



## Research Article

# Ru doping effect on the structural, electronic, transport, optical and dye degradation properties of layered $\text{Li}_2\text{MnO}_3$

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## Abstract

Ru doped  $\text{Li}_2\text{MnO}_3$  compositions show the presence of redox couples  $\text{Mn}^{3+}\text{--Mn}^{4+}$  and  $\text{Ru}^{4+}\text{--Ru}^{5+}$ . Due to the presence of these redox couples in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x=0.05, 0.1$ ), Ru doped compositions show (i) change in structure (ii) large decrease in impedance ( $\sim 10^7$  to  $\sim 10^5$  Ohm) (iii) degrade methyl orange and methylene blue solution (pH-6) in quick time in presence of tungsten (W) bulb and sun light. Synchrotron X-ray powder diffraction studies show the change in lattice parameters with Ru doping at Mn site in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x=0.05, 0.1$ ). Raman and Infrared spectroscopic studies show the shift in Mn–O stretching mode of  $\text{Li}_2\text{MnO}_3$  towards lower wave number with Ru doping. Soft X-ray absorption spectroscopic studies show the presence of mixed valences of  $\text{Mn}^{3+}$ ,  $\text{Mn}^{4+}$ ,  $\text{Ru}^{4+}$  and  $\text{Ru}^{5+}$  in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x=0.05, 0.1$ ) using  $L_{2,3}$  and  $M_4$  edge. UV–Vis diffuse reflectance spectroscopic studies show the optical band gap in visible light range in Ru doped  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x=0.05, 0.1$ ) compositions. The presence of 5 mg of  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  degrades 5 ml of methyl orange solution (10 mg/L) of pH 6 in 5 min and methylene blue solution (10 mg/L) of pH 6 in 3 min of exposure in W bulb light.

**Keywords** Synchrotron X-ray · XAS · Raman · Dye degradation · Optical absorption

## 1 Introduction

Manganese (Mn) containing oxides crystallize in layered, perovskite, spinel, and various other structures, where valence state of Mn make these oxides vulnerable for various technological applications [1–7]. Colossal magnetoresistance, room temperature magnetism, metal to insulator transition, catalytic and Li intercalation are some of the properties which are utilized in devices [1, 2, 5, 6]. Mixed valence states of Mn play a major role in altering the properties of the materials as per the technological application need [2, 6, 7]. In perovskite oxides, ratio of Mn mixed valence  $\text{Mn}^{3+}/\text{Mn}^{4+}$  decides the structural, magnetic and transport properties.  $\text{Mn}^{3+}$  containing oxides show insulating and antiferromagnetic behaviour while  $\text{Mn}^{4+}$  containing oxides also show insulating and antiferromagnetic

properties [2, 6]. When  $\text{Mn}^{3+}$  remains present 67% and  $\text{Mn}^{4+}$  33% then perovskite oxides show metallic and ferromagnetic behaviour. Presence of 50%  $\text{Mn}^{3+}$  and 50%  $\text{Mn}^{4+}$  valence states makes spinel oxides susceptible for charging and discharging in Li ion battery [1, 4, 7].

Hierarchical microstructure of  $\text{Mn}_3\text{O}_4$  has been tried for degradation of methylene blue [8].  $\text{MnO}_2$ , which has +4 valence state of Mn, has been considered as a photocatalyst and known for its cost effectiveness, adsorption/oxidizing abilities, large specific surface area and nontoxic nature [9]. It has been observed that some of the good photocatalysts involve metal cations  $\text{Fe}^{+2}$  in photo-fenton process for degradation of MB, where redox interaction between  $\text{Fe}^{+2}$  and  $\text{Fe}^{+3}$  play an important role to produce hydroxyl ions [10]. Ru is a 4 d transition metal and placed in same group with iron in periodic table. Ru–Mn interaction

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induces mixed valence  $\text{Ru}^{+4}/\text{Ru}^{+5}$  with  $\text{Mn}^{+3}/\text{Mn}^{+4}$  in perovskite oxides and spinel structures [11–14]. When  $\text{Ru}^{+4}$  (0.62 Å) is interact with  $\text{Mn}^{+4}$  (0.53 Å), it undergo redox reaction which leads to  $\text{Mn}^{+3}$  (0.645 Å) and  $\text{Ru}^{+5}$  (0.565 Å) valence states as redox potential of  $\text{Ru}^{+4}/\text{Ru}^{+5}$  (1.07 eV) is comparable with that of  $\text{Mn}^{+3}/\text{Mn}^{+4}$  (1.02 eV) [15].  $\text{Ru}^{+4}/\text{Ru}^{+5}$  redox couple operates at 4.3 V vs Li in the spinel  $\text{LiMn}_2\text{O}_4$  and increases the cycling capacity of Li ion battery [12]. Ru doping brings cycling stability due to the presence of  $\text{Ru}^{+4}/\text{Ru}^{+5}$  redox couple in  $\text{Li}_2\text{Mn}(\text{Ru})\text{O}_3$  rock salt type layered structure [16–19]. Presence of mixed valence  $\text{Ru}^{+4}/\text{Ru}^{+5}$  with  $\text{Mn}^{+3}/\text{Mn}^{+4}$  brings long range of magnetic ordering in  $\text{La}_{0.7}\text{Ca}_{0.3}\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  thin films [14].  $\text{Ru}^{+4}$  containing thin film of  $\text{La}_{0.7}\text{Ca}_{0.3}\text{Mn}_{0.7}\text{Ru}_{0.3}\text{O}_3$  shows colossal magnetoimpedance effects at room temperature [20]. Ru exists in its single valence state  $\text{Ru}^{+4}$  in  $\text{LaMn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x = 0.1, 0.2, 0.3, 0.4$ ) compositions and it shows band gap in the range of  $\sim 1.27$  eV to 1.36 eV [21].  $\text{LaMn}_{1-x}\text{Ru}_x\text{O}_3$  compounds degrade MO solution (pH 2.5) and generate photocatalytic oxygen by water in W bulb light [21]. In this study, we have documented the doping effect of  $\text{Ru}^{+4}$  at  $\text{Mn}^{+4}$  site in  $\text{Li}_2\text{MnO}_3$  on the structure, Mn and Ru valence states, and dye degradation properties using methyl orange (MO) and methylene blue (MB) at nominal pH 6.

## 2 Experimental

Polycrystalline  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x = 0.0, 0.05, 0.1$ ) samples were prepared using high temperature solid state reaction route. In the preparation process, we have weighed the stoichiometric amount of high purity  $\text{LiOH}\cdot\text{H}_2\text{O}$ ,  $\text{MnO}_2$  and  $\text{RuO}_2$ . They were thoroughly mixed in an agate mortar and heated at 950 °C for 12 h in an ambient atmosphere in muffle furnace.  $\text{Sr}_4\text{Ru}_2\text{O}_9$  sample was prepared by taking stoichiometric amount of high purity  $\text{SrCO}_3$  and  $\text{RuO}_2$  oxides. The precursors were thoroughly mixed in an agate mortar and calcined at 850 °C for 36 h in oxygen atmosphere, and subsequently sintered under oxygen atmosphere at 950 °C for 36 h in tubular furnace.  $\text{LiMn}_2\text{O}_4$  sample was prepared by taking stoichiometric amount of high purity  $\text{LiOH}\cdot\text{H}_2\text{O}$  and  $\text{MnO}_2$ . The precursors were thoroughly mixed in an agate mortar and heated at 800 °C for 24 h.  $\text{LaMn}_{0.8}\text{Ru}_{0.2}\text{O}_3$  sample was prepared by taking stoichiometric amount of high purity  $\text{La}_2\text{O}_3$ ,  $\text{MnO}_2$  and  $\text{RuO}_2$  oxides. The precursors were thoroughly mixed in an agate mortar and calcined at 900 °C for 24 h and subsequently sintered at 1050 °C for 24 h in ambient atmosphere. Heating rate was maintained 5 °C/min during heating and cooling. The X-ray powder diffraction patterns (step size 0.015, scan speed 1 s/step) using synchrotron radiation ( $\lambda = 1.09$  Å) were recorded at room

temperature at Indian beamline BL-18B, Photon Factory (PF), KEK, Tsukuba, Japan. The incoming X-ray beam from the bending magnet of the PF storage ring was collimated with a set of beam-defining slits having vertical opening of 0.2 mm and 2 mm in the horizontal direction. The sample was mounted onto an 8-circle goniometer (Huber, Germany) at the focal point of the focusing mirror of the beamline. A slit of 1.5 mm (horizontal) by 0.25 mm (vertical) was mounted just before the detector to increase the signal-to-background ratio. Raman spectra of these powder samples were recorded using Renishaw micro-Raman spectrometer (model RM-2000) and focused  $\text{Ar}^+$  laser beam of 514-nm using Leica microscope. The incident laser power was attenuated to 2 mW, and data acquisition time was set to 50 s for all the samples was used to record the data. The Raman spectra were recorded using Peltier air-cooled CCD detector in the range of 100–3200  $\text{cm}^{-1}$ . Fourier transform infrared (FTIR) spectra (absorbance vs. wavenumber) of the samples were recorded using a FTIR Perkin Elmer spectrometer, using the KBr pellet technique from 400 to 4000  $\text{cm}^{-1}$  at room temperature. Each IR scan recorded after averaging of 25 scans. X-ray absorption spectroscopy (XAS) measurements for Mn  $L_{2,3}$ , and Ru  $M_{4,5}$  were performed at the Soft X-ray absorption spectroscopy (SXAS) beamline (BL-01) of the INDUS 2 synchrotron source source (2.5 GeV, 300 mA) at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, India. This beamline is operating in the energy range 100–1200 eV. Sample pellets were mounted in an ultrahigh vacuum (UHV) chamber with a base pressure of  $10^{-10}$  Torr. SXAS data were collected in total electron yield (TEY) mode at room temperature under ultra-high vacuum conditions. Impedance and capacitance measurements were recorded using novacontrol make Impedance analyzer (Alpha-A high performance frequency analyzer) in the frequency range from 1 Hz to 40 MHz in ambient atmosphere at room temperature. We had used 10.4 mm diameter and 1.2 mm thick pellets polished both side with silver paste for these measurements. The wire length was  $\sim 2$  feet between the impedance analyzer and sample. The reflectance of the  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x = 0.0, 0.05, 0.1$ ) solid samples were recorded using UV–visible diffuse reflectance spectroscopy (DRS) in a Shimadzu UV-2450 spectrophotometer over a wavelength range of 200–800 nm.  $\text{BaSO}_4$  was used as an internal reflectance standard. The absorbance of the Methyl Orange (MO) and Methylene Blue (MB) solution was measured in wavelength range of 200–800 nm to find out the degradation. To find out the band gap of these samples, the diffuse reflectance data were converted to the Kubelka–Munk function by equation [22]:

$$F(R) = (1 - R)^2 / 2R$$

where  $R$  is reflectance,  $F(R)$  is proportional to extinction coefficient  $\alpha$ .

Band gaps were determined by Tauc plots using equation [23]:

$$[\alpha h\nu]^{1/n} = A [h\nu - E_g]$$

where  $\nu$  is frequency,  $A$  is absorption constant,  $h$  is Planck constant and  $E_g$  is band gap. Here,  $n$  denotes the nature of band gap. For indirect band gap  $n=2$  and direct band gap  $n=1/2$  is used.

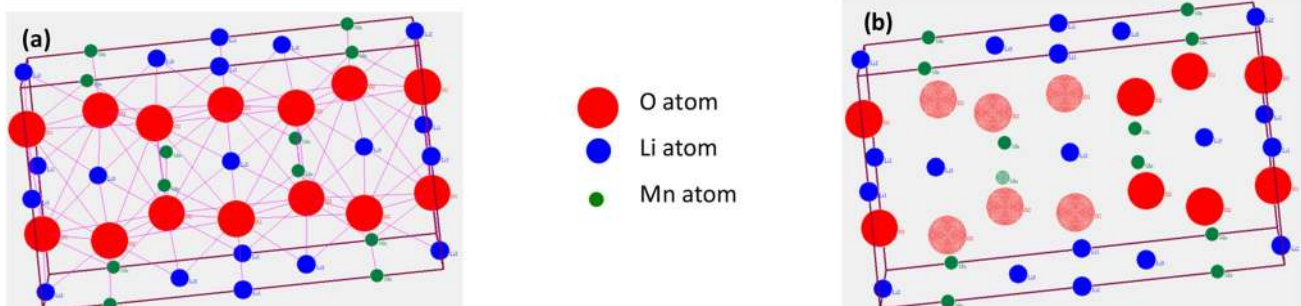
To understand the dye degradation ability of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x = 0.0$  and  $0.1$ ), we have selected methyl orange (MO) and methylene blue (MB) dyes for degradation.  $\text{MnO}_2$  has been used as reference for MO and MB degradation. The photocatalytic degradation of aqueous methyl orange and methylene blue dyes by  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$ , and  $\text{MnO}_2$ , was carried out in a borosil make glass sample vials. Sample vial further placed in ultrasonicator and exposed in visible light of 200 Watt incandescent tungsten (W) bulb (300 to 900 nm) under constant flow of water (to maintain the constant temperature). MO and MB stock solutions of 10 mg/L concentration were prepared in ultra pure water. Hydrochloric acid was used to maintain pH of dye solutions. For dye degradation experiment, we have used 5 mg of catalyst in 5 ml dye solutions of 10 mg/L concentration for all the compositions. Before mixing catalysts in dye solutions, the pH of dye solutions was maintained 6. Ultrasonicator was used for proper mixing of catalyst and dye solution during exposing the mixture in visible light. The distance between 200 W incandescent tungsten(W) bulb and sample vial was maintained 15 cm. Visible part of sample vials (4 cm length and 1.6 cm diameter) was effectively exposed to  $70.77 \text{ mW/cm}^2$  power of radiation. The samples were filtered using whatmann filter paper after exposing in W bulb light and absorbance of dye solutions were recorded in a Shimadzo make UV-Visible spectrometer over a wavelength range of 200–800 nm. The concentration of MB were calculated as  $C_t = C_0(A_t/A_0)$ ,

where  $C_0$  - initial MB concentration,  $A_0$ —initial absorbance (at  $\lambda = 662 \text{ nm}$ ),  $C_t$ —MB concentration at time  $t$ , and  $A_t$ —absorbance (at maxima of peak on  $t$  minute), respectively. The degradation rate % was calculated by  $[(A_0 - A_t)/A_0] \times 100$ .

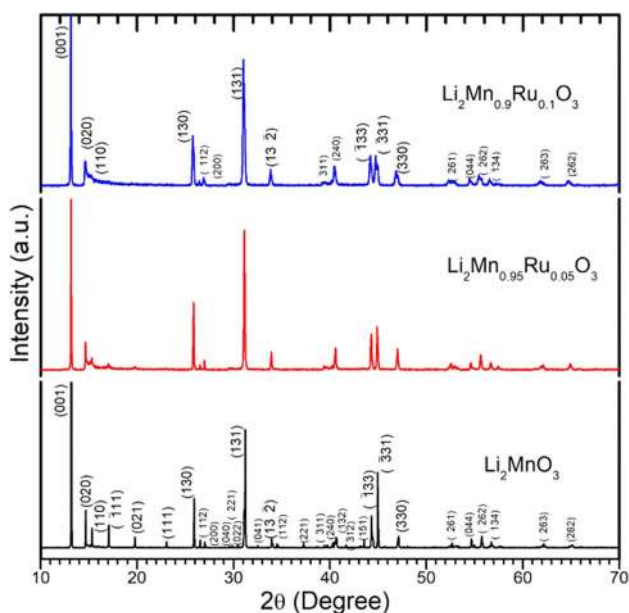
### 3 Results and discussion

$\text{Li}_2\text{MnO}_3$  crystallizes in monoclinic unit cell and space group C2/m (Fig. 1). It is a layered structure, where a layer of Li ions, and a mixed layer of Li and 2Mn ions are alternating between closed packed oxygen layers. In a crystal, Li ions occupy three positions (2b, 2c and 4 h), oxygen ions occupy two positions (4i and 8j) and Mn atom occupies one position (4g) [24, 25]. In  $\text{MnO}_6$  octahedra, two types of Mn–O bonds of 1.90 Å and 1.91 Å exists [24, 25].

Figure 2 shows the synchrotron X-ray powder diffraction patterns of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x = 0.0, 0.05, 0.1$ ] compositions from 10 degree to 70 degree. We have found stoichiometric single phase for  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x = 0.0, 0.05, 0.1$ ] compositions and diffraction patterns matches with the reference code ICSD-202639 and JCPDS-01-084-1634 patterns. All the peaks are matching with the reported results in literature. Parent and Ru doped diffraction patterns show the characteristic peaks (020), (110), (021) and (110) which confirms the crystallization of these compositions in C2/m. Figure 3 shows the close look of the peaks of normalized intensity for all the compositions. It has been observed that the peaks (001), (020), (110), (130) shifts at lower theta with the increase in Ru concentration. Shifting of peaks shows the expansion of unit cell with Ru substitution due to the higher ionic size of  $\text{Ru}^{+4}$  (0.76 Å) than the ionic size of  $\text{Mn}^{+4}$  (0.67 Å). Peaks (202) and (131) merge together with Ru substitution at Mn site. Peak ( $\bar{3}31$ ) shifted towards lower theta value for Ru = 0.05 composition but for Ru-0.1 composition ( $\bar{3}31$ ) peak split into ( $\bar{3}31$ ) and (060). Crystallite size for all the composition has been calculated using Debye Sherrer formula (Crystallite



**Fig. 1** **a** Crystal structure of monoclinic  $\text{Li}_2\text{MnO}_3$ . **b** Shaded atoms (six O and one Mn atoms) show the configuration of  $\text{Mn-O}_6$  octahedra in  $\text{Li}_2\text{MnO}_3$



**Fig. 2** Synchrotron X-ray powder diffraction patterns of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x=0.0, 0.05, 0.1$ ). Ru doped compositions show the single phase as  $\text{Li}_2\text{MnO}_3$ . Peaks are indexed for  $\text{Li}_2\text{MnO}_3$

size ( $\text{\AA}$ ) =  $0.9\lambda/d \cos\theta$ ). Ru doping decreases crystallite size of materials. Table 1 summarizes the results of the analysis of synchrotron X-ray powder diffraction patterns. These results show that Ru has been successfully doped at Mn site in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ]. To explore the shifting of peaks at lower theta value and lowering of crystallite size at micro level by Ru doping at Mn site, we have recorded the Raman spectra of these compositions [12, 26].

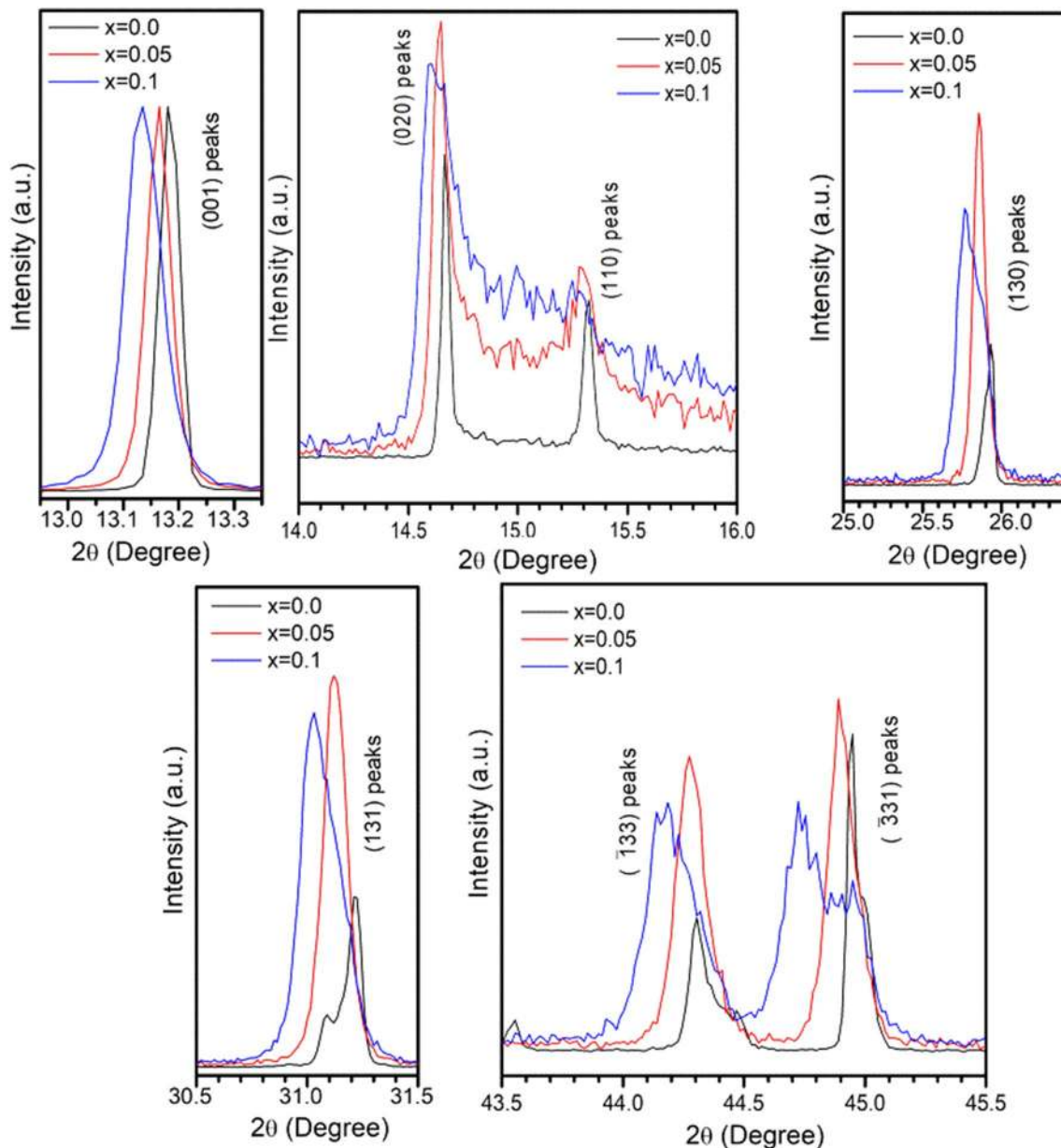
Figure 4 shows the Raman peaks for powder samples of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.0, 0.05, 0.1$ ] compositions. Theoretical calculations predict the 15 Raman active optical modes, in which 7 modes are  $A_g$  and 8 modes are  $B_g$  [27]. In monoclinic space group  $C2/m$ ,  $A_g$  modes are generated from the symmetric vibrations of cations along b-axis.  $B_g$  modes are generated from the symmetric vibrations of cations along a and c-axis. The vibrations of octahedrally coordinated Mn atom at 4g position results 1  $A_g$  and 2  $B_g$  modes, while 1  $A_g$  and 2  $B_g$  modes are due to Li atom at 4h site. O atom at 4i position generates 2  $A_g$  and 1  $B_g$  modes, and remaining 3  $A_g$  and 3  $B_g$  modes can be assigned to vibrations of O atom at 8j site [28, 29]. We have clearly observed 14 active Raman modes in our synthesized  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  samples while other groups have reported only 8 Raman peaks in monoclinic  $\text{Li}_2\text{MnO}_3$  samples [28, 29]. The observed Raman Peaks positions are summarized in Table 2 for  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.0, 0.05, 0.1$ ] compositions. Ru substitution at Mn

site shifts  $A_g$  peak at  $\sim 615 \text{ cm}^{-1}$  of  $\text{Li}_2\text{MnO}_3$  to lower value  $\sim 610.8 \text{ cm}^{-1}$  for  $x=0.05$  composition. This observation is similar to the Ru doped  $\text{LiMn}_2\text{O}_4$  samples where we had observed the peak shifting towards lower wave numbers [12]. Ru as a 4d transition metal having extended orbitals and higher spin orbit coupling constant  $800 \text{ cm}^{-1}$  in comparison with  $100 \text{ cm}^{-1}$  of Mn. It makes Ru–O bond stronger than Mn–O bond which reflect in shifting of  $A_g$  vibrational peak towards lower wave numbers.

For Ru = 0.1 composition, we have observed that Raman peaks splitted into multiple peaks for stretching modes of Mn–O vibrations, it shows that the multiple cations vibration contributing to stretching modes. Figure 5 shows the Infra red (IR) peaks for powder samples of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.0, 0.1$ ] compositions. Theoretical calculations predict the 7  $A_u$  and 11  $B_u$  IR active optical modes [27]. We have found 7 peaks for  $\text{Li}_2\text{MnO}_3$  which are similar with the reported experimental studies in literature [30]. In  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$ , some Raman peaks merge and total 5 peaks have been observed. All the peaks have been shifted towards lower wavenumber with the doping of Ru at Mn site. Presence of multiple peaks and shift of other vibrational peaks in Raman and IR spectra motivated us to find the valence states of transition metals Mn and Ru in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ] compositions.

In Figure 6a, we show Mn-  $L_{2,3}$  absorption edge spectra of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.0, 0.05, 0.1$ ] and  $\text{Li}_2\text{Mn}_2\text{O}_4$  systems together with that of  $\text{Mn}_2\text{O}_3$ ,  $\text{MnO}_2$  (where Mn exist in +3 and +4 valence states) for comparison. The  $L_2$  edge and  $L_3$  edge correspond to the  $2p_{1/2} - 3d$  ( $t_{2g}$  and  $e_g$  orbitals) and  $2p_{3/2} - 3d$  ( $t_{2g}$  and  $e_g$  orbitals) transitions, respectively. Cathode material  $\text{LiMn}_2\text{O}_4$  is known for showing 50–50% of  $\text{Mn}^{+3}$  and  $\text{Mn}^{+4}$  valence states [12]. In  $L_3$  absorption edge, We have observed two peaks at 642.30 eV and 643.39 eV in  $\text{LiMn}_2\text{O}_4$  which are identical to peaks at 642.37 eV in  $\text{Mn}_2\text{O}_3$  and 643.45 eV in  $\text{MnO}_2$  [31]. It shows the presence of  $\text{Mn}^{+3}$  and  $\text{Mn}^{+4}$  valence states in  $\text{Li}_2\text{Mn}_2\text{O}_4$  [31]. In  $\text{Li}_2\text{MnO}_3$  ( $x=0.0$ ), we have found peak at 643.45 eV which is comparable to peak observed in  $\text{MnO}_2$ , it shows the presence of  $\text{Mn}^{+4}$  valence state in  $\text{Li}_2\text{MnO}_3$ . Figure 6b shows the close look of  $L_3$  edge for  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.0, 0.05, 0.1$ ]. In  $\text{Li}_2\text{Mn}_{0.95}\text{Ru}_{0.05}\text{O}_3$  ( $x=0.05$ ), we have observed peaks at 643.35 eV and in  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  ( $x=0.1$ ) we have found peaks at 643.25 eV. These peaks are shifting towards lower energy as Ru concentration is increasing. It confirms the presence of  $\text{Mn}^{+3}$  valence state along with  $\text{Mn}^{+4}$  in  $\text{Li}_2\text{Mn}_{0.95}\text{Ru}_{0.05}\text{O}_3$  and  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$ .

In Figure 7a, we show Ru-  $M_4$  absorption edge spectra of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ] and  $\text{LaMn}_{0.8}\text{Ru}_{0.2}\text{O}_3$  systems together with that of  $\text{RuO}_2$  and  $\text{Sr}_4\text{Ru}_2\text{O}_9$ , where Ru exist in +4 and +5 valence states [11, 15, 32, 33]. The  $M_4$



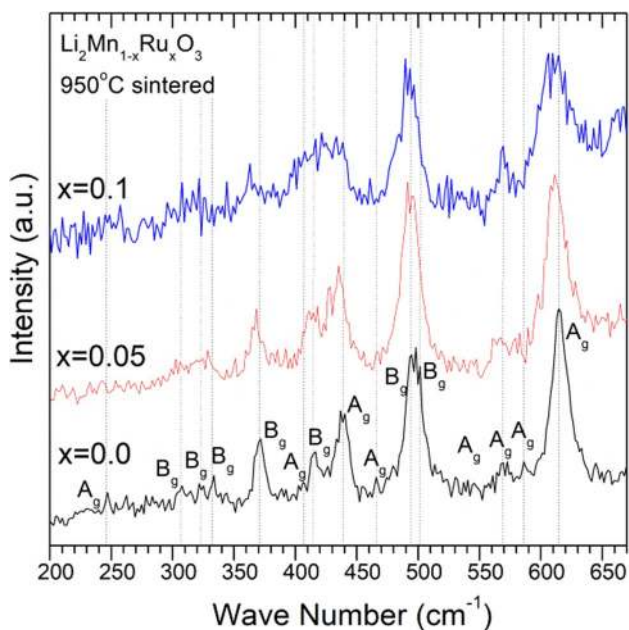
**Fig. 3** Zoomed peaks of synchrotron X-ray powder diffraction patterns of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x=0.0, 0.05, 0.1$ ). Shifting of peaks towards lower theta value shows the expansion of lattice with Ru substitution at Mn in  $\text{Li}_2\text{MnO}_3$

edge and  $M_5$  edge correspond to the electronic transition from Ru- $3d_{5/2}$  to Ru p orbitals and Ru- $3d_{3/2}$  to Ru p orbitals respectively. The  $M_4$  edge of  $\text{RuO}_2$  has been found at 287.95 eV which is similar with the reported by Zhou et al. [33]. Zhou et al. have found  $M_4$  edge of Ru at 288 eV in  $\text{RuO}_2$  nano particles [33]. The  $M_4$  absorption edge has been found at 289.74 eV for  $\text{Sr}_4\text{Ru}_2\text{O}_9$ , which is 1.78 eV more than  $M_4$  edge peak of  $\text{RuO}_2$ . This result shows the presence of +5 valence state of Ru in  $\text{Sr}_4\text{Ru}_2\text{O}_9$ . These results are similar

with findings of Hu et al. [32] where they have shown that Ru remains in +4 and +5 valence states for  $\text{RuO}_2$  and  $\text{Sr}_4\text{Ru}_2\text{O}_9$  respectively [32, 34]. In our observation,  $\text{LaMn}_{0.8}\text{Ru}_{0.2}\text{O}_3$  has been found showing  $M_4$  absorption peak of Ru at 288.05 eV which is very close to the absorption peak (at 287.95 eV) of  $\text{RuO}_2$  [33]. This result is very much similar with the reported result by Patra et al., where it has been found that Ru remains in +4 valence state in  $\text{LaMn}_{0.8}\text{Ru}_{0.2}\text{O}_3$  [21]. In  $\text{Li}_2\text{Mn}_{0.95}\text{Ru}_{0.05}\text{O}_3$  ( $x=0.05$ ), we have

**Table 1** Synchrotron X-ray powder diffraction data acquisition conditions and lattice parameters of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$

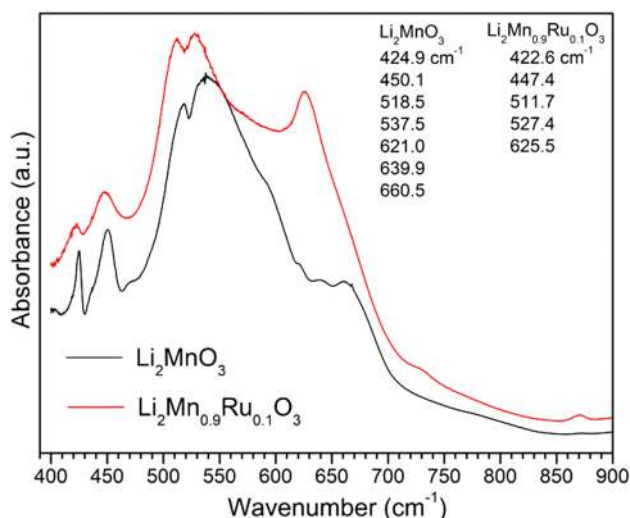
	$\text{Li}_2\text{MnO}_3$	$\text{Li}_2\text{Mn}_{0.95}\text{Ru}_{0.05}\text{O}_3$	$\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$
Space group	C2/m	C2/m	C2/m
a (Å)	4.938	4.944	4.946
b (Å)	8.542	8.561	8.592
c (Å)	5.032	5.037	5.048
$\beta$ (deg)	109.34	109.30	109.43
Angle range	10 to 70	10 to 70	10 to 70
Step size (deg)	0.015	0.015	0.015
X-ray wavelength (Å)	1.09 Å	1.09 Å	1.09 Å
Crystallite size (nm)	135.29	107.34	74.25



**Fig. 4** Raman shift for powder samples of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x=0.0, 0.05, 0.1$ ). Vertical lines show the peak positions for  $\text{Li}_2\text{MnO}_3$

**Table 2** Frequencies of experimentally observed Raman active modes of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$

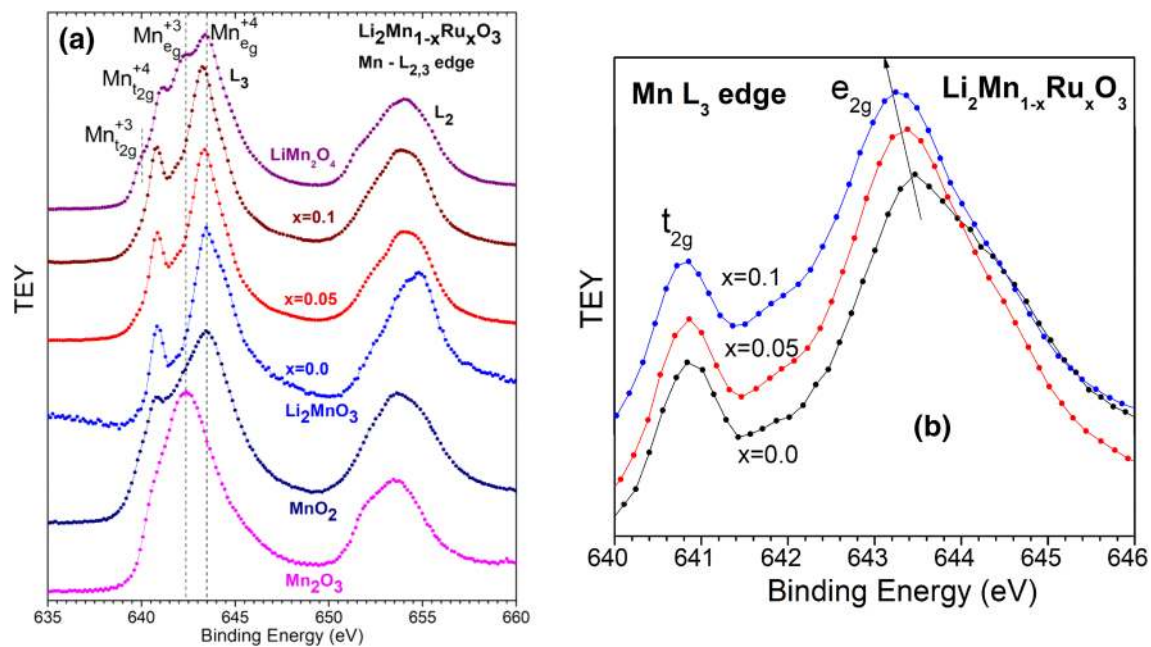
Symmetry	Frequency ( $\text{cm}^{-1}$ ) theory [28, 29]	Frequency ( $\text{cm}^{-1}$ ) experiment		
		$x=0.0$	$x=0.05$	$x=0.1$
$A_g$	621.41	614.7	610.8	609.3, 597.7
	577.03	569.06	565.2	568.05
	448.43	439.25	435.4, 426.9	433.1, 421.2
$B_{2g}$	498.39	501.8	495.7	494.19
	496.74	494.2	491.4	484.5
	425.98	413.6	412.7	Multiple peaks
	376.98	370.9	368.2	362.5



**Fig. 5** Peaks of Infrared spectra for powder samples of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  ( $x=0.0, 0.1$ )

observed multiple peaks at 288.15 and 289.88 eV and similarly in ( $x=0.1$ ) two peaks at 288.02 and 289.88 eV have been observed. These two absorption peaks are similar with the  $M_4$  absorption peak of  $\text{RuO}_2$  and  $\text{Sr}_4\text{Ru}_2\text{O}_9$ . These results show that  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  and  $\text{Li}_2\text{Mn}_{0.95}\text{Ru}_{0.05}\text{O}_3$  contain multi valence states of Ru ( $\text{Ru}^{+4}$  and  $\text{Ru}^{+5}$ ). Fitting of  $M_4$  absorption peak of Ru shows the % amount of Ru valence state in  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  and  $\text{Li}_2\text{Mn}_{0.95}\text{Ru}_{0.05}\text{O}_3$  (Fig. 7b).  $\text{Li}_2\text{Mn}_{0.95}\text{Ru}_{0.05}\text{O}_3$  compound contains 48%  $\text{Ru}^{+4}$  valence state and 52%  $\text{Ru}^{+5}$  valence state.  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  compound contains 32%  $\text{Ru}^{+4}$  valence state and 68%  $\text{Ru}^{+5}$  valence state.

To see the effect of multivalence states of Ru and Mn in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ] on the transport properties of  $\text{Li}_2\text{MnO}_3$ , we have measured the frequency dependent impedance measurements. Figure 8 shows the impedance and capacitance for these compositions in the frequency range  $10^3$  to  $4 \times 10^7 \text{ cm}^{-1}$ . At frequency  $10^3$  Hertz,  $x=0.0$  composition show  $1.38 \times 10^7 \text{ Ohm}$  impedance while  $x=0.05$  and  $0.1$  show  $2.82 \times 10^5$  and  $5.37 \times 10^4 \text{ Ohm}$  respectively. Capacitance is found  $1.05 \times 10^{-11} \text{ F}$  at frequency  $10^3$  Hertz for  $x=0.0$  composition while  $x=0.05$  and  $0.1$  compositions show  $5.15 \times 10^{-10} \text{ F}$  and  $2.71 \times 10^{-9} \text{ F}$  respectively. These measurements show the decrease in impedance and increase in capacitance with the substitution of Ru in  $\text{Li}_2\text{MnO}_3$ . On increasing frequency, impedance further decreases for all the compositions. These observations confirm the presence of  $\text{Mn}^{+3}$  valence state along with  $\text{Mn}^{+4}$  valence state in Ru doped compositions. While synthesis of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.0, 0.05, 0.1$ ] compositions, we have observed that parent  $x=0.0$  composition is in reddish colour and Ru doped compositions  $x=0.05$  and  $0.1$  are in black colour. To find out the absorption capability in



**Fig. 6** **a** XAS spectra of L<sub>2,3</sub> edge for Li<sub>2</sub>Mn<sub>1-x</sub>Ru<sub>x</sub>O<sub>3</sub> [x=0.0, 0.05, 0.1] and LiMn<sub>2</sub>O<sub>4</sub>. XAS spectra of MnO<sub>2</sub> and Mn<sub>2</sub>O<sub>3</sub> used for reference of Mn<sup>3+</sup> and Mn<sup>4+</sup> valence states peaks. **b** L<sub>3</sub> edge of Ru doped Li<sub>2</sub>MnO<sub>3</sub> compositions, which show shift in Mn peaks with Ru substitution

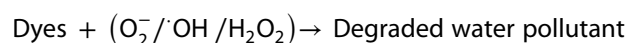
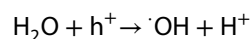
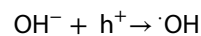
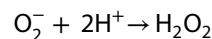
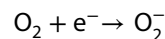
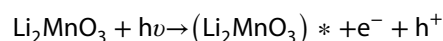
visible light, we have measured UV–vis diffuse reflectance spectroscopic measurements.

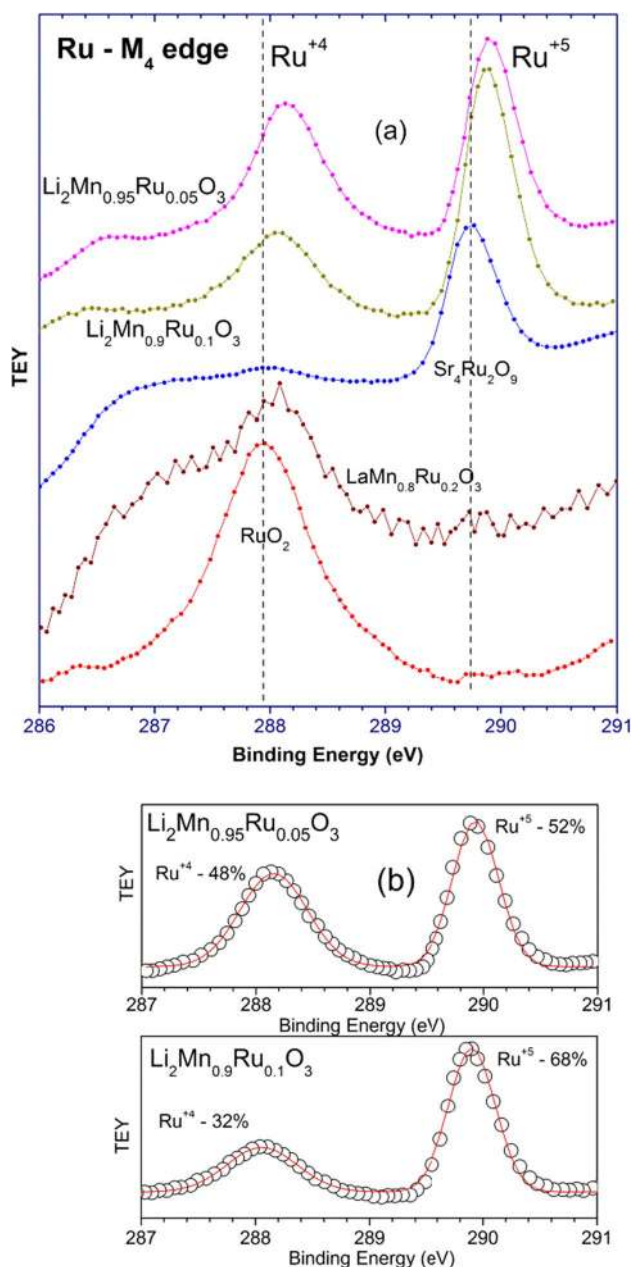
Figure 9 shows the reflectance of the Li<sub>2</sub>Mn<sub>1-x</sub>Ru<sub>x</sub>O<sub>3</sub> [x=0.0, 0.05, 0.1] compositions. TiO<sub>2</sub> (commercial sample) is used as reference for reflectance. Optical reflectance spectra of Li<sub>2</sub>MnO<sub>3</sub> showed a sharp edge at 610 to 750 nm, which is similar with the reported by Tamilarasan et al. [35]. The peaks ~610 nm corresponds to a HOMO–LUMO gap between filled O(2p) states and empty Mn(IV) (3d–4 s) states. Figure 10 shows the band gap of the Li<sub>2</sub>Mn<sub>1-x</sub>Ru<sub>x</sub>O<sub>3</sub> [x=0.0, 0.05, 0.1] compositions, which was calculated using Kubelka–Munk function and Tauc plot [22, 23]. Tauc plot gave an energy band gap 2.17 eV for parent Li<sub>2</sub>MnO<sub>3</sub> which is in agreement with the theoretical estimations [35, 36]. In Ru doped compositions, we have observed some more reflectance peaks near to 480 nm and 577 nm. Band gap calculation suggests the presence of multiple absorption of band gap 1.97, 2.15, 2.33 and 2.41 eV for x=0.1 composition and band gap 1.91, 2.09 and 2.24 eV for x=0.05 composition. These experimental determined optical band gaps are reported by theoretical studies on the systems which have Mn mixed valences.

The optical absorption in Mn containing systems is controlled by electric dipole matrix elements that preserve spins of electrons. Features observed in optical conductivity close to 1 eV, 3 eV have been ascribed due to the d–d charge transfer between Mn ions on different sites, e<sub>g</sub>–e<sub>g</sub>

transitions in perovskite manganite systems [37–39]. These band gap values 1.91, 2.09 and 2.24 eV for x=0.05 composition and band gap 1.97, 2.15, 2.33 and 2.41 eV for x=0.1 composition suggest the optical activity of Li<sub>2</sub>Mn<sub>1-x</sub>Ru<sub>x</sub>O<sub>3</sub> [x=0.05, 0.1] compositions in visible light.

Ranjeh et al. have investigated photocatalytic properties of Li<sub>2</sub>MnO<sub>3</sub> bulk and nano particles using aqueous solution via visible light for degradation of dyes acid red88 and malachite green [40]. Acid red dye degradation was found 17.6% by bulk Li<sub>2</sub>MnO<sub>3</sub> and 40.9% by nano Li<sub>2</sub>MnO<sub>3</sub>. They have shown following mechanism of degradation using Li<sub>2</sub>MnO<sub>3</sub>: [40]





**Fig. 7** **a** XAS spectra of  $M_4$  edge for  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ]. XAS spectra of  $\text{RuO}_2$  and  $\text{Sr}_4\text{Ru}_2\text{O}_9$  used for reference of  $\text{Ru}^{+4}$  and  $\text{Ru}^{+5}$  valence states peaks. **b** Fitting of  $\text{Ru}$ —XAS spectra shows the percentage of  $\text{Ru}^{+4}$  and  $\text{Ru}^{+5}$  valence states. Circles show the experimental data and red line shows the final peak sum of fit on experimental data

It has been shown that cationic additive enhances the degradation capability of  $\text{Li}_2\text{MnO}_3$ . These cations make positive surface of  $\text{Li}_2\text{MnO}_3$  and prevent electron–hole recombination which help generation of  $\text{OH}$  on the  $\text{Li}_2\text{MnO}_3$  surface [40]. We have selected two different type

of dyes, (i) A cationic dye, Methylene Blue (MB) and (ii) an azo dye methyl orange (MO) for degradation capabilities of  $\text{Li}_2\text{MnO}_3$  and its Ru doped compositions. MB is used for printing, leather and in dyeing cotton and, causes various harmful effects such as eye burns, irritation to the skin and gastrointestinal tract [41]. MB is also regarded as significant threat due to its carcinogenic and mutagenic properties [42]. MB containing waste water from industry is essentially needed an efficient treatment technology which give ultimately clean water for safe disposal quickly. Methyl orange is used as an indicator for acid base titration.

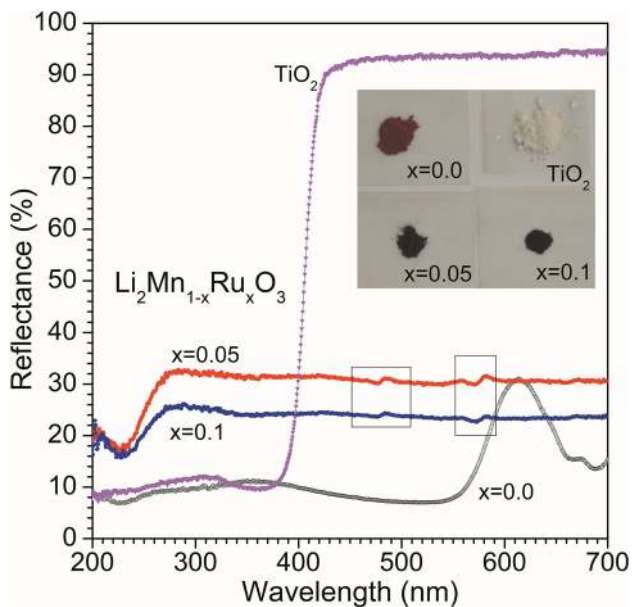
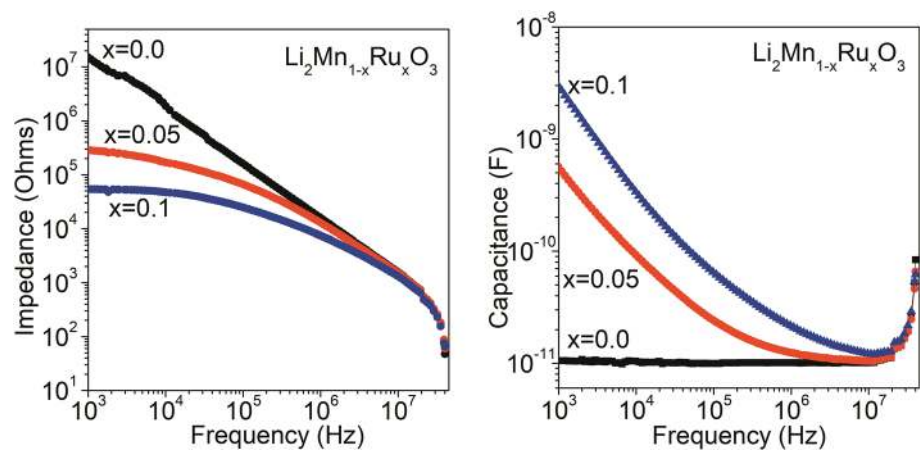
In Figure 11, we have plotted the absorption in the wavelength range 200–800 nm of (i) as prepared MO solution (ii) pH controlled (pH=6) MO solution and (iii) MO solution of pH6 mixed with  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  composition exposed up to 5 min in visible light. Methyl orange absorbs UV–vis light at  $\sim 270$  nm and  $\sim 465$  nm which corresponds to  $n\text{-}\pi^*$  transition. MO solution shows absorption peak  $\sim 465$  nm which shifts to  $\sim 507$  nm after adjusting the pH 6 of the MO solution. After 5 min of ultrasonication and exposure in visible light, MO solution with pH 6 is degraded and no peaks at  $\sim 465$  and  $\sim 507$  nm is visible.  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  composition degrades MO solution 100% in 5 min in the presence of nominal pH6. As prepared MO solution show no degradation either in sunlight or with ultrasonication (Table 3).

In Figure 12, we have plotted the absorption of the MB solution mixed with  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  composition varied time (b) 1 min (c) 2 min (d) 3 min exposure in visible light. Methylene blue show absorption band at high energy due to  $\pi\text{-}\pi^*$  transition of benzene ring while low energy band  $\sim 660\text{--}670$  nm corresponds to  $n\text{-}\pi^*$  transitions (where  $n$  is the free doublet on the nitrogen atom of  $\text{C}=\text{N}$  bond and free doublet of S atom on  $\text{S}=\text{C}$  bond). Insets show the zoomed plot in the wavelength range 400 to 800 nm for corresponding time exposure in visible light. After 1 min of exposure in visible light, MB peak ( $\lambda = 663$  nm) shifts to 619 nm and absorption is very much decreased. After 3 min exposure of visible light, MB is degraded. As prepared MB solution shows no degradation with ultrasonication (Table 4). We have also recorded the degradation using MB solutions (pH6) exposed in Tungston bulb light for 60 min each with (b)  $\text{Li}_2\text{MnO}_3$ , where Mn is present in +4 valence state (c)  $\text{LiMn}_2\text{O}_4$ , where Mn is present in +3 and +4 valence states and (d)  $\text{MnO}_2$ , where Mn is present in +4 valence state. We have found that there is no substantial degradation of MB solution with  $\text{Li}_2\text{MnO}_3$  and  $\text{LiMn}_2\text{O}_4$  while  $\text{MnO}_2$  degrades partially in 60 min.

In Figure 13, we show the efficiency for MB in presence of (i)  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$ , where Mn is present in mixed valence



**Fig. 8** **a** Impedance **b** capacitance versus frequency plots for  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.0, 0.05, 0.1$ ] compositions



**Fig. 9** UV-vis (DRS) spectra for  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.0, 0.05, 0.1$ ] compositions.  $\text{TiO}_2$  used as a reference

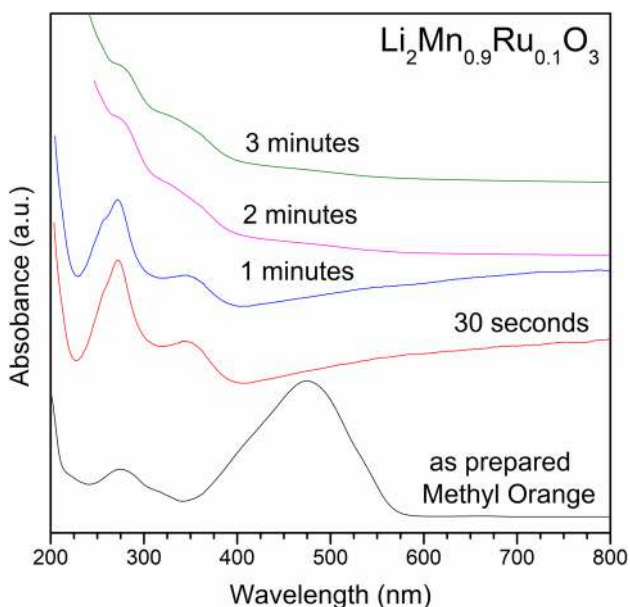
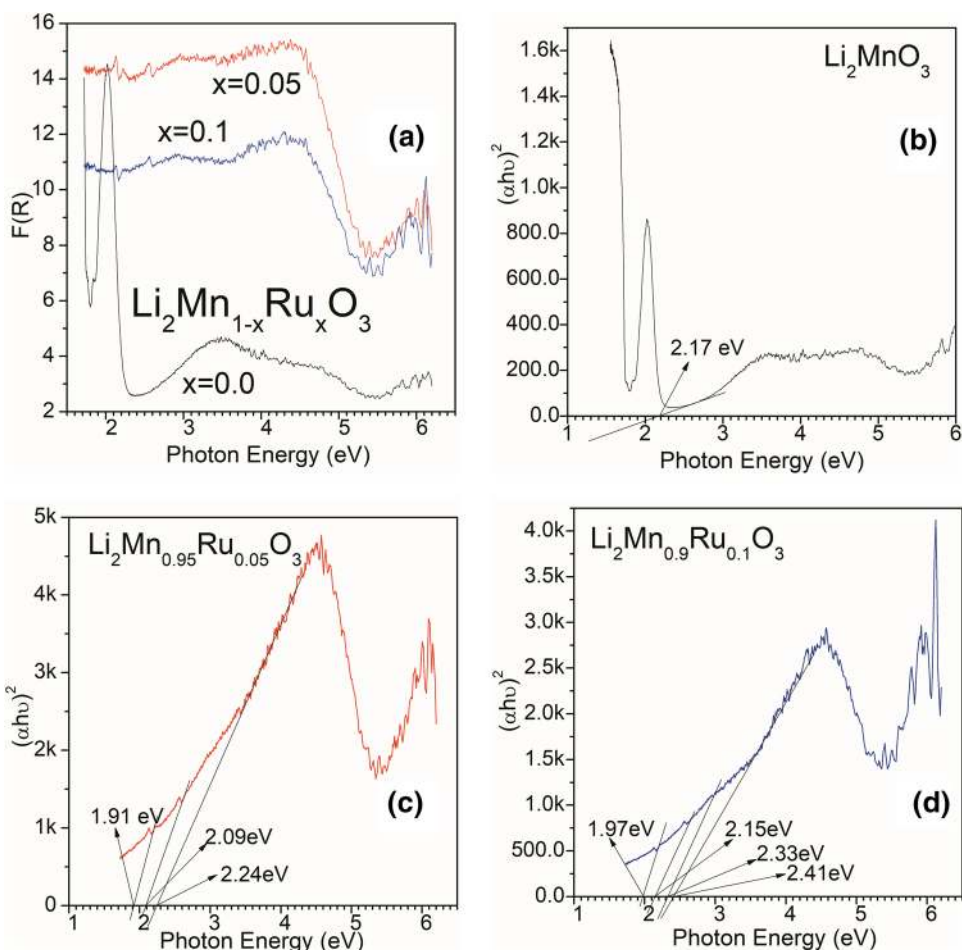
state +3 and +4, and Ru is in mixed valence state +4/+5 (ii)  $\text{Li}_2\text{MnO}_3$ , where Mn is present in +4 valence state and (iii)  $\text{LiMn}_2\text{O}_4$  where Mn is present in +3 and +4 valence states.  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  (Mixed valences containing oxide) shows very fast decomposition of Methylene blue at nominal pH 6, which was not observed with this efficiency earlier in this type of crystalline materials [40].

Synchrotron X-ray diffraction analysis and Raman spectroscopy measurements show the change in structure with the doping of Ru at Mn site in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ]. XRD studies show the change in lattice which suggest the presence of Ru with Mn in the lattice of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ] systems. XAS studies

show the presence of  $\text{Ru}^{+4}/\text{Ru}^{+5}$  and  $\text{Mn}^{+3}/\text{Mn}^{+4}$  redox couples in Ru doped materials. When  $\text{Ru}^{+4}$  doped at  $\text{Mn}^{+4}$  site, due to comparable redox potential of  $\text{Ru}^{+4}/\text{Ru}^{+5}$  (1.07 eV) with that of  $\text{Mn}^{+3}/\text{Mn}^{+4}$  (1.02 eV),  $\text{Ru}^{+4}$  (0.62 Å) converts into  $\text{Ru}^{+5}$  (0.565 Å) and for charge valence same amount of  $\text{Mn}^{+4}$  (0.53 Å) converts into  $\text{Mn}^{+3}$  (0.645 Å) [11, 15]. When  $\text{Ru}^{+4}$  doped at  $\text{Mn}^{+3}$  site in  $\text{LaMnO}_3$  then mixed valence is not observed as shown in Fig. 7 and it also show by patra et al. [21]. It has been shown earlier that  $\text{Mn}^{+3}$  (0.645 Å) (in octahedral coordinated configuration) has comparatively bigger radius than  $\text{Mn}^{+4}$  (0.53 Å) and it has an electron in  $e_g$  orbital. Due to one  $e_g$  electron,  $\text{Mn}^{+3}-\text{O}_6$  octahedral elongate in z axis direction and it brings distortion in lattice. Although, the presence of  $\text{Ru}^{+5}$  (0.565 Å) make up charge balance but due to size mismatch with  $\text{Mn}^{+3}$  (0.645 Å) could not stop distortion in lattice of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ]. Raman and IR spectroscopic studies show the evidence of lattice distortion by changing the peak position and splitting in Ru doped compositions.

Impedance has been observed  $10^2$  times less in  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  in comparison to that of  $\text{Li}_2\text{MnO}_3$  due to the bigger d orbitals of Ru in comparison to Mn and mixed valences  $\text{Ru}^{+4}/\text{Ru}^{+5}$  and  $\text{Mn}^{+3}/\text{Mn}^{+4}$ . Electrons can easily hop in Ru assisted environment in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  in comparison to  $\text{Li}_2\text{MnO}_3$ .  $\text{Mn}^{+3}$  contains 3 electrons in  $t_{2g}$  orbitals while 1 electron in  $e_g$  orbitals while  $\text{Mn}^{+4}$  contains only 3 electrons in  $t_{2g}$  orbitals.  $\text{Ru}^{+4}$  contains 2 paired and 2 unpaired electrons in  $t_{2g}$  orbitals while  $\text{Ru}^{+5}$  contains only 3 electrons in  $t_{2g}$  orbitals. One  $e_g$  electron of  $\text{Mn}^{+3}$  can hop to vacant  $e_g$  orbitals  $\text{Mn}^{+4}$  and  $\text{Ru}^{+5}$  in Ru doped  $\text{Li}_2\text{MnO}_3$  compositions. One  $e_g$  electron of  $\text{Mn}^{+3}$  and presence of 4d orbitals containing Ru modify the impedance and capacitance properties of Ru doped  $\text{Li}_2\text{MnO}_3$  compositions.

**Fig. 10** Band gap calculations using UV-vis (DRS) spectra for **a**  $F(R)$  for all the compositions **b**  $x=0.0$ , **c**  $x=0.05$  **d**  $x=0.1$  in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.0, 0.05, 0.1$ ] compositions



**Fig. 11** Absorbance spectra of the Methyl Orange solutions after reaction with  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  in the given exposure time of W bulb light. Please note disappearance of peak  $\sim 450$  nm on 30 s of exposure of W bulb light

Diffuse reflectance spectroscopic studies suggest the optical absorption in visible light in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.0, 0.05, 0.1$ ] systems. Band gap increases with the increase of Ru content while crystallite size decreased. In the crystalline environment of Ru and Mn in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ], Mn intersite and Ru intersite transitions using  $e_g - e_g, t_{2g} - e_g$  may become allowed by spin orbit coupling, lattice disorder/distortions and mixing of odd parity wave functions. Decreases in crystallite size of the compositions, Mn-Mn intersite, Ru-Mn intersite and spin orbit coupling are the main cause of enhanced band gap of  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  and  $\text{Li}_2\text{Mn}_{0.95}\text{Ru}_{0.05}\text{O}_3$  in comparison to  $\text{Li}_2\text{MnO}_3$ .

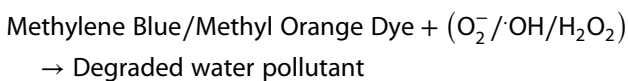
Presence of mixed valences  $\text{Ru}^{+4}/\text{Ru}^{+5}$  and  $\text{Mn}^{+3}/\text{Mn}^{+4}$  assist the process of degradation of MO and MB solutions with faster rate in comparison with  $\text{MnO}_2$ . Compounds  $\text{LaMn}_{1-x}\text{Ru}_x\text{O}_3$  degrades MO dye only at pH 2.5 and takes 15 min [21].  $\text{LaMn}_{1-x}\text{Ru}_x\text{O}_3$  shows the presence of only  $\text{Mn}^{+3}$  and  $\text{Ru}^{+4}$  valence states. Our results show the presence of redox couples  $\text{Mn}^{+3}-\text{Mn}^{+4}$  and  $\text{Ru}^{+4}-\text{Ru}^{+5}$  valence states in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ]. Multiple valence states enhance the process of degradation of 5 ml each of MO and MB dyes in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ]. 5 mg of

**Table 3** Degradation profile of Methyl Orange (MO) dye with  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  and  $\text{MnO}_2$  in different experimental conditions

Conditions for methyl orange (MO) degradation	Degradation time with compounds		
	$\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$	$\text{Li}_2\text{MnO}_3$	$\text{MnO}_2$
In the presence of sunlight (solution pH-6)	~5 min	~30 min	~30 min
In the presence of sunlight (as prepared solution)	No degradation in 1 h	No degradation in 1 h	No degradation in 1 h
Ultrasonicated in W bulb light (solution pH-6)	~3 min	~60 min	No degradation in 1 h
Without ultrasonication exposed in W bulb (solution pH-6)	~5 min	~60 min	
Ultrasonicated in W bulb (as prepared solution)	No Degradation in 1 h	No degradation in 1 h	
Ultrasonicated in dark (absence of light) solution pH-6	30 min	~60 min	

$\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  degrades 5 ml of MO (10 mg/L) up to 100% in 5 min and 5 ml of MB (10 mg/L) in 3 min at pH 6. 5 mg of  $\text{MnO}_2$  does not degrade 5 ml of MO (10 mg/L) in 60 min and 5 ml of MB (10 mg/L) in 60 min at pH 6 [Tables 3,4; Fig. 13]. 20 mg of flower like  $\text{Mn}_3\text{O}_4$  (where Mn in  $\text{Mn}^{+3}$  valence state) degrades 50 ml MB (10 mg/L) up to 80% in 180 min in presence of  $\text{H}_2\text{O}_2$  [8]. 100 mg nano wires of  $\text{MnO}_2$  (where Mn in  $\text{Mn}^{+4}$  valence state) degrades 200 ml MO (40 mg/L) up to 100% in 90 min [9].

Possible degradation mechanism can be summarised by following reactions as shown by Ranjeh et al.:



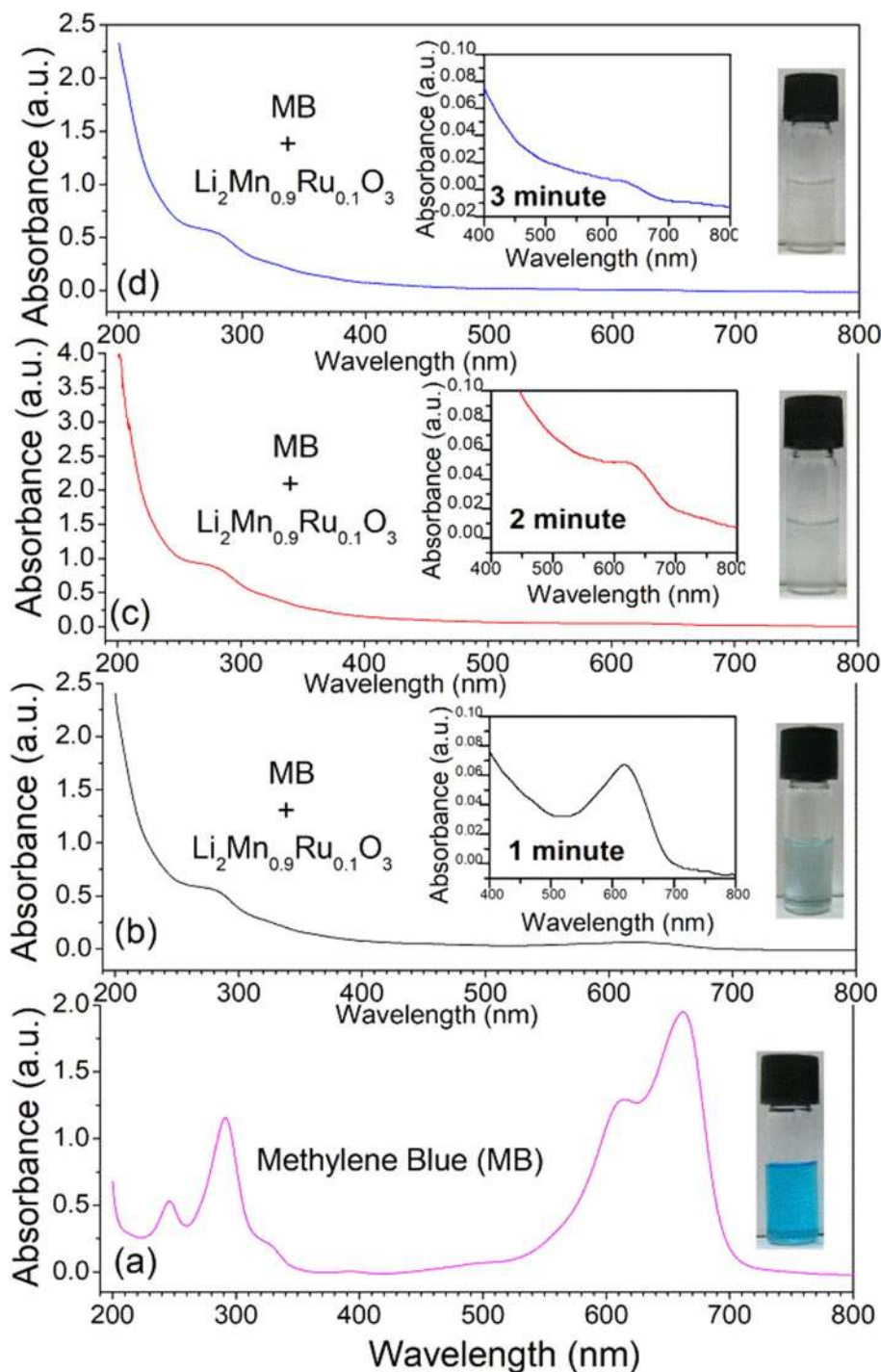
Presence of multiple valence states  $\text{Mn}^{+3}/\text{Mn}^{+4}$  and  $\text{Ru}^{+4}/\text{Ru}^{+5}$  create photo generated electrons and holes by transferring electrons from valence band to conduction band leaving holes in valence band. Electrons react with  $\text{O}_2$  and generate  $\text{O}_2^-$ .  $\text{O}_2^-$  further reacts with  $\text{H}^+$  ions and generates  $\text{H}_2\text{O}_2$ . Holes react with  $\text{OH}^-$  and generate  $\text{OH}^\cdot$  free radicals. So  $(\text{O}_2^-/\cdot\text{OH}/\text{H}_2\text{O}_2)$  react with MO, MB dyes solution and decolourize. If  $\text{H}^+$  ions are not present then these compounds does not degrade MO and MB dyes. In presence of  $\text{H}^+$  and visible light,  $\text{Li}_2\text{MnO}_3$  does not degrade MO and MB dyes up to 24 h.  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ] degrades MO and MB dyes very fast in presence of  $\text{H}^+$  (pH 6) and W bulb/sunlight due to presence of mixed

valence states  $\text{Mn}^{+3}/\text{Mn}^{+4}$  and  $\text{Ru}^{+4}/\text{Ru}^{+5}$ . These materials degrades MB dye very fast in compare to other Mn based systems  $\text{Mn}_3\text{O}_4$ ,  $\text{MnO}_2$  and nano  $\text{Li}_2\text{MnO}_3$  [8, 9, 43]. Easy material preparation of  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  and reusability of these materials is an advantage over other known  $\text{TiO}_2$  based catalysts.

## 4 Conclusions

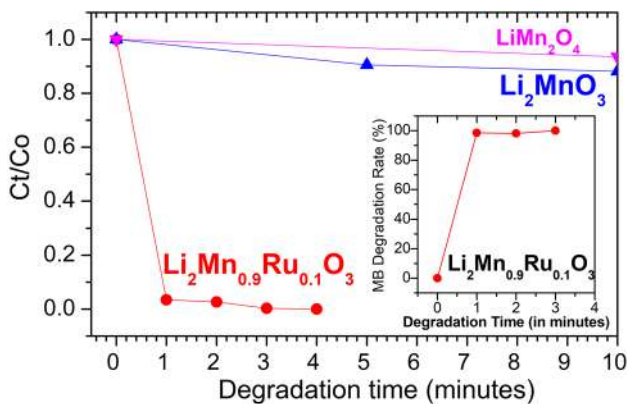
We have optimized the synthesis conditions for inducing the redox interaction between  $\text{Ru}^{+4}$  and  $\text{Mn}^{+4}$  which further results  $\text{Mn}^{+3}-\text{Mn}^{+4}$  and  $\text{Ru}^{+4}-\text{Ru}^{+5}$  valence states in  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  [ $x=0.05, 0.1$ ]. These redox couples in presence of  $\text{H}^+$  ions and W bulb/sunlight enhances the dye degradation process in Ru doped  $\text{Li}_2\text{MnO}_3$ .  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  composition (i) shows  $10^2$  times decreased impedance and (ii) quickly degrades methyl orange and methylene blue solutions at pH 6 which shows its capability as effective dye degradation material which otherwise was neither found in other Mn based systems nor in these types of monoclinic crystals. These Ru doped  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  materials can be use for fast decomposition of other organic dyes which are harmful for environment. Fast degradation of dyes, easy material preparation and reusability can make these materials first choice in industry over other known  $\text{TiO}_2$  based catalysts.

**Fig. 12** Absorption spectra of the MB solutions during the decomposition reaction catalyzed by  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$  in the exposure of visible light for (b) 1 (c) 2 and (d) 3 min



**Table 4** Degradation profile of methylene blue (MB) dye with  $\text{Li}_2\text{Mn}_{1-x}\text{Ru}_x\text{O}_3$  and  $\text{MnO}_2$  in different experimental conditions

Conditions for Methylene Blue (MB) degradation	Degradation time with compounds		
	$\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$	$\text{Li}_2\text{MnO}_3$	$\text{MnO}_2$
In the presence of sunlight (solution pH-6)	~60 min	No degradation in 1 h	No degradation in 1 h
In the presence of sunlight (as prepared solution)	Partial degradation in 1 h	No degradation in 1 h	
Ultrasonicated in W bulb light (solution pH-6)	~3 min	No degradation in 2 h	2 h
Without ultrasonication exposed in W bulb light (solution pH-6)	~60 min		No complete degradation in 2 h
Ultrasonicated in W bulb light (as prepared solution)	No degradation in 2 h		
Ultrasonicated in dark (absence of light) solution pH-6	~30 min		2 h

**Fig. 13** Degradation rate of MB solutions [5 ml of 10 mg/L concentration] under visible light irradiation with 5 mg  $\text{Li}_2\text{Mn}_{0.9}\text{Ru}_{0.1}\text{O}_3$ ,  $\text{Li}_2\text{MnO}_3$  and  $\text{LiMn}_2\text{O}_4$  each

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### Compliance with ethical standards

**Conflict of interest** The authors declare "There are no conflicts to declare".

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