Semiconductor Lasers Reliability Prediction Based on Accelerated Degradation Testing and MOGP Method

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***Abstract*—In order to predict the reliability of semiconductor lasers, an accelerated degradation test (ADT) was proposed as an element of reliability testing. Temperature-stressed ADT was applied for 8 Semiconductor lasers which used in space missions, and the degradation characteristics of output power of semiconductor lasers were studied. Then, a reliability model based multi-output Gaussian process regression (MOGP) was proposed to evaluate the lifetime and reliability for laser diodes. The advantage of the proposed MOGP based method is that it utilizes the output correlation between multiple degradation traces to make the outputs utilize each other's information and provide more accurate prediction than single modeling. Thereby improving the prediction accuracy. Furthermore, verifying applications and cases studies are discussed to prove the generality and practicability of the proposed reliability prediction model. Results show that the accuracy of the proposed MOGP based method is twice that of the SVM method.**

Keywords—Accelerated degradation test; Semiconductor lasers Multi-output Gaussian process regression；Reliability prediction

I. INTRODUCTION

Benefit from its small size, long life, high power, low cost and easy to use, multiple aerospace missions use semiconductor lasers as a core component of the payload [1]. In recent years, payload based on the semiconductor lasers have been further developed in the field of space optical communication, achieving high data rate, large amount of information and good confidentiality. A common failure mode in semiconductor lasers is lumen degradation. In extreme cases, the output power can be reduced to about 70% of its initial value. Due to the lifetime ranging from 20,000 to 100,000h, it is difficult to evaluate the lifetime of semiconductor lasers through accelerated life test and large sample failure data analysis. Considering the degradation characteristics of lasers, it provides a new research direction for the reliability evaluation and residual life prediction of semiconductor lasers.

The issue of degradation on semiconductor lasers has received considerable critical attention. In [2], the mechanisms of degradation that occurs during operation are summarized. The growth of dislocation, which is caused by mechanical stress or nonradiative-recombination-enhanced-defect-motion induces rapid degradation. In [3], A unified reliability model was proposed to evaluate the reliability and lifetime for laser diodes in space radiation environment, such as proton, neutron, gamma and electron radiation. In [4], a combined modelling-experimental approach is introduced to establish the reliability of the selective laser melting process. In [5], the main factors affecting the laser's degradation were analyzed and establishes a reliability automation test system based on LabVIEW. Although these methods are usually effective, one of the main obstacles is the use of specific degradation models. In addition, due to the unexpected new failure mechanism, the above methods are not suitable for dealing with degradation problems.

Large number of tests showed that the output power of different semiconductor lasers manufactured by the same process should have the same degradation trend under the same test environment [6]. For this reason, we propose a reliability prediction method based on MOGP. As a typical Bayesian non-parametric modeling technology, the key idea of MOGP framework is that it utilizes the "output correlation" between multiple degradation traces to make the outputs utilize each other's information and provide more accurate prediction than single modeling.

The remainder of this paper is organized as follows: Section II introduces the corresponding degradation modeling and lifetime prediction method; The applications and case studies are discussed in Section III. The concluding remarks are drawn in Section IV.

II. RELATED WORKS

Fig 1 shows the framework of the proposed method with three major steps included: (1) Degradation path modeling by MOGP and extrapolate failure lifetime of semiconductor lasers. (2) Hypothesis Testing and Parameter Estimation of Failure Distribution Model. (3) Accelerated Model Parameter Estimation.

A. Multi-output Gaussian process (MOGP)

The MOGP intends to approximate output power degradation trends simultaneously by considering the correlations between different Semiconductor lasers. The key of MOGP is to develop a new covariance function to share useful information in the outputs as much as possible.

$$\kappa_{MO-GPR} = \kappa_{yy}(t,t',\theta_t)\times\kappa_c(l,l,\theta_c) \quad (1)$$

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where $\kappa_{yy}(t,t',\theta_t)$ denotes the covariance with respect to the different cycles of data for the same sample. $\kappa_c(l,l,\theta_c)$ captures the correlation between outputs of different Semiconductor lasers.

III. RELATED WORK

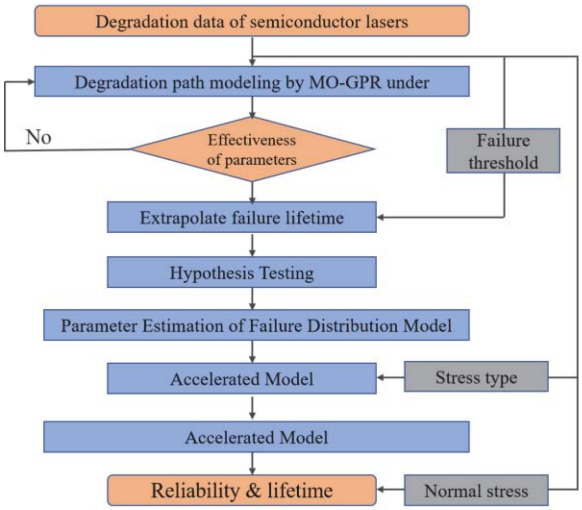

Figure 1. The framework of the proposed method

Assuming, the $n^{(j)}$ measurements are available for the j^{th} semiconductor lasers. The covariance function for Semiconductor lasers can be defined as:

$$K_{MO-GPR} = K_C(l,\theta_c) \otimes K_t(t,\theta_t) \tag{2}$$

The key problem is how to construct a semi-positive covariance matrix and capture the correlation between degradation trends. Once the appropriate covariance is defined, parametrization and prediction can be achieved as the same way of single-output GPs. Free-form parameterization is a general method for parameterization. It uses Cholesky decomposition and parameterizes the correlation covariance matrix with the elements of lower triangular matrix:

$$K_C = \begin{bmatrix} \theta_{c,1} & 0 & \cdots & 0 \\ \theta_{c,2} & \theta_{c,3} & & 0 \\ \vdots & & \ddots & 0 \\ \theta_{c,\mathrm{K-L+1}} & \theta_{c,\mathrm{K-L+2}} & \cdots & \theta_{c,\mathrm{K}} \end{bmatrix} \tag{3}$$

Thus, the total number of hyperparameters required is $k = L(L+1)/2$.

A. Accelerated model

In this article, the Arrhenius model is used to express the accelerated life-time model:

$$\begin{cases} F(t) = 1 - \exp\{-(\mathrm{t}/\eta)^m\} \\ \eta = \mathrm{A} \cdot \exp(\mathrm{E}_a / kT) \end{cases} \tag{4}$$

where m is the scale parameter of Weibull distribution function, k is Boltzmann constant and η is the degradation ratio related to stress level. The Maximum Likehood Estimation(MLE) was also used to estimate the parameters A E_a and m:

$$\ln L \propto -\frac{1}{2}\sum_{i=1}^{K}\sum_{l=1}^{n}\sum_{j=1}^{M}\left\{[\ln(2\pi\Delta t)+\ln(\mathrm{m}^2)+\frac{[(\mathrm{y}_{lij}-\mathrm{y}_{li(j-1)})-A\exp(-\mathrm{E}_a/\mathrm{kT})\cdot\Delta t]^2}{m^2\Delta t}\right\} \tag{5}$$

where y_{lij} is the degradation data of the $L_{th}(i=1,2,...,n)$ sample under the $S_i(i=1,2,...,n)$ stress level. we can get the MLE A, E_a and m by setting $\frac{\partial \ln \mathrm{L}}{\partial A}=0, \frac{\partial \ln \mathrm{L}}{\partial E_a}=0, \frac{\partial \ln \mathrm{L}}{\partial \mathrm{m}}=0$.

IV. ACCELERATED DEGRADATION TEST

A. Design of Experiment

ADT（accelerated degradation test） realizes life prediction by acquiring the variation of product performance with time in accelerated degradation process. According to relevant research, the relative increment of output power (OPI) was selected as the performance indicator to evaluate the reliability of the Semiconductor lasers. We define the failure as a percentage of the initial output power decreases to threshold. The OPI we consider in this paper is defined as follows:

$$OPI = \frac{P_{\mathrm{ref}} - P_{test}}{P_{\mathrm{ref}}} \times 100\% \tag{6}$$

where P_{ref} represents the initial output power value of the semiconductor laser, while P_{test} refers to the observed value during the test.

The faults and related stresses that may affect the performance of semiconductor lasers to determine the most effective accelerating stresses are summarized in Table I. Research shows that the lifetime of semiconductor lasers will be reduced by half every 25 degrees Celsius temperature rise[8]. So temperature is the main accelerate stress in this paper.

TABLE I. KEY STRESSORS OF SEMICONDUCTOR LASERS

No.	***Key component***	***Stressor***	***Failure mechanisms***
1	Facet region	Temperature	Photochemistry etching
2	Active region	Temperature Electricity	mechanical damage defects and point defects; Material Defects, like dislocations,
3	Solder	Temperature	Solder void; Delamination of metallization; Solder stress

Set four sets of stress levels and the spectrum of testing cycle is shown in Fig 2. In particular, the test sample under each testing cycle is eight.

Considering high temperature reserving of this functional unit is 50℃, 50℃ is used to be the lowest accelerated stress, ascending 20℃ a ladder which means temperature stresses are 70℃, 90℃,110℃ for constant failure mechanism. Therefore, the stressor have been divided into 4 levels.

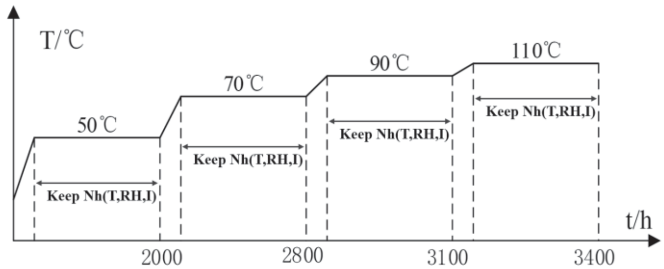

Figure 3. Profile of test cycle

The accelerated test equipment with temperature control module, laser driver module, circuit protect module included is shown in Fig. 3. The working current of all the eight lasers is set to 6A. Accelerated aging tests were carried out for each sample at different heat fin temperatures at 50, 70, 90 and 110 ℃, respectively. Thus, four groups of thermal accelerated aging tests were obtained.

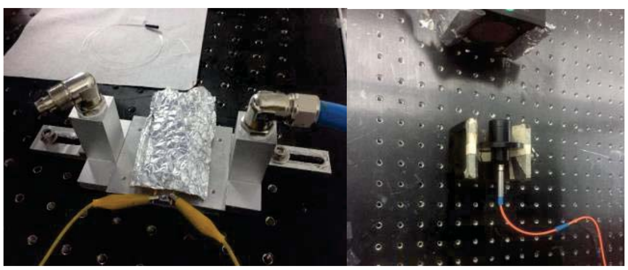

Figure 2. The accelerated test equipment

B. Analysis results

As shown in Fig.4, the degradation paths of 8 samples showed a common downward trend under different stress levels. The failure lifetime is defined as the length of time from present time to failure time.

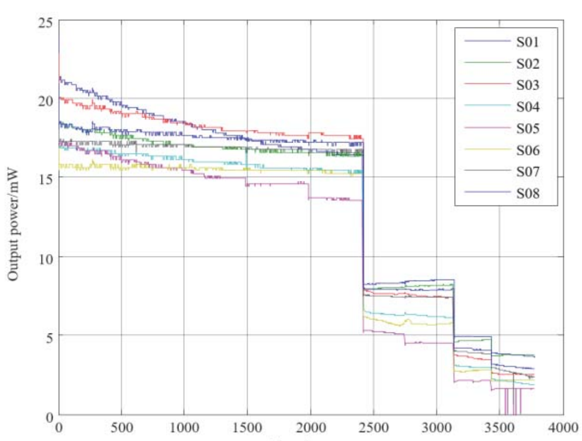

Figure 4. Degradation path

The expected lifetimes in different stress levels can be obtained using Equations (1) and (2). The prediction results of test sample S03 is shown in Fig. 5. Other samples can be treated in the same way. It can be observed from Fig. 5 that the extrapolated lifetime of S03 is 2382h under 70℃.

In order to verify the accuracy of prediction results, it is necessary to calculate the error between prediction and measurement data following the failure lifetime prediction.

Hence, we can compare the predicted values against the true value to obtain a mean error, defined as:

$$RMSE(t) = \sqrt{\frac{\sum_{i=1}^{t} (R_{pre}(i) - R_{true}(i))^2}{t}}$$

In addition, compared with other prediction methods, the comparison of the prediction results is displayed in Fig. 6.

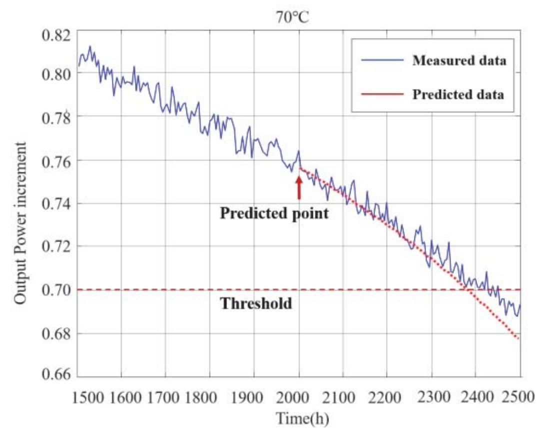

Figure 5. Prediction results for S03 semiconductor lasers by MOGP

The data sources used for comparison are S10 semiconductor laser. Fig. 7 showed the compared relative errors. Results showed that the RMSE of SVM method is 0.135, while the proposed MOGP based method is 0.061.

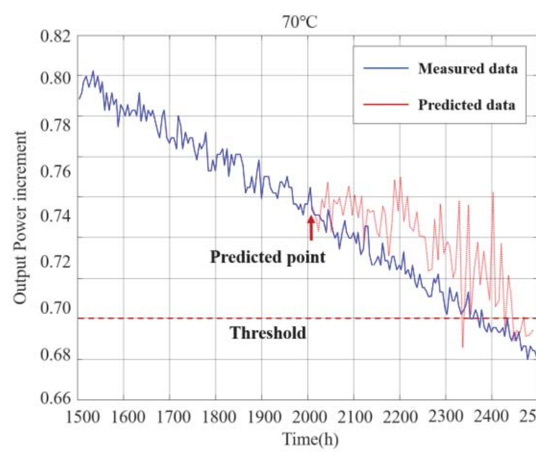

Figure 6. Prediction results for S03 semiconductor lasers by SVM

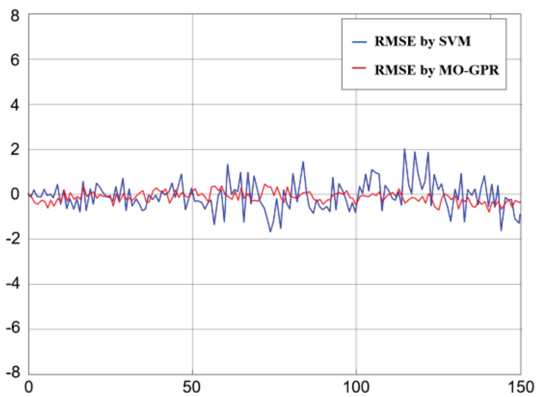

Figure 7. Comparison of Prediction Errors between SVM and MOGP

By this method, the failure lifetime of products under different acceleration stresses can be obtained (Fig.8).

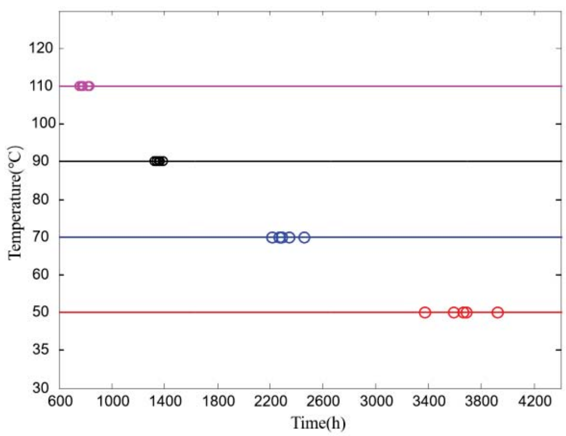

Figure 8. Prediction Errors between MOGP and SVM

As shown in section II, the lifetime of semiconductor lasers follows a Weibull distribution with parameters η and m ,the parameters can be obtained from (5).

TABLE II. PARAMETER ESTIMATION OF ACCELERATED MODEL

Parameter	A	E_a	***m***
Value	0.0002	0.4439	32.9149

For the given normal condition of temperature (T = 20 ℃ or 25 ℃) of semiconductor lasers, the lifetime at different confidence levels can be predicted by substituting the estimated parameters m, A and E_a into (4) .

TABLE III. RELIABLE LIFETIME

Temperature	***Lifetime***	***Confidence*** ***0.95***	
20	4844.34	4633.91	5064.33
25	4329.21	4121.80	4566.25

V. CONCLUSIONS

To the reliability prediction of semiconductor lasers as the research target, the accelerated degradation test under thermal stress have been successfully completed. With the test data, the lifetime model was established and validated, which proved the availability of the model. In addition, the life prediction results obtained by this method and SVM method are compared. From the results, the RMSE error of MOGP-based method is 0.061 while the SVM-based method is 0.135. Through comparison, the accuracy of the proposed MOGP based method is twice that of the SVM method. The advantage of the proposed MOGP based method is that it utilizes the output correlation between multiple degradation traces to make the outputs utilize each other's information and provide more accurate prediction than single modeling. Thereafter, we can conclude that MOGP can be an effective tool for lifetime prediction. The lifetime prediction model under both thermal and electrical stresses will be conducted in the prospective work.

REFERENCES

[1] Welch, David F. "A brief history of high-power semiconductor lasers." IEEE Journal of selected topics in quantum electronics 6.6 (2000): 1470-1477.

[2] Mitsuo Fukuda, "Reliability of semiconductor lasers used in current communication systems and sensing equipment.", Microelectronics Reliability, 47, Issues 9–11,2007,1619-1624

[3] Liu, Yun, et al. "Markov process based reliability model for laser diodes in space radiation environment." Microelectronics Reliability 54.12 (2014): 2735-2739.

[4] Sankhya Mohanty, Jesper H. Hattel, "Numerical Model based Reliability Estimation of Selective Laser Melting Process.", Physics Procedia,56, 2014,379-389

[5] M. Su, G. Lu, H. Xu, Q. Peng and L. Huang, "Design and implementation of semiconductor Laser reliability testing platform," 2018 19th International Conference on Electronic Packaging Technology (ICEPT), Shanghai, 2018, pp. 774-776.

[6] Wang W, Carr M, Xu X, Kobbacy K. A model for residual life prediction based on Brownian motion with an adaptive drift. Microelectron Reliab 2011;2011(51):285–93.

[7] Yamagata, Y., et al. "Failure Mode and Lifetime Analysis of 9×× nm High Power Broad Stripe Laser Diodes." 2018 IEEE International Semiconductor Laser Conference (ISLC). IEEE, 2018.Johnston AH, Miyahira TF. Radiation degradation mechanisms in laser diodes.IEEE Trans Nucl Sci 2004;51(6):3564–71.

[8] Liu, Wenbin, et al. "Lifetest system for assessing reliability of high-power semiconductor laser diodes." 2015 16th International Conference on Electronic Packaging Technology (ICEPT). IEEE, 2015.

[9] Huang, J. S., et al. "Predictive reliability model of 10G/25G mesa-type avalanche photodiode degradation." Applied Physics Research 8.3 (2016): 66-74.

[10] Kong, Xuefeng, Jun Yang, and Xiaolu Fu. "Reliability-based Usage Strategy Optimization for Lifetime Maximization of Solid-state Lasers." 2018 IEEE International Conference on Prognostics and Health Management (ICPHM). IEEE, 2018.

[11] Liu, Xi, et al. "System reliability estimation of high power diode laser with hypo-exponential distribution." 2017 Annual Reliability and Maintainability Symposium (RAMS). IEEE, 2017.