Accelerated Aging Studies of Multi-Section Tunable GCSR Lasers for Dense WDM Applications

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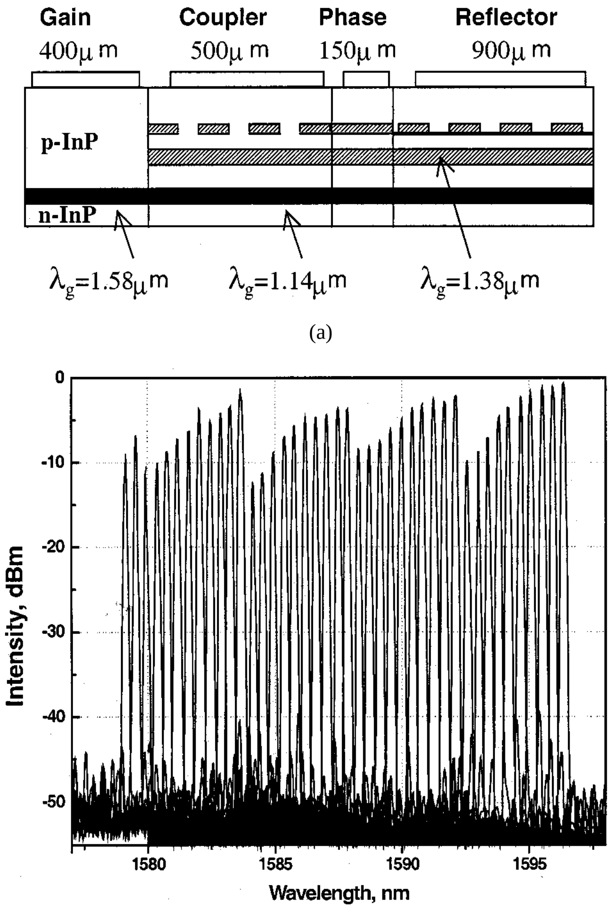
***Abstract*—The first accelerated aging study of wavelength tunable packaged GCSR lasers is reported. Stable power and SMSR were observed during the 5000 hours of operation at elevated temperatures. Frequency shifts of the selected lasing channels were characterized to access potential failures in an optical network. A longer burn-in was found to significantly reduce the amount of the observed shifts, and hence increase the reliability of the device. The effective room-temperature lifetime of GCSR is estimated to be 13.4 y. A new end-of-life criteria is also proposed.**

***Index Terms*—Aging and reliability, multiwavelength WDM applications, tunable semiconductor lasers.**

I. INTRODUCTION

WIDELY-TUNABLE multi-section lasers are key components for future flexible Wavelength Division Multiplexing (WDM) and other network applications [Internet Protocol over WDM (IP-WDM) [1], [2], All-Optical Networking [3], etc]. Grating assisted codirectional Coupler with rear Sampled Grating Reflector (GCSR) [4], [5] and Sampled-Grating DBR (SG-DBR) lasers [6] are the most promising candidates to date due to their wide tuning range, high Side-Mode Suppression Ratio (SMSR), relative simplicity, and potential low-cost of fabrication. However, for system applications, requirements on the reliability of the device are very stringent. In order to ensure wavelength agility and failure-free operation, wavelength tunable devices must not only achieve wide wavelength tuning ranges, but also support stable single-mode operation with high output power and high SMSR for each of these wavelength channels during the operating lifetime of the device (10–20 y). Lasing wavelength, power, and corresponding currents of the device should ideally operate in a "set-and-forget" mode i.e., a specific wavelength should always be accessible with the same values of injected currents. Furthermore, different channels should not exhibit frequency fluctuations, unwanted mode-hops or overlap. Thus, reliability and aging studies are necessary to define stability of these lasers and their expected lifetime in the network. These studies have been conducted on different types of semiconductor lasers [7]–[10], including tunable DBR lasers [9], [10], but have not been reported for GCSR or SG-DBR lasers so far. In this paper, we report on the first accelerated aging test of standard butterfly packaged GCSR tunable lasers. Power output, lasing frequency deviation, and SMSR changes were studied. Effective room-temperature lifetime was estimated to be 13.4 y.



(a)

(b)

Fig. 1. (a) Schematic structure of the GCSR laser and (b) experimentally measured superimposed lasing spectra of a large number of 50 GHz spaced ITU channels.

II. EXPERIMENT

A schematic structure of the multi-section GCSR laser is shown in Fig. 1(a). The device consists of four sections: a gain section, followed by a grating assisted codirectional coupler section, a phase tuning section, and a reflector section with a sampled DBR (S-DBR). By adjusting the current through the coupler section, it is possible to select lasing on one of the reflection peaks of the sampled Bragg grating. The wavelength of the selected Bragg peak and the exact mode position can thereafter be controlled like for a conventional DBR laser, i.e.,

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TABLE I
CONDITIONS OF THE PERFORMED ACCELERATED AGING TESTS

Test number	Number of devices	Number of ITU channels	Aging Currents, mA (Gain, Coupler, Reflector, Phase)	Aging Tempera-ture, °C	Duration, hours	Test objective
1	1	96	(150,15,15,5)	50, 65	600	Study early changes; define appropriate burn-in time
2	4	168	(150,15,15,5)	50	5000	Wavelength, power, SMSR and current stability; device operation lifetime
3	4	322	(150,15,15,5)	60	5000	

by current injection into the Bragg section and phase section, respectively. Hence, a wide continuous tuning range can be achieved by using all three tuning currents. The laser structure and dimensions are more closely described in [11]. Fig. 1(b) shows superimposed lasing spectra of GCSR operation for a number of ITU grid wavelength channels equally spaced 50 GHz apart. The lasing frequency can be tuned to almost any value within the tuning range with ±1 GHz accuracy; the widest GCSR tuning range reported so far is 114 nm [11].

During the reported accelerated aging test, the lasing frequency, power, and SMSR ratio for a large number of channels within each device were systematically measured and recorded in a given periods of time. A preliminary 15-h burn-in at 65 °C eliminated infant defect devices, hence no failures of device operation were observed during the performed test. Table I summarizes the conditions of the accelerated aging measurements that were carried out in this experiment. The first short (600 h long) test was intended to study the changes in early device operation and to estimate the necessary burn-in time to eliminate these changes. (In practice, much shorter burn-in should be used with higher current densities). Further, eight randomly selected devices were operated continuously at 50 and 65 °C for 5000 h (see Table I). Aging currents of the Gain, Coupler, Reflector, and Phase sections were set to 150, 15, 15, and 5 mA correspondingly which are the maximum currents normally needed to obtain the full tuning range of the laser.

III. RESULTS AND DISCUSSION

Fig. 2 shows the changes in coarse tuning curves and peak power vs coupler current with accelerated aging time. The initial coarse tuning curve (time $t = 0$) shows wavelength plateaus separated by 4.5 nm (peak spacing of the S-DBR). Power is stable throughout the whole tuning range with fluctuations corresponding to the mode jumps. As aging time increases, the wavelength plateau positions shift significantly toward shorter wavelengths, while the power fluctuation is insignificant throughout the accelerated operation time. SMSR fluctuations were found to be less then 10% throughout the whole aging time. This means that the gain section degradation has only negligible effect on the aging of the GCSR laser, while the main effect of GCSR degradation is lasing wavelength changes.

The wavelength plateau shift is much more pronounced during the first few hundred hours of the operation time and saturates during further operation. This will be shown in more detail later. A very important observation should be made here: given the same value of a particular injected current throughout the operation time, the lasing wavelength will experience mode hops corresponding to jumps from one plateau to the next. Since the continuous wavelength tuning requires three variable currents to obtain lasing at a given ITU frequency, the probability of such a wavelength jump increases.

Fig. 3 shows measured frequencies of the 96 ITU channels within one device as a function of aging time. A large number

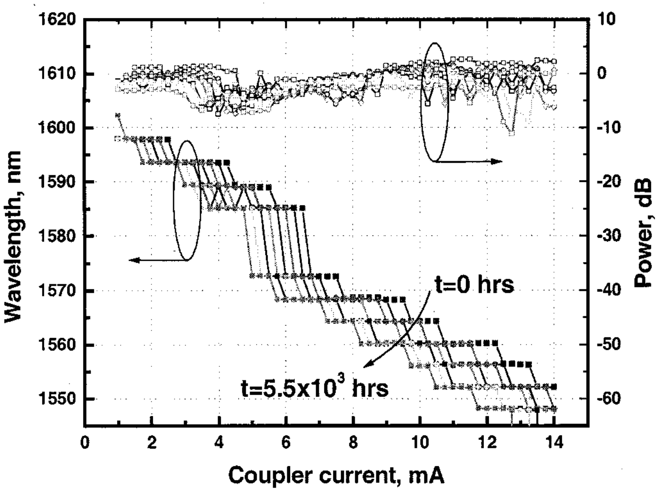

Fig. 2. GCSR coarse wavelength tuning curve and peak power evolution with accelerated aging time.

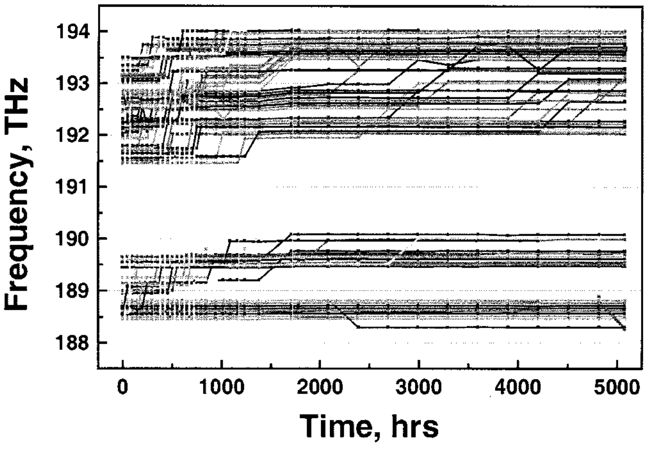

Fig. 3. Absolute frequencies of 96 ITU channels within one device as a function of aging time.

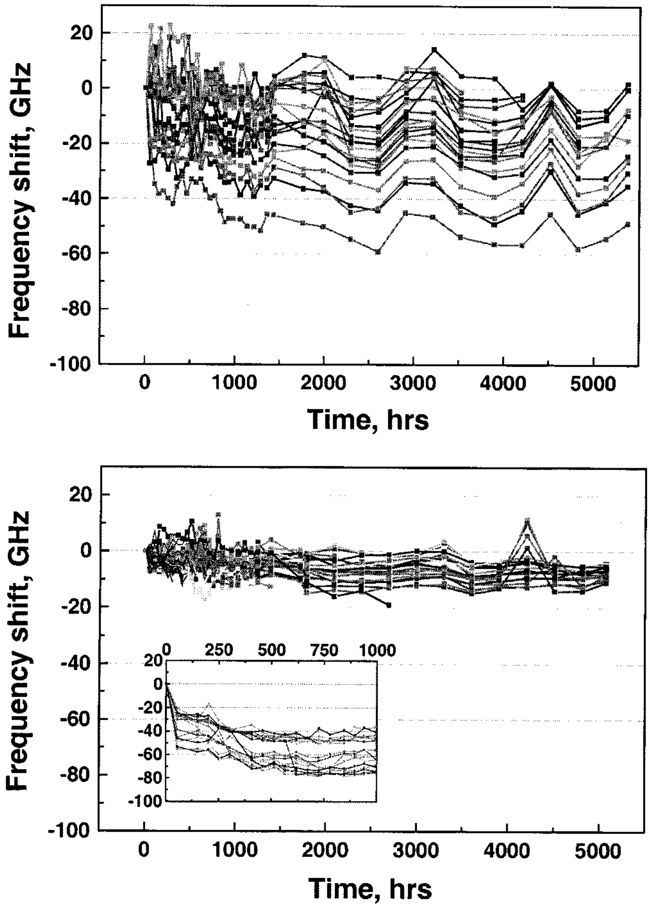

Fig. 4. Normalized frequency drift for (a) device with 37 hours burn-in and (b) 600 hours burn-in. The inset shows enlarged scale frequency shift for the first 1000 hours of the operation time.

of channels are stable and remain at their original frequencies even after a long operation time at elevated temperature (~70% of channels), but there are a number of channels that experience spontaneous mode hopping to a new frequency location (~30% of channels). These abrupt mode jumps are due to the fact that the wavelength plateaus have shifted to their new position (as it was shown in the Fig. 2) and new current values have to be applied to obtain lasing at the original wavelength.

Fig. 4(a) shows normalized frequency shift for the stable channels shown in Fig. 3. It can be seen that as operation time increases channels can experience not only mode hopping that, but also a gradual frequency shift. There is a significant spread in the amount of the final shift—between 0 and 50–60 GHz. However, a major improvement in the frequency stability may be obtained if a device is given an additional burn-in prior to the actual operation time. Fig. 4(b) shows normalized frequency shift for a similar device that had a 600-h burn-in (as in test 1, Table I) prior to the aging test. Frequency shifts for this device are significantly smaller—between 3 and 15 GHz. It is important to notice that the channels exhibiting larger frequency shifts correspond to the shorter wavelengths, obtained with higher tuning currents. This means that frequency drift is nonuniform over the spectral range and depends on the tuning current magnitude. The inset in Fig. 4(b) shows enlarged scale frequency shift for the first 1000 hours of the operation time of a device without burn-in. Most of the changes take place during first several hundred hours of device operation after which the observed frequency shift saturates. If a device is burnt-in for an appropriate amount of time to eliminate these initial changes, it is obvious that its behavior will be very stable.

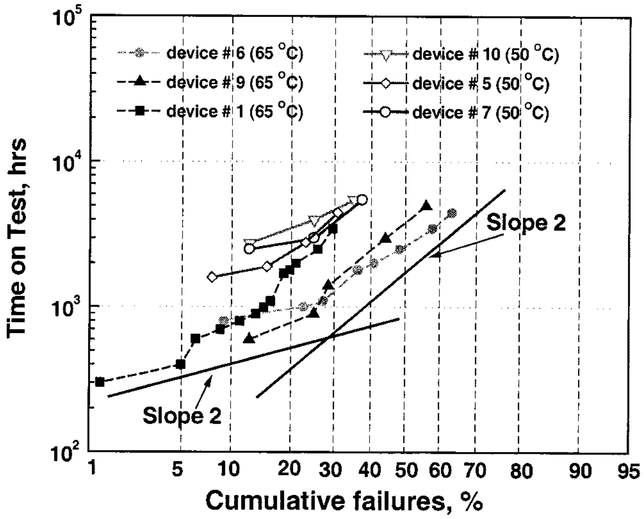

Fig. 5. Lognormal probability plot of cumulative failures versus operation time for six lasers operating at 50 and 60 °C.

The median device lifetime may be found from the log-normal cumulative failure (CF) plot. In our study, we have chosen the end-of-life (EOL) criteria to be a 10 GHz shift of the channel frequency from its original position. Median lifetime can be found as the time when 50% of all channels exhibit frequency shifts equal or greater than 10 GHz. Fig. 5 shows CF plots for six devices operated at 50 and 65 °C. Two different slopes can be observed on the CF curves, this means that we can distinguish two different failure mechanisms. The first linear region is related to rapid changes during initial operation time, it will be eliminated if a proper burn-in is applied. The second linear region is the one that we are interested in and is related to the long-term changes in the laser structure that lead to the frequency drift. As seen from Fig. 5, two of the devices operated at 65 °C reach 80 and 90% failure points and show a median lifetime of 3800 and 2700 h correspondingly. Three devices operated at 50 °C do not reach a 50% failure point, thus the time at which this point will be reached must be extrapolated. The solid squares symbol line corresponds to the device with additional 600 hrs burn in ("device #1" operated at 65 °C), the more stable frequency shift curves for this device were shown in Fig. 4(b). The device shows extremely good time-failure rate characteristics—does not reach a 50% failure point even after 5000 hours of operation at 65 °C. The extrapolated median lifetime for this device is as high as 8700 h.

After the median lifetime at elevated temperatures is found, the Arrhenius equation is used to estimate the median of the device at room temperature:

$$\frac{\tau(T_1)}{\tau(T_2)} = \exp\left(\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right)$$

where $\tau(T_1)$ and $\tau(T_2)$ are the lifetimes corresponding to the temperatures T_1 and T_2, and E_a is the activation energy. The

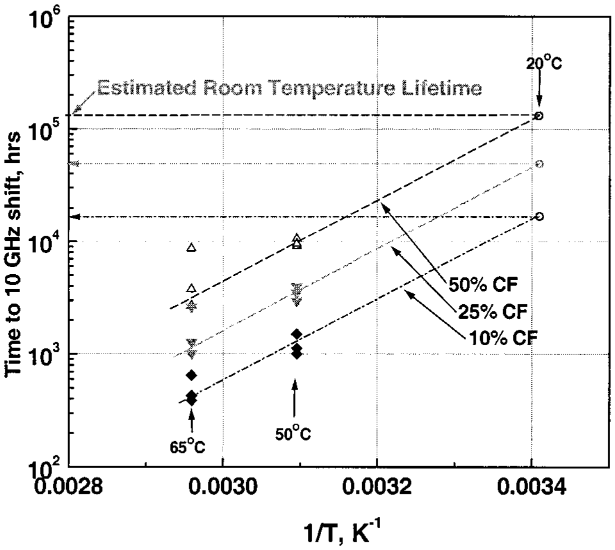

Fig. 6. Arrhenius plot used to estimate median device lifetime at room temperature. 50%, 25%, and 10% CF lifetimes are shown.

Arrhenius plot is shown in Fig. 6, the 50% median lifetimes for different devices are shown with open triangles. The activation energy estimation is 0.68 eV and the median lifetime of the device at $T = 20°\mathrm{C}$ is found to be $117.3 \cdot 10^3$ h which corresponds to 13.4 y. This lifetime is good enough for the device to be employed in terrestrial optical communication systems. Also, the device with additional 600 h burn-in shows that much longer lifetimes could be achieved with proper burn-in conditions.

However, it is anticipated that for set-and-forget operation of tunable lasers in telecommunications networks a criteria that is tighter than 50% CF EOL has to be used. For a comparison here we have also calculated 25% and 10% CF lifetimes, they are shown as solid triangles and diamonds in Fig. 6. Since 25% and 10% CF is a much tighter criteria, they lead to much shorter lifetimes of 5.7 and 1.9 years correspondingly.

IV. CONCLUSIONS

The first 5000 h accelerated aging study of widely-tunable GCSR lasers was carried out. Stable power and SMSR's were measured. Lasing frequency drifts were as high as 20–50 GHz. These values can be significantly reduced by a longer burn-in prior to the aging study or application of the device in a real-life system. Equivalent room-temperature lifetime of the device was estimated to be 13.4 y, but much better results are expected with a proper burn-in scheme.

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