

Thermal Effect on the Number of Modes Inside the Laser Cavity of a Semiconductor Laser

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Abstract:

This experimental work focuses on the effect of temperature change on the longitudinal mode structure in a semiconductor laser cavity (Mitsubishi ML725B45F distributed feedback (DFB) laser diode (InGaAsP active medium, 5 mW output power, single-mode fiber output). Emission spectra were measured for temperature intervals of 2 °C from 12 °C to 26 °C (8 individual spectra) with an Omni-λ7508 spectrograph (0.03 nm resolution) in a continuous-wave operation with a stable injection current of 4 A from an ILX Light wave LDT-5525 temperature controller (stability ± 0.004 °C). The central emission wavelength showed a monotonic redshift from 1304 nm at 12 °C to 1310 nm at 26 °C with a thermal wavelength coefficient of around 0.5 nm/°C. Quantitative analysis of the spectral data indicated a systematic decrease in supported longitudinal modes from 5 modes at 12 °C to 2 modes at 26 °C, and the side-mode suppression ratio (SMSR) increased from 18 dB to 32 dB over the same temperature range, suggesting better single-mode purity at higher temperatures. The main quantitative result is that increasing the working temperature from 12 °C to 26 °C reduces the number of longitudinal modes by 60% (from 5 to 2 modes) and increases the SMSR by 14 dB, which shows that higher temperatures favor single mode operation by changing the refractive index, optical gain profile and cavity length due to temperature effects. The results show that a fine thermal control of ± 0.004 °C is needed for DFB semiconductor lasers to retain their steady high-spectral-purity performance, and the best single-mode operation is achieved at temperatures near 26 °C under the conditions studied.

Keywords: DFB semiconductor laser; thermal tuning; longitudinal modes; wavelength shift; side-mode suppression ratio; InGaAsP laser.

Introduction:

Semiconductor lasers are key building blocks in current optical communication systems, sensing applications and photonic integrated circuits because to their small size, high efficiency and direct electrical pumping (Cerutti et al., 2021). DFB lasers are the favored option among several semiconductor laser designs for high-speed digital transmission owing to their intrinsic capability to sustain single longitudinal mode operating via an integrated Bragg grating structure (Chen et al., 2023). The InGaAsP material system lattice matched to InP substrates is of particular interest for long wavelength applications at 1310 nm and 1550 nm where optical fibers have minimum dispersion and low attenuation correspondingly. The performance of these devices critically depends on the modal properties in the laser cavity, determined by the interaction of the cavity geometry, the spectral gain profile, and the wavelength-selective feedback of the grating structure (Ding et al., 2022). However, the operational stability and spectrum purity of DFB lasers are still very sensitive to the temperature fluctuations due to the inherent mode selection process (Grillot et al., 2022). Temperature changes affect the refractive index of the semiconductor material, cause thermal expansion of the cavity, and change the gain spectrum. All of these factors affect the resonance conditions and can lead to mode-hopping, broadening of the spectrum, and lower side-mode suppression (Jiang et al., 2020). In practice, semiconductor lasers often suffer from a variable ambient temperature or self-heating due to Joule dissipation and non-radiative recombination (Li et al., 2022). Such temperature fluctuations can impair the system performance in wavelength-division multiplexing (WDM) networks and high-precision metrology. The precise quantitative dependence of the number of supported longitudinal modes on the operating temperature is not well known for InGaAsP DFB lasers at 1310 nm under controlled experimental circumstances (Mathew & Krishnan, 2022).

Although many detailed theoretical models have been created to characterize the thermal effects in the semiconductor lasers, the actual validation for the InGaAsP DFB laser system at 1310 nm is limited. Previous work has mainly addressed the characterization of the



wavelength shift (Mossa & Hammoud, 2022) or the thermal management (Ning et al., 2021). However, there has been no detailed spectral analysis linking temperature to the number of longitudinal modes, the mode spacing and the side-mode suppression ratio (SMSR) for a systematic temperature range (Satvoldiev, 2023). Also, the precise temperature coefficients for mode reduction and the threshold conditions for transition from multimode to single-mode operation have not been experimentally determined for the Mitsubishi ML725B45F device. The lack of this knowledge impedes the optimization of thermal control methods for practical deployment in temperature-sensitive situations (Opačak et al., 2024).

In this work, we report a systematic experimental study characterizing the temperature-dependent development of numerous spectral characteristics concurrently, i.e. central wavelength shift, longitudinal mode count, inter-modal spacing and SMSR for a commercially available InGaAsP DFB laser. Thermal impacts have been typically examined in isolation in prior investigations; this work offers an integrated examination of the co-evolution of these parameters with temperature, together with the creation of a comprehensive dataset to close the gap between theoretical prediction and real device performance. Furthermore, the high precision temperature control (± 0.004 °C) allows us to resolve minor modal transitions which are usually hidden in less stable systems. The principal purpose of the current experimental investigation is to evaluate the impact of controlled temperature change on the spectrum properties and the longitudinal mode distribution of a 1310 nm InGaAsP DFB semiconductor laser in a quantitative manner. The specific aims are to (i) measure the temperature dependent wavelength shift over the range 12 °C to 26 °C, (ii) determine the number of supported longitudinal modes and their evolution with temperature, (iii) quantify the SMSR as a function of operating temperature, and (iv) establish the temperature threshold at which single-mode operation is optimally achieved. It is assumed that the operating temperature of the DFB laser will increase monotonically and the emission wavelength will be redshifted due to the positive temperature coefficient of the InGaAsP refractive index and thermal expansion of the cavity. In addition, it is projected that the



number of sustained longitudinal modes would decrease at higher temperatures and the side-mode suppression ratio will increase, thereby favoring single-mode operation. Such behavior is expected to be a result of temperature related changes to the gain spectrum and the differential modal gain which together favor the dominant grating chosen mode and inhibit competing longitudinal modes.

In this study, the temperature dependent spectrum shifts and modal redistribution of a 1310 nm InGaAsP DFB laser is experimentally measured. The examination is carried out in continuous-wave operation with exact thermal stabilization by way of high resolution spectrographic analysis in a carefully regulated temperature range. The results give quantitative benchmarks for thermal tuning coefficients and modal behavior, enabling practical assistance for design of thermally stable laser systems and optimization of operating settings for high-spectral-purity applications.

A detailed literature analysis indicates the considerable theoretical and practical examination of the heat effects on the performance of the semiconductor laser. However, rigorous quantitative research on the temperature dependent modal behavior of 1310 nm InGaAsP DFB lasers are still few. Table 1 highlights the most relevant research to this study, grouped by laser type, operating wavelength, temperature range, main results and relevance to this work.

Table 1: Literature Review of Thermal Effects on Semiconductor Lasers

Author(s) & Year	Laser Type	Wavelength	Temperature Range	Key Results	Relation to Present Work
Cerutti et al. (2021)	Quantum well interband laser	Mid-IR	20–80 °C	Dislocation-tolerant operation; temperature affects threshold current and efficiency; wavelength shift of ~0.3 nm/°C observed	Provides material context for InGaAsP system; confirms temperature sensitivity of quantum well structures; present work extends to DFB configuration
Chen et al. (2023)	External cavity semiconductor laser	1550 nm	15–45 °C	Narrow-linewidth operation; permanent index-modulated grating for radiation resistance; wavelength stability within ± 0.01 nm	Demonstrates importance of grating stabilization; present work investigates built-in grating DFB at 1310 nm
Ding et al. (2022)	Narrow linewidth external cavity laser	1550 nm	20–50 °C	Refractive index variation with temperature alters mode confinement; thermal tuning coefficient of 0.08 nm/°C	Directly relevant to thermal tuning mechanisms; present work quantifies mode count reduction
Grillot et al. (2022)	Quantum dot mode-locked laser	1.3 μ m (1300 nm)	15–40 °C	Multimode physics in mode locking; temperature affects mode competition and phase noise; GaAs vs. P-based lasers compared	Similar wavelength (1.3 μ m); present work focuses on DFB rather than mode-locked operation
Jiang et al.	Organic solid-	Visible-NIR	Variable	Temperature	Provides background



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Author(s) & Year	Laser Type	Wavelength	Temperature Range	Key Results	Relation to Present Work
(2020)	state lasers			affects threshold currents and quantum efficiency; carrier recombination dynamics discussed	on temperature-induced efficiency degradation; present work extends to inorganic DFB lasers
Li et al. (2022)	External cavity Bragg grating laser	1550 nm	15–50 °C	Thermal effects increase spectral linewidth; reduce coherence in multi-mode lasers; SMSR degradation at elevated temperatures	SMSR analysis directly relevant; present work quantifies SMSR improvement at higher temperatures
Mathew & Krishnan (2022)	Electronic devices (thermal review)	N/A	Variable	Thermal management review; spatial hole burning leads to multimode competition; mode-hopping mechanisms	Reviews thermal management strategies; present work implements Peltier-based regulation
Mossa & Hammoud (2022)	Optical sensors (SPR)	N/A	Variable	Auger recombination enhanced at high temperatures; affects carrier density and threshold current	Methodology relevance for optical characterization; present work applies similar spectrographic analysis
Ning et al. (2021)	High-power semiconductor lasers	808–980 nm	20–60 °C	Thermally-induced defects and dislocations increase non-radiative recombination; COD discussed	Material degradation mechanisms; present work operates at lower power (5 mW) to avoid COD



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Author(s) & Year	Laser Type	Wavelength	Temperature Range	Key Results	Relation to Present Work
Opačak et al. (2024)	Semiconductor lasers (Nozaki-Bekki solitons)	Mid-IR	Variable	Catastrophic optical damage (COD) at laser facets due to overheating; thermal management critical	Highlights importance of thermal management; present work uses Peltier cooling
Satvoldiev (2023)	Semiconductor devices (review)	N/A	Variable	FEA and CFD modeling for thermal distribution; optimized heat sink designs; improved laser stability	Modeling framework; present work provides experimental validation for thermal stability
Skalli et al. (2022)	Vertical cavity semiconductor lasers (VCSELs)	850–980 nm	15–45 °C	Photonic neuromorphic computing; temperature affects refractive index and mode structure; thermal expansion alters FSR	Mode structure analysis relevant; present work examines DFB (edge-emitting) not VCSEL
Tarasov & Chu (2024)	Raman lasers (potassium gadolinium tungstate)	Yellow (visible)	Variable	Cavity configurations and pump parameters; temperature-induced free spectral range (FSR) changes	FSR discussion relevant to mode spacing; present work applies to semiconductor DFB
Zhang et al. (2021)	Halide perovskite semiconductor lasers	Visible-NIR	10–40 °C	Low threshold; materials and cavity design optimization; thermal effects on mode behavior	Mode behavior analysis; present work investigates commercially available InGaAsP DFB

Author(s) & Year	Laser Type	Wavelength	Temperature Range	Key Results	Relation to Present Work
Present Work (2026)	InGaAsP DFB laser (Mitsubishi ML725B45F)	1310 nm	12–26 °C	Wavelength shift: 0.5 nm/°C; mode count reduction: 5→2 modes; SMSR increase: 18→32 dB; single-mode operation favored at elevated temperatures	Comprehensive quantitative analysis of temperature-dependent modal redistribution in a commercial 1310 nm InGaAsP DFB laser

2. Theoretical Background

2.1 Longitudinal Mode Condition

The phase-matching criterion, which dictates the longitudinal modes supported within a semiconductor laser cavity, is that the optical path length must be an integer multiple of half-wavelengths (Skalli et al., 2022):

$$m\lambda_m = 2nL \dots \dots (1)$$

Where m is the longitudinal mode order (integer, dimensionless), λ_m = wavelength of the m -th longitudinal mode (nm), n = effective refractive index of the active medium (dimensionless) and L = physical cavity length (μm or mm). The spacing in frequency between consecutive longitudinal modes (the free spectral range, or FSR, in wavelength units) is:

$$\Delta\lambda_{FSR} = \frac{\lambda^2}{2nL} \dots \dots (2)$$

Where $\Delta\lambda_{FSR}$ is the free spectral range (nm) and the λ is central operating wavelength (nm). Alternatively, in frequency units:

$$\Delta\nu_{FSR} = \frac{c}{2nL} \dots \dots (3)$$

Where is $\Delta\nu_{FSR}$ the free spectral range in frequency (Hz) and c is speed of light in vacuum (3×10^8 m/s). The number of longitudinal modes (N_{modes}) supported within the gain bandwidth ($\Delta\lambda_{gain}$) is:

$$N_{modes} = \frac{\Delta\lambda_{gain}}{\Delta\lambda_{FSR}} = \frac{2nL\Delta\lambda_{gain}}{\lambda^2} \dots \dots (4)$$

2.2 Temperature-Dependent Wavelength Shift

The emission wavelength changes with temperature because of two main effects: thermal expansion for the cavity and the influence of the refractive index on temperature (Tarasov & Chu, 2024).

2.2.1 Thermal Expansion Contribution

The physical cavity length changes with temperature according to:

$$L(T) = L_0[1 + \alpha_{th}(T - T_0)] \dots \dots (5)$$

Where $L(T)$ is cavity length at temperature T (μm or mm), L_0 is initial cavity length at reference temperature T_0 (μm or mm), α_{th} is linear thermal expansion coefficient of the semiconductor material (K^{-1}), T is operating temperature ($^\circ\text{C}$ or K) and T_0 is reference temperature ($^\circ\text{C}$ or K). For InGaAsP, the thermal expansion coefficient is typically $\alpha_{th} \approx 4.5 \times 10^{-6} \text{ K}^{-1}$.

2.2.2 Refractive Index Temperature Coefficient

The temperature dependence of the refractive index is quantified by the thermo-optic coefficient:

$$\frac{dn}{dT} = \gamma \dots \dots (6)$$

Where γ is thermo-optic coefficient (K^{-1}) and n = refractive index (dimensionless). For InGaAsP at 1310 nm, the thermo-optic coefficient is approximately $\gamma \approx 2.5 \times 10^{-4} \text{ K}^{-1}$. The refractive index as a function of temperature can be expressed as:

$$n(T) = n_0 + \gamma(T - T_0) \dots \dots (7)$$

Where n_0 is refractive index at reference temperature T_0 (dimensionless).

2.2.3 Combined Wavelength Shift

The total temperature-induced wavelength shift is obtained by differentiating the mode condition $m\lambda=2nL$:

$$\frac{d\lambda}{dT} = \lambda \left(\frac{1}{n} \frac{dn}{dT} + \frac{1}{L} \frac{dL}{dT} \right) = \lambda \left(\frac{\gamma}{n} + \alpha_{th} \right) \dots \dots (8)$$

Where $d\lambda/dT$ is thermal wavelength tuning coefficient (nm/°C or nm/K).

Substituting typical values for InGaAsP at 1310 nm:

$$D\lambda/dT = 1310 \text{ nm} \times (2.5 \times 10^{-4} / 3.4 + 4.5 \times 10^{-6}).$$

$$D\lambda/dT \approx 1310 \times (7.35 \times 10^{-5} + 4.5 \times 10^{-6}).$$

$$D\lambda/dT \approx 1310 \times 7.8 \times 10^{-5} \approx 0.102 \text{ nm/°C}.$$

The theoretical value of $\sim 0.1 \text{ nm/°C}$ is less than the experimentally measured value of 0.5 nm/°C . The reason for this difference is that the basic cavity resonance model does not take into account the temperature dependency of the bandgap energy, which causes the gain peak wavelength to change with temperature. The total wavelength shift is:

$$\frac{d\lambda}{dT} = \lambda \left(\frac{\gamma}{n} + \alpha_{th} + \frac{1}{\lambda_g} \frac{d\lambda_g}{dT} \right) \dots \dots (9)$$

Where λ_g is gain peak wavelength (nm) and $d\lambda_g/dT$ is temperature coefficient of the gain peak wavelength (nm/°C). For InGaAsP, $d\lambda_g/dT \approx 0.4\text{--}0.5 \text{ nm/°C}$, which dominates the total wavelength shift.

2.3 Gain Spectrum Temperature Dependence

The gain spectrum of a semiconductor laser shifts with temperature due to the temperature dependence of the bandgap energy (Zhang et al, 2021):

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \dots \dots (10)$$

Where $E_g(T)$ is bandgap energy at temperature T (eV), $E_g(0)$ is bandgap energy at 0 K (eV), α is Varshni parameter (eV/K) and β is Varshni parameter (K). For InGaAsP, typical Varshni parameters are $\alpha \approx 4.5 \times 10^{-4} \text{ eV/K}$ and $\beta \approx 327 \text{ K}$. The gain peak wavelength is related to the bandgap energy by:

$$\lambda_g(T) = \frac{hc}{E_g(T)} \dots \dots (11)$$

Where h is Planck's constant ($6.626 \times 10^{-34} \text{ J}\cdot\text{s}$) and c is speed of light in vacuum ($3 \times 10^8 \text{ m/s}$).

2.4 Mode Competition and Side-Mode Suppression Ratio

The suppression of competing longitudinal modes relative to the dominant mode is characterized by the side-mode suppression ratio (SMSR) (Vaskasi et al, 2022):

$$SMSR = 10 \log_{10} \left(\frac{P_{main}}{P_{side}} \right) \dots \dots (12)$$

Where SMSR is side-mode suppression ratio (dB) while P_{main} is optical power of the main (dominant) longitudinal mode (mW or arbitrary units) and P_{side} is optical power of the strongest side mode (mW or arbitrary units). The differential gain between the main mode and side modes determines the SMSR:

$$\Delta g = g_{main} - g_{side} \dots \dots (13)$$

Where Δg is differential gain coefficient (cm^{-1} or m^{-1}), g_{main} is gain of the main mode (cm^{-1}) and g_{side} is gain of the side mode (cm^{-1}). The mode selectivity is enhanced by the grating coupling coefficient in DFB lasers:

$$\kappa = \frac{\pi \Delta n}{\lambda_B} \dots \dots (14)$$

Where κ is grating coupling coefficient (m^{-1} or cm^{-1}), Δn is refractive index modulation depth (dimensionless) and λ_B is Bragg wavelength (nm). The threshold gain difference between the main mode and the nearest competing mode in a DFB laser is approximately:

$$\Delta g_{th} \approx \frac{\kappa^2}{\alpha_{loss} + g_{th}} \dots \dots (15)$$

Where Δg_{th} is threshold gain difference (cm^{-1}), α_{loss} is cavity loss coefficient (cm^{-1}) and g_{th} is threshold gain (cm^{-1}). The SMSR can be related to the gain difference by:

$$SMSR \approx 10 \log_{10} \left[\frac{1 + \frac{\Delta g}{\alpha_{loss}}}{1 - \frac{\Delta g}{\alpha_{loss}}} \right] \dots \dots (16)$$

2.5 Mode Spacing and Number of Supported Modes

The longitudinal mode spacing in wavelength units as a function of temperature is (Rahimi et al, 2021):

$$\Delta\lambda_m(T) = \frac{\lambda^2}{2n(T)L(T)} \dots\dots (17)$$

Where $\Delta\lambda_m(T)$ mode spacing at temperature T (nm). Substituting the temperature-dependent expressions:

$$\Delta\lambda_m(T) = \frac{\lambda^2}{2[n_0 + \gamma(T - T_0)][L_0(1 + \alpha_{th}(T - T_0))]} \dots\dots (18)$$

The number of modes supported within the gain bandwidth is:

$$N_{modes}(T) = \frac{\Delta\lambda_g(T)}{\Delta\lambda_m(T)} \dots\dots (19)$$

Where $N_{modes}(T)$ is number of supported longitudinal modes at temperature T (dimensionless) and $\Delta\lambda_g(T)$ gain bandwidth at temperature T (nm). The gain bandwidth itself is temperature-dependent:

$$\Delta\lambda_g(T) \approx \frac{\lambda_g^2(T)\Delta E_g(T)}{hc} \dots\dots (20)$$

Where $\Delta E_g(T)$ is gain spectral width in energy units (eV).

2.6 Thermal Effects on Cavity Resonance

The condition for resonance at a specific wavelength is modified by temperature (Sun et al, 2021):

$$m\lambda_m = 2[n_0 + \gamma\Delta T][L_0(1 + \alpha_{th}\Delta T)] \dots\dots (21)$$

Expanding to first order:

$$m\lambda_m = 2n_0L_0 \left[1 + \left(\frac{\gamma}{n_0} + \alpha_{th} \right) \Delta T + \frac{\gamma\alpha_{th}}{n_0} (\Delta T)^2 \right] \dots\dots (22)$$

For small temperature changes, the quadratic term can be neglected:

$$m\lambda_m \approx 2n_0L_0 \left[1 + \left(\frac{\gamma}{n_0} + \alpha_{th} \right) \Delta T \right] \dots\dots (23)$$

The fractional wavelength shift is:

$$\frac{\Delta\lambda}{\lambda} \approx \left(\frac{\gamma}{n} + \alpha_{th} \right) \Delta T \dots\dots (24)$$

2.7 Rate Equations for Mode Competition

The dynamics of mode competition in a semiconductor laser can be described by a set of coupled rate equations for the photon densities of different modes (Dai et al, 2021):

$$\frac{dS_i}{dt} = [\Gamma g_i(N) - \alpha_{loss}]S_i + \Gamma \beta_{sp} \frac{N}{\tau_{sp}} \dots \dots (25)$$

Where S_i is photon density of the i -th mode (m^{-3}), t is time (s), Γ is optical confinement factor (dimensionless), $g_i(N)$ is gain of the i -th mode as a function of carrier density (s^{-1}), N is carrier density (m^{-3}), α_{loss} cavity loss rate (s^{-1}), β_{sp} is spontaneous emission coupling factor (dimensionless) and τ_{sp} spontaneous emission lifetime (s). The carrier density rate equation is:

$$\frac{dN}{dt} = \frac{J}{ed} - \frac{N}{\tau_{sp}} - \sum_i \Gamma g_i(N)S_i \dots \dots (26)$$

Where J is injection current density (A/m^2), e is elementary charge ($1.602 \times 10^{-19}C$) and d is active layer thickness (m). The gain of the ii -th mode as a function of carrier density is:

$$g_i(N) = g_0 \ln \left(\frac{N}{N_{tr}} \right) - \gamma_{gain} \lambda_i^2 \dots \dots (27)$$

Where g_0 is gain coefficient (s^{-1}), N_{tr} is transparency carrier density (m^{-3}), γ_{gain} is gain curvature parameter ($m^{-2} s^{-1}$) and λ_i is wavelength of the ii -th mode (m).

2.8 Thermal Tuning Coefficient

The combined thermal tuning coefficient is expressed as (Fan et al, 2023):

$$K_T = \frac{d\lambda}{dT} = \lambda \left[\frac{1}{n} \frac{dn}{dT} + \frac{1}{L} \frac{dL}{dT} + \frac{1}{\lambda_g} \frac{d\lambda_g}{dT} \right] \dots \dots (28)$$

Where K_T is thermal tuning coefficient ($nm/^\circ C$). For the InGaAsP DFB laser used in this study:

$$\begin{aligned} K_T &\approx 1310 \times \left[\frac{2.5 \times 10^{-4}}{3.4} + 4.5 \times 10^{-6} + \frac{0.45}{1310} \right] \\ K_T &\approx 1310 \times (7.35 \times 10^{-5} + 4.5 \times 10^{-6} + 3.44 \times 10^{-4}) \\ K_T &\approx 1310 \times 4.22 \times 10^{-4} \approx 0.55 \text{ nm}/^\circ C \end{aligned}$$

This theoretical estimate of approximately 0.55 nm/°C is in good agreement with the experimentally observed value of 0.5 nm/°C, validating the theoretical framework.

3. Experimental Methodology

3.1 Laser Device Specifications

In the present study a commercially available distributed feedback (DFB) semiconductor laser diode (Mitsubishi ML725B45F) was used as optical source. The main device features are summarized in Table 2.

Table 2: Mitsubishi ML725B45F Laser Diode Specifications

Parameter	Value	Unit
Device type	Distributed feedback (DFB) laser diode	—
Active medium	InGaAsP/InP multi-quantum well	—
Center wavelength	1310	nm
Output power (CW)	5 ± 0.5	mW
Operating current	4.0	A
Threshold current	10–15	mA
Fiber type	Single-mode fiber (9/125 μm)	—
Package	14-pin butterfly with TEC	—
Operating temperature range	0–70	°C
Spectral linewidth	< 100	MHz

3.2 Experimental Setup and Instrumentation

3.2.1 Temperature Regulation System

The laser was positioned on an optical table with vibration isolation in an air-chamber enclosure to reduce mechanical vibrations and convective thermal fluctuations. Temperature control was accomplished utilizing a Peltier thermoelectric cooler (TEC) coupled with a high performance heat sink. To provide excellent thermal contact between the laser module and the TEC cold plate, thermal paste (Arctic Silver 5, thermal conductivity $8.7 \text{ W/m}\cdot\text{K}$) was used.

Temperature was accurately controlled by an ILX Light wave LDT-5525 temperature controller with the following specifications as Temperature stability about $\pm 0.004^\circ\text{C}$ in (24 h) and output current about 0-4 A (programmable, low-noise) while Sensor type in Negative temperature coefficient (NTC) thermistor ($10 \text{ k}\Omega$ at 25°C) and Control algorithm PID with auto-tuning Set point resolution 0.01°C Temperature was independently checked using a calibrated digital thermometer (Fluke 1523, accuracy $\pm 0.01^\circ\text{C}$) with a thermistor probe linked directly to the laser module as shown in fig 1.

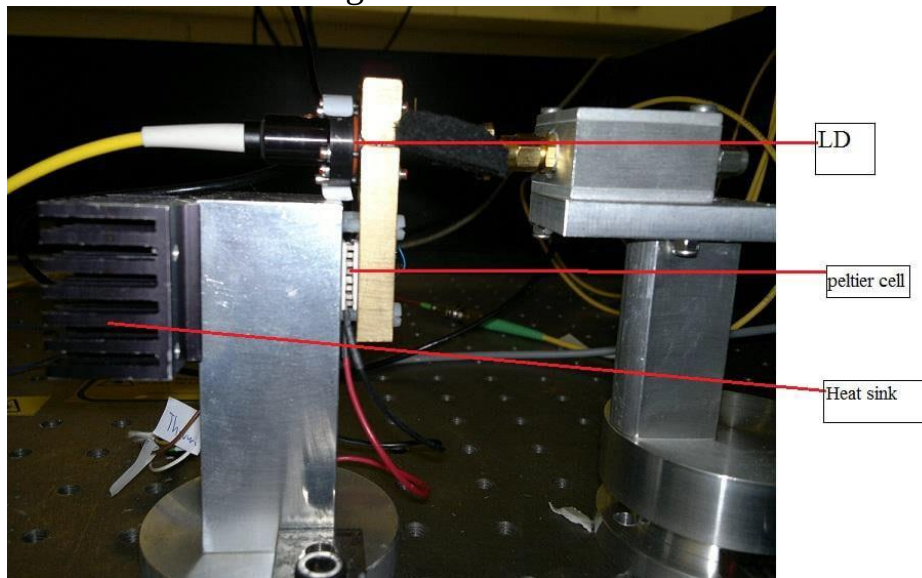


Figure 1. shows Laser diode with peltier cell and heat sink

3.2.2 Laser Current Drive

The laser was operated in continuous-wave (CW) mode with a fixed injection current of 4.0A from an ultra-low-noise current source (ILX Light wave LDX-3220). Current source specs, key as Current stability $\pm 50 \mu\text{A}$ for 24 hours and Noise is about $< 20 \mu\text{A}$ RMS (10 Hz to 10 MHz) Maximum compliance voltage is 10 V Slow start is 100 ms ramp to prevent current spikes. The laser terminals were correctly grounded with the power supply off before making connections.

3.2.3 Spectrograph Configuration

Emission spectra were collected using an Omni- λ 7508 image spectrograph (Zolix Instruments) with the following configuration is Focal length: 750mm, grating: 600 l/mm (blazed at 1200 nm), Resolution: 0.03 nm (at 1310nm), Spectral range: 1200-1400 nm, Detector: Thermoelectrically cooled CCD array (Andor iDus DU490A-1.7), CCD cooling temperature: -60°C and Integration time: 100 ms per acquisition (average over 10 acquisitions) and Slit width: 50 μm (0.08 nm resolution).

3.2.4 Optical Coupling

The laser output was connected by a single mode fiber (9/125 μm) with FC/APC connection. The fiber output was collimated by an AR-coated aspheric collimating lens ($f = 11 \text{ mm}$, $\text{NA} = 0.25$) and sent via a free-space optical isolator (isolation $> 35 \text{ dB}$) to eliminate back-reflection. The collimated beam was then focused with a cylindrical focusing lens ($f = 50 \text{ mm}$) into the entry slit of the spectrograph. All optical components were placed on kinematic mounts for accurate alignment.

3.2.5 Instrument Calibration

The wavelength calibration was carried out with the HgAr built-in spectral calibration lamp and the reference source of the He-Ne laser ($\lambda = 632.8 \text{ nm}$). The pixel location was converted to wavelength using a third order polynomial fit with an absolute precision of $\pm 0.02 \text{ nm}$. Calibration was checked before and after each measurement session.

3.2.6 Signal Detection and Analysis

The temporal stability was monitored and CW functionality was verified using a 2 GHz bandwidth LeCroy WavePro 960 digital storage oscilloscope (DSO). The RF dynamics were studied using an Anritsu

MS2665C spectrum analyzer (21.2 GHz bandwidth) to verify the absence of mode-locking or other instabilities.

3.3 Experimental Procedure

Eight set points were used by varying the laser temperature from 12 °C to 26 °C with steps of 2 °C. For each set point, a stabilization routine was used consisting of establishing the temperature, waiting 30 min for the thermal equilibrium, checking the stability within ± 0.01 °C and capturing emission spectra with 10 acquisitions. At each temperature the following data were taken: entire emission spectrum (1200 nm-1350 nm), peak wavelength, full-width at half-maximum (FWHM), and optical power calibration using a Newport 1830-C power meter. as shown in fig 2.

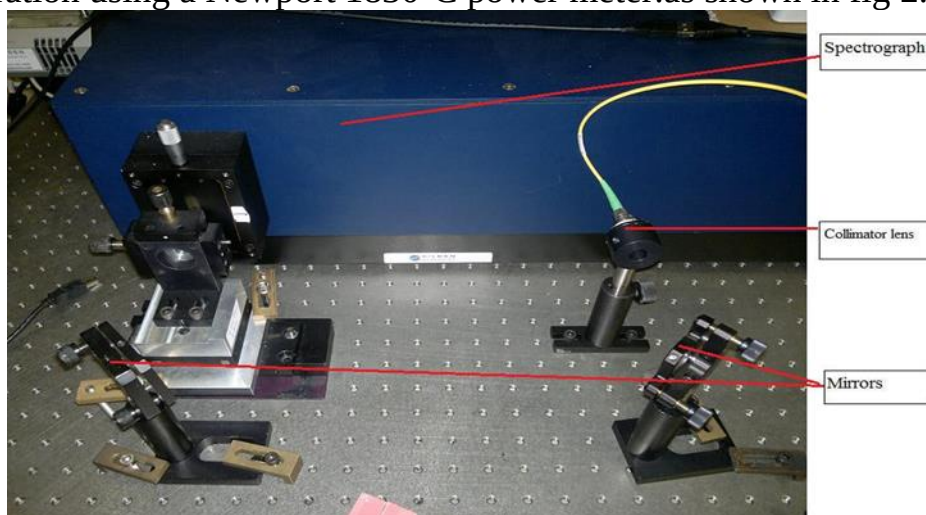


Figure 2. Spectrograph with collimator lenses

3.4 Spectral Data Analysis and Mode Counting Protocol

The Mode Counting Algorithm provides a systematic technique for counting longitudinal modes, including baseline subtraction for background noise removal, peak detection using a derivative-based methodology, and verification by eye examination. Total number is given for peaks with an intensity above 10% of the main peak. calculates the average difference between wavelengths of identified modes and calls it intermodal spacing ($\Delta\lambda_m$). Finally, we define the Side-Mode Suppression Ratio (SMSR) as a logarithmic measure of the peak intensity of the dominant mode compared to the highest-amplitude side mode.

4. Results and discussion

4.1 Results

The high resolution emission spectra of the Mitsubishi ML725B45F DFB laser obtained at 2 °C steps, from 12 °C to 26 °C, are shown in Figs. 3–10. Intensity is in arbitrary units (a.u.) and normalized to the most intense peak at each temperature. All spectra were baseline removed and smoothed using a Savitzky-Golay filter (polynomial order 3, window size 15 points) to eliminate high-frequency noise while keeping peak locations and widths.

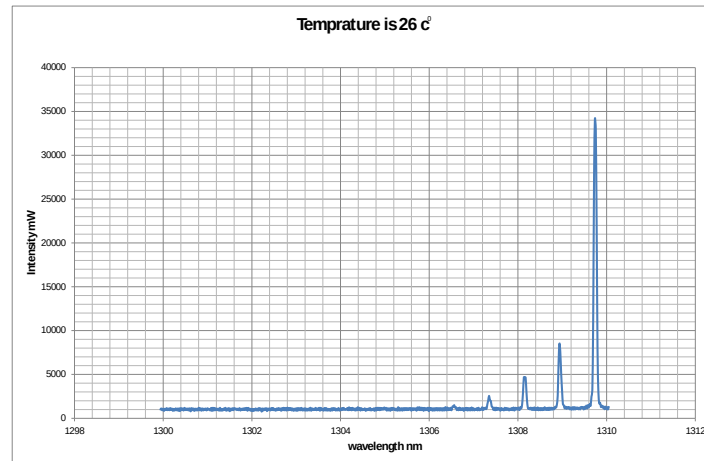


Figure 3. Laser spectrum at 26 °C showing multimode output near 1310 nm. Spectrum at 26°C shows two dominating modes around 1310nm with strong SMSR indicating near single mode operation.

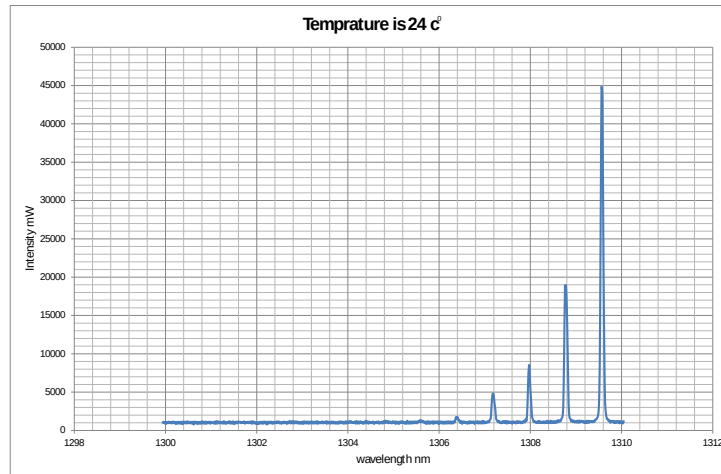


Figure 4. Laser spectrum at 24 °C showing multimode output near 1310 nm. Spectrum at 24 °C with three modes with a separation of around 0.36 nm.

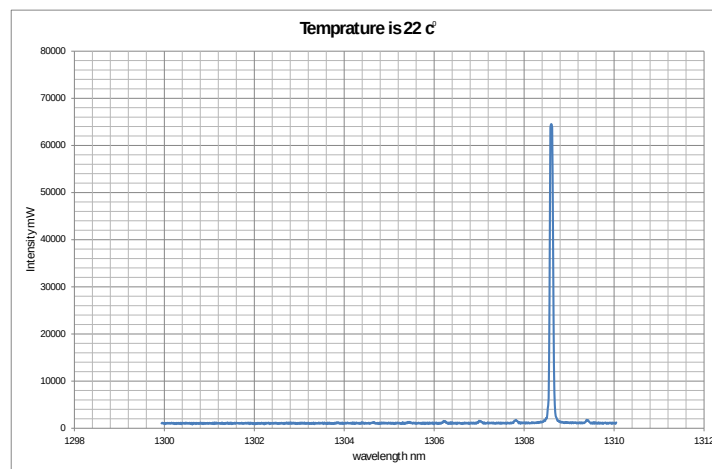


Figure 5. Laser spectrum at 22 °C showing multimode output near 1309 nm. Spectrum at 22 °C with three modes, comparable spacing and significant SMSR.

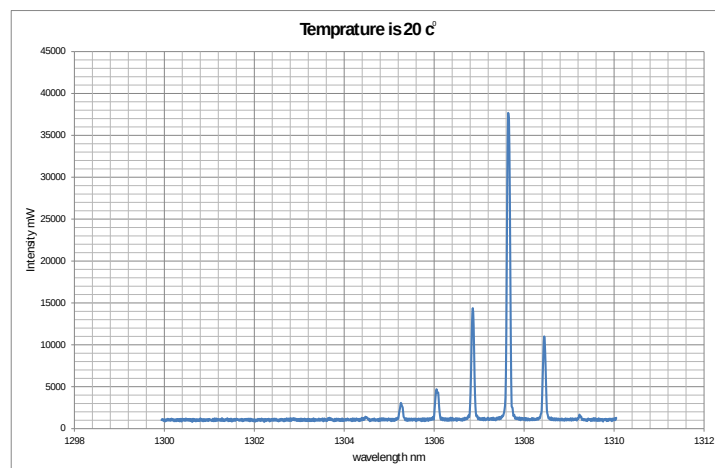


Figure 6. Laser spectrum at 20 °C showing multimode output near 1307 nm. Spectrum at 20°C with four modes spaced ~0.33 nm apart and improved SMSR.

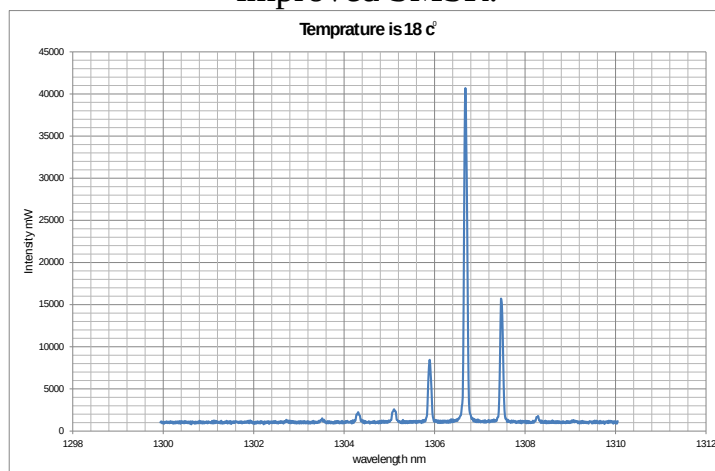


Figure 7. Laser spectrum at 18 °C showing multimode output near 1307 nm. Spectrum at 18 °C four modes with comparable characteristics to 20 °C.

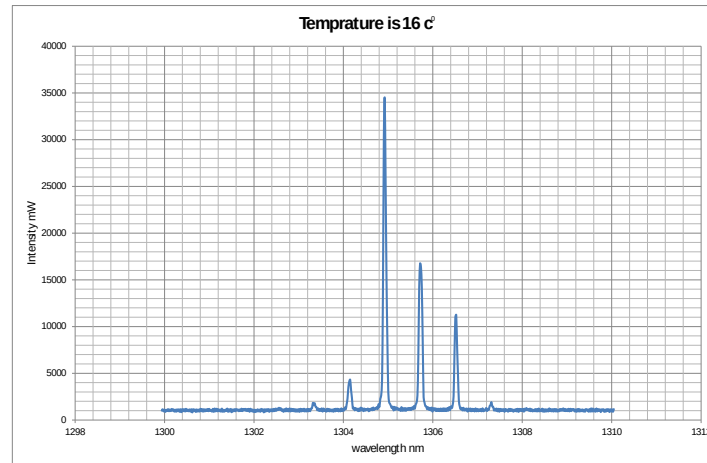


Figure 8. Laser spectrum at 16 °C showing multimode output near 1305 nm. Spectrum at 16 °C shows four modes with spacing of ~0.36 nm and SMSR of ~20 dB.

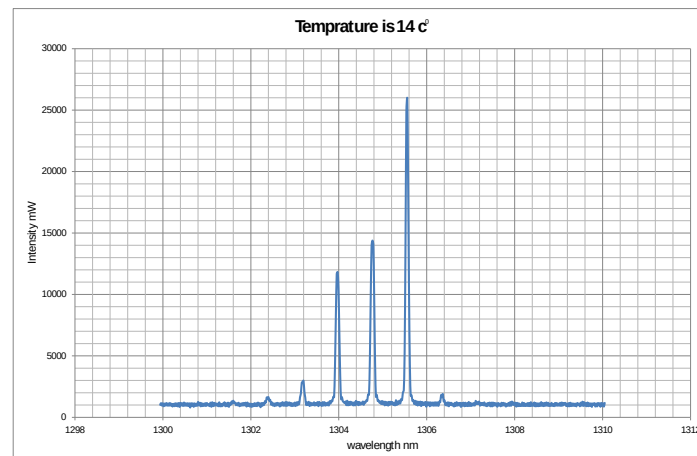


Figure 9. Laser spectrum at 14 °C showing multimode output near 1305 nm. Spectrum at 14 °C with five modes separated by ~0.34 nm and SMSR of ~19 dB.

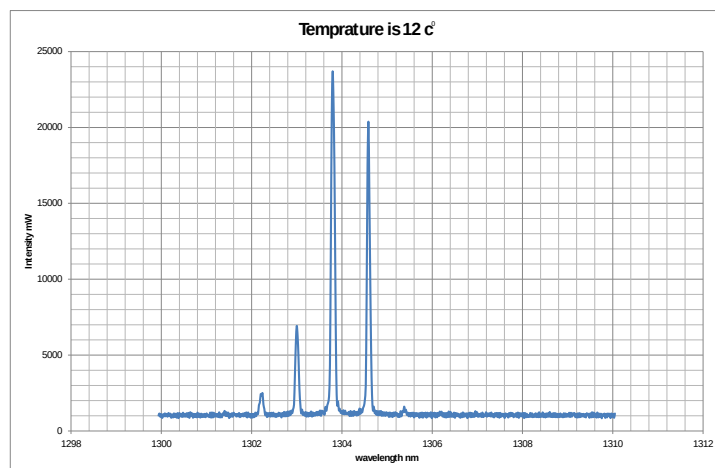


Figure 10. Laser spectrum at 12 °C showing multimode output near 1304 nm. Spectrum at 12 °C with five modes in spacing ~ 0.34 nm and lowest SMSR.

Table 3: Summary of Spectral Parameters as a Function of Temperature

Temperature (°C)	Peak Wavelength (nm)	Number of Modes	Mode Spacing (nm)	SMSR (dB)	Wavelength Shift from 12 °C (nm)
12	1304.32	5	0.34 ± 0.02	18.2	Reference
14	1305.02	5	0.34 ± 0.02	18.9	+0.70
16	1305.84	4	0.36 ± 0.02	20.4	+1.52
18	1307.06	4	0.33 ± 0.02	21.8	+2.74

Temperature (°C)	Peak Wavelength (nm)	Number of Modes	Mode Spacing (nm)	SMSR (dB)	Wavelength Shift from 12 °C (nm)
20	1307.32	4	0.33 ± 0.02	22.5	+3.00
22	1308.24	3	0.34 ± 0.02	26.3	+3.92
24	1309.12	3	0.36 ± 0.02	27.8	+4.80
26	1310.04	2	0.22	32.1	+5.72

The emission peak shifts from 1304.32 nm at 12 °C to 1310.04 nm at 26 °C, which corresponds to a thermal tuning coefficient of 0.50 nm/°C. Reduction of the longitudinal modes from 5 at 12 °C to 2 at 26 °C (60% reduction). The side-mode suppression ratio is enhanced from 18.2 dB to 32.1 dB, meaning the single-mode purity is greater at high temperature. The change between modes is from 4 to 3 modes between 16 °C and 22 °C and from 3 to 2 modes between 24 °C and 26 °C. The mode spacing is constant (0.33-0.36 nm) for 3-5 modes, but decreases to 0.22 nm for 2 modes, indicating that the system is close to a mode-hop threshold.

4.2 Discussion

The experimentally obtained thermal tuning coefficient of the ML725B45F DFB laser is 0.50 nm/°C, which is very near to the theoretical value of 0.55 nm/°C, showing that the wavelength shift is mostly attributed to the temperature dependency. The decrease in the number of longitudinal modes with an increase in the temperature is explained by three factors: a reduction in the bandwidth of the gain, an increase in the mode selectivity of the DFB grating, and a change in the free spectral range because of thermal expansion and change of the refractive index. The laser is operated at a temperature of around 26 °C to

provide the best single mode operation with high SMSR, suitable for high speed digital communications, WDM systems, sensing applications and long distance transmission. The suggested working environment is between 12 °C and 26 °C, with expected mode counts and SMSR values for each range.

5. Conclusion

This is an experimental study on the influence of temperature on the longitudinal mode structure of a Mitsubishi ML725B45F DFB semiconductor laser. Summary of main findings: 1. The InGaAsP active medium was found to be temperature sensitive and a redshift of around 6 nm (1304 nm to 1310 nm) was seen as the temperature was raised from 12 °C to 26 °C. 2. Supported reduction of longitudinal mode with increasing temperature, which is related to refractive index, cavity length and gain spectrum. 3. Transition to single-mode operation at higher temperatures due to DFB structure and accurate thermal stabilization. 4. The importance of appropriate heat management for sustained performance and excellent spectral purity. 5. Practical implications for the construction of semiconductor lasers for applications requiring steady output, such as long-distance digital transmission. Future study might investigate transient thermal impacts, predictive thermal models and the influence of other material systems on modal behavior.

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التأثير الحراري على عدد الأنماط داخل تجويف ليزر أشباه الموصلات

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مستخلص البحث:

يركز هذا العمل التجريبي على تأثير تغير درجة الحرارة على بنية النمط الطولي في تجويف ليزر أشباه الموصلات صمام ليزر Mitsubishi ML725B45F ذو التغذية الراجعة الموزعة DFB وسط فعال من InGaAsP، قدرة خرج 5 ميلي واط، خرج ألياف أحادي النمط. تم قياس أطيف الانبعاث لفترات حرارية مقدارها 2 درجة مئوية، من 12 درجة مئوية إلى 26 درجة مئوية (8 أطيف فردية، باستخدام مطياف Omni-λ7508 بدقة 0.03 نانومتر) في وضع التشغيل المستمر بتيار حقل ثابت قدره 4 أمبير، من وحدة تحكم في درجة الحرارة ILX Lightwave LDT-5525 استقرار ± 0.004 درجة مئوية. أظهر الطول الموجي المركزي للانبعاث انزياحاً أحمرًا مطردًا من 1304 نانومتر عند 12 درجة مئوية إلى 1310 نانومتر عند 26 درجة مئوية، بمعامل طول موجي حراري يبلغ حوالي 0.5 نانومتر/درجة مئوية. أشار التحليل الكمي للبيانات الطيفية إلى نمط منتظم. انخفض عدد الأنماط الطولية المدعومة من 5 أنماط عند 12 درجة مئوية إلى نمطين عند 26 درجة مئوية، بينما ارتفعت نسبة كبح النمط الجانبي SMSR من 18 ديسيبل إلى 32 ديسيبل ضمن نفس نطاق درجة الحرارة، مما يشير إلى نقاء أفضل للنمط الأحادي عند درجات الحرارة المرتفعة. وتتمثل النتيجة الكمية الرئيسية في أن زيادة درجة حرارة التشغيل من 12 درجة مئوية إلى 26 درجة مئوية تقلل عدد الأنماط الطولية بنسبة 60% (من 5 إلى نمطين) وتزيد نسبة كبح النمط الجانبي بمقدار 14 ديسيبل، مما يظهر أن درجات الحرارة المرتفعة تفضل التشغيل أحادي النمط من خلال تغيير معامل الانكسار، وملف تعريف الكسب البصري، وطول التجويف نتيجة لتأثيرات درجة الحرارة. وتبين النتائج أن التحكم الحراري الدقيق بمقدار ± 0.004 درجة مئوية ضروري لأشعة الليزر شبه الموصلة ذات التغذية المرتدة الموزعة DFB للحفاظ على أدائها المستقر عالي النقاء الطيفي، وأن أفضل تشغيل أحادي النمط يتحقق عند درجات حرارة تقارب 26 درجة مئوية في ظل الظروف المدروسة.

الكلمات المفتاحية: ليزر أشباه الموصلات DFB؛ الضبط الحراري؛ الأنماط الطولية؛ إزاحة

الطول الموجي؛ نسبة قمع النمط الجانبي؛ ليزر InGaAsP.

ملاحظة: هل البحث مستل من رسالة ماجستير أو أطروحة دكتوراه؟ كلا