Deep-red emitting $\text{Mg}_2\text{TiO}_4\text{:Mn}^{4+}$ phosphor ceramics for plant lighting

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Abstract: In this study, deep-red emitting $\text{Mg}_2\text{TiO}_4\text{:Mn}^{4+}$ phosphor ceramics were synthesized by the high temperature solid-state reaction method. The ceramics can be excited by the 465 nm blue light and had a narrow emission with a full width at half maximum (FWHM) value of 31 nm. The peak wavelength was located at 658 nm, which matched the demanded wavelength for photosynthesis. The crystal field strength (D_q) and the Racah parameters (B and C) were estimated by the Tanabe–Sugano diagram. The thermal conductivity of the $\text{Mg}_2\text{Ti}_{(0.999)}\text{O}_4\text{:0.001Mn}^{4+}$ ceramic was 7.535 W/(m·K) at room temperature, which was one order of magnitude higher than that of the traditional packaging method using the silicone gel. A set of phosphor converted LEDs were fabricated by mounting the phosphor ceramics onto the 460 nm blue LED chips and the CIE coordinates can move from the blue region to the purple light region with the thickness of the ceramic increasing. These results indicated that the $\text{Mg}_2\text{TiO}_4\text{:Mn}^{4+}$ phosphor ceramic was suitable for plant lighting when combined with a blue LED chip.

Keywords: solid state reaction; optical properties; thermal conductivity; ceramic phosphor

1 Introduction

In the past few decades, it has been proved that artificial light sources can improve the growth of plants [1]. But the conventional light sources such as the incandescent lamps, the metal-halide lamps, the fluorescent lamps, and the high-pressure sodium lamps,

suffer from low energy efficiency because the green and yellow spectral parts of these light sources are unsuitable for plant growth [2]. Due to that the blue light (400–500 nm) and the red light (640–680 nm) affect photosynthesis and phototropism, the artificial light source should contain blue and red light [3–5]. As a new generation lighting technology, light emitting diode (LED) has the advantages of long lifetime, narrow emission bandwidth, and adjustable output, which makes it possible to achieve a specific spectral

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composition [6]. The combination of red and blue LEDs has been widely used in the greenhouse lighting for plant cultivation and horticulture [7]. However, due to the difference in the spectral drifting and the degradation rates between the red and the blue LED chips, the ratio of red light to blue light is unstable [8]. To this end, another path to obtaining the stable light source for plant growth is using the red phosphor excited by the blue LED instead. Hence, a reliable red phosphor for plant growth is brought into focus.

At present, most of the red phosphors in the market are the Eu^{2+} doped nitrides $(\text{Ca}, \text{Sr})\text{AlSiN}_3:\text{Eu}^{2+}$, which have red luminescence of high efficiency under the 460 nm or the 405 nm excitation [9]. However, the harsh synthesis conditions of nitrides and the environmentally harmful mining process of rare earth materials make it costly [10]. Tetravalent manganese (Mn^{4+}) doped materials have been considered as an ideal candidate for rare-earth free red phosphors excited by the blue LED owing to their low cost and nice photoluminescence properties. In most instances, Mn^{4+} ions occupy the octahedral sites in the host lattices, and its 3d states will be split into the t_{2g} and the e_g states. The electron interaction further leads the energy level of Mn^{4+} to a more complicated situation. The broad excitation bands in the near ultraviolet (nUV) and the blue region of Mn^{4+} are associated with the ${}^4\text{A}_{2g} \rightarrow {}^4\text{T}_{1g}$ and ${}^4\text{A}_{2g} \rightarrow {}^4\text{T}_{2g}$ transitions while the red emission is associated with the ${}^2\text{E}_g \rightarrow {}^4\text{A}_{2g}$ transition. The emission peak of Mn^{4+} doped materials is closely related to the host matrix, such as fluorides and oxides [11,12]. Hence, selecting a suitable host material is the key point to obtain the luminescence properties needed by plant lighting.

Mn^{4+} doped fluorides have a strong excitation band corresponding well with blue LED chips, but the sharp red emission is usually peaked at < 640 nm [13], and the use of toxic HF solution is harmful to the environment. By contrast, Mn^{4+} doped oxides usually present a deep-red emission, which is more suitable for plant lighting. Among the oxide matrices, Mg_2TiO_4 has been considered as a particularly noteworthy host matrix for Mn^{4+} due to its excellent stability. Figure 1 shows the inverse spinel structure of Mg_2TiO_4 . The distribution of the atoms in the Mg_2TiO_4 unit cell can be described as the structural formula $\text{Mg}[\text{MgTi}]\text{O}_4$ [14] (where [] denotes the octahedral site). All of the Ti^{4+} cations and half of the Mg^{2+} cations randomly occupy octahedral sites and the rest of Mg^{2+} occupy tetrahedral sites.

Fig. 1 (a) Unit cell of Mg_2TiO_4 . (b) $[\text{Mg}/\text{TiO}_6]$ octahedron in the Mg_2TiO_4 . (c) $[\text{MgO}_4]$ tetrahedron in the Mg_2TiO_4 .

Compared with the Mg^{2+} cations (0.720 Å, CN = 6) in the octahedral sites, the ionic radius of Ti^{4+} (0.605 Å) is closer to that of Mn^{4+} (0.530 Å) [15], and there is no charge difference between the Ti^{4+} and the Mn^{4+} , so the Mn^{4+} tends to replace the Ti^{4+} site in Mg_2TiO_4 , resulting in an efficient red emission peaked at about 658 nm [16,17]. Therefore, $\text{Mg}_2\text{TiO}_4:\text{Mn}^{4+}$ is a promising red phosphor that can be excited by the blue LED for plant lighting.

However, the emission intensity of $\text{Mg}_2\text{TiO}_4:\text{Mn}^{4+}$ is sensitive to the temperature, which greatly limits its application in illumination [18]. Compared with powders, phosphor ceramics have a higher thermal conductivity that can efficiently dissipate the heat [19]. Here, translucent $\text{Mg}_2\text{TiO}_4:\text{Mn}^{4+}$ ceramics were fabricated and the optical as well as the thermal properties were analyzed and discussed.

2 Experimental

2.1 Materials synthesis

$\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:x\text{Mn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) ceramics were prepared by a traditional high temperature solid-state reaction method with high purity MgO (99.99%, Aladdin, China), TiO_2 (99.9%, Macklin, China), and MnO_2 (99.99%, Aladdin, China). First, stoichiometric amounts of the raw materials were weighed, and then mixed by ball milling for 12 h in ethanol. The mixtures were dried at 80 °C for 12 h, and the dried mixtures were screened with a 100-mesh sieve. The fine powders were pressed to pellets ($\Phi 15$ mm) followed by cold isotactic pressing at 200 MPa and finally sintered at 1650 °C for 5 h in an oxygen atmosphere. Then the ceramics were cooled down to room temperature naturally, cut and polished for the

subsequent measurements.

2.2 Characterizations

The phases purity of the as-obtained samples was analyzed by X-ray diffraction (Rigaku, Model Mini Flex 600, Japan) using Cu K α irradiation ($\lambda = 1.5418 \text{ \AA}$) with the X-ray tube operated at 40 kV, 15 mA. The morphology of the fracture surface of the phosphor ceramic was observed by scanning electron microscope (SEM) (Tescan, MIRA3, Czech Republic). The reflectance spectra were recorded by an ultraviolet–visible–NIR spectrophotometer (Perkin Elmer, Model Lambda 1050, USA). The steady photoluminescence (PL), photoluminescence excitation (PLE) spectra, dynamic emission decay curves, and temperature-dependent PL spectra were recorded by a fluorescence spectrophotometer (Edinburgh Instruments, FLS-1000, UK). The quantum efficiency (QE) was measured by an integrating sphere coated with Teflon lining attached to the spectrophotometer at room temperature. The thermal conductivity of the phosphor ceramic was studied by the laser flash method (Netzch, LFA-457, Germany). The CIE coordinates of the blue LED chips packaged with the prepared ceramic of different thicknesses were measured in an integrating sphere, which was connected to a CCD detector with an optical fiber.

3 Results and discussion

Figure 2 shows the X-ray diffraction (XRD) patterns of the as prepared $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:x\text{Mn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) powders. The XRD positions of all samples were well corresponded to the ICSD 82912 card of $\text{Mg}[\text{MgTi}]\text{O}_4$, indicating that the doping of Mn^{4+} did not transform the crystal structure. A weak peak appeared at 22° was corresponded to SiO_2 , which may be introduced during the milling process since agate balls were used. Since the radius of Mn^{4+} ($0.530 \text{ \AA}$) is smaller than that of Ti^{4+} ($0.605 \text{ \AA}$), with the concentrations of Mn^{4+} increased, the diffraction peaks of the $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:x\text{Mn}^{4+}$ phosphor showed a slight shift to higher 2θ angles.

Figure 3 shows the SEM images of the fracture surface of the Mg_2TiO_4 host and the $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:x\text{Mn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) ceramics. Relatively dense microstructure can be observed from the images while a certain number of pores existed in the grains. Such intragranular pores

Fig. 2 XRD patterns of $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:x\text{Mn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) powders.

were mainly caused by the rapid grain growth velocity during the sintering process, and the doping of MnO_2 can hardly restrain the grain growth. These pores can increase the light scattering in the ceramic and as a result, more blue light can be absorbed instead of leaking from the ceramics and more red light can be extracted from the ceramics [20–22]. Hence, the proper ratio of the transmitted blue light and converted deep-red light can be achieved by a piece of thinner ceramic. Although the existence of pores had adverse effects on the thermal conductivity [23], in this work, the thermal conductivity maintained a relatively high value, which will be discussed below.

The optical reflectance spectra of all the ceramic samples are shown in Fig. 4. It can be detected that doping of Mn^{4+} brought a strong absorption band in the near ultraviolet (nUV) region, which was caused by the combined action of spin-allowed $^4\text{A}_{2g} \rightarrow ^4\text{T}_{1g}$ and spin-forbidden $^4\text{A}_{2g} \rightarrow ^2\text{T}_{2g}$ transitions. Another strong absorption band located around 487 nm was from the spin-allowed $^4\text{A}_{2g} \rightarrow ^4\text{T}_{2g}$ transition. The absorption band in the deep ultraviolet region ($240\text{--}310 \text{ nm}$) might be caused by a $\text{O}^{2-}\text{--Mn}^{4+}$ ligand-to-metal charge transfer (LMCT) [24]. With the doping concentration of Mn^{4+} increased, an absorption band began to appear around 520 nm , which may be due to the metal-to-metal charge transfer (MMCT) when the distance between the Mn^{4+} cations became shorter [25].

Figure 5 shows the PLE spectra of $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:x\text{Mn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) ceramics, with the 658 nm emission monitored. In good agreement with optical reflectance spectra, two broad

Fig. 3 SEM images of the fracture surface of the Mg_2TiO_4 host and the $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:\text{xMn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) ceramics.

Fig. 4 Optical reflectance spectra of the Mg_2TiO_4 host and the $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:\text{xMn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) ceramics; the inset graph showed the digital photograph of these ceramics.

excitation bands were shown in the nUV and the blue light region, respectively, so the ceramics can be excited by the ultraviolet as well as the blue LED chips. Due to the smaller ionic radius of Mn^{4+} ($0.530 \text{ \AA}$)

compared with that of Ti^{4+} ($0.605 \text{ \AA}$), the $[\text{TiO}_6]$ octahedron will shrink when the Ti^{4+} was substituted by the Mn^{4+} , strengthening the crystal field splitting energy (D_q) [26]. From the Tanabe–Sugano diagram, the excitation band of $\text{Mg}_2\text{TiO}_4:\text{Mn}^{4+}$ will be blue-shifted with the increasing D_q . On the other hand, the excitation intensity ratio of nUV band to blue band decreases with increasing Mn^{4+} concentration, implying the modification of the crystal field may lead to the enhancement of the excitation intensity of the ${}^4\text{A}_{2g} \rightarrow {}^4\text{T}_{2g}$ transition.

The PLE spectrum of $0.1\% \text{ Mn}^{4+}$ doped Mg_2TiO_4 can be well fitted by 4 Gaussian peaks. Two strong peaks located at $28,902 \text{ cm}^{-1}$ and $20,534 \text{ cm}^{-1}$ were corresponded to the spin-allowed ${}^4\text{A}_{2g} \rightarrow {}^4\text{T}_{1g}$ and ${}^4\text{A}_{2g} \rightarrow {}^4\text{T}_{2g}$ transitions, respectively. Between these two peaks, a weaker peak at $24,343 \text{ cm}^{-1}$ was corresponded to the spin-forbidden ${}^4\text{A}_{2g} \rightarrow {}^2\text{T}_{2g}$ transition. Another peak at $32,265 \text{ cm}^{-1}$ was attributed to the LMCT transition [24].

Figure 6 shows the PL spectra of the $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:\text{xMn}^{4+}$

Fig. 5 (a) PLE spectra of the $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:x\text{Mn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) ceramics. (b) Peak fitting of the PLE spectrum of the $\text{Mg}_2\text{Ti}_{(0.999)}\text{O}_4:0.1\%\text{Mn}^{4+}$ sample.

Fig. 6 PL spectra of $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:x\text{Mn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) ceramics. The inset graph shows the full width at half maximum of PL spectrum of $\text{Mg}_2\text{Ti}_{(0.999)}\text{O}_4:0.001\text{Mn}^{4+}$.

($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) ceramics under the 465 nm excitation. All the samples had a red emission with a sharp peak at 658 nm due to the ${}^2\text{E}_g \rightarrow {}^4\text{A}_{2g}$ transition. The strongest emission appeared when the concentration was 0.1%, and the

Fig. 7 Measurements of quantum efficiency for the $0.1\% \text{Mn}^{4+}$ doped Mg_2TiO_4 ceramic.

Fig. 8 Tanabe-Sugano diagram of Mn^{4+} .

full width at half maximum (FWHM) was 31 nm, as shown in the inset graph of Fig. 6. The quantum efficiency of the $0.1\% \text{Mn}^{4+}$ doped Mg_2TiO_4 ceramic under the 465 nm excitation was also measured and shown in Fig. 7. The calculated external (η_e), internal (η_i) quantum efficiencies, and absorption efficiency (α) in Fig. 7 were 15.2%, 26.5%, and 57.3% respectively. In addition, over 53% of the emission energy was located in the range between 640 and 680 nm. As the maxima of photosynthesis efficiency were around 640–680 nm for quantum yield and around 660–680 nm for action spectrum [27], Mn^{4+} doped Mg_2TiO_4 had the potential to be a promising candidate for plant lighting.

The relationship between the energy level of Mn^{4+} and the crystal field splitting energy D_q of Mg_2TiO_4 can be explained by the Tanabe-Sugano diagram [28–31], as seen in Fig. 8, and the crystal field splitting energy D_q and Racah parameters B and C can be obtained by following equations.

$$D_q = E(^4A_{2g} \rightarrow ^4T_{2g})/10 \quad (1)$$

$$D_q / B = 15(x-8)/(x^2-10x) \quad (2)$$

$$x = [E(^4A_{2g} \rightarrow ^4T_{1g}) - E(^4A_{2g} \rightarrow ^4T_{2g})] / D_q \quad (3)$$

$$E(^2E_g \rightarrow ^4A_{2g}) / B = 3.05C / B + 7.9 - 1.8B / D_q \quad (4)$$

where the transition energy $E(^4A_{2g} \rightarrow ^4T_{2g})$, $E(^4A_{2g} \rightarrow ^4T_{1g})$, and $E(^2E_g \rightarrow ^4A_{2g})$ can be roughly estimated from fitting peak energy (20534 cm^{-1} , 28902 cm^{-1} , and 15198 cm^{-1}), as shown in Fig. 5(b). The crystal field splitting energy D_q , Racah parameters B and C for Mn^{4+} doped Mg_2TiO_4 were finally calculated to be 2053 cm^{-1} , 842, and 3006, indicating that the Mn^{4+} cations were located in a strong crystal field environment in the Mg_2TiO_4 host.

However, from the Tanabe–Sugano diagram, the energy level of 2E_g is almost independent of the crystal field splitting energy. The different positions of emission peak between Mn^{4+} doped Mg_2TiO_4 and other hosts were caused by the nephelauxetic effect. Brik *et al.* established a non-dimensional linear correlation to explain the relationship between the emission energy level (2E_g) and the nephelauxetic ratio (β_1) [32]. The nephelauxetic ratio β_1 can be calculated by Eq. (5).

$$\beta_1 = \sqrt{(B/B_0)^2 + (C/C_0)^2} \quad (5)$$

where B_0 and C_0 are the Racah parameters of the Mn^{4+} free ion, equal to 1160 and 4303, respectively.

Figure 9 shows the dependence of the Mn^{4+} 2E_g energy level on the β_1 value in different hosts. The solid straight line represented the linear function of the β_1 parameter. The region between the two dash lines represented the acceptable deviation of the data from the linear function. The nephelauxetic ratio β_1 in this

Fig. 9 Dependence of Mn^{4+} 2E_g energy level on the β_1 value in different hosts [33–50].

work was finally calculated to be 1.0074 and was drawn on the diagram as the blue square. The data point of this work showed a little deviation from the fitted straight line but was included in the area restricted by the two dash lines, as shown in Fig. 8, indicating that the higher 2E_g energy level of the Mn^{4+} in the Mg_2TiO_4 host than other oxides was owing to a weaker nephelauxetic effect.

Figure 10 shows the luminescence decay curves of the $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:x\text{Mn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) ceramics under the 465 nm excitation, with the 658 nm monitored. The decay curves almost remained unchanged at low doping concentrations. However, when the doping concentrations were increased to 0.3% and 0.5% , an initial faster decay appears. The luminescence lifetime values can be obtained by fitting the curves with a double exponential decay function, as shown in Eq. (6) and Eq. (7) [51].

$$I = A + B_1 \exp(-t/\tau_1) + B_2 \exp(-t/\tau_2) \quad (6)$$

$$\tau_s = (B_1\tau_1^2 + B_2\tau_2^2) / (B_1\tau_1 + B_2\tau_2) \quad (7)$$

where A , B_1 , and B_2 are constants, I represents the emission intensity at time and t , and τ_1 and τ_2 represent the two luminescence lifetime values of the ceramics. The fitting results are shown in Table 1. The average luminescence lifetime values first decreased slightly; with the Mn^{4+} concentration further increasing, the average distance between Mn^{4+} and Mn^{4+} was shortened, and the ion–ion interaction of transition metal ions occurs more frequently, resulting in the fast decay of luminescence [52].

Temperature-dependent emission spectra of 0.01% Mn^{4+} doped Mg_2TiO_4 ceramic under the 465 nm

Fig. 10 Luminescence decay curves of the $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:x\text{Mn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) ceramics under the 465 nm excitation.

Table 1 Luminescence lifetime values of the $\text{Mg}_2\text{Ti}_{(1-x)}\text{O}_4:x\text{Mn}^{4+}$ ($x = 0.01\%$, 0.05% , 0.07% , 0.1% , 0.3% , and 0.5%) ceramics

Concentration (%)	0.01	0.05	0.07	0.10	0.30	0.50
τ_s (ms)	0.528	0.528	0.527	0.525	0.494	0.383

excitation from 304 to 424 K are shown in Fig. 11. The emission band had no obvious change while the emission intensity decreased gradually with increasing temperature. At 364 K, the emission intensity dropped to 51% of that at room temperature, owing to the thermal quenching effect [53]. In the traditional packaging process, the phosphor powder was wrapped in silicone gel; when excited by the high-power LED chips, a lot of heat would generate in the phosphor, and the temperature of phosphor will easily reach up to 364 K or even above due to the weak heat dissipation capacity of silicone gel. Such a high temperature would cause serious thermal quenching and the emission intensity of $\text{Mg}_2\text{TiO}_4:\text{Mn}^{4+}$ phosphor would plunge. To reduce the accumulation of heat and help heat spreading, phosphor ceramics with high thermal conductivity are required.

The thermal conductivity values of 0.1% Mn^{4+} doped Mg_2TiO_4 ceramics at 303 K, 373 K, 423 K, 473 K, and 573 K are shown in Table 2. Benefiting from the dense micro-structure, the ceramic has a much higher thermal conductivity (7.545 W/(m·K) at room temperature) compared with the traditional packaging method using silicone gel (0.1–0.4 W/(m·K)) [54]. The high thermal conductivity was conducive to keep the ceramics working at a relatively low temperature, which can keep the phosphor away from thermal quenching.

Fig. 11 Temperature-dependent emission spectra of the $\text{Mg}_2\text{Ti}_{(0.999)}\text{O}_4:0.01\%\text{Mn}^{4+}$ sample excited at 465 nm from 304 to 424 K.

Table 2 Thermal conductivity values of the $\text{Mg}_2\text{TiO}_4:0.01\%\text{Mn}^{4+}$ ceramic at 303 K, 373 K, 423 K, 473 K, and 573 K

Temperature (K)	303	373	423	473	573
Thermal conductivity (W/(m·K))	7.545	6.527	5.549	5.277	4.432

A prototype of the light source for plant lighting was fabricated by mounting the 0.1% Mn^{4+} doped Mg_2TiO_4 ceramic samples of four different thickness (0.6 mm, 1.2 mm, 1.8 mm, and 2.4 mm) onto the surface of a 460 nm blue LED chip. Driven by a 300 mA current at 8.9 V, the CIE coordinates of these four light sources were (0.1604, 0.0562), (0.2316, 0.0872), (0.39990, 0.1627), and (0.4857, 0.1956), respectively. As presented in the CIE chromaticity diagram (see Fig. 12), the color of the light source can be changed from blue to purple by adjusting the thickness of the ceramics. The CIE coordinates, luminous flux, and luminous efficacy of the LED chip packed with 1.8 mm thick ceramic driven by increasing current were listed in Table 3. By increasing the driven current, the luminous efficacy did not drop much until the power achieved 9 W, indicating the ceramic with high thermal conductivity had a positive effect on relieving the thermal quenching of luminescence.

Fig. 12 CIE chromaticity diagram of the blue LED chip packaged with $\text{Mg}_2\text{TiO}_4:0.1\%\text{Mn}^{4+}$ ceramics of different thickness; the inset graph gives a photo of the purple light emission.

Table 3 CIE coordinates, luminous flux, and luminous efficacy of 1.8 mm thick ceramic driven by increasing current

Current (mA)	x	y	Luminous flux (lm)	Luminous efficacy (lm/W)	Voltage (V)	Power (W)
200	0.3497	0.1591	2.2301	1.327	8.397	1.618
300	0.3517	0.1527	2.9719	1.139	8.69	2.609
500	0.3395	0.1462	4.1484	0.912	9.099	4.551
900	0.3181	0.1366	5.6476	0.643	9.764	8.788

4 Conclusions

In summary, the Mg_2TiO_4 ceramics with different amounts of Mn^{4+} doping concentrations have been synthesized via the high temperature solid-state reaction method. All the samples had deep-red emission under the 465 nm blue light excitation. The external, internal quantum efficiencies of the 0.1% Mn^{4+} doped Mg_2TiO_4 ceramic were 15.2%, 26%, respectively. And over 53% of the emission energy was useful to plant growth. The thermal conductivity of ceramics was 7.545 W/(m·K), about 20 times higher than that of the silicone gel, which can be helpful to avoid the thermal quenching effect by keeping the phosphor material at a relatively low working temperature. The ceramics plates were mounted to the 460 nm blue LED chips and the color of these light sources can be adjusted by changing the thickness of the ceramics. All these results indicated that the Mn^{4+} doped Mg_2TiO_4 ceramics are promising for plant lighting.

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