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Abstract: The price of spinel has sharply risen in recent years, and its market acceptance is extending. Among the many sources of spinel, Man Sin in Myanmar is the most famous for its bright neon pinkish red to reddish pink color, named "Jedi" spinel commercially. In this paper, spinel samples with the bright neon pinkish red to reddish pink from Man Sin in Myanmar were studied nondestructively with X-ray fluorescence spectrometer (EDXRF), Fourier transform infrared spectrometer (FTIR), fluorescence spectroscopy, a UV-Vis spectrophotometer and Raman spectroscopy. The results show that the samples from Man Sin in Myanmar are the magnesia-alumina spinels. The high content of the red-chromogenic element Cr, an intermediate content of V and Zn, and a low content of the chromogenic element Fe may be responsible for the distinctive neon color of the spinel samples. The presence of Ti may also serve as a basis for the identification of its origin in Man Sin in Myanmar. The fluorescence spectrum analysis of spinels shows them to have multiple excitation peaks in the region 600–800 nm, which are caused by the jump of Cr^{3+} between the ${}^{2}E \rightarrow {}^{4}A_{2}$ inter-energy band lattice. The amount of Zn affects the fluorescence spectrum intensity of spinels. The higher the Zn content, the stronger the fluorescence intensity. The spinel structure is uncomplicated and four more obvious absorption peaks appear in the IR spectrum, and the direction of the absorption peaks is shifted if a homogeneous substitution of the AB₂O₄ structure occurs; the Raman spectra of spinel samples have four vibrational peaks at 100–2000 cm⁻¹, 310 cm⁻¹, 407 cm⁻¹, 665 cm⁻¹ and 763 cm⁻¹, which has spinel species-identification significance.

Keywords: spinel from man sin; myanmar; gemological characteristics; color mechanism; spectroscopy

1. Introduction

In recent years, spinel has become increasingly recognized for its unique charm. Spinel minerals in meteorites are being researched [1]. Spinel auctions are on an upward trend in volume, and carat-unit price, reaching a total of \$10,612,400 in 2019 from \$263,500 in 2011 [2]. The red color is valued in the market, especially the bright neon pinkish red and reddish pink spinel with the unique name "Jedi", which was first introduced in 2002 from Myanmar [3]. Samples of "Jedi" spinels from Man Sin are challenging to obtain. Spinels of other origins, such as Vietnam and Tanzania, that have a pinkish red and reddish pink color will market for less than spinels from Man Sin in Myanmar because they do not show the vivid neon color [2]. Research on the "Jedi" spinel from Man Sin in Myanmar is feeble at this stage. There is no uniform classification of this type of spinel color in gem laboratories, and no standard definition of the color of "Jedi" spinel by any international testing agency.

The spinel samples in this study are from Man Sin in Myanmar, with their bright neon pinkish red to reddish pink color being recognized as "Jedi" spinel by Myanmar and Thai jewelers. The study of the gemological characteristics, inclusions, chemical composition and spectroscopy of the "Jedi" spinel from Man Sin in Myanmar will help to investigate the cause of the peculiar neon color and may also provide implications for gemological and



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mineralogical studies of spinel. Furthermore, it can be used to distinguish "Jedi" spinels from other regions with different geological backgrounds and geneses.

The spinel group minerals have the chemical general formula AB₂O₄, in which divalent oxygen ions are cubically and tightly packed in the structure, with the packing layer perpendicular to the tertiary axis [4]. Group 'A' are ions such as Mg²⁺, Fe²⁺, Mn²⁺, Zn²⁺ and Ni²⁺; trivalent cations are the main ions constituting group 'B', such as Al³⁺, Fe³⁺, Cr³⁺ and Co³⁺ [5]; 'A' ions are filled in the tetrahedral vacancies, B ions are in octahedral vacancies, i.e., A²⁺ ions are four-coordinated, while B³⁺ ions are six-coordinated. Natural gem-quality spinel is mostly ortho-clinic material; pure magnesia-alumina spinel is colorless, while a heterochromatic gem contains trace elements causing color. When a spinel contains Cr³⁺, its allowable leap ${}^{4}A_{2g} \rightarrow {}^{4}T_{1g}$ (4F), ${}^{4}T_{2g}$ (4F) leads to significant absorption bands at 390 nm and 550 nm, giving the spinel a brilliant red color [6].

2. Regional Geological Setting

Spinel is produced in the Man Sin mine in Myanmar, which is close to the famous gemstone-producing area of Mogok. Mogok, also called the Mogok Stone Tract, is an area known for its high-quality ruby and sapphire deposits [7,8]. It is a segment of the Mogok Metamorphic Belt (MMB) [9], which consists of Paleozoic and Mesozoic advanced metamorphic sedimentary and intrusive rocks. The smectite tracts in this area consist mainly of gneisses, dacites, calc-silicates and quartzites, interbedded with various felsic to basal igneous rocks, where the gneisses and dacites are faulted with mica schist [10,11].

The location of the Man Sin mine (Figure 1), where the Jedi spinel was born, is 22°58′18″ N and 96°32′32″ E [2]. The surrounding rocks of the deposit are mainly metamorphic rocks formed by contact metamorphism of soluble rocks, such as limestone and dolomite, by magma intrusion. The Man Sin mine in Myanmar, similar to other spinel deposits in the world, has a ruby symbiosis, with the mines producing mainly rubies, and spinel is only an accessory mineral to the ruby deposits. The soil of the weathered layer of the mine has a large amount of gravel, which is rich in rough gemstones and washing the residue can leave gravel containing rough gemstones [2,12].



Figure 1. Geological map of the Mogok and Man Sin area (Modified from [8,11,13]).

3. Materials and Methods

3.1. Materials

The experimental samples of spinel consist of thirteen stones (Figure 2), all from the Man Sin mine in Myanmar, two faceted finished stones (MS-1, MS-2) and eleven rough stones (MS-3, MS-4, MS-5, MS-6, MS-7, MS-8, MS-9, MS-10, MS-11, MS-12, MS-13), measuring 4.4 mm \times 7.1 mm or less. The surface of the rough stones is freshly faceted and does not require polishing. A detailed petrographic study was carried out using a ZEISS Temi2000-C gemological microscope, linked to a Nikon DS-Ri1 high-resolution microscope camera.



Figure 2. The spinel samples from Man Sin: Faceted finish stones MS-1, MS-2, rough stones MS-3, MS-4, MS-5, MS-6, MS-7, MS-8, MS-9, MS-10, MS-11, MS-12, MS-13.

3.2. Methods

3.2.1. X-ray Fluorescence (EDXRF)

X-ray fluorescence (EDXRF) analysis was performed at China University of Geosciences (Beijing) using an ARLQUANT'XEDXRF analyzer and a Thermo Scientific EDXRF instrument with 3.15 A current and 6.6 A vacuum pump, at 230 V. This has an accuracy of 0.1 ppm.

3.2.2. Raman Spectroscopy

Raman spectroscopy was performed at the China University of Geosciences (Beijing) (CUGB) using a HORIBA LabRAM HR-Evolution Raman spectrometer. The Raman spectrometer recorded in the 100–2000 cm⁻¹ range and with 4 cm⁻¹ resolution, with an excitation light source λ = 532 nm and 3 s exposure time.

3.2.3. Fourier Transform Infrared (FTIR) Spectroscopy

Fourier transform infrared spectroscopy was performed at the School of Gemology of the China University of Geosciences (Beijing). The instrument used for the experiment was the BRUKER Fourier transform infrared spectrometer–Bruker Tensor 27, manufactured by BRUKER Spectrometer, Germany. The experimental conditions were as follows: the power supply was 85~265 V, the power frequency was 47~65 Hz, the temperature range was 18~35 °C, the humidity range was less than 70%, the scan time of the sample was 3 scans, the scan time of the background was 8 scans, the resolution was 4 cm⁻¹, the grating set to 6 mm, 10 KHz, the spectral range set to 400~2000 cm⁻¹, and the number of scans per sample was 50~100. The experimental detection mode in this paper was chosen to detect in reflection mode, i.e., non-destructive mode. Due to the instrument's limitation, the sample's test area was only in the range of 400 cm⁻¹ to 1500 cm⁻¹, and vibration peaks below 400 cm⁻¹ could not be detected.

3.2.4. UV-Vis Spectrophotometry

UV-Vis spectrophotometry was performed at the School of Gemology of China University of Geosciences (Beijing). The instrument was a UV-3600 ultraviolet-visible spectrophotometer spectrometer. Experimental conditions were as follows: wavelength test range of 200 nm–900 nm, light-source conversion wavelength 310 nm, detection unit: external (double detector), grating conversion wavelength 720 nm, detector conversion wavelength 900 nm, sampling interval 0.5 s and detection-mode selection reflection method.

3.2.5. Fluorescence Spectroscopy

Fluorescence spectroscopy was performed using a HORIBA Scientific Fluoromax-4 model spectrofluorometer (Kyoto, Japan). After testing the excitation peaks of the samples, the working center wavelength of the laser source was set at 550 nm, and the scanning range was 600–800 nm

3.2.6. DiamondView

DiamondView was performed at China University of Geosciences (Beijing) using IIDGR DiamondView.

4. Results and Discussion

4.1. Gemological Characteristics and Inclusions

The color of "Jedi" spinel from Man Sin in Myanmar is characterized by a high saturation of neon color, with very bright reddish pink and pinkish red color in both the rough stone and the faceted stones (Figure 2), and it is difficult to see the dark areas in the faceted cut stones. The surface features of the rough simple are flat, smooth, fine, transparent euhedral crystals with a bright, glassy luster and shell-like fracture (Figure 3a). Some spinel samples may show contact twinning, and an inner concave angle can be observed. The double crystal surface is equally flat and smooth, resembling bright glass luster after polishing, and a triangular growth pattern and triangular etched pit growth texture on the surface are visible (Figure 3b). The samples are rich in inclusions, including cleavage, two-phase or multi-phase, and solid mineral inclusions. The richness of the inclusions varies. The most obvious ones in most samples are healing fissures (Figure 3c), and octahedral inclusions containing solid inclusions inside (Figure 3d). All samples fluoresced neon and red moderately to strongly under long-wave UV radiation and were inert to short-wave UV.

MS-1 sample was magnified under the gem microscope, and an octahedral morphology of negative crystalline solid inclusion was seen at the long side of the crown near the girdle (Figure 3d). There was opaque solid material in the middle of the inclusion, which was subjected to the Raman test. Laser Raman spectroscopy of spinel-sample inclusions was used for a more in-depth study. A LabSpec 6 laser Raman spectrometer manufactured by Horiba Scientific was used at China University of Geosciences (Beijing)—excitation source $\lambda = 532$ nm, ND filter: 25%, sweep, and wave number range 100–1700 cm⁻¹.



Figure 3. (a) Fine transparent octahedral crystals (MS-13); (b) Spinel twin with inner concave angle. Goose row-like distribution of fine octahedral spinel inclusions, and external brown solid inclusions (MS-7); (c) Massive healing fractures containing liquid inclusions (MS-2); (d) Octahedral mineral inclusions in spinel with solid black-brown inclusions (MS-1).

The test results (Figure 4) show that there are 110 cm^{-1} , 175 cm^{-1} , 205 cm^{-1} , 299 cm^{-1} , 339 cm^{-1} , 400 cm^{-1} , 792 cm^{-1} , 835 cm^{-1} , 910 cm^{-1} and 1096 cm^{-1} characteristic peaks, which are composite peaks of dolomite and scheelite. Among them, 175 cm^{-1} , 299 cm^{-1} , 792 cm^{-1} and 1096 cm^{-1} refer to the Raman spectra of dolomite [14]; 110 cm^{-1} , 205 cm^{-1} , 339 cm^{-1} , 400 cm^{-1} , 835 cm^{-1} and 910 cm^{-1} refer to the Raman spectra of scheelite [15].

The mechanism of formation is the main crystal followed by cleavage, as a formation of hydrothermal fluid enters a cleavage leading to the recrystallization of the main crystal, leaving a cavity. The residual formation of hydrothermal fluid with dolomite and scheelite components then enters the cavity, forming an octahedral negative crystal inclusion. This characteristic inclusion indicates the hydrothermal genesis of Man Sin spinel in Myanmar and is a barite-type deposit [16].

4.2. Major Element Geochemistry

The "Jedi" spinel from Man Sin is mainly Mg-Al spinel, with an average content of 94.439 wt% of Mg-Al (Table 1). In addition to the main elements, the types and percentages of all trace elements of all samples were compared. Thirteen samples contained chromogenic elements, Cr, V and Fe [17], and ten samples contained the chromogenic element Ti. The content of Ti among the chromogenic elements is low. The overall average percentage of ZnO in samples MS-1 to MS-13 was 0.572 wt%, except for sample MS-2, which contained a high amount of ZnO (content ratio of 2.303 wt.%). FeO is low in Man Sin spinel samples with only 0.179 wt%. The average content of Cr₂O₃ reached 1.009 wt%, and the average content of V₂O₃ is 0.189 wt% (Table 2).



Figure 4. Raman spectroscopy octahedral morphology of negative crystalline solid inclusion (MS-1). Blue markings indicate the characteristic peaks of scheelite; red markings indicate the characteristic peaks of dolomite.

Table 1. EDXRF data of 'Jedi' spinel from Man Sin (weight%).

Sample	MS-1	MS-2	MS-3	MS-4	MS-5	MS-6	MS-7	MS-8	MS-9	MS-10	MS-11	MS-12	MS-13
Al ₂ O ₃	68.585	70.045	66.82	69.787	67.005	68.026	67.623	67.197	65.853	67.467	66.35	67.96	68.654
MgŎ	24.691	24.114	29.098	23.736	23.961	23.648	29.598	28.924	29.23	28.197	25.248	28.304	27.597
Cr_2O_3	3.412	1.084	1.257	1.195	0.996	0.633	0.322	0.672	0.761	0.966	1.092	0.298	0.427
SiO ₂	1.301	1.027	1.156	3.617	5.636	5.636	0.82	1.001	2.47	1.508	4.42	1.411	1.067
ZnŌ	0.18	2.303	0.351	0.292	0.448	0.919	0.105	0.416	0.26	0.334	0.949	0.265	0.617
V_2O_3	0.034	0.092	0.114	0.36	0.409	0.182	0.331	0.353	0.112	0.114	0.146	0.071	0.133
FeO	0.244	0.395	0.127	0.426	0.157	0.179	0.101	0.102	0.093	0.1	0.151	0.076	0.181
TiO ₂			0.012	0.344	0.302	0.032	0.096	0.032	0.011	0.122	0.026	0.13	
K ₂ Õ	0.095	0.086	0.027	0.055	0.066	0.066		0.021	0.097	0.083	0.127	0.115	0.065
CāO	0.008	0.017	0.02	0.111	0.102	0.102	0.03	0.027	0.035	0.043	0.097	0.041	0.034
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* FeO represents the total content of ferrous oxide (FeO) and ferric oxide (Fe $_2O_3$) for the entire text.

 Table 2. EDXRF Chemical fingerprinting of "Jed"
 spinel from Man Sin (weight%).

Sample	Al ₂ O ₃	MgO	Cr ₂ O ₃	SiO ₂	ZnO	V_2O_3	FeO	TiO ₂	K ₂ O	CaO
Range	65.853–70.045	23.648–29.598	0.298–3.412	0.820–5.636	0.105–2.303	0.034–0.409	0.076–0.426	0.00–0.344	0.021–0.127	0.008–0.111
Average	67.798	26.642	1.009	2.390	0.572	0.189	0.179	0.111	0.075	0.051

In order to investigate the difference between the chemical composition of "Jedi" spinel from Man Sin in Myanmar and other spinel origins, data from previous studies [18] of Mahenge in Tanzania and Vietnam were selected and analyzed. "Jedi" spinels have a characteristic neon color, which is not present in the samples from other areas; the spinels from the Mahenge Kiswila and Ipanko mines in Tanzania are bright pink to bright deep pink, and the spinels from the Cong Troi and An Phu mines in Vietnam are pink to red.

Cr, V and Fe are common spinel chromogenic elements, and Zn is also high in the sample, so these four elements were selected for the ternary diagram to see the sample distribution. Chemical elemental ternary diagram analysis was performed on samples MS-1 to MS-13 and samples from Tanzania and Vietnam (Figure 5). There are significant regional differences in elemental content. The "Jedi" spinels from Man Sin in Myanmar are

significantly enriched in $Cr_2O_3 + V_2O_3$ red chromogenic clusters and have a significantly lower FeO content than the Tanzanian spinel (Figure 5a). Comparing Cr_2O_3 - V_2O_3 -FeO, the Cr_2O_3 and V_2O_3 content is significantly higher than that for the Vietnamese spinels, and the FeO content is significantly lower than that for the Vietnamese spinels (Figure 5b). Comparing the Cr_2O_3 - V_2O_3 - ZnO_2 distribution, the "Jedi" spinels from Man Sin in Myanmar still show high Cr_2O_3 and higher ZnO_2 than the spinel from Vietnam. Excluding Cr_2O_3 , which has the most significant difference in content, comparing FeO- ZnO_2 - V_2O_3 , the spinels from Man Sin in Myanmar have lower FeO than spinels from Tanzania and Vietnam, higher ZnO_2 and V_2O_3 than spinels from Vietnam, similar content ZnO_2 and V_2O_3 from Tanzania.



Figure 5. Chemical determination ternary diagrams that allows the determination of spinels from Man Sin (MS), Tanzania-Kiswila (TZ), Tanzania-Ipanko (TZ'), Vietnam-Cong Troi (VN), Vietnam-An Phu (VN'). (a) FeO-ZnO-Cr₂O₃+V₂O₃ ternary diagram; (b) FeO-Cr₂O₃-V₂O₃ ternary diagram; (c) -ZnO-Cr₂O₃+V₂O₃ ternary diagram; (d) FeO-ZnO-V₂O₃ ternary diagram [18].

When comparing the chemical elements of the Man Sin 'Jedi' spinel with the pink and red spinels from Tanzania and Vietnam (Figure 6), there are significant regional differences in elemental content. The Cr_2O_3 content of Man Sin 'Jedi' spinel, 1.009 wt%, is significantly higher than spinels from Tanzania and Vietnam. Furthermore, the average content of Ti is ten times higher than that in Tanzania and Vietnam's mineral deposits [18].

4.3. Spectroscopy

4.3.1. UV-Vis Spectrophotometer

The thirteen samples share a relatively homogeneous character between 300 and 800 nm (Figure 6a), with a uniform broad absorption band between 300 and 430 nm, a more pronounced broad absorption band between 480 and 595 nm, and a distinct absorption peak at 686 nm for MS-1. There is complete absorption in the violet region and a wide absorption band in the yellow-green region, absorbing all the violet light, transmitting

blue light, absorbing part of the yellow-green light, and transmitting in the red region; this selective absorption results in the red color of the thirteen spinel samples. When the spinel contains Cr^{3+} , it allows the leap ${}^{4}A_{2g} \rightarrow {}^{4}T_{1g}(4F)$, ${}^{4}T_{2g}(4F)$, leading to a clear absorption band at 550 nm. The splitting of the ${}^{4}A_{2g}(4F)$ spectral term in the ${}^{3}d_{3}$ electron arrangement of the Cr^{3+} ion leads to absorption by the leap of electrons between energy levels, and the ${}^{4}A_{2g}(4F) \rightarrow {}^{4}T_{2g}(4F)$ leap absorbs red light at 696 nm. A distinct fluorescence peak called the "N-Line" is formed. The absorption peak at 435 nm corresponds to a photon energy of 2.86 eV, and the absorption peak at this position can produce an absorption peak in the violet region, which is caused by the V³⁺ jump ${}^{3}T_{1g}(3F) \rightarrow {}^{3}T_{1g}(3P)$ [19,20]. The absorption peak at 686 nm is also caused by Cr^{3+} [21].



Figure 6. (a) UV-Vis Spectrophotometer of 'Jedi' spinel from Man Sin; (b) UV-Vis spectrophotometer of MS-1 and MS-7.

The experimental results show that mainly Cr and V color the 'Jedi' spinel produced in Man Sin [18]. In MS-1, for example, where the Cr_2O_3 (3.412 wt%) content is significantly higher than V_2O_3 (0.034 wt%), the sample showed a distinct red hue. Taking MS-7 as an example, when the Cr_2O_3 (0.322 wt%) and V_2O_3 (0.331 wt%) contents are almost the same, the sample showed a slightly orange hue. The absorption peaks of both were the same. After 610 nm, the reflectance of sample MS-1 was more potent than that of MS-7; thus, the red saturation of sample MS-1 is more potent than that of sample MS-7 in the spectral performance of the UV-Vis spectrum by the naked eye. Spinels with a higher Cr content will contain more red hues; V will confer the orange hues on the spinel [22]. The absorption peak around 555 nm is caused by the joint absorption of Cr^{3+} and V^{3+} , and the V^{3+} absorption appears at 393 nm [19].

A high content of Zn may also have an effect on the reflection spectrum of the sample as well as the sample color [23]. Taking sample MS-2 and sample MS-3 as an example, the difference in Cr_2O_3 (MS-2 1.084 wt%; MS-3 1.257 wt%) and V_2O_3 (MS-2 0.092 wt%; MS-3 0.114 wt%) content is not significant, and there is a massive difference in the content of ZnO₂ between MS-2 (2.303 wt%) and MS-3 (0.351 wt%) samples. The different shades of pink are due to the difference in absorption in the blue and red regions. In the UV-Vis spectrum (Figure 7), the reflectance of MS-2 in the blue-violet region is significantly higher than that of the MS-3 sample. A large amount of blue-violet light reflected by MS-2 mixes with the reflected red light to form a more pronounced pink color compared to MS-3. The spinel from Vietnam has a bright purple color and contains a high amount of ZnO. Compared with the Afghan purple spinel with low ZnO content, the Vietnamese purple spinel reflects a higher amount of blue-violet light in the blue-violet region [24]. The bright pink color of the MS-2 sample is supposed to be caused by the high content of ZnO that enhances



the reflectivity of spinel in the blue-violet region. Zn and Ti may function concurrently to change the structure of spinel, consequently inducing nuanced differences in red hues [23].

Figure 7. Effect of Zn on UV-Vis spectrophotometer.

4.3.2. Raman Spectroscopy

The Raman spectroscopy test results (Figure 8) show sharp and clear spectral peaks, and the fluorescence background does not affect the Raman data signal. There are four straightforward vibrational modes within the observation range of 100–2000 cm⁻¹, namely $F_{2g}(1)$ (311 cm⁻¹), E_g , $F_{2g}(3)$, and A_{1g} , corresponding to 310 cm⁻¹, 407 cm⁻¹, 665 cm⁻¹, and 763 cm⁻¹, respectively, where the Raman vibration $F_{2g}(2)$, which should have been generated at 562 cm⁻¹, was not observed because the signal was too weak to be observed. The Raman signal $F_{2g}(1)$ (311 cm⁻¹) is generated by Mg jumping at the tetrahedral position [25]. The E_g peak is the most significant absorption peak in the spinel Raman spectrum formed by Al-O bending vibration, A_{1g} is caused by Mg symmetric bending vibration within the tetrahedron; the attribution of $F_{2g}(3)$ (665 cm⁻¹) is controversial, and Ohoro et al. suggest that the cause of its generation is similar to that of $F_{2g}(1)$ (311 cm⁻¹) [26], resulting from the asymmetric stretching vibration of the MgO₄ cell, while Caracas et al. believe that the appearance of this signal represents the vibration of the octahedral unit cell, and A_{1g} (763 cm⁻¹) is widely identified as being caused by the symmetric stretching vibration of Mg-O in the tetrahedral cell [27–29].

4.3.3. Fourier Transform Infrared (FTIR) Spectroscopy

A spinel is structurally a highly symmetric group of cubic centroids, which leads to a relatively simple infrared spectrum in the 400–1000 cm⁻¹ range, with four vibrational modes appearing (Figure 9). A weaker absorption of 840 cm⁻¹ and a stronger absorption of 629 cm⁻¹ at position C appear. C is related to octahedral lattice vibrations with frequencies dependent on the bonding between the three-valent cation and oxygen, independent of mass. The 578 cm⁻¹ absorption at position B and the absorption peak of 462 cm⁻¹ at position A are related to the metal cation motion [30]. The frequencies of A and B depend on the mass and radius of the three-valent and two-valent cations since they contain octahedra and tetrahedra involved in the complex vibrations simultaneously. The direction of the absorption peaks is shifted in the AB_2O_4 structure if homogeneous substitution of the analog occurs [31,32].



Figure 8. Raman Spectroscopy of 'Jedi' spinel from Man Sin.



Figure 9. Fourier transform infrared (FTIR) spectroscopy of 'Jedi' spinel from Man Sin.

4.3.4. Fluorescence Spectroscopy

The samples were tested and found to have multiple fluorescence peaks at 649 nm, 655 nm, 664 nm, 673 nm, 684 nm, 695 nm, 705 nm, 715 nm and 720 nm, concentrated in

the range 650–750 nm. All these absorption peaks are caused by Cr^{3+} jumping between the ${}^{2}E \rightarrow {}^{4}A_{2}$ inter-energy band lattice. At 673 nm is the anti-Stokes sidebands; 715 nm and 720 nm are Stokes phono sidebands. The fluorescence peak at 684 nm is generated by the transfer of Cr^{3+} located in the octahedron between the ${}^{2}E_{g} \rightarrow {}^{4}E_{2g}$ inter-energy band. The slightly weaker fluorescence peak at 695 nm is due to the broad emission region in the octahedron, and that between 720 nm and 800 nm can be attributed to the Cr^{3+} transition occurring at ${}^{4}T_{2}(F) \rightarrow {}^{4}A_{2}(F)$ with auto transformation [33].

The spectral fluorescence peaks of samples MS-1, MS-2, and MS-3 are all excitation peaks of Cr (Figure 10). MS-2 has the highest ZnO content and the highest intensity of the excitation peak. MS-1 has significantly higher Cr_2O_3 content than MS-3 (Table 3), but the intensity of the excitation peaks is similar due to the lower ZnO content. Within a certain ratio, the increase in Zn content helps to increase the excitation peak intensity of Cr [33].



Figure 10. Fluorescence spectroscopy with a photo under DiamondView of 'Jedi' spinel from Man Sin. (a) MS-1; (b) MS-2; (c) MS-3.

	MS-1	MS-2	MS-3
Cr ₂ O ₃	3.412	1.084	1.257
ZnO	0.18	2.303	0.351

Table 3. EDXRF Cr₂O₃ and ZnO data of MS-1, MS-2, MS-3 (wt%).

The observation of fluorescence intensity is more intuitive when using DiamondView to take pictures (Figure 10) of spinel samples at wavelengths less than 225 nm in short-wave

UV. Contributing to this difference in fluorescence intensity is the difference in Zn content, where Zn undergoes homogeneous substitution with Mg in spinel, and the difference in band-gap energy between ZnAl₂O₄ (3.8 eV) and MgAl₂O₄ (~6.8–7.2 eV.) The jump of ZnAl₂O₄ is at a lower energy level than the ²E_g jump of Cr³⁺ and more light is available for Cr³⁺ excitation. The band-gap energy of MgAlO₄ is almost twice of ZnAl₂O₄ (~6.8–7.2 eV). It corresponds to a leap with more energy than the ²E_g leap of Cr³⁺, which results in the fluorescence of Cr³⁺ being largely unexcited in MgAl₂O₄ [33,34].

5. Conclusions

The bright neon pinkish red and reddish pin color of "Jedi" spinels from Man Sin in Myanmar is due to their high content of Cr, V, Zn, Ti, and a minuscule amount of the chromogenic factor Fe. The high content of the chromogenic factor Cr gives the spinel a red hue, and the presence of the chromogenic factor V gives it an orange hue. The presence of Zn and Ti compensates for the crystal structure and enhances the reflection of visible light in the blue-violet region, which, when mixed with visible red light, gives the spinel a pinkish hue.

A "Jedi" spinel from Man Sin in Myanmar has a strong fluorescence caused by Cr excitation. The fluorescence spectrum has several excitation peaks in the region of 600–800 nm, and the 600–700 nm absorption peaks are all caused by the leap of Cr^{3+} between the $^{2}E\rightarrow^{4}A_{2}$ inter-energy band lattice. The increase in the content of Zn enhances the fluorescence excitation spectrum of Cr, and the fluorescence excitation makes the spinel look neon.

The spinel is rich in healed cleavage. Furthermore, it has octahedral solid inclusions composed of dolomite and scheelite, which are characteristic inclusions indicating the hydrothermal genesis of the spinels from Man Sin in Myanmar. The presence of Ti can be used as a basis for the origin of the "Jedi" spinel from Man Sin in Myanmar. The Raman signal 311 cm⁻¹ is generated by Mg jumping at the tetrahedral position, and the signal 763 cm⁻¹ is caused by the symmetric stretching vibration of Mg-O in the tetrahedral cell.

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