Improving the characteristics of the modulation response for fiber Bragg grating Fabry–Perot lasers by optimizing model parameters

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A unified and comprehensive study on the small-signal intensity and frequency modulation characteristics of a fiber Bragg grating Fabry–Perot (FBG–FP) laser are numerically investigated. The effect of injection current, temperature, external optical feedback (OFB), nonlinear gain compression factor, fiber grating (FG) parameters and spontaneous emission factor on modulation response characteristics are presented. The rate equations of the laser model are presented in the form that the effect of temperature (T) and external optical feedback (OFB) are included. The temperature dependence (TD) of laser response is calculated according to the TD of laser cavity parameters instead of directly using the well-known Parkove equation. It is shown that the optimum external fiber length ($L_{ext}$) is 3.1 cm and the optimum range of working temperature for FGFP laser is within ±2 °C from the FBG reference temperature ($T_r$). Also, the antireflection (AR) coating reflectivity and the linewidth enhancement factor have no significant effect on the modulation spectra. It also is shown that modulation response is extremely sensitive to the OFB level, high injection current and gain compression factor. The study indicates clearly that good dynamic characteristic can be obtained by system parameters optimization.

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1. Introduction

Semiconductor laser diodes (SLDs) have been widely used in wavelength division multiplexing (WDM) networks due to small size, low power consumption, fast response, and its ability to perform direct modulation at high bit rates [1–3]. For future advanced high data rate optical systems, the most important characteristics required for SLDs are the stable dynamic single-mode operation (DSM), high channel selectivity and ability to support high speed transmission at reasonably low cost [4–14]. However, operation and performance of the SLDs in such advanced applications are influenced by some intrinsic and external dynamic phenomena. It has been shown; that the performances of SLDs are affected by external optical feedback (OFB) variations [15–20]. Depending on the level of OFB, the reflected light causes variations in the threshold gain, output power, and output spectrum. In addition, the gain spectrum, threshold current, and other cavity parameters of SLDs are significantly fluctuated due to the temperature variation [5, 8, 13–20]. Generally, distributed feedback (DFB) lasers are used as light sources in current WDM systems. However, the emission wavelength of DFB laser is highly temperature and injection current dependent, which requires being accurately controlled [9, 11–13, 19].

In recent year, fiber Bragg grating Fabry-Perot (FBG–FP) laser is proposed as an alternative light source for WDM systems due to high wavelength stability [13, 14, 21]. The emission wavelength of FBG–FP laser does not depend on chip temperature and injection current [5, 12–14, 21], since it only depend on the Bragg wavelength of fiber grating (FG) and the modulating signal can be applied to the active region of the semiconductor section to produce intensity modulation (IM) or frequency modulation (FM). In addition, precise adjustment of the Bragg wavelength in FG can be easily achieved compared to the emission wavelength of commonly used distributed feedback (DFB) lasers [9–21]. Therefore, FBG–FP laser is promising as a light source of a future dense WDM system.

In this paper, a unique and comprehensive numerical study for the modulation response characteristics of FBG–FP laser is presented. The rate equations of the laser model are presented in the form that the effect of temperature and OFB are included. The effect of OFB and temperature on IM and FM spectra is
investigated by considering their effects on threshold carrier density. In addition, the effect of injection current, nonlinear gain compression factor, grating reflectivity, and external cavity parameters is also presented.

2. Theory

A schematic diagram of FBG–FP laser is shown in Fig. 1(a). The model consisting of three main sections, first section is the 1550 nm Fabry–Perot (FP) laser of length $L_p$. It is assumed that the reflectivity of the chip front facet $R_0$ is very low, while the rear facet has a finite reflectivity $R_1$. The second section is a fiber of length $L_{ext}$ and the third is the fiber Bragg grating (FBG) with amplitude reflectivity $R_{FBG}$. The round-trip time of photons inside the internal and the external cavity are $\tau = 2n_d a/c$ and $\tau_e = 2L_{ext}(n_d e/e)$, respectively, with $c = 3 \times 10^8$ cm/s is the velocity of light in vacuum, $n_d$ is the group refractive index, and $n_{ext}$ is the fiber refractive index. The external cavity is established by the coupling of the front facet reflectivity $R_0$ and FBG reflectivity $R_{FBG}$ which is dependent on the laser frequency $\omega$. The configuration in Fig. 1(a) can be conveniently analyzed as a simple two-mirror laser system (as shown in Fig. 1(b)), by replacing the FP laser diode output facet reflectivity $R_o$ by an effective reflection coefficient $R_{eff}$ as [22]

$$R_{eff} = \frac{R_o^2 + R_{FBG}^2 + 2R_o R_{FBG} \cos(\omega \tau_e)}{1 + R_{FBG}^2}$$  \hspace{1cm} (1)

where, $\omega \tau_e$ is the phase of the reflected light that travels through the external cavity. In Eq. (1), $R_{FBG} = C_o R_{ext}$ is the amount of optical feedback reflection coupled into FP laser diode, where $C_o$ is the amplitude coupling coefficient between the FP laser diode and FG. The $R_{ext} = |R_{FBG}|^2$ is the power reflectivity of FBG that is given as [23, 24]

$$R_{ext} = \frac{(k L_{FG} \sin \theta_{FG} Q_{FG})}{(k L_{FG} \sin \theta_{FG} Q_{FG})} \quad (k L_{FG} \sin \theta_{FG} Q_{FG})$$  \hspace{1cm} (2)

where $L_{FG}$ is the grating length, $\Delta \beta$ is the wavelength detuning, $k$ is the coupling strength, $Q = (k^2 - \Delta \beta^2)^{1/2}$, and $\Omega = Q = (\Delta \beta^2 - k^2)^{1/2}$. The phase coefficient for light reflection $\theta_{eff}$ is derived from the differential equations reported by Kallamani and O’Mahon as [23, 24]

$$\theta_{eff} = \begin{cases} \tan^{-1} \left( \frac{\sin \theta_{FG} Q_{FG}}{\cos \theta_{FG} Q_{FG}} \right) & \text{if } (k L_{FG}^2 > (\Delta \beta L_{FG})^2) \\ \tan^{-1} \left( \frac{\sin \theta_{FG} Q_{FG}}{\cos \theta_{FG} Q_{FG}} \right) & \text{if } (k L_{FG}^2 < (\Delta \beta L_{FG})^2) \end{cases}$$  \hspace{1cm} (3)

By considering the phase changes introduced by the optical filter into Eq. (1), then $R_{eff}$ can be written as

$$R_{eff} = \frac{R_o^2 + R_{FBG}^2 + 2R_o R_{FBG} \cos(\omega \tau_e - \theta_{eff})}{1 + R_{FBG}^2} \cos(\omega \tau_e - \theta_{eff})$$  \hspace{1cm} (4)

The temperature dependence (TD) of threshold current in FBG–FP laser under the effect of OFB can be defined as [25]

$$I_{th,OFB} = q V N_{th,OFB} T (\alpha + B N_{th,OFB} + C(T) N^2_{th,OFB})$$  \hspace{1cm} (5)

where $q$ is the electronic charge, $V$ is the active region volume, $\alpha$ and $C$ describe the nonradiative recombination rate and Auger process, respectively, while $B$ is the radiative recombination coefficient. The $N_{th,OFB}$ is the TD carrier density at threshold condition, which by modifying the well-known carrier density expression [25], it can be rewritten as

$$N_{th,OFB} = N_t (T) + \frac{1}{I} \frac{p}{v_g (1 + \tau_{p,OFB} (T) T)}$$  \hspace{1cm} (6)

where $N_t (T)$, $\alpha (T)$, and $\tau_{OFB}$ are the TD of transparency carrier density, gain coefficient, and photon lifetime with considering OFB effect, respectively. The term $\Gamma$ in Eq. (6) denotes the confinement factor and $v_g (T) = c n_d (T)$ is the group velocity. The TD of the model can be defined as [13]

$$X(T) = X_0 + \frac{\Delta X}{T} (T - T_0)$$  \hspace{1cm} (7)

where $X_0$ is the initial value found at the reference temperature ($T_0$), which in this study it is considered at the room temperature (25 °C). Since the OFB only affects on the photon lifetime presented in Eq. (6), $\tau_{OFB}(T)$ can be modeled as

$$\tau_{p,OFB} = \frac{1}{v_g (T) I_{tot,OFB} (T)}$$  \hspace{1cm} (8)

where $x_{tot,OFB}$ is the total cavity loss that is given as [25, 26]

$$x_{tot,OFB} = x_{int} + \frac{1}{2L_d} \ln \left( \frac{1}{R \bar{R}_{eff}} \right)$$  \hspace{1cm} (9)

where $x_{int}$ is the TD of internal cavity losses [25, 26], and $(1/2L_d \ln (1/R \bar{R}_{eff}))$ represent the mirror losses [25, 26]. Finally, we can express the TD of $N_{th,OFB}$ as

$$N_{th,OFB} = N_t (T) + \frac{\Delta X}{T} \ln \left( \frac{1}{R \bar{R}_{eff}} \right) + \frac{1 + 2R_o \cos \theta_{eff}(\omega - \theta_{eff}) + R_{FBG}^2}{R (1 + 2R_o \cos \theta_{eff}(\omega - \theta_{eff}) + R_{FBG}^2)}$$  \hspace{1cm} (10)

Eq. (10) gives general expression for threshold carrier density that is used to calculate the net stimulated emission rate in the active region. According to Eq. (5), any increase in threshold carrier density, $N_t$, leads to increase threshold current $Ith$. Therefore, a high injection current is required to start lasing. However, as the injection current is increased, the laser output becomes unstable, thereby, drop the output power. These fluctuations generate a phase different in the emitted photons. Consequently, for coherent optical systems, a low $N_t$ is necessary to avoid high injection current operation.

3. Modulation characteristics

By considering the effect of temperature and OFB described in the previous section, the modulation characteristics of FBG–FP laser can be obtained by modifying the well-known coupled rate equations [26], which describes the relation between the carrier number $N(t)$, photon number $P(t)$, and optical phase $\phi(t)$ as

$$\frac{dN(t)}{dt} = \frac{I (t)}{q} - \frac{N(t)}{\tau_{p,OFB}} - g \frac{N(t) - N_0}{1 + e^{P(t)}}$$  \hspace{1cm} (11a)
\[
\frac{dP(t)}{dt} = g N(t) - N_o P(t) - \frac{P(t)}{t_{p,OFB}} + R_{sp,OFB}
\]
(11b)

\[
\frac{dP(t)}{dt} = \frac{\alpha}{2} g N(t) - N_o - \frac{\text{arg}(R_{OFB})}{t_d}
\]
(11c)

where, \(I(t)\) is the injected current, \(\tau_{c,OFB} = \sqrt[3]{V/\alpha}\) is the carrier lifetime, \(g\) is the gain slope constant coefficient, \(\varepsilon\) is the nonlinear gain compression factor, \(R_{sp,OFB}\) represents the contribution of the spontaneous emission of the lasing mode, \(\alpha\) is the linewidth enhancement factor, and \(N\) is the time-average carrier number. For a small-signal modulation regime, the laser current is defined as [26]

\[
I(t) = I_0 + I_s(t)
\]
(12)

where \(I_0\) is the DC value of the current injected into the active region and \(I_s(t)\) is the amplitude of the modulation AC current component. For a small-signal modulation, the state variables can be written as their steady-state values plus modulation terms as

\[
N(t) = N_o + N_s(t), \quad |N_s(t)| < N_o
\]
(13a)

\[
P(t) = P_o + P_s(t), \quad |P_s(t)| < P_o
\]
(13b)

\[
\varphi(t) = \varphi_o + \varphi_s(t), \quad |\varphi_s(t)| < \varphi_o
\]
(13c)

By substituting Eq. (12) and (13) into Eq. (11) and eliminating the steady-state values, Eq. (11) can be rewritten as

\[
\begin{bmatrix}
\frac{dN_s(t)}{dt} \\
\frac{dP_s(t)}{dt} \\
\frac{d\varphi_s(t)}{dt}
\end{bmatrix} =
\begin{bmatrix}
-\frac{\alpha}{4} \frac{(R_{OFB})}{V} - \frac{\tau_{OFB}}{C_0} & -\Gamma g (1 - \Gamma e P_o) \\
\frac{\Gamma g (1 - \Gamma e P_o)}{C_0} & 0 \\
0 & \frac{\Gamma g (1 - \Gamma e P_o)}{C_0}
\end{bmatrix}
\begin{bmatrix}
N_s(t) \\
P_s(t) \\
\varphi_s(t)
\end{bmatrix} + \begin{bmatrix}
I_s(t)/q \\
0 \\
0
\end{bmatrix}
\]
(14)

Eq. (14) shows that the modulation current cause to change the carrier and photon populations inside the active region, which produce the optical phase effect. However, because of intrinsic laser resonance, the modulation response is frequency dependent. Thus it is more convenient to convert the equations in the frequency domain.

The output power after passing through the FG is related to the photon number \(N_p\) is given by [23]

\[
P_{out} = \frac{(1 - R_{eff}) \sqrt{R_1}}{(1 - R_{eff}) \sqrt{R_1} + (1 - R_1) \sqrt{R_{eff}}} h \nu \eta \kappa m P
\]
(15)

where \(h\nu\) is the photon energy of the emitted light.

3.1. Intensity modulation (IM)

The transfer function of the intensity modulation (IM) is given by [26]

\[
IM(\omega) = \frac{P(\omega)}{I(\omega)}
\]
(16)

By taking the Fourier transform for Eq. (14), the IM frequency response becomes as

\[
IM(\omega) = \frac{[G_{\omega,OFB} + R_{sp,OFB}]}{[\omega^2 - \Omega_{OFB}^2 - \Psi_{OFB}^2 + (2\omega \Psi_{OFB})^2]^{1/2}}
\]
(17)

where \(R_{sp,OFB} = \delta \omega_c / \Omega\), \(\Omega_{OFB} = \sqrt{G_{\omega,OFB} / \omega_c}\) is the relaxation oscillation frequency (ROF) defined [26] as

\[
\text{ROF} = \frac{1}{2\pi} \left[ A_{m} + B_{m}N_{th,ofb} + C_{m}N_{th,ofb} \right]^{-1/2}
\]
(18)

and \(\Psi\) is the decay rate of the relaxation oscillation defined as [26]

\[
\Psi_{OFB} = \frac{1}{2} \frac{R_{sp,OFB}}{P_{OFB}} + \frac{\tau_{OFB}}{V} \left( N - N_{th} \right) + \frac{G_{\omega,OFB}}{\tau_{c,OFB}}
\]
(19)

Eq. (16) represents a general form to study the influence of FBG and temperature in addition to the other model parameters on FGFP laser IM spectra.

3.2. Frequency modulation (FM)

The transfer function of the frequency modulation (FM) is given by [26]

\[
FM(\omega) = \frac{\delta \nu(\omega)}{\nu(\omega)}
\]
(20)

where \(\delta \nu(\omega)\) represent the shift in the lasing frequency during modulation. This phenomenon is referred to as frequency chirping and given as [27]

\[
\delta \nu(t) = \frac{1}{2\pi} \delta \varphi_s(t)
\]
(21)

From Eq. (14), the FM transfer function become

\[
FM(\omega) = \frac{\beta_{\omega,OFB}}{4\pi \Omega} \left[ \omega^2 - \Omega_{OFB}^2 - \Psi_{OFB}^2 + (2\omega \Psi_{OFB})^2 \right]^{1/2}
\]
(22)

Eq. (20) characterizes the FM response of FGFP laser with arbitrary OFB and external cavity length. In addition to that, Eq. (20) shows that FM will exhibit a resonance phenomenon at the resonant frequency of the laser diode.

4. Results and discussion

In our simulations, it is considered a FBG–FP laser with uniform FBG operating at 1550 nm wavelength with grating length of 4 mm is used. The other parameters used in the analysis for the laser diode and external cavity are shown in Table 1.

<table>
<thead>
<tr>
<th>Diode parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_d = 400) mm</td>
<td>Cavity length</td>
</tr>
<tr>
<td>(d = 0.1) mm</td>
<td>Active region thickness</td>
</tr>
<tr>
<td>(w = 2) mm</td>
<td>Active region width</td>
</tr>
<tr>
<td>(N_m = 1 \times 1024) m(^{-3})</td>
<td>Transparency carrier density</td>
</tr>
<tr>
<td>(\Delta n = 1 \times 108) sec(^{-1})</td>
<td>Nonradiative recombination coefficient</td>
</tr>
<tr>
<td>(B = 1 \times 10^{-16}) m(^3)/sec</td>
<td>Radiative recombination coefficient</td>
</tr>
<tr>
<td>(C = 3 \times 10^{-19}) m(^3)/sec</td>
<td>Auger recombination coefficient</td>
</tr>
<tr>
<td>(g_m = 1000) m(^{-3})</td>
<td>Internal cavity loss</td>
</tr>
<tr>
<td>(\Gamma = 0.34)</td>
<td>Field confinement factor</td>
</tr>
<tr>
<td>(R_1 = 0.9)</td>
<td>High reflectivity of the left facet</td>
</tr>
<tr>
<td>(R_0 = 1 \times 10^{-2})</td>
<td>Antireflection coating reflectivity</td>
</tr>
<tr>
<td>(n_m = 4)</td>
<td>Group refractive index</td>
</tr>
<tr>
<td>(e = 1 \times 10^{-17}) cm(^3)</td>
<td>Gain comparison factor</td>
</tr>
<tr>
<td>(g = 3.6 \times 10^{17}) cm(^3)/sec</td>
<td>Gain slope constant coefficient</td>
</tr>
<tr>
<td>(a_g = 2.5 \times 10^{-20}) m(^2)</td>
<td>Differential gain</td>
</tr>
<tr>
<td>(\zeta = 3)</td>
<td>Linewidth enhancement coefficient</td>
</tr>
<tr>
<td>(\Delta \nu_0 = 1 \times 10^{-5})</td>
<td>Spontaneous-emission factor</td>
</tr>
<tr>
<td>(I_{th} = 36) mA</td>
<td>DC applying current</td>
</tr>
<tr>
<td>(I_{ext} = 8.1) mA</td>
<td>Threshold current</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fiber grating parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n_{ext} = 1.44)</td>
<td>Fiber refractive index</td>
</tr>
<tr>
<td>(L_{ext} = 3.1) cm</td>
<td>External cavity length</td>
</tr>
<tr>
<td>(L_{gc} = 4) mm</td>
<td>Grating length</td>
</tr>
<tr>
<td>(k = 5) cm (^{-1})</td>
<td>Grating coupling strength parameter</td>
</tr>
<tr>
<td>(\delta \varphi = 0.9)</td>
<td>Power reflectivity of FG</td>
</tr>
</tbody>
</table>
The typical L–I characteristics of FGFP laser at room temperature, which in this study it is considered at 25°C is shown in Fig. 2. The threshold current (I_{th}) is 8.1 mA and the slope efficiency is 0.21 W/A. Output power of 9.2 mW is obtained at 50 mA injection current. Excellent linearity is obtained between the current and the output power.

The dependence of FGFP laser L–I characteristics on the ambient temperature variation is investigated in Fig. 3 by changing the temperature 50°C (from room temperature to 75°C). With the increase of temperature, the Bragg wavelength is shifted due to the change in the fiber reflective index [4–6, 12–14], which causes a significant reduction in the effective reflectivity (R_{eff}) (Eq. (4)). Thus, the total cavity loss (Eq. (9)) is increased due to the increase of the mirror loss, therefore; the laser threshold current (Eq. (5)) is increase and the output power is reduced.

To clarify the result that obtained in Fig. 3; Fig. 4 shows the effect of temperature on R_{eff}. As it is expected from Eq. (7), the result in Fig. 4 confirms that the maximum R_{eff} occurs at the reference temperature T_0 (25°C). The lowest threshold current is achieved within around the 23 to 27°C, which is around ±2°C beside of the reference temperature T_0 (Eq. (7)). The reduction in output power with temperature in Fig. 3 is due to the variation of R_{eff} against temperature as shown in Fig. 4. Output power and threshold current depend strongly on R_{eff} as given in Eq. (5)—(15).

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![Fig. 2. L–I characteristics of FBG–FP laser at room temperature.](image)

![Fig. 3. Effect of ambient temperature variation on the L–I characteristics of FBG–FP laser.](image)

![Fig. 4. Temperature effect on the effective reflectivity.](image)

![Fig. 5. Small-signal modulation response of FBG–FP laser at different injection current (a) IM response and (b) FM response.](image)
response is decreased and at the same time, ROF is shifted towards higher frequency, which causes to increase the maximum allowable modulation bandwidth. Comparing the results with DFB laser at 25 mA injection current reported by Quan and Hui (2009) [28], shows that by using the FBG–FP laser, the peak value of IM spectrum reduced by around 6 dB and for FM spectrum reduced by 10 dB.

The effect of ambient temperature (T) variation on IM and FM spectra is shown in Fig. 6(a) and (b), respectively. The effect of temperature is calculated according to the TD of the laser cavity parameters, not by using the well-known Parkove equation. It has been shown, by increasing the temperature from 15 to a reference temperature \( T_0 = 25 \) °C, the ROF is shifted to the higher frequency and the amplitude response is significantly reduced. However, by further increment of temperature from 25 to 35 °C, ROF is shifted back towards the lower frequency and the amplitude increased. This behavior occurred due to the reduction in the OFB level that forced the laser operation to transition back from the strong regime to the weak regime [16]. Thus, results suggest that the reference temperature \( T_0 \) as the optimum operation temperature for this laser, which provide the minimum peak value spectrum and large flat frequency range operation.

To support the results that obtained in Fig. 6, Fig. 7 shows the effect of temperature on the ROF. As the result implies, the highest ROF is achieved within around the 23 to 27 °C, which is around ±2 °C beside of the reference temperature \( T_0 \) (Eq. (7)).

The variation of the ROF in Fig. 7 is due to the variation of the \( R_{\text{eff}} \) against temperature as it is discussed in Fig. 4. ROF (Eq. 18) depend strongly on the \( R_{\text{eff}} \). Thus, based on the results that obtained in Figs. (3), (4), (6) and (7), the results suggest that
temperature of the laser should be controlled within a range of 23 °C to 27 °C to provide the optimum performance. This range of temperature tolerance is high enough and does not require a very accurate and costly temperature controller compared with DFB lasers.

Fig. 8(a) and (b) shows the effect of external OFB on the normalized IM and FM response spectra for various reflectivity values from weak to moderate and strong OFB levels. The reflectivity values considered in this study are 10, 30, 50, 70, and 90%, which are obtained from the grating strength coupling coefficient ($k_{LFG}$) values of 0.6, 0.9, 1.2, 1.4, and 2.1, respectively, according to Eq. (2). As the result implies, IM and FM spectrum peak values are reduced when the reflectivity is increased due to transition the laser operation from weak regime to the strong regime. In addition, at strong OFB level, the decay rate of ROF is increased, which damps the maximum value of the response spectra. In addition, the ROF is increased by increasing the reflectivity value and saturated for both IM and FM spectra, respectively around the $R_{ext} > 70\%$, which is due to the fluctuations reduction of the gain spectrum in the active region.

Gain compression factor $\varepsilon$ is another important phenomenon for semiconductor lasers, which exhibits very high gain compression. Gain compression is caused by several mechanisms such as spatial hole burning, spectral hole burning and other nonlinearities. It is observed that the normalized peak amplitude value of IM and FM spectra decreases with the increase of $\varepsilon$ as shown in Fig. 9(a) and (b), respectively. This is due to the increasing of the decay rate of ROF which depends on $\varepsilon$ (Eq. (19)). Modulation bandwidth increases with increasing $\varepsilon$ as in [29,30]. As result implies although $\varepsilon$ affects the amplitude and modulation bandwidth, there is no significant effect on RPSS in the IM and FM spectra.

Fig. 10(a) and (b) show the normalized IM and FM response spectra modulation of FBG–FP laser at various external fiber lengths ($L_{ext}$) of 1.6, 2.3 and 3.1 cm. As shown, the amplitude and the bandwidth of IM and FM spectra changes with $L_{ext}$. According to Eq. (1), the effective reflectivity $R_{eff}$ is dependent on $\cos(\gamma \tau_e)$, where $\tau_e$ is depend on $L_{ext}$ as $\tau_e = 2 L_{ext} n_{ext}/c$. Thus, any change in the $L_{ext}$ will affect on $R_{eff}$ based on the cosine function as the inset figure shown. By any changes in $L_{ext}$, $R_{eff}$ value will be changed within a fixed range with the minimum and maximum reflectivity of around 74 and 95%, respectively. The shortest $L_{ext}$ 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 provides the maximum reflectivity value, but the longer external cavity length caused to increase the delay time ($\tau_e$). Therefore, the shortest $L_{ext}$ can provide the optimum performance. In terms of IM and FM responses, the higher $R_{eff}$ value provides the minimum IM and FM, which here it is occurred at
the $L_{\text{ext}}$ of around 3.1 cm. Thus, external fiber length $L_{\text{ext}}$ of around 3.1 cm shows the optimum performance to produce low peak value in response spectra. In addition, it is observed that changes in $L_{\text{ext}}$ do not affect the ROF. Based on the results have obtained in [29], optimizing the external cavity length $L_{\text{ext}}$ has a significant effect on suppressed the resonance peak spectral splitting (RPSS) from the modulation response spectra.

Fig. 11(a) and (b) show the effect of amplitude coupling coefficient ($C_o$) on the normalized IM and FM response. By increasing $C_o$, the peak values of IM and FM spectra are reduced due to the increment of optical power level. As given in [31], Ahmed et al. show that high coupling between active and passive cavities lead to a lack of the RPSS appearance.

To consider the effect of antireflection (AR) coated reflectivity on normalized IM and FM spectra, AR was increased and decreased to see its effect on the magnitude of discontinuity of the FBG–FP modulation response spectra. As seen in Fig. 12(a) and (b), there is no magnitude discontinuity for high value of AR coated reflectivity although discontinuity is almost suppressed for low value of AR coating reflectivity and zero value of the AR coated reflectivity could lead to continuous response in [29]. The results show that response modulation of FBG–FP laser does not strongly depend on AR coating reflectivity. Also, the RPSS does not strongly depend on high value of AR coated. The result demonstrates that AR coating reflectivity value of $1 \times 10^{-2}$ is sufficient for the laser to operate at low peak spectra value and low fabrication complexity.

Fig. 13(a) and (b) shows the normalized IM and FM responses function to the modulation frequency at different values for spontaneous emission factor $\beta_{\text{sp}}$ (1/10$^{-5}$, 3/10$^{-5}$ and 5/10$^{-5}$). As shown in Fig. 9(a), the increase of $\beta_{\text{sp}}$ not affected the IM response. In contrast, FM peak value is reduced when $\beta_{\text{sp}}$ increased from $3 \times 10^{-5}$ to $5 \times 10^{-5}$. However, the modulation response of FBG–FP laser not changes strongly with $\beta_{\text{sp}}$ and there is no appear to the RPSS. In addition, it is observed that when $\beta_{\text{sp}}$ changed, ROF not affect.

5. Conclusion

A comprehensive numerical study on intensity and frequency modulation characteristics of a FBG–FP laser is successfully conducted. The results show that with laser parameters optimization, modulation response with low peak amplitude, high flat frequency operation, high temperature stability, and high output power can be obtained. It has been shown, through simulation, FBG–FP laser modulation response is extremely sensitive to the OFB, high injection current and gain compression factor. Furthermore, AR coated reflectivity and $\beta_{\text{sp}}$ parameters have no
significant effect on the FBG–FP laser modulation response. The benefit of this study is that the designer can predetermine the requirements that should be taken into account when considering the FGFP laser to be used in an optical communication system.

References