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Design and Simulation Based Analysis of Electrical, Optical and Thermal Performance of 1550 nm Distributed Feedback Laser Diode

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ABSTRACT

Distributed Feedback (DFB) laser diodes that operate at 1550 nm are key components in modern optical communication systems. Their spectral purity and wavelength stability make them ideal for high-capacity Fiber-optic links.The main goal of this study is to identify an optimized laser structure that maintains reliable single-mode operation under realistic conditions while achieving a lower threshold current.The optical analysis of the proposed DFB laser structure used Lumerical MODE and FDTD simulation tools. The optical results showed strong mode selectivity with lasing centred at the desired 1550 nm wavelength indicating effective single-mode performance. The electrical performance was studied with Lumerical CHARGE, focusing on carrier transport and recombination in the multilayer semiconductor structure. The analysis included current-voltage (I-V) characteristics and threshold current density estimation. Thermal characteristics of the device were evaluated using Lumerical HEAT simulations. The results emphasize the importance of thermal management in ensuring stable optical output and long-term device reliability. Overall, the optimized DFB laser design shows stable single-longitudinal-mode operation at 1550 nm, with a significantly reduced threshold current and better spectral purity than traditional structures. The integration of efficient carrier confinement and regulated thermal dissipation supports consistent device performance across a wide range of operating conditions. This work highlights the effectiveness of Lumerical's integrated multiphysics simulation framework for the organized design and improvement of DFB laser diodes. The proposed design approach and analytical method offer valuable insights for developing high-performance 1550 nm DFB lasers aimed at Dense Wavelength Division Multiplexing (DWDM) systems and next-generation optical communication networks.

Keywords: *Ansys Lumerical; Bragg grating; single-mode semiconductor lasers; 1550 nm wavelength.*

1. Introduction

Optical communication systems are crucial for transmitting data globally. The Distributed Feedback laser diode stands out because it works well with fibers. The 1550 nm wavelength is particularly suitable for long-distance and high-speed optical communication systems. It has the least distortion and is safe. A distributed-feedback laser (DFB laser) has its entire resonator designed as a periodic structure within the laser gain medium that acts as a distributed Bragg reflector at the laser wavelength. DFB lasers are a significant improvement over traditional Fabry–Perot lasers. In DFB lasers, a periodic Bragg grating runs along the active region or waveguide. This grating offers distributed optical feedback by reflecting light that meets the Bragg condition, enforcing a single longitudinal mode of operation[5][7]

A DFB laser diode primarily serves as the optical signal in long-distance, high-capacity optical communications. It finds use in various applications, including fiber sensors, 3D sensors, gas sensors, and disease diagnosis like respiratory and vascular monitoring. For gas sensing, it can function as a light source to detect methane leaks around factory pipes. The grating reduces unwanted side modes and significantly narrows the spectral linewidth. DFB lasers show high side mode suppression ratios, excellent wavelength stability, and low chirp. These features make them ideal for high-speed modulation and long-distance optical transmission[3][2]

However, quarter-wave-shifted DFB lasers face several performance challenges. These include high threshold current, temperature sensitivity, mode instability, and carrier recombination losses. Addressing these issues requires careful design that considers optical, electrical, and thermal effects together[1]

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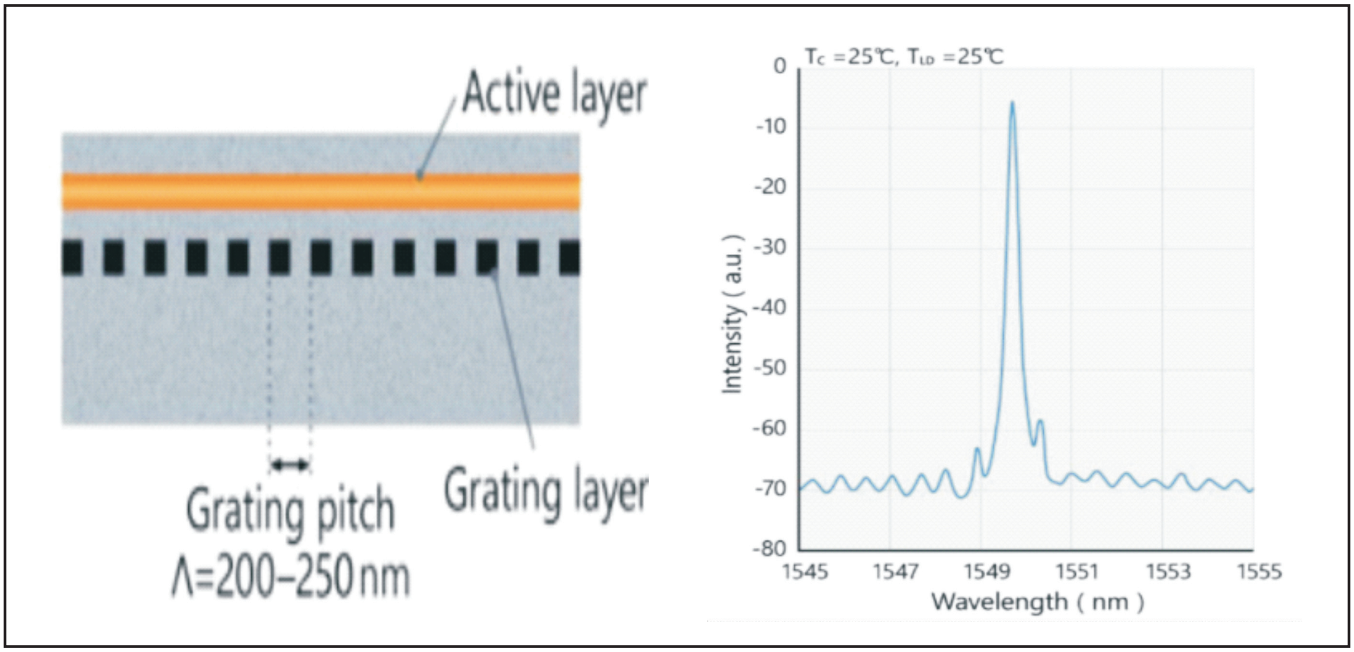

Fig. 1: *Example DFB-LD spectrum for 1550nm*

Despite their benefits, a number of limitations affect the performance of DFB lasers:

1. Large threshold current.
2. Temperature dependence.
3. Mode instability.
4. Carrier recombination losses.

It is important to realize that all these issues must be taken into account and optimised simultaneously within optical, electrical and thermal domains.

The DFB grating is characterized by a grating period Λ= 240–245 nm , designed to satisfy the Bragg condition for emission at the target wavelength. The coupling coefficient (κ) is 80–150 cm^{-1}, representing the index modulation strength of the periodic grating.

2. Materials

The InGaAs/InP material system was chosen for the proposed DFB laser due to its established suitability for 1550nm emission, good lattice matched growth on an InP substrate which provides low loss growth, and the availability of mature material parameter databases. InP has a direct band gap of 1.35 eV (~920nm). The lattice matched InGaAs alloy system can be used to produce bandgap energies from 0.75 eV (the lattice matched In0.53Ga0.47As alloy) to 1.35 eV (InP, where the emission wavelength is ~920nm), that is to say, the band gap wavelengths can be from ~920nm to 1650nm. The material for the quantum wells in the active region and targeting 1550nm emission was chosen to be compressively strained InGaAs with ~1% compressive strain. The use of compressive strain in quantum wells is to increase the differential gain through valence band engineering, where the heavier hole and lighter hole split apart, increasing the threshold carrier density and improving T0 characteristic temperature [9].

The cladding layers are made up of InP. This layer both provides optical confinement due to its low refractive index when compared with the SCH/active layers and also contains the p-n junction layers which carry the current. The cladding layer for carriers,de consists of P-doped InP (1.5*10cm3 zinc doping) whereas the cladding layer for the n-side consists of n-doped InP (silicon doping at approximately 1.5*10cm3). The p InGaAs contact layer (doped 1.5*10cm3 give good low resistance ohmic contact to the metal electrode) is used to establish electrical connection to the p-contact layer of InP via the electrode.

3. Methodology

Simulation Platform Lumerical Multiphysics : All of the simulations were run within Lumerical Device Suite (2020 R2). The Device Suite is one interface to the optical, electrical and thermal solvers that exist within the system and these solvers use a specific language within Lumerical to solve. The 4 main solvers that were used are: MODE Solutions, FDTD Solutions, CHARGE and HEAT. These solvers were all designed to solve for a specific domain of physics, but could be linked to all of the other solvers, receiving values from them and passing values to them. Within Lumerical data can be transferred between the optical, electrical and thermal simulators either through common material databases and/or by scripted parameter passing. [4] [6]

A SiO-based optical waveguide is a structure that guides light by using a low-loss dielectric material (silicon oxide family) where light is confined due to a refractive index contrast between the core and surrounding cladding. [17]

- Core: SiO / SiO_2 (or doped silica)
- Cladding: lower-index oxide or air
- Guiding mechanism: total internal reflection

4. Observations and Results

The optical performance of the laser structure were simulated with the MODE and FDTD solver and the electrical performance were simulated with the CHARGE solver and the thermal performance were simulated with the HEAT solver. The wavelength was selected to be 1550 nm as this point experiences minimum loss and dispersion in the fiber optical cables.

Table 1: *Device Structure and Parameters*

Layer	Material	Thickness
Substrate	InP	2.0 µm
n-Cladding	InP	1.5 µm
Active Region	InGaAs	0.2 µm
p-Cladding	InP	1.5 µm
Contact Layer	InGaAs	0.1 µm

Overall height of the device: 5.3
Overall width of device:3µm

Table 2: *Doping Parameters*

Layer	Doping Type	Concentration
Substrate	n-type	$1 \times 10^{18?}??^{3}$
n-Cladding	n-type	$1 \times 10^{18?}??^{3}$
Active Region	lightly doped	$1 \times 10^{18?}??^{3}$
p-Cladding	p-type	$1 \times 10^{18?}??^{3}$
Contact Layer	p-type	$5 \times 10^{18?}??^{3}$

Table 3: *Material Properties*

Material	Bandgap	Thermal Conductivity
InP	1.34 eV	(68, W/mK)
InGaAs	0.75–0.8 eV	(5–10, W/mK)

The active region was modeled with a doping concentration of $1x10^{18}$ cm^{3} to maintain numerical stability and represent the simulated device configuration. While practical DFB laser active regions are commonly intrinsic or unintentionally doped, the selected doping level was adopted within the simulation framework and does not alter the qualitative performance trends presented in this study.

Fig. 2 The material used for the substrate and the cladding layer was InP due to their higher bandgap energy, high stability and good lattice match to InGaAs. The overall electrical simulation was carried out under forward bias.

5. Conclusion

To conclude, electro-optical-thermal analysis, MODE, FDTD, CHARGE, and HEAT solvers are used to simulate thoroughly 1550 nm InP/InGaAs semiconductor laser and Si-based optical waveguide structure. The combined optical, electrical, electromagnetic and thermal simulation is a facile way to study the characteristic of the design photonic structure. [7] [8]

The overall simulation result indicates the designed InP/InGaAs photonic structure exhibits favorable optical, electrical, electromagnetic, and thermal performance for the 1550nm application. In addition, it verifies the validity of chosen materials, geometric dimensions, doping concentration, Bragg grating Properties and thermal boundary conditions and therefore is favorable to the efficient laser device fabrication and it can be used for photonic integrated circuit [10] [8].

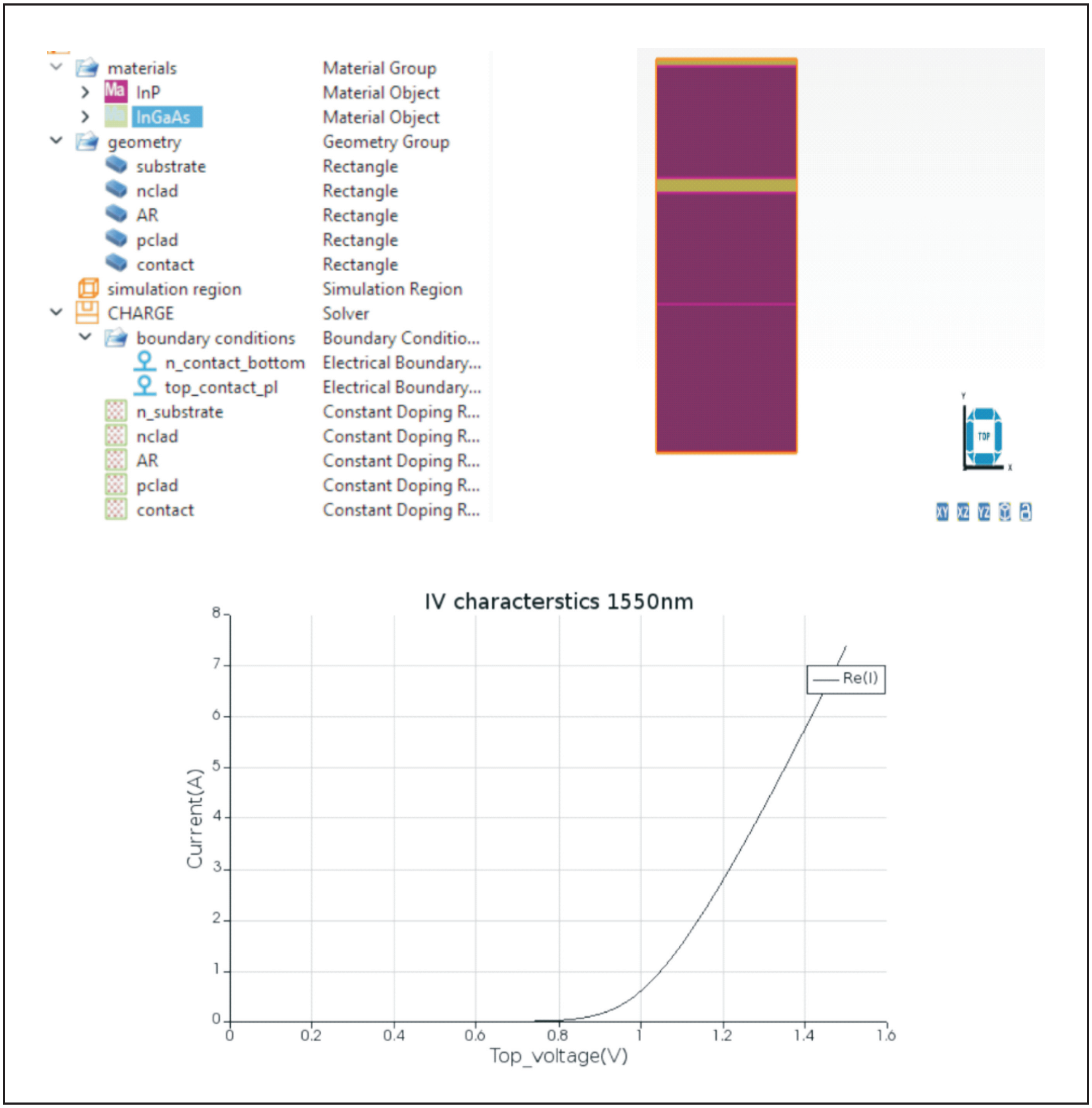

Fig. 2: *I-V Characteristics: The I-V curve plotted was an exponential curve after turn-on of between 0.8V-1.0V*

This structure can be employed to the following applications easily.

1. Optical fiber communication systems
2. Photonic integrated circuits
3. Distributed feedback laser systems
4. Optical filtering devices
5. Silicon photonics platforms
6. High speed optical interconnect

It lays foundation for the design of efficient and stable integrated photonics devices.

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Conflict of Interest Statement

The author declares no financial or commercial conflict of interest related to this research.

Ethical Declarations

The authors declare that this research does not involve human participants, animals, or any procedures requiring ethical approval. All data used in this study were obtained and processed in accordance with applicable ethical and legal guidelines.

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