Characterization of Turn-On Time Delay in a Fiber Grating Fabry-Perot Lasers

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Abstract: In this paper, turn-on time delay characteristics of a fiber grating Fabry–Perot (FGFP) laser are numerically investigated by considering all the carrier recombination rate (CRR) $R(N)$ coefficients (nonradiative, $A_{nr}$; radiative, $B$; and Auger coefficient, $C$). The results show that the turn-on time delay significantly reduces by increasing the injection current ($I_{inj}$) and/or the initial value of carrier density ($N_i$). Meanwhile, the turn-on time delay increases by increasing the CRR coefficients. However, its effect can be minimized by increasing $I_{inj}$ and/or $N_i$. In addition, the turn-on time delay can be reduced by increasing the external optical feedback (OFB) level. Moreover, it is shown that the optimum external-cavity length ($L_{ext}$) is 3.1 cm. Furthermore, an antireflection (AR) coating reflectivity value of $10^{-2}$ is sufficient for the laser to operate at good turn-on time delay and low fabrication complexity. The obtained results can provide an important idea for the practical fabrication of the FGFP laser used in the dense wavelength-division multiplexing (DWDM) systems and optical access networks.

Index Terms: External-cavity semiconductor lasers, fiber Bragg grating (FBG), turn-on time delay.

1. Introduction

The implementation of wavelength-division multiplexing (WDM) and dense WDM (DWDM) is becoming necessary to support huge data transmission [1]–[6]. This requires a laser source with very fast response, high wavelength stability, narrow linewidth, low static and dynamic chirp, and reasonable cost [6]–[22]. In addition, since temperature variations cause fluctuations in the laser operating frequency, gain spectrum, threshold current, and other cavity parameters, therefore, the laser sources employed in WDM/DWDM applications are required to be able to operate over a wide range of temperature without any drift in operating wavelength [23]–[28].

Generally, in current WDM systems, distributed feedback (DFB) laser diodes are commonly used as light sources. However, the emission wavelength of a DFB laser highly depends on injected current and temperature, which requires an accurate controller. Usually, thermoelectric (TE) coolers are used to achieve adequate stability in the transmitted wavelength. However, a very accurate controller is required for DWDM where the channels are closely spaced, thereby adding significant cost [6]–[25].
In recent years, a fiber grating Fabry–Perot (FGFP) laser has been emerging as an alternative light source for WDM system. The emission wavelength of an FGFP laser depends on the Bragg wavelength of fiber grating (FG) and, thus, independent of chip temperature and injection current [6]–[8], [15]–[22], [29], [30]. Therefore, an FGFP laser is promising as a light source of future DWDM systems [6], [12]–[22]. In a semiconductor laser diode (SLD), a certain time is needed for the carrier population \((N)\) to reach its threshold value \((N_{th})\) known as turn-on time delay \((t_{on})\) [31]–[40]. This delay is due to the sudden change in an SLD’s injection current \((I_{inj})\) from its initial value \((I_{o})\), which is below the threshold current \((I_{th})\), to any current value \((I)\) greater than \((I_{th})\). Moreover, it is known that when an SLD is turned on by the bias current, it takes a relatively long time before it reaches its steady-state. This long time may lead toward a significant error rate in the overall system performance due to the dominance of spontaneous emission [32]–[38]. In addition to that, it might fail to operate due to the long turn-on delay and high \(N_{inj}\) [32], [34], [37], [38], [39]. Thus, turn-on time delay, i.e., \(t_{on}\), is an important parameter that plays significant roles in determining the performance of an SLD. To date, several experimental and theoretical studies have been reported on reducing the turn-on time delay of different types of SLDs [31], [32], [35], [40]. However, based on our best knowledge, there is no study reported on turn-on time delay characteristics of an FGFP laser, which is the focus of this paper.

Generally, the turn-on time delay depends strongly on the functional form of the carrier recombination rate (CRR) \(R(N)\) defined as [32]

\[
R(N) = A_{nr}N + BN^2 + CN^3
\]  

(1)

where \(A_{nr}\) is the nonradiative recombination rate, \(B\) is the radiative recombination coefficient, and \(C\) is the Auger recombination rate. However, due to the complexity of the \(R(N)\) equation, some researchers solved the equation by neglecting one or two of \(R(N)\) coefficients to obtain an analytical expression for \(t_{on}\) [32], [34]. Besides accuracy issue in this approximation, it cancels the effect of some important coefficients. In [32], Agrawal and Dutta have solved the carrier density rate equation to calculate \(t_{on}\) according to the assumption that \(R(N)\) is either equal to \(A_{nr}N\) or \(BN^2\). In [34], Krehlic and Sliwczynski calculated \(t_{on}\) by assuming that the parameters \(A_{nr}\) and \(B\) in (1) are equal to zero. On the contrary, in [35] and [40], Zhang et al. and Ab-Rhaman and Hassan have studied the effect of \(R(N)\) coefficients on \(t_{on}\) by considering the exact form of (1). However, the results reported in [35] on the effect of CRR coefficients \((A_{nr}, B, \text{and } C)\) on the turn-on time delay are generally not accurate compared with practical models [41]. This is because, in practice, any increase in the \(R(N)\) coefficients \((A_{nr}, B, \text{and } C)\) increases the threshold current (due to the increase in the cavity loss); thereby, the turn-on time is increased. However, the results in [35] suggest that the turn-on time delay reduces by increasing the recombination rate coefficients.

On the other hand, turn-on time delay is temperature dependent (TD), and it increases with the increase in temperature due to the increment of threshold carrier density \((N_{th})\) and laser threshold current \((I_{th})\), which are both TD [23]–[28], [31], [32]. In addition, \(N_{th}\) and \(I_{th}\) are strongly affected by the external optical feedback (OFB) [42]–[46]. However, based on our knowledge, there is no report that studied the effect of temperature and external OFB on turn-on time delay characteristics for any SLD coupled with fiber Bragg grating (FBG).

In this paper, the characteristics of the turn-on time delay for an FGFP laser is presented by deriving an exact numerical expression in terms of the CRR coefficients \((A_{nr}, B, \text{and } C)\), carrier density \((N)\), injection current \((I_{inj})\), and temperature \((T)\). In addition, the external-cavity parameters [i.e., including FBG reflectivity \((r_{FBG})\), external-cavity length \((L_{ext})\), and coupling coefficient \((C_0)\) between the Fabry–Perot (FP) laser cavity and FG] are considered in the expression. Moreover, the temperature dependence (TD) of the turn-on time delay \((t_{on})\) is modeled according to the TD of the laser parameters, instead of using the well-known Pankove relationship. By using the exact numerical expression, a comprehensive study on the turn-on time delay characteristics of an FGFP laser is successfully investigated.

2. Theoretical Model

A schematic diagram of the FGFP model is shown in Fig. 1. FGFP consists of three main sections; the first section is the FP laser as the gain medium with length \(L_d\). It is assumed that the reflectivity of the
chip front facet \((R_2)\) is very small to suppress FP modes and to stabilize the external-cavity mode, while the rear facet has a finite reflectivity \(R_1\). The second part is a fiber of length \(L_{\text{ext}}\), and the third is the FBG with reflectivity \(R_{\text{FBG}}\). The round-trip times of photons inside the internal and the external cavity are \(\tau_d = 2n_dL_d/c\) and \(\tau_e = 2L_{\text{ext}}n_{\text{ext}}/c\), respectively, where \(c\) is the velocity of the light in the vacuum, \(n_d\) is the group refractive index of the FP laser diode, and \(n_{\text{ext}}\) is the fiber refractive index.

Based on the arrangement shown in Fig. 1(b) and (c), the effective reflection coefficient \(r_{\text{eff}}\) at \(z = L_d\) is given as [47]

\[
|r_{\text{eff}}(v)| = R_2 + r_{\text{ext}} \left(1 - |R_2|^2\right) \exp\left(-j2\pi v \tau_e\right)
\]  

(2)

where \(r_{\text{ext}}\) and \(v\) are the reflection coefficients of the FG external cavity and the optical frequency, respectively. In (2), the external cavity with the reflection coefficient \(r_{\text{ext}}\) can be calculated by taking into account the Bragg grating reflectivity \(R_{\text{FBG}}\) and coupling efficiency \(C_o\) between the FP laser and the FG. From [48], the amplitude of \(r_{\text{ext}}\) is

\[
R_{\text{ext}} = |r_{\text{ext}}|^2 = C_o^2 \times R_{\text{FBG}}.
\]  

(3)

The Bragg grating reflectivity \(R_{\text{FBG}}\) obtained as [49]

\[
R_{\text{FBG}} = |r_{\text{FBG}}|^2 = \begin{cases} 
\frac{(kL_{\text{FG}})^2 \sin^2(\Omega L_{\text{FG}})}{(\Delta\beta L_{\text{FG}})^2 \sin^2(\Omega L_{\text{FG}}) + (qL_{\text{FG}})^2 \cos^2(\Omega L_{\text{FG}})} & \text{if } (kL_{\text{FG}})^2 > (\Delta\beta L_{\text{FG}})^2 \\
\frac{(kL_{\text{FG}})^2 \sin^2(\Omega L_{\text{FG}})}{(\Delta\beta L_{\text{FG}})^2 \cos^2(\Omega L_{\text{FG}}) + (qL_{\text{FG}})^2 \sin^2(\Omega L_{\text{FG}})} & \text{if } (kL_{\text{FG}})^2 < (\Delta\beta L_{\text{FG}})^2
\end{cases}
\]  

(4)

where \(L_{\text{FG}}\) is the grating length, \(\Delta\beta\) is the wavelength detuning, \(k\) is the coupling strength, \(q = \sqrt{k^2 - \Delta\beta^2}\), and \(\Omega = iq = \sqrt{\Delta\beta^2 - k^2}\). If the reflection coefficients \(R_2\) and \(r_{\text{ext}}\) are considered to be real and positive [42], then (2) yields as

\[
|r_{\text{eff}}| = R_2 \left(1 + F_{\text{ext}} \cos(2\pi \nu \tau_e)\right)
\]  

(5)

where the coefficient \(F_{\text{ext}}\) is an external-cavity coefficient defined as [50]

\[
F_{\text{ext}} = \frac{F_{\text{ext}}}{R_2} \left(1 - |R_2|^2\right).
\]  

(6)

Then, the effective reflectivity of the FBG external cavity \(R_{\text{eff}}\) becomes

\[
R_{\text{eff}} = |r_{\text{eff}}|^2 = |R_2(1 + F_{\text{ext}} \times \cos(2\pi \nu \tau_e))|^2.
\]  

(7)
By considering the effect of the temperature and external OFB, the equation of FGFP laser threshold current [31], [32] can be rewritten as
\[ I_{th, OFB}(T) = eVN_{th, OFB}(T)R(T, N_{th, OFB}) \]  
(8)
where \( e \) is the electron charge, \( V \) is the volume of the active region, and \( R(T, N_{th, OFB}) \) is the modified CRR of (1) [31], [32], which can be rewritten as
\[ R(T, N_{th, OFB}) = A_{nr} + BN_{th, OFB}(T) + C(T)N^2_{th, OFB}(T) \]  
(9)
where \( C(T) \) describes the TD Auger process. The \( N_{th, OFB}(T) \) in (8) is the well-known TD carrier density equation at threshold condition [31], which, by considering the effect of temperature and external OFB, can be defined as
\[ N_{th, OFB}(T) = N_t(T) + \frac{1}{\Gamma v_g(T)a(T)\tau_{p, OFB}(T)} \]  
(10)
where \( N_t(T) \), \( a(T) \), and \( \tau_{p, OFB}(T) \) are the TD parameters that are known as transparency carrier density, gain constant, and photon lifetime (with the OFB effect), respectively. \( \Gamma \) denotes the confinement factor, and \( v_g(T) = (c/n_d(T)) \) is the TD group velocity. The TD of the model parameters is given by [21]
\[ X(T) = X_o + \frac{\partial X}{\partial T}(T - T_o) \]  
(11)
where \( X_o \) is the initial value found at the reference temperature \( (T_o) \), which, in this study, is considered at the room temperature (25 °C). Since the external OFB only affects the photon lifetime in (9), \( \tau_{p, OFB}(T) \) can be modeled as [31], [32]
\[ \tau_{p, OFB}(T) = \frac{1}{v_g(T)\alpha_{tot, OFB}(T)} \]  
(12)
where \( \alpha_{tot, OFB}(T) \) is the laser cavity total loss that is defined as [31], [32]
\[ \alpha_{tot, OFB}(T) = \alpha_{int}(T) + \frac{1}{2L_d}\ln\left(\frac{1}{R_1R_{eff}}\right) \]  
(13)
where \( \alpha_{int}(T) \) is the internal cavity loss, and \( ((1/2L_d)\ln(1/R_1R_{eff})) \) is the mirror loss. Finally, \( N_{th, OFB}(T) \) can be expressed as
\[ N_{th, OFB}(T) = N_t(T) + \frac{\alpha_{int}(T) + \frac{1}{2L_d}\ln\left(\frac{1}{R_1R_{eff}}\right)}{\Gamma a(T)} \]  
(14)

3. Turn-On Time Delay Characteristics

When the laser is turned on, a stimulated emission process started as the injection current \( (I_{inj}) \) increases from its initial value \( (I_o) \) to a value \( (I) \) greater than threshold current \( (I_{th}) \). The time taken for the stimulated emission process to start is the turn-on time delay \( (t_{on}) \), where, during this time, the photon density will stay essentially zero [31], [32]. The carrier density rate equation of a single-mode semiconductor laser can be written as [31], [32], [35]
\[ \frac{dN}{dt} = \frac{I_{inj}}{eV} - N(A_{nr} + BN + CN^2) - g\frac{N - N_0}{1 + \varepsilon P} \]  
(15)
where \( \varepsilon \) is the nonlinear gain compression factor, and \( P \) is the photon density, respectively. In the time period \( (0 < t < t_{on}) \), the stimulated emission rate can be neglected because the photon
density is essentially zero. Thus, the carrier density rate equation can be rewritten as [31], [32], [33], [39], [40]

\[
\frac{dN}{dt} = \frac{l_{inj}}{eV} - A_N N + BN^2 + CN^3.
\]  

(16)

Note that (15) and (16) are based on a simple rate equation model describing diode lasers without incorporating any barrier recombination or other leakage processes. The use of improved rate equation models [51], [52], taking into account the carrier recombination in barrier and quantum-well regions, had previously been used to understand the frequency modulation [51] and current injection efficiency [52]–[55] in quantum-well laser systems. The improved model is important for providing guidance in the frequency modulation optimization [51], [56], carrier leakage suppression [55], device efficiency improvement [53], [54], and lasing characteristics optimization [52], [57] in various quantum-well lasers. The goal of the current study is to illustrate the effect of the FG on the turn-on delay time in FP lasers; thus, the carrier dynamics in the active region of the diode lasers were modeled without taking into account any barrier recombination or other leakage processes.

It is known that \( t_{on} \) is the time needed for carrier density \( N \) to increase from a specified initial value \( \langle N_i \rangle \) to threshold value \( \langle N_{th} \rangle \). According to that, \( t_{on} \) is calculated by integrating the carrier density rate shown in (16) [32]

\[
t_{on} = \int_{N_i}^{N \rightarrow N_{th,OFB}} \frac{eV}{l_{inj} - eV(N_a + BN + CN^2)} dN.
\]  

(17)

Equation (17) is numerically solved to investigate the turn-on time delay characteristics of an FGFP laser. After taking into account the effect of external-cavity parameters [i.e., including FBG reflectivity \( r_{FBG} \), external-cavity length \( L_{ext} \), and coupling coefficient \( C_0 \) between the FP laser cavity and FG], the numerical solution for (17) can be rewritten as [58]

\[
t_{on} = \ln \left( \frac{\langle N \rangle_{N=N_{th,OFB}}}{\langle N \rangle_{N=N_i}} \right)
\]  

(18)

where \( \langle N \rangle \) is the solution of the unlimited integration of (17). To include the effect of the initial carrier density \( \langle N_i \rangle \) value, (18) is rewritten as

\[
t_{on} = \ln \left( \frac{\langle N \rangle_{N=N_{th,OFB}}}{\langle N \rangle_{N=N_i}} \right)
\]  

(19)

where \( \rho \) represents the ratio of the initial carrier density \( \langle N_i \rangle \) to its threshold value \( \langle \rho = N_i / N_{th,OFB} \rangle \), which is \( 0 \leq \rho < 1 \). Thus, (19) describes the time needed for the carrier density \( \langle N \rangle \) to increase from its initial value \( N_i \) to reach the threshold level \( N_{th,OFB} \). The solution of (19) can be written as

\[
t_{on} = eV \sum_{m=1}^{3} \Pi_m \ln \left[ \Theta(\Pi_m, N) \right] |_{N=N_{th,OFB}}^{N=N_{th,OFB}}
\]  

(20)

\[
= eV \sum_{m=1}^{3} \Pi_m \ln \left[ \Theta(\Pi_m, N) \right] |_{N=N_{th,OFB}}^{N=N_{th,OFB}} - eV \sum_{m=1}^{3} \Pi_m \ln \left[ \Theta(\Pi_m, N) \right] |_{N=N_{th,OFB}}^{N=N_{th,OFB}}
\]  

(21)

\[
= eV \sum_{m=1}^{3} \Pi_m \ln \left[ \frac{\Theta(\Pi_m, N_{th,OFB})}{\Theta(\Pi_m, \rho N_{th,OFB})} \right]
\]  

(22)

where

\[
\Theta(\Pi_m, N) = B + (A_N B \xi + 9C_l_{inj})\Pi_m + \left[ (2B^2 - 6A_N C)\xi \Pi_m + 3C \right] N
\]  

(23)
where \( m \) is an integer positive number \((m = 1 \rightarrow 3)\), and \( \Pi_m \) is the \( m \)th root of polynomial \( \Xi(\Pi) \) defined as

\[
\Xi(\Pi) = C + \xi(B^2 - 3A_nC)\Pi + \left[ \xi^2(18A_nBC_{inj} - 4B^3I_{inj}) + \xi^3(4A_n^3C - A^2B^2) \right] \Pi^3
\]

where \( \xi = eV \). The \( m \)th root of \( \Xi(\Pi) \) can be written as

\[
\Pi_1 = \frac{1}{6 \xi R_2} + 2(3A_nC - B^2) \frac{\xi}{R_4}
\]

\[
\Pi_2 = \frac{-1}{2} \left( \frac{1}{6 \xi R_1} + 2(3A_nC - B^2) \frac{\xi}{R_4} \right) + \frac{\sqrt{3}}{2} \left( \frac{1}{6 \xi R_1} - 2(3A_nC - B^2) \frac{\xi}{R_4} \right)
\]

\[
\Pi_3 = \frac{-1}{2} \left( \frac{1}{6 \xi R_1} + 2(3A_nC - B^2) \frac{\xi}{R_4} \right) - \frac{\sqrt{3}}{2} \left( \frac{1}{6 \xi R_1} - 2(3A_nC - B^2) \frac{\xi}{R_4} \right)
\]

where

\[
R_1 = \xi^2 A_n^2(4A_nC - B^2) + \xi B_{inj}(18A_nC - 4B^2) + 27C^2I_{inj}^2
\]

\[
R_2 = \left[ \xi^2 R_1 \left( -108C + 12\sqrt{3}R_3^{1/2} \right) \right]^{1/3}
\]

\[
R_3 = \frac{R_4}{R_1}
\]

\[
R_4 = 4\xi^2B^2(20.25A_n^2C^2 - 9A_nB^2C + B^4) + 108\xi BC_{inj}I_{inj}(4.5A_nC - B^2) + 729C^4I_{inj}^2
\]

Finally, by using (22)–(31), \( t_{on} \) can be rewritten as

\[
t_{on} = \xi \Pi_1 \ln \left[ \Theta(\Pi_1, N_{th,OBF}) \right] + \xi \Pi_2 \ln \left[ \Theta(\Pi_2, \rho N_{th,OBF}) \right] + \xi \Pi_3 \ln \left[ \Theta(\Pi_3, \rho N_{th,OBF}) \right]
\]

\[
= \Theta(\Pi_1, N_{th,OBF}) + \Theta(\Pi_2, \rho N_{th,OBF}) + \Theta(\Pi_3, \rho N_{th,OBF})
\]

4. Results and Discussion

For investigating the characteristics of turn-on time delay on an FGFP laser, a uniform FBG operating at 1550-nm wavelength is used in the simulation. The parameters used in the analysis are presented in Table 1. All these values are fixed throughout the paper, except otherwise stated.
Fig. 2 shows the turn-on delay time \( t_{on} \) for an FGFP laser model as a function of the carrier density ratio \( \rho = N_i/N_{th,OFB} \) for different values of the injection current at reference temperature \( T_o \) \( (T_o = 25 \, ^\circ\text{C}) \). The result shows that by the increase in \( \rho \), the turn-on time delay is reduced. This result agrees with the assumption that when \( N_i \) reaches \( N_{th} \), the turn-on time delay will reach zero. As a result, when the laser biased is near the threshold carrier density \( N_{th} \), the turn-on time delay can be eliminated [32]. On the other hand, by increasing the injection current, the turn-on time delay is reduced. The effect of injection current is reduced when the laser is operated at high bias level or high \( \rho \), and vice versa. This behavior is consistent with the measured results that are obtained in [39]. These results provide significant information to avoid biased laser in the region near or below the threshold current to introduce a significant error in overall system performance. This effect is due to injection laser by an inappropriate current level that causes long turn-on time delay [36]–[39].

Fig. 3 shows comparison between the actual turn-on delay time and the approximation model as a function of \( \rho \).

Fig. 2. Turn-on delay as a function of \( \rho \) for different injection current.

Fig. 3. Comparison between the actual turn-on delay time and the approximation model as a function of \( \rho \).
As the result implies, there are significant differences between the actual turn-on time delay compared with the approximation. In addition, for determining the worst approximation that can be used for calculating turn-on time delay, all other possible cases, such as \( A_{nr} = 0, B = 0, \) and \( C = 0, \) are presented in this figure. In the case of \( C = 0, \) the difference from the actual case is very large; thereby, it is the worst approximation. This result is consistent with that given in [43] about the strong dependence of the turn-on time delay on parameter \( C \) rather than on the other recombination coefficients \( (A_{nr} \text{ and } B). \)

Since the turn-on time delay depends strongly on threshold carrier density \( N_{th} \) [32] [see (17), (22), and (32)], therefore, the TD of \( N_{th} \) is analyzed according to the TD of laser cavity parameters. Fig. 4 shows the effect of temperature on the FGFP laser threshold carrier density \( N_{th,OFB} \) and photon lifetime \( \tau_{p,OFB}, \) respectively, based on (14) and (12). By increasing temperature from 15 °C to 25 °C, \( N_{th,OFB} \) decreases nonlinearly with temperature to reach its minimum value at the reference temperature \( T_o, \) which, in this study, is considered at the room temperature (25 °C). This behavior is attributed to the increase in \( \tau_{p,OFB} \) due to the increase in the effective reflectivity \( R_{eff} \) with temperature according to (11); thus, an effective reduction in the total cavity loss \( \alpha_{tot} \) [see (13)]
occurs. However, further increment in temperature from 25 °C to 35 °C leads to increase in $N_{th,OFB}$ due to decrease in the $\tau_{\rho,OFB}$ value. The latter decreases with temperature due to the increase in $\alpha_{tot}$. From the results obtained in Fig. 4, to get a low threshold carrier density, the laser should operate in temperature around $\pm 2$ °C around the reference temperature $T_o$ [see (7)].

Fig. 5 shows the effect of temperature variation on turn-on time delay as a function of $I_{inj}=1.3I_{th}$. The effect of temperature is calculated according to the TD of the laser cavity parameters, not by directly using the well-known Pankove relationship. In this paper, temperature is varied from 15 °C to 35 °C. As shown in the figure, by increasing the temperature from 15 °C to 25 °C, the turn-on time delay is significantly reduced. However, by further increment of temperature from 25 °C to 35 °C, the turn-on time delay is increased. It is clear that temperature significantly affects the turn-on time delay due to the strong TD of threshold carrier density $N_{th}$ [see (17), (22), and (32)], as shown in Fig. 4. However, the effect of temperature can be reduced by increasing $\rho$. This is because when $\rho \to 1$, i.e., $N_i \to N_{th}$, therefore, $t_{on} \to 0$. Thus, when the laser source is turned on from an initial value of the carrier density close to $N_{th}$, the turn-on time delay is significantly low [31], [32].
Fig. 6 shows the effect of turn-on time delay $t_{on}$ against current ratio $\frac{I_{inj}}{I_{th}(T_o)}$ at different temperature and $\rho = 0.5$. By increasing the temperature from 15 °C to 25 °C, the turn-on time delay is significantly reduced. Further reduction in $t_{on}$ can be obtained by increasing the injection current,
which is due to the transition of laser operation from the weak to the strong OFB regime. However, by increasing the temperature from 25 °C to 35 °C, the turn-on time delay is significantly increased. This behavior is a result of the reduction in the effective reflectivity with temperature due to the shift

Fig. 9. Effect of CRR coefficients on laser threshold current. (a) Nonradiative coefficient $A_{nr}$. (b) Radiative coefficient $B$. (c) Auger coefficient $C$. 

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in Bragg wavelength [see (11)], where the maximum value of the effective reflectivity occurred at temperature $T_o$. Thus, the laser operation transition returns to the weak from the strong OFB regime that leads to increase in total cavity loss [42]–[46]. This is due to the strong dependence of $\alpha_{\text{tot,OFB}}$ on the effective reflectivity value [see (13)], which leads to increase in the threshold carrier density. Thus, the turn-on time delay value increases due to the strong dependence of the turn-on time delay on the threshold carrier density, as shown in (32).

To clarify the results that were obtained in Figs. 4–6, Fig. 7 shows the effect of temperature on the effective reflectivity, as given in (7). As expected from (11), the result in Fig. 7 confirms that the maximum effective reflectivity occurs at the reference temperature $T_o$ (25 °C). From the figure, more than 40% effective reflectivity is obtained at a temperature range between 23 °C and 27 °C. Thus, as expected, the lower turn-on time delay is achieved within the temperature ±2 °C away from the reference temperature $T_o$ [see (7)]. This turn-on time delay variation with temperature is due to the variation of the effective reflectivity against temperature (see Fig. 7). Thus, turn-on time delay depends strongly on the effective reflectivity, as given in (7)–(31). The results suggest that the temperature of the laser should be controlled within a range of 23 °C–27 °C (±2 °C beside the reference temperature $T_o$) to provide optimum performance. Therefore, according to the results obtained in Figs. 5–7, besides controlling temperature variation within ±2 °C from the reference temperature $T_o$.
temperature $T_0$, the effect of temperature on the turn-on time delay can be eliminated either by increasing $\rho$ or increasing laser injection current.

A good understanding of the carrier recombination mechanisms in semiconductor diodes is essential for designing laser diodes with high static and dynamic performance. In particular, it is important to minimize the nonradiative recombination processes that reduce the efficiency of these devices [38], [59]. Figs. 8(a)–(c) shows the effect of the CRR coefficients $A_{nr}$, $B$, and $C$ on the turn-on time delay as a function of current ratio ($I_{inj}/I_{th}(T_0)$), respectively. As shown in Fig. 8, by increasing any of the CRR coefficients ($A_{nr}$, $B$, and $C$), the turn-on time delay is increased due to the increase in the time of CRR $R(N)$ according to (9). This is because by increasing the $R(N)$ value, the laser threshold current is increased according to (8). It is important to mention here that this result is completely in contrast to the one reported in [35]. We believe the true result is the one shown in Fig. 8, where the turn-on time delay can be reduced by reducing $A_{nr}$, $B$, and/or $C$ [41]. On the other hand, as shown in Fig. 8, the effect of injection current for reducing turn-on time delay is much more significant as compared with the effect of CRR coefficients.

To confirm the validity of the results that is given in Fig. 8, we have studied the effect of CRR coefficients ($A_{nr}$, $B$, and $C$) on the laser threshold current characteristics according to (8). As shown
in Fig. 9, any increase in the CRR coefficients ($A_{nr}$, $B$, and $C$) leads to increase in the threshold current. Thus, from the physical and practical point of view, any increase in the laser threshold current leads to increase in the laser turn-on time delay. Therefore, according to the results obtained in Figs. 8 and 9, we believe that the results reported in [35] are generally inaccurate.

The effect of external OFB reflectivity ($R_{ext}$) [as given in (3)] on the turn-on time delay as a function of $v/C$ at the reference temperature $T_o$ ($T_o = 25 \degree C$) and injection current $I_{inj} = 1.3I_{th}$ is presented in Fig. 10. Fig. 10(a) and (b) shows the effect of FBG reflectivity ($R_{FBG}$) and coupling coefficient ($C_o$), respectively. From the figures, by increasing FBG reflectivity and/or coupling coefficient, the turn-on time delay is reduced. This is because any increase in the external OFB level or coupling coefficient level reduces the total cavity loss of the laser diode [27], [36], [42]–[46], [60], [61], which caused to increase the photon lifetime and decrease the threshold carrier density as shown in Fig. 4, thus, reduce the laser threshold current as given in (8). In addition, similar to what is observed in the previous results, the turn-on time delay reduces when the injection current is increased.

Fig. 11(a) shows the turn-on time delay of an FGFP laser at various external-cavity fiber lengths $L_{ext}$ (the distance from the back facet mirror of an FP laser to the beginning of grating in the fiber) of 1.6, 2.35, and 3.1 cm. The minimum delay time occurred at $L_{ext} = 3.1$ cm. According to (7), the effective reflectivity $R_{eff}$ depends on $\cos(2\pi v \tau_a)$, where $\tau_a$ depends on $L_{ext}$ as $\tau_a = 2L_{ext}/c$. Thus, any change in $L_{ext}$ will affect $R_{eff}$ based on the cosine function, as shown in Fig. 11(b). Any change in $L_{ext}$, $R_{eff}$ value will change within a fixed range with the minimum and maximum reflectivity of around 74% and 95%, respectively. The shortest external-cavity length ($L_{ext} > 0$) that provides the maximum $R_{eff}$ value is around 3.1 cm. The maximum reflectivity is repeated with a period of around 3.1 cm. Even though 6.2, 9.3, and so on can also provide the maximum reflectivity value, but longer $L_{ext}$ increases the delay time ($\tau_a$). Therefore, the optimum $L_{ext}$ is 3.1 cm.

The reflectivity of the antireflection (AR) coating front facet ($R_o$) of an FP laser is one of the important parameters in determining performance of the external-cavity-based lasers. It has been found that the bistability, multistability, mode-hopping-induced instability, and continuous frequency tuning range are dependent on the reflectivity of the AR coating of the laser diode [60]–[62]. It has also been shown that by reducing the AR coating reflectivity as low as possible, the system performance can be improved [8], [9], [29], [30], [63], [64]. Fig. 12 shows the effect of AR coating reflectivity on turn-on time delay as a function of $\rho$ at the reference temperature $T_o$ ($T_o = 25 \degree C$) and injection current $I_{inj} = 1.3I_{th}$. With the decrease in the AR value from $1 \times 10^{-1}$ to $1 \times 10^{-5}$, the turn-on time delay value reduced. This is due to the increment of the effective reflectivity $R_{eff}$ from 0.87 to 0.92 according to (7). However, by decreasing the AR value from $1 \times 10^{-2}$ to $1 \times 10^{-5}$, there is no.
significant effect on the turn-on time delay since $P_{\text{eff}}$ varies only by 0.006 (from 0.92 to 0.926). The result demonstrates that an AR coating reflectivity value of $1 \times 10^{-2}$ is sufficient for the laser to operate at good turn-on time delay and low fabrication complexity.

5. Conclusion
In this paper, a comprehensive study on turn-on time delay characteristics of an FGFP laser is numerically investigated by considering the exact expressions. Unlike the study reported in [32] and [35], in this paper, it has been shown that the turn-on time delay can be reduced (not increased) by reducing any of the CRR coefficients (nonradiative, $A_{\text{nr}}$; radiative, $B$; and Auger recombination, $C$). In addition, turn-on time delay is increased by increasing the temperature. However, the effect of temperature can be reduced by increasing injection current and/or $\rho$. Besides injection current and $\rho$, the turn-on time delay can be reduced by increasing the external OFB reflectivity. Moreover, performance of the FGFP laser is improved by optimizing external-cavity length ($L_{\text{ext}}$) and AR coating reflectivity. These results have potential impacts for understanding and optimization of FGFP lasers, and these works can be used as guidelines to design and operate these lasers for high-speed transmission systems.

References


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