applied optics

Disparity between online and offline tests in accelerated aging tests of LED lamps under electric stress

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Received 15 July 2016; revised 16 August 2016; accepted 16 August 2016; posted 17 August 2016 (Doc. ID 270656); published 13 September 2016

The accelerated aging tests under electric stress for one type of LED lamp are conducted, and the differences between online and offline tests of the degradation of luminous flux are studied in this paper. The transformation of the two test modes is achieved with an adjustable AC voltage stabilized power source. Experimental results show that the exponential fitting of the luminous flux degradation in online tests possesses a higher fitting degree for most lamps, and the degradation rate of the luminous flux by online tests is always lower than that by offline tests. Bayes estimation and Weibull distribution are used to calculate the failure probabilities under the accelerated voltages, and then the reliability of the lamps under rated voltage of 220 V is estimated by use of the inverse power law model. Results show that the relative error of the lifetime estimation by offline tests increases as the failure probability decreases, and it cannot be neglected when the failure probability is less than 1%. The relative errors of lifetime estimation are 7.9%, 5.8%, 4.2%, and 3.5%, at the failure probabilities of 0.1%, 1%, 5%, and 10%, respectively.

OCIS codes: (000.2190) Experimental physics; (120.4800) Optical standards and testing; (230.3670) Light-emitting diodes.

http://dx.doi.org/10.1364/AO.55.007511

1. INTRODUCTION

As a new generation of lighting source, the light-emitting diode (LED) has been widely applied in various lighting fields [1–3]. How to estimate the lifetime and reliability of LED products has always been a hotspot of research. Currently, LED accelerated aging tests are mainly based on several standards, such as IES LM-79-08, LM-80-08, TM-21-11, and so on [4–8]. The operation is recommended at three case temperatures with aging time of at least 6000 h for each. The optical parameters are measured under working temperature of 25°C and rated current (voltage). This method is an offline test, which is the common way to acquire lifetime and reliability in accelerated aging tests at present [9–14]. Cai *et al.* [15] indicated that in order to obtain the optical parameters accurately, 2 h were required for the sample cooling down and preheating. The measurement of optical parameters under accelerated states is an online test, which possesses the advantage of continuity of aging procedure with less testing time. Narendran *et al.* [16,17] and Chen *et al.* [18] proposed online test approaches by using life-test chamber and heat-resistant optical cable, respectively. Ke *et al.* [19] experimentally investigated the disparities between the two modes in luminous flux degradation and chromaticity coordinate shift in an accelerated aging test under thermal stress.

For indoor LED products, it is an effective method to estimate the lifetime and reliability by loading higher levels than normal electric stresses. Meneghesso *et al.* [20] investigated the degradation mechanisms of GaN-based LEDs under the elevated currents of 50 and 100 mA. Trevisanello *et al.* [21] took the elevated currents to study the degradation behaviors of two families of 1 W LEDs and then analyzed the failure mechanisms. Levada *et al.* [22] arranged accelerated aging tests for two different packing GaN-based LEDs under the DC currents of 50 and 100 mA, and applied the Weibull statistical model to estimate the lifetime at 20 mA. Wang and Chu [23] reported accelerated degradation tests for LED-based light bars under high current and thermal stresses, and the deduction of the failure time of the light bar under working conditions. All the optical parameters mentioned above were obtained by offline tests.

In the accelerated aging tests under electric stresses, the inverse power law model is always used to describe the degradation behavior of light output and to deduce the lifetime of LED products. It is worth noting that the electric stress in the model is the one at accelerated conditions, and so the degradation of light output should be acquired by an online test. However, in the accelerated aging test of LED products under electric stress, how much the disparity is between online test and offline test in the estimation of lifetime and reliability of LED products has not been studied and reported yet, to the best of our knowledge.

In this paper, two cases of accelerated aging tests under electric stresses for a type of LED lamps are conducted, with one test at voltage of 260 V and another at 300 V. The online and offline tests are achieved with an adjustable AC voltage stabilized power source. The acquired luminous fluxes for each sample are fitted by the exponential decay law to obtain the correspondent accelerated lifetime and the degradation rate. Bayes estimation is used to give the cumulative failure probability of each lamp, and the Weibull distribution of failure probability for the lamps is obtained by the least square method. The reliability of the lamps under a rated voltage of 220 V is estimated by use of the inverse power law model. The comparison between online tests and offline tests is given.

2. THEORETICAL ANALYSIS

A. Exponential Decay Law and the Inverse Power Law Model

During the process-of-aging test, the luminous flux of LED lamp decreases over time according to the exponential decay law [8,14]:

$$\Phi = B \times e^{-\alpha t}, \tag{1}$$

where Φ is the luminous flux of the LED lamp, B is the prefactor, α is the degradation rate, and t is the aging time in hours. The normalized Φ is known as the lumen maintenance.

The lifetime of LED lamps under electric stress satisfies the inverse power law model [22]:

$$L = AU^{-n}, \tag{2}$$

where L is the lifetime, U is the accelerated voltage, A is a constant, and n is a constant about the structure and material of the LED lamp. The lifetime of $L_{70\%}$ is used in this research, which is defined as the time when the luminous flux degrades to 70% of its initial value [24]:

$$L = L_{70\%} = -\frac{\ln(0.7)}{\alpha}. \tag{3}$$

According to Eqs. (2) and (3), the degradation rate can be calculated:

$$\alpha = -\frac{\ln(0.7)}{AU^{-n}}. \tag{4}$$

As can be seen, the luminous flux degradation rate of α is related to the accelerated voltage of U, and so the optical parameters should be acquired by an online test.

B. Bayes Estimation

For the aging test of a small number of samples, Bayes estimation [25–27] is used to acquire the cumulative failure probability of each lamp. Suppose the number of the samples is l for one group, and the cumulative failure probability of the i-th failure lamp is F_i. The hierarchical prior density function of $\pi(F_i)$ is expressed as follows:

$$\pi(F_i) = \iint_D \pi(F_i|a, b)\pi(a, b)\mathrm{d}a\mathrm{d}b, \qquad i = 1, 2, \ldots l, \tag{5}$$

where a and b are hyperparameters, the range $D = \{(a, b):0 < a < 1, 1 < b < c, a, b \in R\}$, c is a constant with $c > 1$, $\pi(a, b)$ is the prior distribution of two hyperparameters of a and b, and $\pi(F_i|a, b)$ is the prior distribution of F_i which meets the beta distribution. Their expressions are as follows:

$$\begin{cases} \pi(a, b) = \frac{1}{c-1} \\ \pi(F_i|a, b) = \frac{F_i^{a-1}(1-F_i)^{b-1}}{B(a,b)}, \end{cases} \tag{6}$$

where $B(a, b) = \int_0^1 t^{a-1}(1-t)^{b-1}\mathrm{d}t$. The hierarchical posterior density of F_i can be calculated by the sample information together with a priori information:

$$h(F_i|r_i) = \frac{L(r_i|F_i)\pi(F_i)}{\int_0^1 L(r_i|F_i)\pi(F_i)\mathrm{d}F_i}, \tag{7}$$

where r_i represents the number of cumulative failure samples at the i-th failure time and $L(r_i|F_i)$ is the likelihood function of samples. The Bayes estimation of failure probability denoted by $\hat{F}_{iB}$ can be calculated by

$$\hat{F}_{iB} = \int_0^1 h(F_i|r_i)F_i\mathrm{d}F_i. \tag{8}$$

C. Weibull Distribution

The failure probability of LED lamps over time is consistent with two-parameter Weibull distribution [22,28,29]:

$$F_j(t) = 1 - e^{-\left(\frac{t}{\eta_j}\right)^{m_j}}, \tag{9}$$

where j represents the j-th stress, $F_j(t)$ is the failure probability, m_j represents the so-called shape parameter, and η_j represents the characteristic lifetime. $F_j(t)$ is calculated by

$$F_j(t) = \hat{F}_{iB}. \tag{10}$$

Then the shape parameter and the characteristic parameter in Eq. (9) can be obtained by the use of the least square method.

D. Derivation of Lifetime Under Rated Voltage

Suppose the characteristic lifetime is η_1 under elevated voltage of U_1, and it is η_2 under elevated voltage of U_2. According to Eq. (2), the constant of n can be obtained by

$$n = -\frac{\ln(\eta_1/\eta_2)}{\ln(U_1/U_2)}. \tag{11}$$

The characteristic lifetime of η_0 under the rated voltage of U_0 is given by

$$\eta_0 = \eta_1\left(\frac{U_0}{U_1}\right)^{-n}. \tag{12}$$

3. EXPERIMENTS

The test samples, which are denoted by SJ, are LED lamps manufactured by the Sanjin Company. The electric power is 5 W, the rated voltage is 220 V, and the chromatic temperature

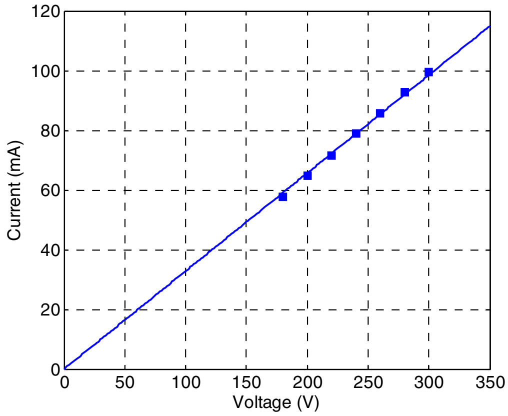

Fig. 1. Relationship between the voltage and current for one sample.

is 3000 K. Figure 1 shows the relationship between the voltage and current for one sample. As the voltage increases, the current increases linearly. Referring to the selection of the accelerated stresses in Ref. [23], we adopt 260 V and 300 V as the electric accelerated stresses in these tests. Sixteen lamps from the same batch are selected and divided into two groups. As shown in Table 1, group 1 contains eight LED lamps that are under the accelerated voltage $U_1 = 260$ V for 1584 h, and group 2 contains eight LED lamps that are under the accelerated voltage $U_2 = 300$ V for 1080 h. The voltages are supplied by an AC voltage stabilized power source, as shown in Fig. 2. Before the accelerated aging tests, samples have experienced environmental tests of vibration, current, and high-low temperature.

The measurement equipment, which consists of an integrating sphere of 1.5 m and an adjustable AC voltage stabilized power source, is shown in Fig. 3. There is a standard lamp holder E27 in the center of the integrating sphere, and the lamp holder is connected with the power source. The optical parameters are measured every 72 h or 96 h. During the testing process, the measurement conditions can be changed by adjusting the power source. When the voltage is set as the accelerated voltage, the optical parameters under accelerated condition can be obtained, which is the online test. When the voltage is set as the rated voltage, the optical parameters under working conditions can be obtained, which is the offline test. In this research, the samples must be lighted for at least 30 min to reach their stable condition before the measurement starting. It is noted that the online test mentioned in this research is not a real online test but a "pseudoonline" test. The only difference between the online and offline test here is the voltage adopted in measurements.

Table 1. Conditions of the Sample Groups of Accelerated Aging Tests

	Number of Samples	Accelerated Aging Voltage (V)	Testing Time (h)
Group 1	8	260	1584
Group 2	8	300	1080

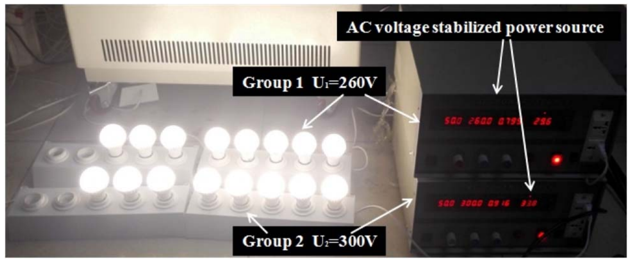

Fig. 2. Accelerated aging tests under 260 V and 300 V.

Fig. 3. Measurement equipment of optical parameters.

4. RESULTS AND ANALYSIS

A. Degradation of the Luminous Flux

Figure 4 shows the degradations of the lumen maintenance over aging time for the samples in group 1 (a) from online tests and (b) from offline tests. Figure 5 shows the results for the samples

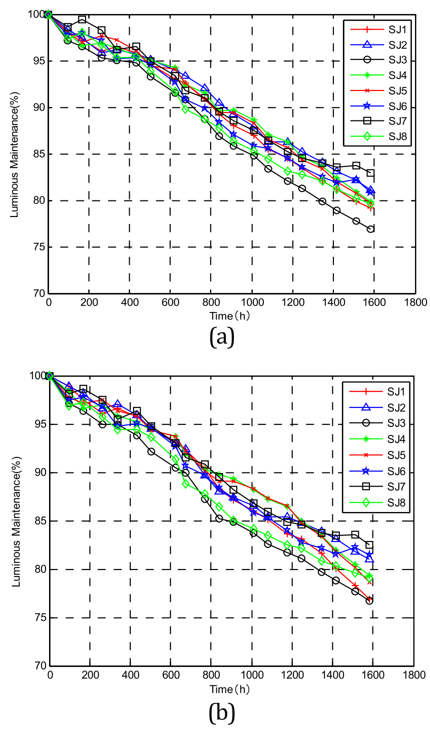

Fig. 4. Luminous flux degradation over time under 260 V. (a) Online tests; (b) offline tests.

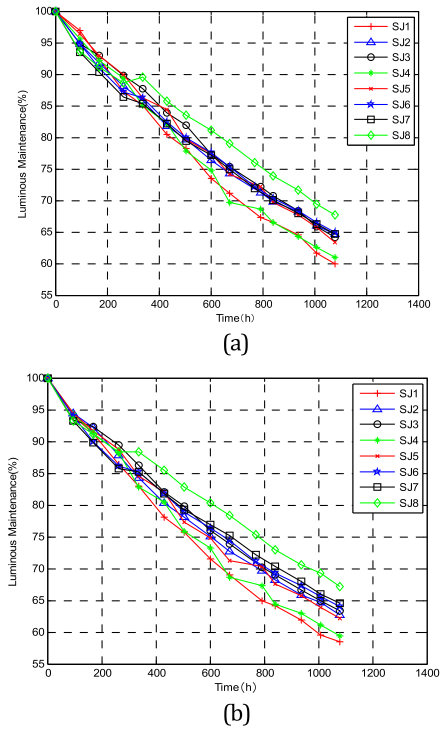

Fig. 5. Luminous flux degradation over time under 300 V. (a) Online tests; (b) offline tests.

in group 2. The lumen maintenance of each lamp is fitted according to Eq. (1). Table 2 lists the degradation rates of α and the root mean squared error (RMSE) of the fittings for the two groups.

It can be seen that the degradation rate of the lumen maintenance increases with the increase of accelerated voltage. In online tests, the value of α is in a range from 3.59E – 4 to 4.85E – 4 under the accelerated voltage of 300 V, and it is in a range from 1.26E – 4 to 1.65E – 4 under the accelerated voltage of 260 V. In offline tests, the value of α is in a range from 3.70E – 4 to 5.27E – 4 under the accelerated voltage of 300 V, and it is in a range from 1.34E – 4 to 1.59E – 4 under the accelerated voltage of 260 V. For the same sample, the values of α from online tests are always lower than those from offline tests for the two groups of accelerated aging tests. The biggest difference of α is 6.3% of sample 1 for group 1, and it is 8.8% of sample 5 for group 2. It can be seen that most of the RMSEs in online tests are lower than those in offline tests, except for three samples of 3, 4, and 7 in group 1. The exponential fitting of the luminous flux degradation in online tests possesses a higher fitting degree than that in offline tests.

Table 2. Degradation Rate α and RMSE of Fitting

		Online Tests		Offline Tests	
Testing Voltage	No.	α	RMSE	α	RMSE
260 V	1	1.42E – 4	9.31E – 3	1.51E – 4	1.18E – 2
	2	1.27E – 4	8.15E – 3	1.34E – 4	8.41E – 3
	3	1.65E – 4	7.64E – 3	1.71E – 4	6.84E – 3
	4	1.31E – 4	9.67E – 3	1.34E – 4	8.62E – 3
	5	1.33E – 4	1.02E – 2	1.35E – 4	1.04E – 2
	6	1.40E – 4	7.71E – 3	1.41E – 4	8.77E – 3
	7	1.26E – 4	9.53E – 3	1.29E – 4	8.57E – 3
	8	1.50E – 4	7.62E – 3	1.59E – 4	9.26E – 3
300 V	1	4.85E – 4	8.05E – 3	5.27E – 4	1.10E – 2
	2	4.24E – 4	1.11E – 2	4.53E – 4	1.22E – 2
	3	4.12E – 4	5.65E – 3	4.37E – 4	9.51E – 3
	4	4.76E – 4	1.06E – 2	5.06E – 4	1.22E – 2
	5	4.22E – 4	6.65E – 3	4.59E – 4	1.22E – 2
	6	4.15E – 4	1.26E – 2	4.33E – 4	1.62E – 2
	7	4.22E – 4	1.67E – 2	4.23E – 4	1.92E – 2
	8	3.59E – 4	1.46E – 2	3.70E – 4	1.47E – 2

B. Analysis of Working Lifetime

According to Eq. (3) and the values of α listed in Table 2, the lifetimes of each sample under different stresses are calculated. Lifetimes of samples for each group are arranged from small to large, and then the cumulative failure probability of each lamp is calculated by Bayes estimation. Table 3 lists the results of online tests and Table 4 lists those of offline tests, where $\tau_{260\,\text{V}}$ and $\tau_{300\,\text{V}}$ represent the lifetimes $L_{70\%}$ under 260 V and 300 V, respectively, and $\hat{F}_{iB}(\%)$ represents the cumulative failure probability by Bayes estimation. Figure 6 shows the curves of the cumulative failure probability with respect to the lifetime for two groups. It can be seen that the variations

Table 3. Lifetimes and Cumulative Failure Probabilities of Online Tests

No.	1	2	3	4	5	6	7	8
$\tau_{260\,\text{V}}$ (h)	2166	2383	2513	2553	2676	2731	2816	2836
$\tau_{300\,\text{V}}$ (h)	735	749	841	845	845	860	865	992
$\hat{F}_{iB}$ (%)	13.7	22.8	32.0	41.1	50.3	59.4	68.6	77.7

Table 4. Lifetimes and Cumulative Failure Probabilities of Offline Tests

No.	1	2	3	4	5	6	7	8
$\tau_{260\,\text{V}}$ (h)	2090	2244	2360	2529	2638	2661	2668	2771
$\tau_{300\,\text{V}}$	667	705	777	787	815	824	843	964
$\hat{F}_{iB}$ (%)	13.7	22.8	32.0	41.1	50.3	59.4	68.6	77.7

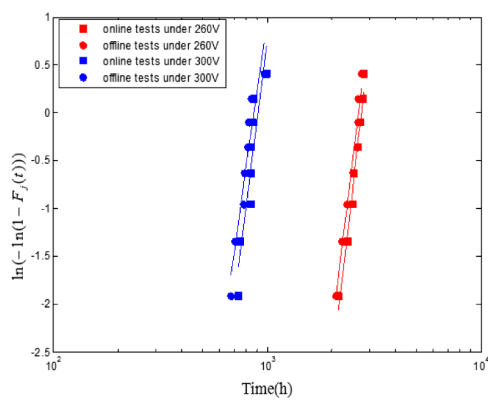

Fig. 6. Relationship between the failure probability and the lifetime.

Table 5. η_j and m_j of Online and Offline Tests

	Online Tests		Offline Tests	
	Group 1	Group 2	Group 1	Group 2
η_j (h)	2763	906	2682	867
m_j	8.456	7.723	7.789	6.864

of $\ln(-\ln(1 - F_j(t)))$ over $\ln(t)$ are in a good linearity for both online tests and offline tests. The changing trends of the four curves are similar, which accord with the Weibull distribution given by Eq. (9). Least square method is used to fit the failure probability with respect to the lifetime to obtain characteristic lifetimes of η_j and the shape parameters of m_j in Weibull distribution under different stresses. The results are listed in Table 5. It can be seen that the characteristic lifetimes acquired by online tests are larger than those by offline tests for both groups.

With Eq. (11) and the characteristic lifetimes of the two groups listed in Table 5, the constant of n in Eq. (2) is calculated, and then the characteristic lifetime of η_0 under the rated voltage of 220 V is obtained by Eq. (12). The characteristic lifetime of η_0 is 10,155 h for online tests and it is 10,023 h for offline tests.

C. Reliability Analysis

We estimate the lifetimes of the eight lamps of group 1 at the voltage of 220 V according to the Weibull distribution, with η_0 and m_1 given above. Figure 7(a) shows the failure probability distributions as a function of aging time for online and offline tests. The part of failure probability less than 10% is marked by a red dotted line, and the partial enlarged view is shown in Fig. 7(b). It can be seen that at the failure probability of 0.1%, 1%, 5%, and 10%, the lifetime is, respectively, 4486, 5894, 7145, and 7781 h for online tests, and it is, respectively, 4130, 5550, 6845, and 7508 h for offline tests.

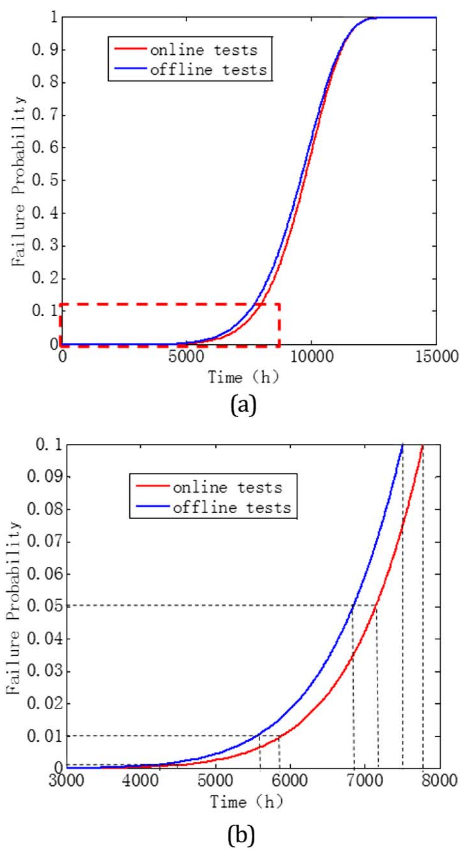

Fig. 7. (a) Failure probability distributions of online and offline tests and (b) partial enlarged view of the part marked in red dotted line.

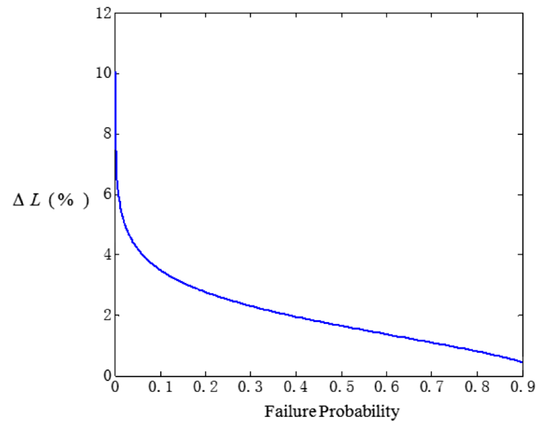

Fig. 8. Relative error of offline test.

The relative error of the lifetime in offline test ΔL is defined as

$$\Delta L = \frac{L_{\text{online}} - L_{\text{offline}}}{L_{\text{online}}} \times 100\%, \tag{13}$$

where L_{online} is the lifetime obtained in the online test, and L_{offline} is the lifetime obtained in the offline test. At the failure probabilities of 0.1%, 1%, 5%, and 10%, the relative errors of the lifetimes in the offline test are 7.9%, 5.8%, 4.2%, and 3.5%, respectively. Figure 8 shows the relative error of the lifetime as a function of the failure probability.

5. CONCLUSIONS

Accelerated aging tests of one type of LED lamps under electric stress are conducted to investigate the influence of the measurement conditions (online or offline tests) on lifetime and reliability prediction. Using the adjustable AC voltage stabilized power source connected with a standard lamp holder E27 in the center of an integrating sphere, the online and offline measurement conditions can be simulated.

The experimental results indicate that the exponential fitting of the luminous flux degradation in online tests possesses a higher fitting degree in most cases, and the degradation rates acquired in online tests are always lower than those acquired in offline tests. This indicates that the lifetime prediction in offline tests is always underestimated. The reliability of the lamps is obtained by using Bayes estimation and Weibull distribution. It is shown that as the failure probability decreases, the relative error of the lifetime by the offline test increases. The relative errors of lifetimes are 7.9%, 5.8%, 4.2%, and 3.5%, at the failure probabilities of 0.1%, 1%, 5%, and 10%, respectively. As the failure probability is less than 1%, the lifetime estimation error by the offline test cannot be neglected.

The conclusions about degradation of the luminous flux and reliability analysis are only applicable for the type of LED lamps we used. For other types of lamps, correspondent experiments need to be done, and these will be our next research task.

Funding. 863 Program (2015AA03A101, 2013AA03A116); Chinese Academy of Sciences (CAS) (KZCC-EW-102).

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