.19             | 24.26             | -5.81             | 74.72                    | 29.57                    | -2.28                    |
|                  | 67.51             | 41.95             | -1.43             | 73.28                    | 46.64                    | 8.53                     |
|                  | 63.43             | 39.78             | -3.94             | 68.94                    | 46.24                    | 2.54                     |
|                  | 70.68             | 18.37             | 3.2               | 74.09                    | 24.08                    | 6.25                     |
| 3 mm             | 60.77             | 54.55             | -6.72             | 67.55                    | 59.25                    | -1.09                    |
|                  | 60.89             | 53.88             | -3.54             | 67.64                    | 58.73                    | -0.79                    |
|                  | 61.50             | 34.14             | -6.65             | 66.46                    | 40.64                    | -2.28                    |
|                  | 58.37             | 53.03             | 1.02              | 65.56                    | 58.16                    | 8.53                     |
|                  | 53.66             | 50.88             | -2.77             | 60.65                    | 56.9                     | 2.54                     |
|                  | 60.38             | 26.37             | 3.95              | 65.16                    | 33.67                    | 6.25                     |
| 4 mm             | 60.4              | 54.57             | -5.56             | 62.16                    | 64.31                    | 2.64                     |
|                  | 59.92             | 54.66             | -3.56             | 62.23                    | 63.97                    | 2.89                     |
|                  | 42.27             | 54.12             | -6.25             | 60.23                    | 49.02                    | -0.2                     |
|                  | 59.01             | 51.82             | 4.72              | 59.83                    | 61.33                    | 13.97                    |
|                  | 56.87             | 46.95             | 0.44              | 54.79                    | 61.74                    | 7.88                     |
|                  | 33.46             | 52.3              | 5.27              | 58.22                    | 41.41                    | 9.42                     |
| 5 mm             | 49.87             | 62.93             | -2.44             | 57.95                    | 66.21                    | 6.96                     |
|                  | 49.93             | 62.63             | -0.66             | 58.00                    | 66.01                    | 7.17                     |
|                  | 48.49             | 48.52             | -4.78             | 55.48                    | 54.82                    | 2.87                     |
|                  | 46.91             | 61.58             | 8.94              | 55.36                    | 64.80                    | 19.38                    |
|                  | 42.12             | 59.18             | 4.69              | 50.41                    | 63.05                    | 13.56                    |
|                  | 46.00             | 39.42             | 7.12              | 52.80                    | 47.25                    | 12.99                    |
| 6 mm             | 46.15             | 63.56             | -2.44             | 54.52                    | 63.16                    | 4.74                     |
|                  | 46.19             | 63.37             | -0.66             | 54.57                    | 63.06                    | 6.25                     |
|                  | 44.16             | 52.88             | -4.78             | 51.78                    | 55.56                    | 0.40                     |
|                  | 43.06             | 61.93             | 13.16             | 46.91                    | 61.24                    | 17.07                    |
|                  | 38.44             | 59.32             | 9.15              | 48.93                    | 58.34                    | 13.36                    |
|                  | 41.10             | 44.11             | 9.41              | 47.45                    | 47.25                    | 12.02                    |
| 7 mm             | 51.64             | 63.56             | -2.44             | 54.52                    | 65.84                    | 4.74                     |
|                  | 51.67             | 63.37             | -0.66             | 54.57                    | 65.79                    | 6.25                     |
|                  | 48.82             | 52.88             | -4.78             | 51.78                    | 60.27                    | 24.35                    |
|                  | 48.64             | 48.43             | 13.16             | 46.91                    | 63.75                    | 18.91                    |
|                  | 43.99             | 59.32             | 9.15              | 48.93                    | 61.23                    | 16.79                    |
|                  | 45.09             | 44.11             | 9.41              | 47.45                    | 47.25                    | 12.02                    |
| 8 mm             | 40.52             | 62.27             | -2.44             | 49.14                    | 64.83                    | 19.49                    |
|                  | 40.54             | 62.21             | -0.66             | 49.17                    | 64.81                    | 19.65                    |
|                  | 38.07             | 56.91             | -4.78             | 46.37                    | 62.42                    | 14.47                    |
|                  | 37.27             | 60.03             | 17.10             | 45.98                    | 59.59                    | 32.46                    |
|                  | 33.00             | 56.88             | 14.80             | 42.25                    | 54.84                    | 27.64                    |
|                  | 34.18             | 49.54             | 17.10             | 42.25                    | 54.84                    | 27.64                    |
| 9 mm             | 38.28             | 61.13             | -2.44             | 49.14                    | 63.64                    | 23.03                    |
|                  | 38.31             | 61.11             | -0.66             | 49.17                    | 63.64                    | 23.17                    |
|                  | 35.84             | 57.30             | -4.78             | 46.37                    | 60.83                    | 18.25                    |
|                  | 34.98             | 58.58             | 17.10             | 45.98                    | 57.86                    | 35.60                    |
|                  | 30.86             | 55.24             | 14.80             | 42.25                    | 55.10                    | 30.99                    |
|                  | 31.68             | 50.57             | 17.10             | 42.25                    | 55.10                    | 27.74                    |
D65 light source and A light source. Taking sample R as an example, the absorption spectrum of light passing through synthetic ruby along any crystal direction can be calculated by the following formula:

$$A_m = x \times R_{down \ a} + y \times R_{down \ b} + z \times R_{down \ c}$$

where $A_m$ is the absorption spectrum in either direction, $R_{down \ a}$ is Roa's UV–Vis absorption spectrum, $R_{down \ b}$ is Rob's UV–Vis absorption spectrum, $R_{down \ c}$ is Rec's UV–Vis absorption spectrum, $x$, $y$, $z$ are the Cartesian coordinates of the ray path length, and the ray path length is constrained to lie on a sphere with a radius of $r$.

As shown in Fig. 5, the color of the synthetic ruby under D65 and A light source increases with the increase of the light path length, from the original light pink to purple-red and finally to deep red. When the light path length is 1 mm and 20 mm, the effect of different light sources on the color of ruby is not obvious. When the light path length is 5 mm and 10 mm, the color difference between the two light sources can be observed from the figure. Therefore, only when the length of the light path is in the appropriate range, that is, the length of the light path is not too large or too small, the light source will have a significant effect on the color of the ruby.

Figure 5 also shows the difference in colour between the a-axis (o-light direction) and the b-axis (e-light direction) of the synthetic ruby. This has to do with the pleochroism of ruby. When the light path length is 1 mm, the effect of different light sources on the color of ruby is not obvious. When the light path length is 5 mm and 10 mm, the color difference between the two light sources can be observed from the figure. Therefore, only when the length of the light path is in the appropriate range, that is, the length of the light path is not too large or too small, the light source will have a significant effect on the color of the ruby.

### Table 1. Synthetic ruby color parameters with light path length from 1 to 10 mm.

| Light path length | $L^*$ D65 | $a^*$ D65 | $b^*$ D65 | $L^*$ A | $a^*$ A | $b^*$ A |
|-------------------|----------|----------|----------|---------|--------|--------|
| 10 mm             |          |          |          |        |        |        |
| L* for daylight D65| 36.32    | 36.35    | 33.95    | 32.96   | 28.96  | 29.59  |
| $a^*$ for daylight D65| 59.90    | 59.89    | 57.04    | 57.06   | 53.57  | 50.80  |
| $b^*$ for daylight D65| 14.46    | 15.74    | 9.98     | 26.12   | 23.03  | 20.24  |
| L* for incandescent light A| 44.96    | 44.99    | 42.47    | 41.50   | 37.19  | 37.78  |
| $a^*$ for incandescent light A| 62.38    | 62.39    | 60.25    | 59.41   | 56.15  | 54.74  |
| $b^*$ for incandescent light A| 26.19    | 26.33    | 21.76    | 38.21   | 33.73  | 30.78  |

**Figure 4.** The spectral power distribution of the CIE D65 light source representing daylight (color temperature 6504 k), the spectral power distribution of the incandescent CIE A light source (color temperature 2856 k) and the color matching function spectrum $x(\lambda), y(\lambda), z(\lambda)$. 

$$x^2 + y^2 + z^2 = r^2$$

where $x^2 + y^2 + z^2 = r^2$.
The influence of light path length and light source on the color of synthetic ruby. Figures 6, 7, 8 show the sample color parameters $L^*$, $C^*$, $h^*$ for different light path lengths under D65 and A light sources. Take $R_{oa}$, $R_{ob}$, $R_{oc}$, $R_{oa}$, $R_{ob}$, and $R_{oc}$ with different light path lengths as a set of samples.

Figure 6 shows whether it is D65 light source or A light source, when the light path length increases, the lightness will decrease, showing a negative correlation ($R^2 = 0.952$). This is consistent with the perception of the human eye. The lightness under the A light source is higher than the lightness under the D65 light source. When
the length of the light path increases from 1 to 5 mm, the lightness drops rapidly, indicating that when the length of the light path is very small, its change has a significant impact on the lightness.

Figure 7 shows that under D65 and A light sources, the chroma C* of synthetic rubies with different light path lengths increases first and then decreases. Under the D65 light source, when the light path length is less than 7 mm, the chromaticity C* increases with the increase of the light path length, reaching the maximum value of 63.58; When the path length is greater than 7 mm, the color saturation reaches saturation and begins to decrease. Under A light source, it is bounded by 10 mm.

In addition, the chroma values of $R_{oe}$ and $R_{oe}$ under the two light sources are significantly lower than $R_{oa}$ and $R_{oa}$, which is caused by the pleochroism of the ruby. But under the D65 light source, when the light path length is 10 mm to 15 mm, the chroma value is close. This is because $R_{oa}$ and $R_{oa}$ reached the highest chroma and began to decline at 7 mm, while $R_{oe}$ and $R_{oe}$ continued to increase with the increase of the light path length because of the small chroma, and did not start to decrease until 12 mm. The color temperature of A light source is lower than that of D65 light source, so the chroma C* of $R_{oa}$ and $R_{oa}$ starts to decrease at 10 mm, while $R_{oe}$ and $R_{oe}$ start to decrease at 14 mm.

Figure 8 shows that the hue angle $h°$ increases with the increase of the light path length under the two light sources, and the increasing amplitude gradually decreases. The hue angle under A light source is generally higher than that under D65 light source. But under the D65 light source, the hue angle $h°$ decreases when $R_{oa}$ (e light direction) is 1 mm to 3 mm, and $h°$ begins to increase after 3 mm, this phenomenon does not appear under the A light source. This is because when the length of the light path increases, the color changes from pink to light pink, and the chromaticity coordinate $a^*$ increases significantly, resulting in a decrease in hue angle $h°$. The A light source has a yellow hue, making the hue angle $h°$ greater than that under the D65 light source, so the hue angle will not decrease due to the increase in the length of the light path.
The influence of light path length on the color difference ΔE*ab. The color of synthetic ruby is plotted in CIE 1976 L*a*b* color space. In the three-dimensional space, the line connecting the points under the two light sources represents the Euclidean distance, which is the color difference ΔE*ab. Project the three-dimensional L*a*b* color coordinates to the two-dimensional a*b* plane (color circle), and draw a connecting line between the D65 light source and the A light source. In addition, link the change in the length of the light path with the color difference, draw a connecting line for each path length, and draw them in the same plane. The left end of the connecting line represents the color coordinate under the D65 light source, and the right end represents the color coordinate under the A light source. As shown in Fig. 9, take Roa and Rec as examples for drawing.}

Roa and Rec are the o-light direction and e-light direction of synthetic ruby respectively. It can be seen from Fig. 9 that as the length of the light path increases, the connecting lines are distributed in an upward trend in the two-dimensional a*b* plane. The color difference ΔE*ab in Roa and Rec both increases first and then decreases. When the light path length is 12 mm, the color difference ΔE*ab reach the maximum, which are 14.85 and 15.06 respectively. In order to further explore the influence of the light path length on the color when the light source changes, the light path length is increased to 25 mm.

As shown in Fig. 10, increasing the light path length to 25 mm, the color difference ΔE*ab continues to decrease, indicating that as the light path length increases, the influence of the light source on the color is weakened. By comparing Fig. 10a,b, it is found that the color difference ΔE*ab changes of the two samples in the o-light and e-light directions are different, which is related to the color and pleochroism of the samples.

The influence of UV–Vis absorbance peak area on the color of synthetic ruby. The strong absorption band at 545 nm in the ultraviolet–visible spectrum is caused by Cr³⁺, which absorbs yellow-green light in visible light and transmits red light, which has an important influence on the color of ruby. By calculating the first derivative of the ultraviolet–visible spectrum, the points with zero derivative near 473 nm and 652 nm are determined as the starting and ending points, and the absorption peak area at 545 nm is calculated (Fig. 11).

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**Figure 7.** The chroma C* of synthetic rubies with different light path lengths under two light sources. (a) Synthetic ruby chroma C* under D65 light source. (b) Synthetic ruby chroma C* under A light source.
Select a part of the data of different 545 nm absorption peak areas under D65 light source to plot 12. At the same time, it can be seen from Fig. 11 that the 545 nm absorption peak area is positively correlated with the light path length. Figure 12 shows that the hue angle $h^\circ$ is positively correlated with the peak area at 545 nm. When the absorption peak area increases, the hue angle $h^\circ$ increases. The $R^2$ of the hue angle under the D65 light source is 0.996. $h^\circ$ changed from −11.86 (that is, 348.14) to 36.75. The lightness $L^*$ is negatively correlated with the peak area at 545 nm. As the peak area increases, the ruby absorbs more visible light, and the lightness decreases. The chroma $C^*$ first increases and then decreases with the absorption peak area, which is related to the changes of $L^*$ and $h^\circ$. When $h^\circ$ increases, $L^*$ decreases. When the length of the light path increases to a certain length, the decrease in brightness $L^*$ has a significant impact on chroma $C^*$, making chroma $C^*$ begin to decrease.

Conclusion
When the length of the light path is increased from 1 to 20 mm, the synthetic ruby changes colour from light pink to deep red. At the same time, due to the pleochroism of ruby, there is a difference in colour between the o light and e light directions of ruby. As the length of the light path increases, the difference becomes smaller.

Lightness $L^*$ increases as the length of the light path increases. When the light path length is 1 mm to 5 mm, its subtle changes will cause a significant decrease in lightness; The hue angle $h^\circ$ increases with the increase of the light path length, but under the D65 light source, when the light path length is 1 to 3 mm, the $R_{uu}$ color shifts red, causing the hue angle $h^\circ$ to decrease; As the length of the light path increases, the chroma $C^*$ increases, but when the length of the light path increases to a certain length, the decrease of the lightness $L^*$ causes the chroma to start to decrease.

The color difference $\Delta E^*_{D65,A}$ first increases and then decreases with the increase of the light path length. When the length of the light path reaches about 10 mm, the color difference reaches its maximum value. At this time, the light source has the greatest influence on the color. When the length of the light path continues to increase, the influence of the light source on the color is weakened.
In the UV–visible spectra, the strong absorption band at 545 nm caused by Cr\(^{3+}\) has a significant relationship with the colour of ruby. The strong absorption band at 545 nm has a positive correlation with the light path length. The larger the area of the band at 545 nm, the lower the lightness and the higher the hue angle, which means the ruby colour is redder.

**Methods**

**UV–Vis spectroscopy.** The UV-3600 UV–VIS spectrophotometer (Shimadzu, Tokyo, Japan) was used to carry out the UV–Vis spectra. The test conditions were described as follows: the range of wavelength, 200–900 nm; slit width 2 nm; scanning speed medium; sampling interval 0.5 s; scanning mode, single.

**CIE1931 XYZ colour matching functions.** The International Commission on Illumination proposed the CIEXYZ color system in 1931, and the tristimulus value XYZ can be obtained by matching the isoenergetic spectrum. The tristimulus value can calculate the color based on the spectrum collected from the surface of the object or the transmission through the object:

\[
X = \int_{\text{380}}^{780} k\phi(\lambda)\Xi(\lambda)d\lambda \approx \sum_{\text{380}}^{780} k\phi(\lambda)\Xi(\lambda)\Delta\lambda
\]

\[
Y = \int_{\text{380}}^{780} k\phi(\lambda)\Upsilon(\lambda)d\lambda \approx \sum_{\text{380}}^{780} k\phi(\lambda)\Upsilon(\lambda)\Delta\lambda
\]

\[
Z = \int_{\text{380}}^{780} k\phi(\lambda)\Zeta(\lambda)d\lambda \approx \sum_{\text{380}}^{780} k\phi(\lambda)\Zeta(\lambda)\Delta\lambda
\]

\[
k = \frac{100}{\int_{\text{380}}^{780} S(\lambda)\Upsilon(\lambda)d\lambda}
\]

Figure 9. \(R_\text{oa}\) (o light direction) and \(R_\text{oc}\) (e light direction) color difference \(\Delta E^*_{ab}\) are distributed in two-dimensional \(a^*b^*\) plane, the left end of the connecting line is the color coordinate of D65 light source, and the right end is the color coordinate of light source A.
Colour space conversion. In order to describe easily colors, the color tristimulus values in CIEXYZ are non-linearly converted to obtain the color parameters L*, a*, b* in the CIE1976L*a*b* color space system. The formula for conversion is as follows:

\[
L^* = 116 \left( \frac{X}{X_n} \right)^{\frac{1}{3}} - 16
\]  

\[
a^* = 500 \left[ \left( \frac{X}{X_n} \right)^{\frac{1}{3}} - \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} \right]
\]  

\[
b^* = 200 \left[ \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} - \left( \frac{Z}{Z_n} \right)^{\frac{1}{3}} \right]
\]

For D65 light source, Xn = 95.04, Yn = 100, Zn = 108.88. For light source A, Xn = 109.85, Yn = 100, and Zn = 35.58. Xn, Yn, Zn are the colorimetric data obtained from the CIE1931 standard colorimetric observer (2°).

CIE1976 L*a*b* colour system. The CIE1976L*a*b* color space is the most widely used in the field of colorimetry. The system consists of plane chromaticity axes a* and b* and vertical axis L*. a* stands for red; −a* stands for green; b* stands for yellow; −b* stands for blue. The chroma C* and hue angle h° can be calculated based on chromaticities a* and b*. 
To calculate the colour difference of rubies under different sources of illumination, we chose the CIE Lab \((\Delta E_{ab}^*)\) color difference formula:

\[
C^* = \sqrt{a^{*2} + b^{*2}} \tag{20}
\]

\[
h = \arctan \frac{b^*}{a^*} \tag{21}
\]

Figure 11. The absorption peak area (X) at 545 nm. Taking the sample Roa as an example, the point where the first derivative is equal to zero is selected as the starting point and the end point of the 545 nm absorption peak range, and the absorption peak area is obtained by integrating from 473 to 652 nm. The top right is the ultraviolet–visible light absorption spectra of different light path lengths.

Figure 12. \(L^*\) and \(h^\circ\) of synthetic ruby with different UV–visible spectral peak areas under D65 light source.
\[ \Delta E_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \]  

where \( \Delta a^* = a^*_{D65} - a^*_{A} \), \( \Delta b^* = b^*_{D65} - b^*_{A} \) and \( \Delta L^* = L^*_{D65} - L^*_{A} \) and \( \Delta h^* \) is the hue angle difference under different sources of illumination:

\[ \Delta h = h_{D65} - h_{A} \]  

where \( \Delta C^* \) is the chroma difference under different sources of illumination:

\[ \Delta C^* = C^*_{D65} - C^*_{A} \]  

Data availability

The dataset for this study is available from the corresponding author upon reasonable request.

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B.Y. and Y.G. chose raw materials as samples and conducted experiments and data analysis together, B.Y. and Z.Y.L wrote the main manuscript texts and prepared figures, and Y.G. revised and corrected the manuscript texts.

Competing interests
The authors declare no competing interests.

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