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Suppression of Optical Feedback in Laser Diodes Using Multilayered Broad-band Ultra-low Reflective Facets-coating

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The multilayered anti-reflection coating (ARC) has been designed and implemented on the facets of edge-emitting laser diode in order to achieve ultra-low reflectivity over a broad wavelength range for suppression of optical feedback in the laser cavity. The design of the multilayer ARC has been obtained by a self-developed program based on genetic algorithm (GA) to achieve low-reflectivity of the order of 0.1 % over a spectral width of 50 nm around the central lasing wavelength of 818 nm and successfully implemented on the laser-diode facets. The effects of facets coating on the optical power emission and the spectral response of the lasers have been investigated. It is demonstrated that the simple design of multilayered ARC obtained using a self-developed GA can successfully reduce the optical feedback from the cavity and prevent the lasing action from the structure, which can be very useful for the fabrication of superluminescent Light Emitting Diodes (SLEDs).

Keywords: Thin film, Genetic algorithm, Reflectivity, Facet coating, LabVIEW.

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1. INTRODUCTION

Superluminescent light emitting diode (SLED) is a semiconductor light source that shows relatively a broad spectral bandwidth of optical emission with low coherence like LEDs and high optical power like laser diodes. SLED has a device structure apparently very similar to laser diodes, except that the optical feedback is not efficient to achieve lasing action. Due to the elimination of optical feedback, the cavity modes are suppressed which results in optical emission with a low ripple or smooth spectra. In other words, the SLED combines the spatial coherence of a laser diode with the temporal incoherence of an LED. This combination is extremely useful for a wide range of applications including fiber-optic gyroscopes [1], optical coherence tomography (OCT) systems [2], optical time-domain reflectometers (OTDRs) [3], and wavelength-division multiplexing (WDM) testing systems [4].

One of the most crucial device features needed to achieve high-power SLED operation is low facet reflectivity to prevent lasing even at the required high pumping levels. The low facet reflectivity is also essential in order to reduce the SLED output spectrum modulation, i.e. Fabry-Perot resonances due to residual facet reflectivity, and achieve the desired ripple-free output spectrum. Several methods have been reported to suppress lasing action such as an unpumped, absorbing region [5] or the proton implanted absorbing region [6] at the facet. Tilting [7], or bending [8] the injection contact with respect to the output facet has also been used for reducing the optical feedback. However, all these techniques require compound structure and involve complex fabrication processes. The simplest and one of the most effective ways to achieve low reflectivity at the facet are to coat the facet with an anti-reflection (AR) coating [9]. Facet-coating is quite an efficient and inexpensive method for reducing the facet reflectivity even for high-power operation. It also protects the facets of edge emitting semiconductor light sources from environmental influences.

In the present work, we report the design and implementation of multilayered ARC to achieve the ultra-low reflectivity over a broad wavelength range. Although, the standard schemes are available for AR coatings, generally these schemes give low reflectivity over relatively a narrow wavelength band. However, the SLEDs and other semiconductor light emitters require the reflectivity modulations over broader wavelength range, which demands a more efficient algorithm. Here, we have used a self-developed numerical simulation program based on genetic algorithm (GA) to design the multilayered stack of the thin-film. The designed thin-film structure has been implemented on both the facets of edge emitting laser diodes (LDs) in order to test its effectiveness in suppressing the Fabry-Perot cavity modes. The *L-I* characteristics and spectral response of the laser diode are measured before and after the AR coating on the facets in order to understand the effect of multilayer ARC in suppressing the optical feedback. The detailed results are analyzed and discussed in the results section.

2. DESIGN OF MULTILAYER ANTI-REFLECTION COATING USING GENETIC ALGORITHM

GA is stochastic global search optimization algorithm inspired by Darwin's theory of natural selection [10]. It is essentially mimicking the process of natural evolution underlying the idea of survival of fittest where the fitness of each individual is modified by successive iteration through the processes of selection, crossover and mutation. There are some characteristics of the GA that make it a very efficient algorithm. For example, it does

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not require any information about initial design and has very less chance of the trapping in local minima, even in a complex dimensional space.

The algorithm is implemented by developing an interactive numerical simulation program to design multilayer AR stacks using LabVIEW as programming tool. Before beginning the design optimization process, in order to obtain the optimum AR design, the proper selection of algorithm parameters like population size (N_{pop}) and range of search space and probability of various genetic operators such as crossover and mutation operators are very essential. The detailed study of these parameters and operators were systematically carried out elsewhere in the literature [11]. Hence, we have utilized the same optimized parameters from the literature in the present work in order to find the optimum design of multilayer AR coating for facet coating of LDs.

In the beginning of design optimization process, various input parameters such as wavelength range, number of layers (NOL), name and sequence of coating materials for each specified layer, range of minimum and maximum thickness of layers [d_{min}, d_{max}], angle of incidence, probability of crossover and mutation and number of iteration (NOI) are fed into the program to search optimum design of multilayer AR coating. Next, the program reads various input parameters and accordingly generates an initial population of multilayer AR designs randomly with fixed number of layers within the given range of layer thicknesses [d_{min}, d_{max}]. After the generation of initial AR designs, each AR design is tested by using suitable figure of merit, also, referred as fitness function. In present work, we have considered the averaged reflectivity of multilayer AR stack over the wavelength range of interest as a fitness function, which is defined as,

$$R_{\text{averaged}}(\lambda) = \frac{\left\{ \sum_{k=1}^{p} [R_{cal}(\lambda_k, T) - R_{desired}\ (\lambda_k)] \right\}}{p} \quad (1)$$

where $R_{cal}(\lambda_k)$ is the calculated value of reflectivity at wavelength (λ_k) for a given set of layer thicknesses $T = (t_1, t_2, t_3, \dots, t_n)$, where n indicates the number of layers in the AR stack, using transfer matrix method described elsewhere [12] and $R_{desired}(\lambda_k)$ is our expected reflectivity, which is taken to be zero in the present case. P is the total number of wavelength steps of spectrum. After evaluating the fitness of each AR design, they are followed by selection, crossover and mutation operator to reproduce new AR designs. This process is repeated till optimum design is obtained in terms of layer thickness. Table 1 represents the important GA terminology in the context of multilayer AR design problem. Fig. 1 shows simplified flow-chart of the GA based program for AR stack design. The obtained design from GA, which is selected for the laser diode facets, is shown in Table 2.

3. DEPOSITION OF MULTILAYER AR STACK

The deposition of multilayer AR stack was accomplished under the high vacuum (10^{-6} mbar) using a 3 kW e-beam evaporation system equipped with 180 °C bend e-beam gun facility (Hind High Vacuum Co. (P) Ltd.). The deposition of multilayer AR films at laser diodes facets requires a high degree of control on the deposition conditions. The multilayer AR coatings are to be deposited, on the facets of edge emitting LDs consist of GaAs based active layer materials, to get desired optical performance. Thus, initially, the optimization of an individual layer was carried out on GaAs test substrate. The thickness and deposition rate of each layer of the stack are monitored by a quartz crystal oscillator during the growth of thin-films. The thickness and refractive index of an individual layer is further confirmed by using self-developed numerical simulation program based on GA, which is discussed in detailed elsewhere in literature [13] after post growth of film. After the optimization of an individual layer, a complete AR stack is deposited on GaAs test substrate. Finally, an optimized multilayer AR stacks deposited on the facets of laser diode with a GaAs substrate kept in close vicinity to the laser diode during the deposition for the estimation of the coated multilayer AR stacks. The test-substrate and the laser diode are rotated with constant rpm inside the vacuum chamber during deposition. The substrate temperature is attained using radiant heaters. The reflectivity of the AR coated substrates is measured using ex-situ reflectivity measurement set up developed at our laboratory. The *L-I* characteristic and spectral response of laser diodes are measured in pulse mode before and after the facets coating using laser diode characterization facility developed at our laboratory [14].

Table 1 – GA terminology equivalent to multilayer AR design problem

GA terms	Equivalent multilayer AR stack design problem terms
Initial population	Number of randomly generated multilayer AR stack designs
Individual	A particular AR stack, consisting of the thickness of each layer
Search space	Range of minimum and maximum thicknesses of the layer
Fitness function	Averaged reflectivity of the multilayer AR stack over the wavelength range of interest

Table 2 – Multilayer AR stacks design for facet coating of LED

Number of layers	**Coating materials**	**Layer thickness in Å**
Substrate	GaAs	Infinite
1	MgF_2	283
2	Si	203
3	MgF_2	1530
Incident medium	Air	Infinite
Average reflectivity (%)		0.0138
Reflectivity (%) at center wavelength (818 nm)		0.0103

4. RESULTS AND DISCUSSION

The optimized multilayered AR coating is deposited on the laser diode facets as well as the GaAs test substrate. Fig. 2 shows the simulated and experimentally measured reflectivity spectra on coated test-substrate. As shown in Fig. 2, the nature of simulated and experimental reflectivity spectra is in very good agreement. We obtained as low as 0.1 % reflectivity over the desired

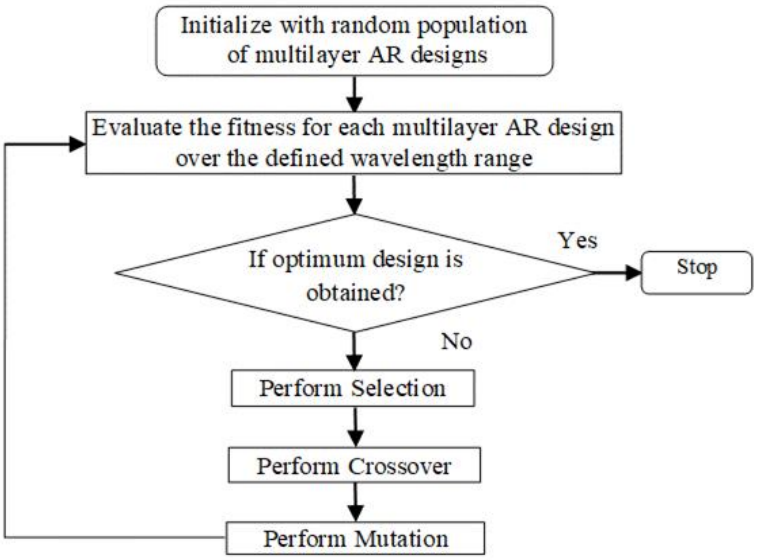

Fig. 1 – Flow chart of GA for AR stack design

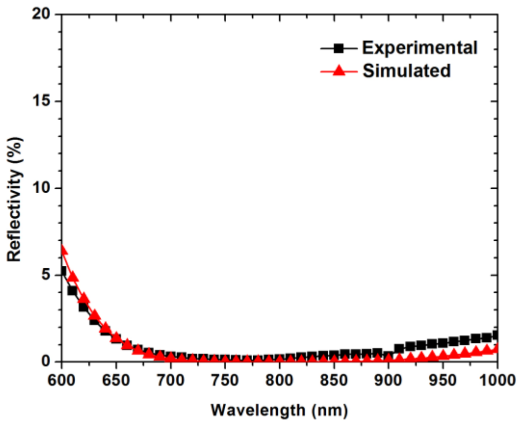

Fig. 2 – Simulated and experimental reflectivity spectra for the optimized multilayer AR coating on GaAs test substrate

wavelength range as shown in the Fig. 2. Although, the obtained reflectivity is much higher than the simulated one, the overlapping nature of the simulated experimental spectra indicate that the quality and the control of multilayer stack deposition is very precise. Also, the higher value of reflectivity obtained experimentally above 850 nm is because of back-reflection from the GaAs test substrate as it becomes transparent whereas in the simulation program, we assume the substrate to be infinite, thus by neglecting the reflection from the back surface.

In order to understand the effects of AR coating on the performance of the laser diode, we measured the *L-I* characteristics of the laser diode before coating, after applying ultra-low reflective coatings on one facet and after applying the coating on both the facets. The *L-I* characteristics measurements are carried out in pulsed mode with pulse with of 400 μs and the duty cycle of 0.25 %. Fig. 3a shows the comparison of *L-I* characteristics of the laser diode before coating and after one facet coating. As shown in Fig. 3a, the laser diode shows a sharp threshold at about 330 mA with good slope efficiency. We obtained 450 mW optical power per facet at 800 mA from uncoated facets as shown in Fig. 3a. However, after applying the AR coating on one of the facets, the *L-I* characteristics exhibit significant changes. In case of one facet coated diode, the reflectivity of the coated facet is very low, of the order of 0.1 % at 818 nm where as the uncoated facet has the normal reflectivity of about 30 % due to GaAs-Air interface. Hence, in this case, we measured the *L-I* characteristics from both, coated and uncoated facet, and the difference of power from the two facets is evident as shown in the Fig. 3a. The coated facets emit more light because of low reflectivity compared to the uncoated facet. However, as seen from Fig. 3, even after applying the AR coating on one of the facets, the sharp change in the optical power is still observed from both the facets, almost at the higher current. The threshold current in this case is found to have increased to 430 mA whereas the overall power reduces from the original value before coating. This can be explained by the fact that the mirror loss increases with decreasing the reflectivity of one of the facets [15], which leads to the requirement of higher current for the transparency condition.

The comparison of *L-I* characteristics of uncoated laser diode and the laser diode coated with AR coating on both the facets is shown in Fig. 3b. As shown in the figure, the sharp threshold seen in the *L-I* characteristics before coating totally disappears after coating both the facets with the AR film and the *L-I* curve shows the continuous increment in the slop. This indicates that the increased mirror loss and reduced optical feedback from the facets now prevents the lasing in the structure. This effect clearly visible in near the threshold current, which is shown in the Fig. 3c. Also, the non-linear nature of the *L-I* curve hints towards the presence of superluminescence emission [16].

To further investigate this behavior, we measured the spectral response of the laser diode before and after AR coatings on both the facets, which is shown in Fig. 4. Fig. 4a shows the spectral response of laser diodes at different drive currents near the threshold value before AR coating. As seen from the Fig. 4, the laser diode exhibits distinct Fabry-Perot cavity modes. As the current increases, one of the modes become dominant with a few

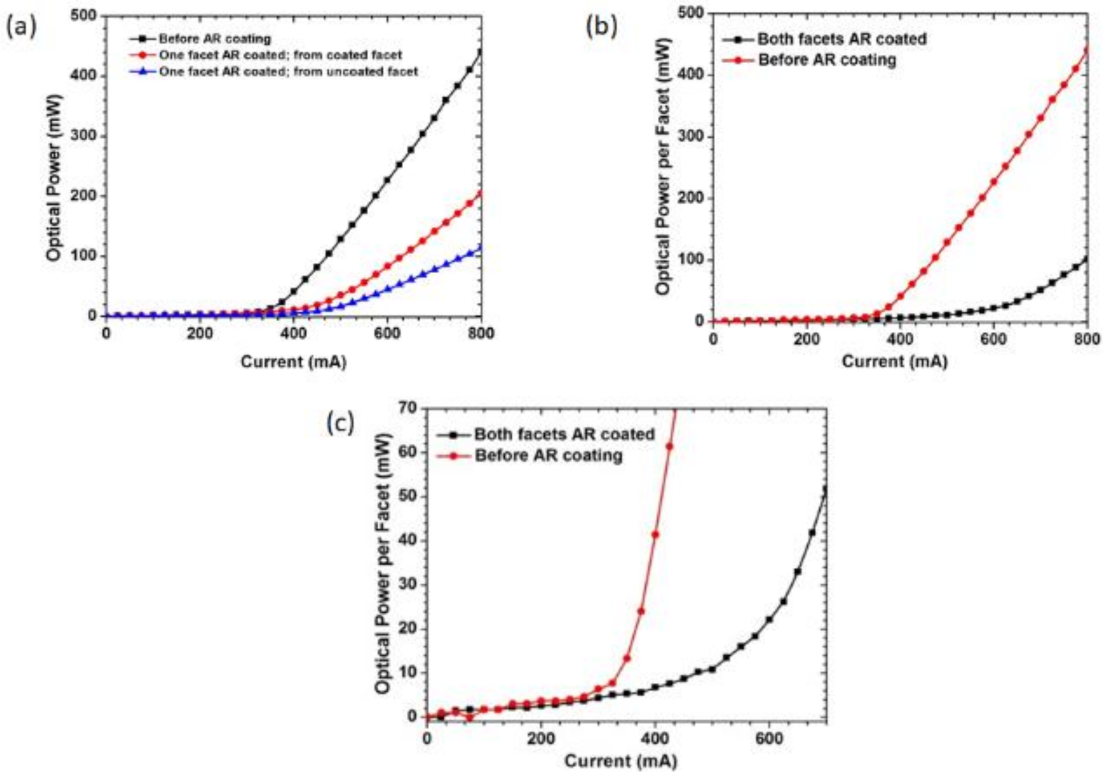

Fig. 3 – *L-I* characteristics of laser diode before AR coatings and after AR coating on one facet (a); comparison of *L-I* characteristics before and after AR coating on both the facets (b); comparison of *L-I* characteristics before and after AR coating on both the facets zoomed in at near the threshold current (c)

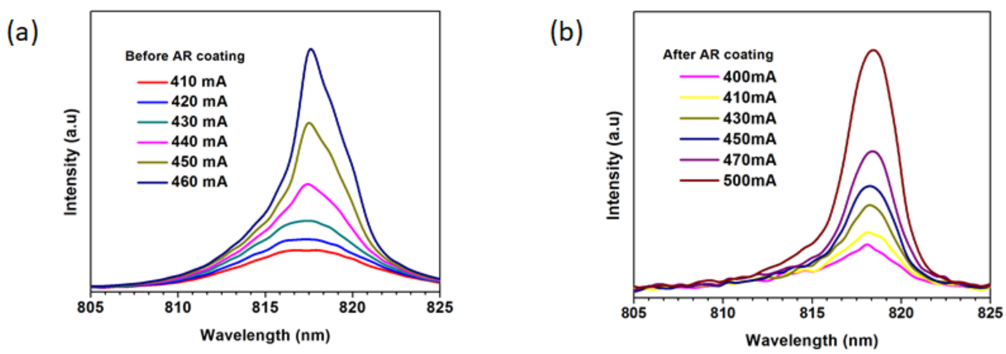

Fig. 4 – Spectral response of laser diode at different drive currents before (a) and after (b) AR coatings on both the facets

week modes still present. Thus, the peak is highly asymmetric because of presence of multiple oscillating modes in the spectrum. However, as seen from Fig. 4b, the spectral response of laser diode after AR coatings on both the facets is quite symmetric and smooth. This clearly indicates that the application of ultra-low reflective coatings on both the facets effectively remove the optical feedback [17]. The lack of optical feedback from the mirrors at the facets eliminates the multiple oscillating cavity modes and ripples to make the spectrum smooth and symmetric.

5. CONCLUSIONS

We have designed and successfully implemented multilayer ultra-low AR films on the facets of laser diode. The deposited AR film provides as low as 0.1 % reflectivity on the laser diode facets over the spectral width of 50 nm around the central lasing wavelength at 818 nm. The obtained *L-I* characteristics after multilayer AR coating of laser diodes clearly indicate the effect of reflectivity modulation on the facets. The suppression of optical feedback is confirmed by observing the spectral response of laser diode before and after multilayer AR coating. Finally, it is demonstrated that the simple dielectric AR coating on the facets could be a very useful technique for suppression of optical feedback to eliminate the resonant cavity for fabrication of SLEDs.

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