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Fuzzy logic approach to Henry factor for distributed feedback laser case

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Abstract: In this study, a simple approach for intelligent modeling of the Henry factor (α-alpha parameter, antiguiding factor, phase-amplitude coupling factor) or the so-called linewidth enhancement factor, which is an actual analysis and design parameter for semiconductor laser diodes and optical communication systems, is proposed based on the fuzzy logic (FL) phenomenon. The proposed FL-based model easily computes the Henry factor in terms of different wavelengths and injection current levels (i.e. the inputs of the model). The experimental data belong to a distributed feedback laser, obtained from amplified spontaneous emission spectra, which is among the techniques required for the characterization of semiconductor lasers. For the Henry factor, the suggested method's approximation provides predictions within the accuracy level of 95%–99.99%.

Key words: Linewidth enhancement factor, fuzzy logic, distributed feedback laser diode

1. Introduction

Distributed feedback (DFB) lasers are attractive light sources for a wide range of applications and play an important role in long-haul high-bit-rate optical communication systems due to their low cost, small size, high efficiency, reliability, and inherent temperature stability [1,2]. They offer stable single-mode operation, which requires an accurate control of the spatial-hole-burning and narrow linewidth (i.e. low Henry factor) in order to ensure high bandwidths [3]. The Henry factor [4] is a crucial design parameter for the high-speed modulation of DFB lasers used in these systems. It describes many dynamical properties that are related to the interaction of refractive index change and optical gain as functions of the charge carrier density in the active region. It is also a required parameter for simulations of laser dynamics in terms of different application areas. The Henry factor (α) is defined as the ratio of the partial derivatives, with respect to the carrier density (N), of the real and imaginary parts of the refractive index, $n = n_r + jn_i$.

$$\alpha = \frac{\frac{\partial n_r}{\partial N}}{\frac{\partial n_i}{\partial N}} \tag{1}$$

Because the carrier-induced changes are usually small compared to the refractive index, the expression above can be shown to be equivalent to the ratio of the change in the real part of the complex susceptibility with carrier density to the change in the imaginary part with carrier density, which can be also expressed as follows:

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$$\alpha = \frac{\frac{\partial \chi_r}{\partial N}}{\frac{\partial \chi_i}{\partial N}} \tag{2}$$

where $\chi = \chi_r + j\chi_i$ is the complex susceptibility.

The Henry factor is obtained after rigorous and lengthy mathematical calculations, which involve different approximations, assumptions, and estimations that are pointed out in [5,6]. In addition to that, the measurement of this factor is difficult since it significantly varies with the operating wavelength, carrier density, and other factors. The detailed estimation methods for the Henry factor are also given in [7]. In terms of the measurement side, there are several methods proposed in the literature [7,8].

Similar to the Henry factor, the other optical characteristic quantities like optical gain [9] and refractive index change with injection current [10] show similar behavior in the theoretical and measurement sides. The mathematical modeling of these quantities yields important and useful information about the whole system performance at the design stage since the measurement setups are extremely expensive. In the literature, there are many theoretical mathematical models proposed for laser diodes and optical-based systems [11–35]. In recent years, there were also intelligent models proposed for optical gain [36–49], the Henry factor [50–53], refractive index change with injection current [54], and all other characteristic quantities [41,55–61] for the purpose of quick design and simulation of such systems.

With the inclusion of fuzzy logic (FL) methodology, time-consuming steps can be eliminated. In addition to that, during the debugging and tuning cycle one can change the system by simply modifying rules instead of redesigning the system. Moreover, since FL is rule-based, there is no need to be an expert in high- or low-level programming languages; hence, the focus of the user may be directed toward the application instead of programming. As a result, FL substantially reduces the overall development cycle [62–72].

As illustrated in Figure 1, in this study, for the first time to our knowledge, the Henry factor for a DFB laser is modeled using the FL phenomenon with the use of amplified spontaneous emission spectra with respect to different wavelength and injection current levels. The recommended approximation provides fast and reliable predictions that can save engineers from tiresome and expensive experimental setups and rigorous calculations. The FL approach provides the predictions of the Henry factor against the wavelength and the injection currents within the accuracy level of 95%–99.99%. The experimental data used in this study were acquired from a DFB laser diode [73].

2. Architecture of the FL-based intelligent model for the Henry factor of the DFB laser diode

Figure 1 shows the basic structure of the intelligent FL-based model for the Henry factor of the DFB laser diode. The Henry factor of the FL-based intelligent model is a classical model and consists of fuzzification, knowledge base, decision-making logic, and defuzzification units. The fuzzification unit is the definition of fuzzy sets, and the determination of the degree of membership of crisp inputs, the injection current and wavelength, in appropriate fuzzy sets. The fuzzy sets are represented by membership functions (MFs), which are triangular, trapezoidal, and bell-shaped entities. The triangular MFs are the most convenient ones and are used in this study as illustrated in Figure 2. The number of MFs and their initial-final values are determined using the system knowledge and intuition.

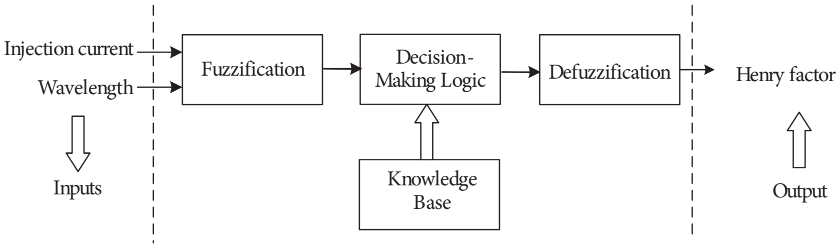
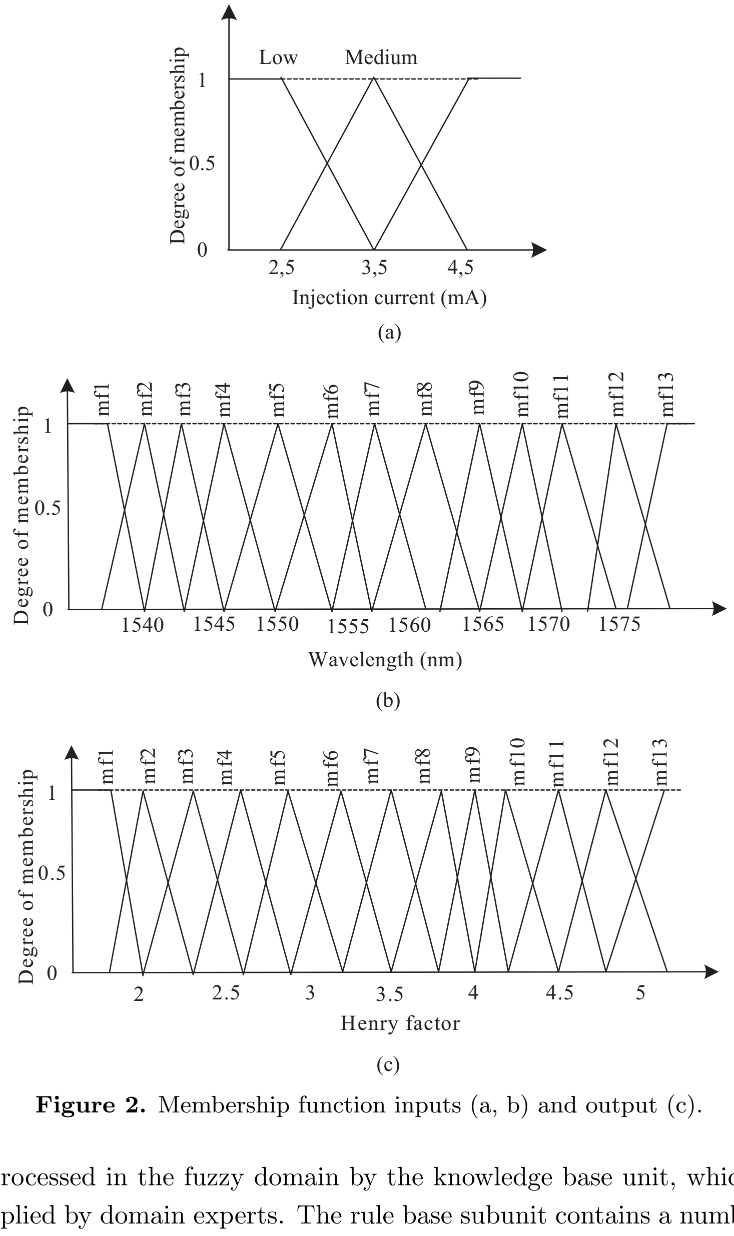


Figure 1. Henry factor of the proposed FL-based model.



(a)

(b)

(c)

Figure 2. Membership function inputs (a, b) and output (c).

These are then processed in the fuzzy domain by the knowledge base unit, which is composed of a rule base and data base, supplied by domain experts. The rule base subunit contains a number of fuzzy if-then rules that describe the link between the inputs and the output. Table 1 shows the rule base of the proposed FL-based intelligent model. The linguistic variables mf1 and mf13 are used in Table 1. They correspond to the smallest and largest MFs, respectively. The data base subunit defines the MFs of the fuzzy sets used in the fuzzy rules.

The decision-making logic unit applies the rule base to the fuzzy values coming from the fuzzification unit to make decisions. Initially, the fuzzy values are presented to the rule base in order to determine the active rules. Afterwards, this rule is employed in the max-min fuzzy method for the prediction the Henry factor of the DFB laser diode [36,37,41].

Finally, the defuzzification unit translates back the fuzzy numbers into single real-world values. This can be done in different ways, such as max-min defuzzification, centroid defuzzification, and so forth. In this study, the most commonly used accurate technique, namely the centroid defuzzification technique (also known as center of gravity or center of area defuzzification), has been used [74].

Table 1. Rule base for the Henry factor of the DFB laser diode.

	Injection current (mA)		
Wavelength (nm)	Low	Medium	High
mf1	mf1	mf2	mf4
mf2	mf1	mf2	mf3
mf3	mf2	mf3	mf4
mf4	mf2	mf3	mf5
mf5	mf3	mf4	mf7
mf6	mf2	mf4	mf8
mf7	mf3	mf5	mf7
mf8	mf5	mf6	mf11
mf9	mf5	mf7	mf11
mf10	mf5	mf8	mf12
mf11	mf6	mf7	mf13
mf12	mf6	mf10	mf12
mf13	mf9	mf12	mf13

3. Evaluation of the results and discussion

The FL-based intelligent model consists of 2 input parameters, injection current and wavelength. The single output parameter is the Henry factor, which affects several fundamental aspects of semiconductor lasers in terms of different application areas. Figure 3 shows the results of the experimental, theoretical, and FL-based

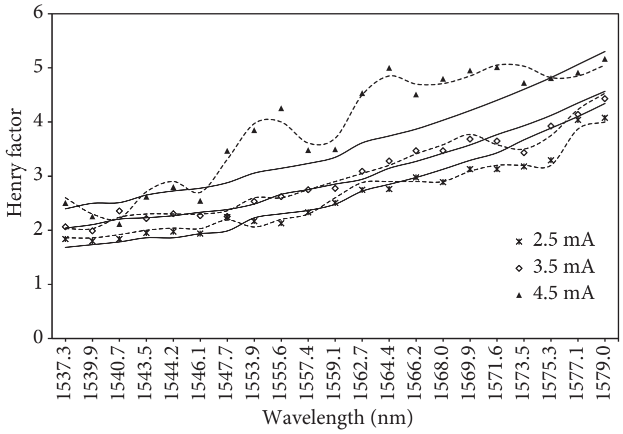


Figure 3. The comparison of the experimental, theoretical, and FL-based model results for the Henry factor prediction for the DFB laser diode.

intelligent model for different wavelengths and injection current levels for the computation of the Henry factor of DFB laser diodes. In Figure 3, symbols are experimental, solid curves are theoretical, and dotted lines are FL-based intelligent model results. As can be clearly observed, the FL-based results are very close to the experimental results, which eliminates the drawbacks of the theoretical results [39].

The results of the FL-based intelligent model performance are shown in Table 2, where MSE is the mean square error, RMSE is the root mean square error, and MAE represents the mean absolute error values. The term r is the correlation coefficient, which is close to unity. The total error from all experimental results is under 10% and, for the MSE, this error is around 1%, which is highly accurate. The performance results also show that the FL-based model results agree with the experimental results, validating the model. It can also be seen that the FL-based results are much better than the theoretical results and thus can be used reliably in the design process.

Table 2. The FL model's performance results.

Performance	Experimental-FL	Experimental-Theoretical
MSE	0.011345	0.13506203
RMSE	0.099514	0.36750787
MAE	0.089404	0.23942222
r	0.994444	0.930635

4. Conclusions

In this study, a FL-based approach has been successfully applied to the Henry factor of the DFB laser diode. The results show that the FL-based model is capable of generalizing between input and output variables with reasonably good predictions. The overall evaluation of the experimental results show that the FL-based approach provides acceptable predictions within the range of 95% to 99.9% while evaluating the performance of optical systems in the design phase. Since the Henry factor is a key parameter and has great importance, as it is one of the main features that distinguish the behavior of semiconductor lasers with respect to other types of lasers in the case of analysis and design, the simulation results provide highly reliable predictions that also increase the system performance to be constructed at the design stage of the complete system. Thus, the suggested methodology presents cheap and clear guidance to the system engineer from the outset, contributing towards the reduction of the time spent on design and implementations involving DFB laser diode applications.

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