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Shock-wave-induced luminescence of phosphor powders

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ABSTRACT

Luminescence generated by a plate-impact-induced shock wave has been detected from a Ce-doped phosphor powder, Ce^{3+}:$Y_3Al_5O_{12}$. The observed luminescence spectrum shows two strong bands in the visible region: one at ~410 nm and the other at ~530 nm. The second band is very similar to the well-known luminescence band of Ce:YAG corresponding to the $T_{2g} \rightarrow {}^2F$ transition, but the first band is hardly observed in the photoluminescence spectrum. One possible mechanism for the first band is the radiative transition from the higher energy excited level of Ce^{3+} to the ground level, namely $E_g \rightarrow {}^2F$.

1. Introduction

Various kinds of luminous phenomena are observed when shock waves propagate in material media. Thermal radiation of up to several thousand K is often observed because of the fast adiabatic nature of shock compression, which can be measured to determine shock temperatures as effective emission temperatures by fitting the thermal radiation spectrum to a blackbody or greybody radiation spectrum. When a shock wave propagates in a powdered material, intense interparticle collisions occur because the powder particles are accelerated to extremely high velocities on the order of km/s, which can induce hot spots and surface jetting [1]. Atomic and molecular emission can also be observed during such events, and these emissions may be categorized as triboluminescence (TL) or mechanoluminescence (ML): the emission of light caused by the application of mechanical stress [2]. TL has been known for a very long time and generally recognized as being the same as normal luminescence such as photoluminescence (PL), but some aspects of TL still remains unclear [3,4]. The investigation of TL, in most cases, has been carried out by using mechanical rubbing or fracture as the TL generation methods. A TL spectrum induced by a shock wave was first reported by Tsuboi et al. for an organic crystal sample using laser-driven shock waves. It was introduced as a novel method to excite TL and monitor the dynamic behavior by taking the advantage of shock wave compression where the initiation of the applied stress is clearly specified in time-resolved measurements [5]. Investigations of luminescence emission by shock waves is very rare [5,6] and still at its early stage.

Shock compression of powdered materials has been the subject of interest for its unique shock–compression response such as shock dissipation property and shock-induced chemical reactions [7,8]. Shock-wave-induced luminescence study would provide important information to better understand the unique shock–compression response because the luminescence excitation mechanism is strongly related to the interaction between powder particles, where various events such as surface jetting, ejection and bombardment of charged particles, etc. take place. It could also provide new insight into phenomena of triboluminescence. In this letter, we report luminescence emitted from a Ce-doped ceramic powder (Ce^{3+}:YAG) under shock loading, which appears quite different from the PL spectrum. The observed luminescence spectrum shows a relatively strong band which does not exist in the PL spectrum. The possible origin of this unknown luminescence band is proposed based on the discussion of the comparison between the unusual luminescence observed under shock loading and the usual PL spectra.

2. Experimental

A schematic of the experimental set-up employed in this study is shown in Figure 1. Impact experiments were conducted using a propellant gun with a 30 mm inner-bore diameter. The granular powder sample used was a well-known phosphor, Ce^{3+}:YAG (NICHIA corporation, <5 μm). An unpressed powder sample with a thickness of 0.2–0.4 mm and a diameter of ~15 mm was sandwiched between a 1-mm-thick stainless steel (SUS304) base plate and a 5-mm-thick LiF single crystal window. The sample density was ~1.5 g/cm^3. In order to generate a shock wave, a 3-mm-thick stainless steel impactor was accelerated by the propellant gun and struck the base plate at the maximum speed of 1.5–1.6 km/s. An

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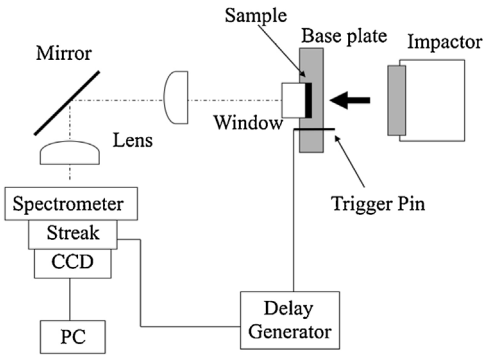

Figure 1. Schematic of time-resolved luminescence spectrometer to measure shock-wave-induced luminescence emission. The luminescence is observed when the shock wave reaches the sample/window interface.

electrical self-shorting pin on the base plate was used to obtain an electric trigger pulse for the streak camera. Luminescence emission was observed when the shock wave reached the sample/window interface. The shock wave reverberates between the base plate and the window, and the sample pressure increases until the equilibrium pressure is reached. The luminescence was collected by an optical fiber and introduced into a spectrometer (Hamamatsu C5094SK, 150 lines/mm). Dispersed light was then transmitted to a streak camera (Hamamatsu C7700, 1.03 μs window) and recorded by a charge-coupled device camera (Hamamatsu C4742-95). One pixel on the CCD camera corresponds to 0.97 ns in time and 0.285 nm in wavelength. The beam divergence at the CCD camera is ~15 pixels in time and ~13 pixels in wavelength, which roughly correspond to the resolution of this system. Calibration of wavelength was done using atomic lines of a mercury lamp. Shock pressures of the powder (first shock pressures) were estimated using the shock velocity of the sample measured previously [9]. The high-speed plate impact method was used for the first time in this work to induce triboluminescence. Photoluminescence excitation (PLE) spectra and PL emission spectra of the ambient powder sample were also measured using a fluorescence spectrophotometer (Hitachi F4500). The Hugoniots used were $U_s = 4.58 + 1.49U_p$ for SUS304 and $U_s = 5.15 + 1.35U_p$ for LiF window [10].

3. Results and discussion

A representative streak image of luminescence emission observed when the shock wave struck the Ce^{3+}:YAG powder and the corresponding luminescence spectrum are shown in Figure 2. In Figure 2(a), the ordinate represents time, which runs from top to bottom, with the full scale corresponding to 1.03 μs. The abscissa represents wavelength, which increases toward the right, with the full scale corresponding to 356.4 nm. Figure 2(b) shows a luminescence spectrum extracted from (a) by taking the horizontal cross section. A PL spectrum measured under ambient conditions is also presented for comparison, which was measured using the same time-resolved luminescence spectrometer (Figure 1) with an excitation light source of 355 nm laser pulse (the third harmonic of nanosecond pulsed Nd:YAG laser). The shock-wave-induced luminescence spectrum in Figure 2(b) is very broad covering the whole visible region because it contains a thermal radiation component resulting from adiabatic compression of residual gas in the powder sample [9]. Two bands are clearly seen in the spectrum: one at ~410 nm and the other at ~530 nm. The 530 nm band appears very similar to that of the PL spectrum, but the 410 nm band does not exist in the PL spectrum. In order to obtain clearer spectra by eliminating the thermal radiation component, we tried to remove the residual gas from the powder sample by adding a small amount

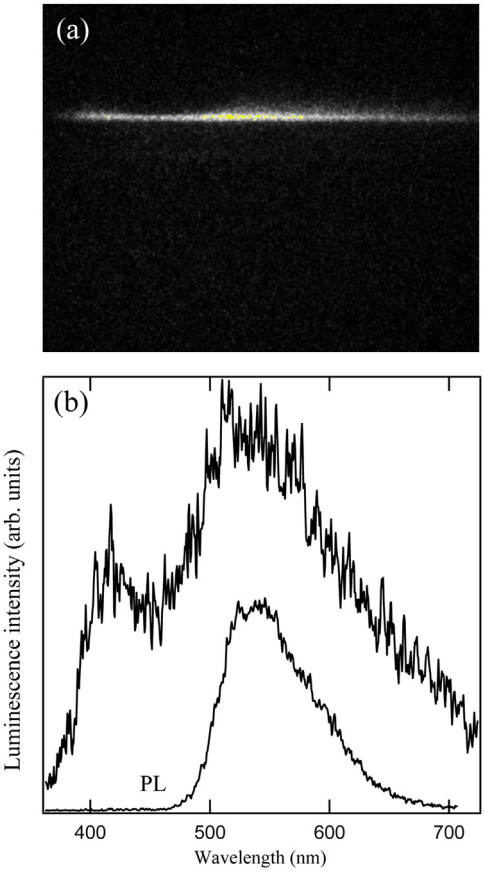

Figure 2. (a) A streak image of luminescence emission from Ce^{3+}:YAG powder under shock compression. The ordinate represents time with the full scale corresponding to 1.03 μs and the abscissa represents wavelength with the full scale corresponding to 356.4 nm. (b) The luminescence spectrum extracted from the streak image (a) by taking the horizontal cross section at the instant of the shock wave reached at the sample/window interface (~0.33 μs). A PL spectrum with 355 nm excitation is shown for comparison. The abscissa of (a) is the same as that of (b). The impact velocity (V_{imp}) was 1.560 km/s and the shock pressure of the sample was ~5.1 GPa.

of nonreactive liquid to fill the voids in the powder, although it changes the hydrodynamics. We have tried several liquids and found acetone worked well. The results are shown in Figure 3, where shock-wave-induced luminescence spectrum and the ambient PL spectrum for the acetone-containing powder sample are presented. Compared to Figure 2(b), the thermal component is significantly reduced and the two bands are better resolved. The peak positions of the two bands are not changed. We have confirmed that the luminescence intensity decreased for weaker shocks and also that no luminescence emission was observed for non-doped YAG powder.

The ground electronic configuration of Ce^{3+} ion is $4f^1$ which splits into two spin-orbit states, $^2F_{5/2}$ and $^2F_{7/2}$, $^2F_{5/2}$ being the ground electronic state which is lower in energy than $^2F_{7/2}$ by ~0.19 eV [11]. The excited electronic configuration, $5d^1$, splits into T_{2g} and E_g levels under cubic crystal field. Figure 4 shows the PLE spectrum monitored at 540 nm. Two intense absorption bands at ~340 nm and ~453 nm correspond to $^2F \rightarrow E_g$ and $^2F \rightarrow T_{2g}$, respectively. A weak absorption band is also observable at ~233 nm, which may actually consist of two absorption bands as reported in Ref. [12]. Figure 5 shows a PL emission spectrum with 233 nm excitation measured by the fluorescence spectrophotometer. A very weak emission at 350–430 nm is observed. This emission was also detected with 330 nm excitation, but the intensity was much lower. A very similar emission at the similar wavelength region is reported for polycrystalline Ce^{3+}:$CaGa_2S_4$ measured at a low temperature