Reflectivity Evolution of Draw Tower Gratings at Elevated Temperatures

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The thermal stability of the Draw Tower Grating (DTG) reflectivity was measured at different elevated temperatures and the data was applied to the empirical aging prediction model of T. Erdogan. Good agreement between the theoretical model and the experimental results was found for the tested temperature range. This model can be used to make accelerated aging predictions. This is particularly useful to estimate the required pre-annealing time and temperature in order to stabilize the DTGs at a lower operating temperature.

Introduction

The thermal stability of Ultraviolet (UV)-inscribed grating plays an important role, especially in temperature sensing applications. The reflectivity (R) and related Bragg wavelength (λ_B) variations in high temperature environments can be related to the presence of thermally reversible refractive index changes. T. Erdogan introduced an empirical approach to construct an aging prediction model in UV-inscribed gratings [1]. The thermal stability of the FBGS Draw Tower Gratings (Type I DTGs) [2] will be systematically studied at different elevated temperatures and the aging curve approach will be applied to the data in order to construct the aging prediction model on the DTGs.

DTG reflectivity measurements

We monitored the reflected optical power from the same batch of DTGs at different elevated temperatures ranging from 100°C to 450°C with 50°C increments. At the beginning, we characterized the initial reflectivity of each DTG by using the cut-back method at ambient temperature. Then, two stripped DTGs were inserted freely hanging into a tube furnace (9173, Fluke) for 3000 minutes when the furnace was kept at constant temperature (isothermal). The optical interrogator SM125-500 (Micron Optics) was used to record the evolution of the reflected optical power every 30 seconds. The experimental setup is shown in Fig. 1. The results were normalized to the initial reflectivities in order to take out the intrinsic reflectivity difference between different DTG samples.

For didactical reason, the Integrated Coupling Coefficient (η =ICC=$\tanh^{-1}\sqrt{R}$) will be introduced rather than the reflectivity R. The experimental isothermal curves for the stripped DTGs are presented as colored lines in Fig. 2. Similar behavior can be seen for samples placed at the same elevated temperature, indicating that the tests were reproducible. All curves experience a sudden drop in ICC at the beginning and then gradually approach a steady state. The drop in ICC gets more significant the higher the temperature gets.

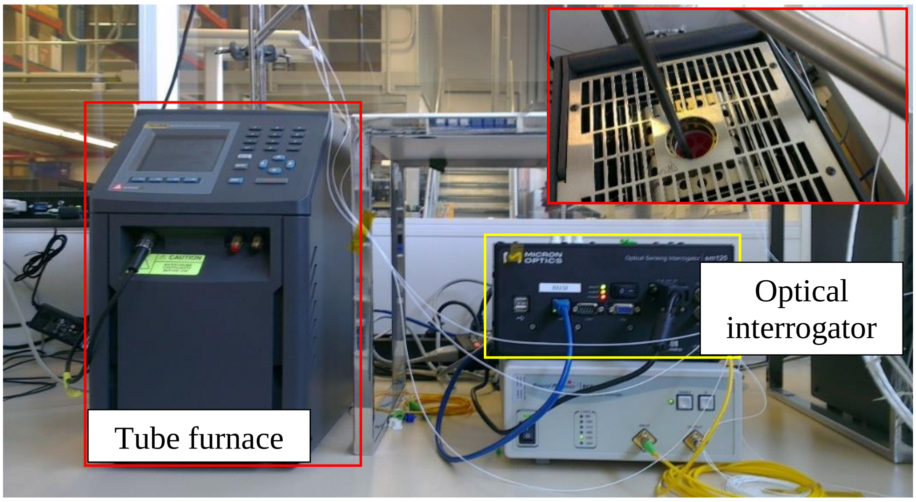

Figure 1: The experimental setup of the accelerated aging experiment

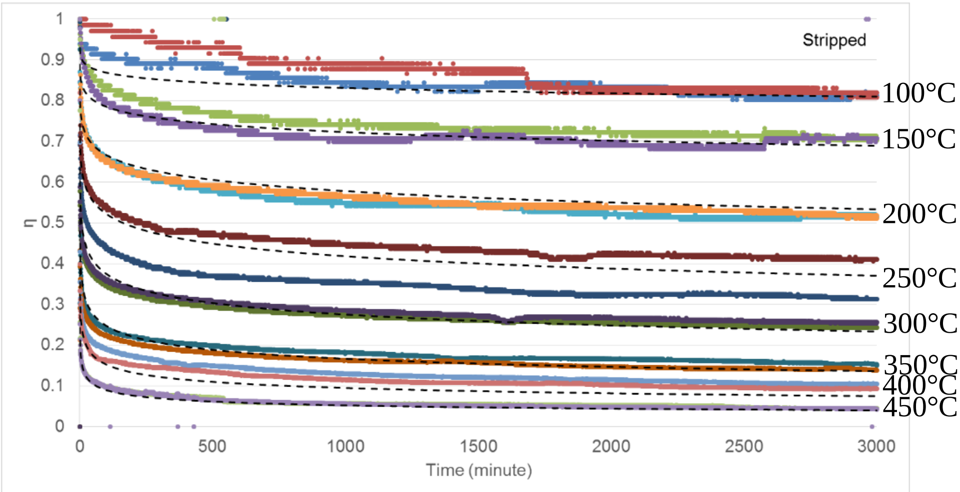

Figure 2: The experimental (colored lines) and the theoretical (black dashed lines) isothermal aging curves for the stripped DTGs

Aging prediction model

We can express the evolution of the ICC for each DTG as a function of the demarcation energy $E_d = k_B T.ln(\nu.t)$ as suggested in the aging curve approach [1] with κ_B the Boltzman constant, T the absolute temperature (in Kelvin), ν the attempt frequency and t the time (in minutes). The proposed mathematical model describes the relation between η and E_d as shown in equation 1:

$$\eta = \frac{1}{1+exp\left(\frac{E_d-\Delta E}{T_0 k_B}\right)} \quad \text{(Equation 1)}$$

with T_o and ΔE two extra fit parameters. The demarcation energy depends both on temperature and time. It can be seen as an accumulative energy threshold in removing a certain thermal reversible refractive index of UV-inscribed gratings. Therefore, the model allows one to include all the isothermal curves on a single graph. The attempt frequency should be chosen so that all experimental aging curves will have the best overlap. Here, the best overlap was found for $\nu = 1 \cdot 10^{13}$ min^{-1}. The result is shown by the colored lines in Fig. 3. The theoretical curve, shown by the black dashed line in Fig. 3, was found by curve fitting of all the experimental curves based on the proposed model. The deduced fitting parameters are ΔE = 1.579 eV and T_o = 2871 K.

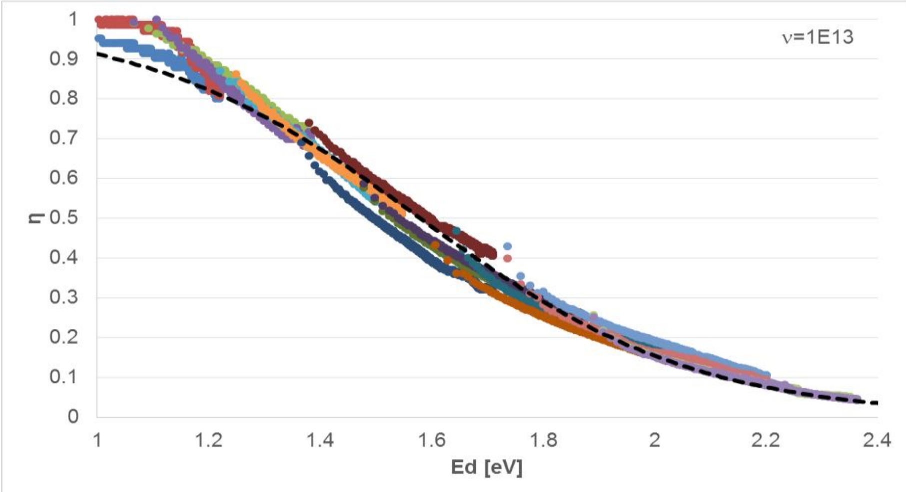

Figure 3: The experimental aging curves (colored) and the fitted curve (dashed) as a function of E_d

The calculated isothermal aging curves from the theoretical model are shown as the black dashed lines in Fig. 2. A good correspondence can be found, especially at higher temperatures or for longer annealing times, indicating the validity of the theoretical model. This behavior can be expected from the fit presented in Fig. 3, since the deviations are less at intermediate and high value of E_d and larger at lower value of E_d.

Accelerated aging predictions

The main benefit to apply this model is to perform accelerated aging predictions, meaning to predict the reflectivity evolution in order to stabilize the DTG in its future service temperature. The idea is to achieve the same amount of E_d either by placing the sample at low temperature T_1 for a longer time period t_1 or by placing the sample at high temperature T_2 for a shorter time period t_2 as written in equation 2:

$$E_d = \kappa_B T_1 \ln(\nu t_1) = \kappa_B T_2 \ln(\nu t_2) \qquad \text{(Equation 2)}$$

Normally, the last option is more preferable in practical application. We can illustrate this with an example. If we simulate the theoretical aging curve at 200°C, as shown by the red line in Fig. 4, the ICC drops rapidly at the beginning and then slightly decreases to around 54% of its initial value. It can be seen that this grating is not stable for the first 3000 minutes (=50 hours). If instead the grating is first placed at 250°C for 4 hours and then move back to its service temperature of 200°C, we can see that the ICC quickly drops to 48% of its initial value during the aging period but at 200°C the ICC evolution almost immediately becomes stable, see the blue curve in Fig. 4. Although the eventual ICC is almost 10% lower than the untreated one, the performance of the annealed sample is definitely preferred above the untreated one because of its increased stability. Using equation 2, we can calculate the equivalent time at 200°C that corresponds to the annealing step of 4 hours at 250°C and it amounts 169 hours. So the blue curve at 200°C corresponds to the ageing curve at 200°C with an initial offset of 169 hours. In this way, the equivalent time can be regarded as an offset that can be used to calculate the further evolution of the sample after the pre-annealing step.

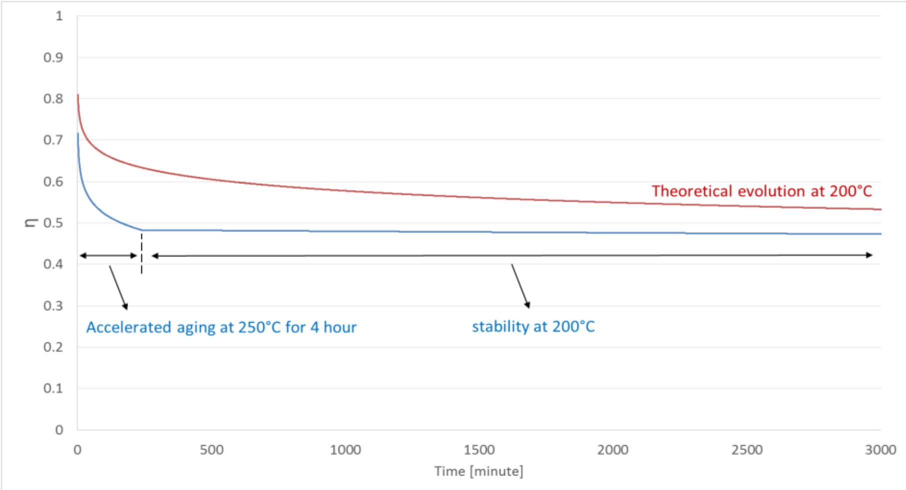

Figure 4: An example of the accelerated aging simulation on DTGs.

Conclusions

We experimentally determined the isothermal curves on stripped Type I DTGs. The results have been successfully applied to the aging prediction model as proposed in literature. Good agreement was found between the theoretical values and the experimental data. An example of an accelerated aging simulation was presented, showing that we can effectively stabilize the reflectivity variation of the DTGs in a controlled manner.

References

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[2] FBGS International NV. *DTG® Technologies* [Online]. Available: http://www.fbgs.com/technology/dtg-technology/