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RESEARCH ARTICLE

A Numerical Analysis for Optimizing the Gratings Length and Coupling Coefficient for High Reflectivity and Low Cavity Loss in Fiber Grating Fabry-Perot Laser Model

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Abstract: The effects of gratings length (kL_{FG}) and amplitude coupling (C_o) coefficients on the effective reflectivity (R_{eff}) and the total cavity loss (α_{tot}) of an external cavity laser source (ECLS) based fiber Bragg gratings (FBGs) are numerically analyzed for designing a laser source operating in strong feedback regime (Regime V). In this study, FBG is used as a wavelength selective element to control the properties of the laser output by controlling the fiber gratings reflectivity level. The study is performed by modifying full analytical expressions for the R_{eff} and the α_{tot} based on laser coupled-wave equations. Results show that R_{eff} is strongly dependent on kL_g and C_o. Also, it is found that α_{tot} has been reduced significantly with increasing C_o, especially at high value for kL_G (kL_{FG}> 1.5).

Keywords: External cavity lasers source (ECLS), Effective reflectivity, Fiber Bragg Gratings (FBGs), Fiber lasers (FLs), Total cavity loss.

1. INTRODUCTION

Fiber Bragg gratings (FBGs) have been widely used in optical fiber communications [1]; sensing [2] and lasers [3]. The most significant feature of an FBG is the relatively narrow band width of its reflection spectrum. The reflection wavelength is determined by the grating period while the reflectivity is proportional to the depth of the index modulation. Usually, the index modulation can be as large as 0.001 with UV exposure of Ge-doped fiber and the reflectivity can be close to unity over the reflection band [4]. Whatever the characteristics a FBG possesses, the reflectivity is fixed after it is fabricated. This property limits the application of an FBG [5 - 10].

On the other hand, the incessant increase in the users of optical communication systems demands for very high speed data transmission [11, 12]. Having the ability of high speed modulation, semiconductor laser diodes (SLDs) become an excellent option for wavelength division multiplexing (WDM) systems. However, a major obstacle preventing closer WDM channel spacing is the drift of emission wavelength [13, 14]. Therefore, with the development of dense WDM (DWDM) systems, lasers with narrow linewidth, high side mode suppressed ratio (SMSR), low cost, and stable dynamic single-mode operation are indispensable [15].

In recent years, fiber grating Fabry-Perot (FGFP) laser model is proposed as an alternative light source for DWDM systems, which can generate output with high wavelength stability [11 - 15]. This is because the emission wavelength of FGFP laser depends only on the Bragg wavelength of fiber gratings (FGs), thus, independent of chip temperature and injection current. Moreover, the lasing wavelength tuning can be performed accurately because the grating period of FBG can be controlled with high accuracy of ±0.1 nm [2, 4 - 6]. Therefore, precise adjustment of the Bragg wavelength in FG is easier in comparison to the emission wavelength of distributed feedback (DFB) lasers.

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Conversely, the dynamic behavior of the laser diode (LD) coupled with gratings fiber can be divided into five regimes based on the reflected intensity level [9]. In regime I, the reflected level is quite small; the laser linewidth is increased or decreased depending on the phase of the delayed light coupled into the LD. With the increase of the reflected level; the LD will operate in regime II, where mode hopping among several external cavity modes can be observed. Further increase in the reflected level will bring the LD into regime III and IV, where the linewidth of the LD is drastically broadened and the chaos can be seen in these regimes. In the new regime V, where there is very high reflected level, the internal and external cavities behave like a single cavity and the laser oscillates in a single mode [10]. Therefore, optimizing the external cavity parameters (*i.e.* gratings length (kL_{FG}) and amplitude coupling (C_o) coefficients) for high reflected level is very important for satisfying the DWDM systems requirements.

Although many experimental and theoretical studies have been reported on the external cavity semiconductor laser (ECSL) source based FBGs characteristics [9]. However, the effects of the gratings length (kL_{FG}) and coupling (C_o) coefficients on the ECSL based FBGs performance are yet to be investigated. In this paper, we have conducted successfully a numerical analysis on the effects of kL_{FG} and C_o on the effective reflectivity (R_{eff}) and the total cavity loss (α_{tot}) of an FGFP laser model. The obtained results can provide an important data for designing and practical fabrication of this advanced laser type. The paper is structured as follows: The effective reflectivity and total cavity loss in fiber grating Fabry-Perot (FGFP) laser model is given in the next section. The simulation results are discussed in Section 3 followed by the conclusion.

2. EFFECTIVE REFLECTIVITY AND TOTAL CAVITY LOSS IN FGFP LASER MODEL

Fiber grating Fabry-Perot (FGFP) Lase model consists of three main sections as shown in Fig. (**1a**). The first section is the Fabry-Perot laser diode (FP-LD) of length L_d. It is assumed that the reflectivity of the chip front facet (R_o) is very low to suppress FP mode oscillation and to stabilize the external cavity mode, while the rear facet has high reflectivity (R_1). The second section is a fiber of length L_{ext}; and the third is the FBG with reflection coefficient of r_{FBG}. The FP-LD and the FBG are optically coupled through a coupling lens, and thus external cavity is constructed.

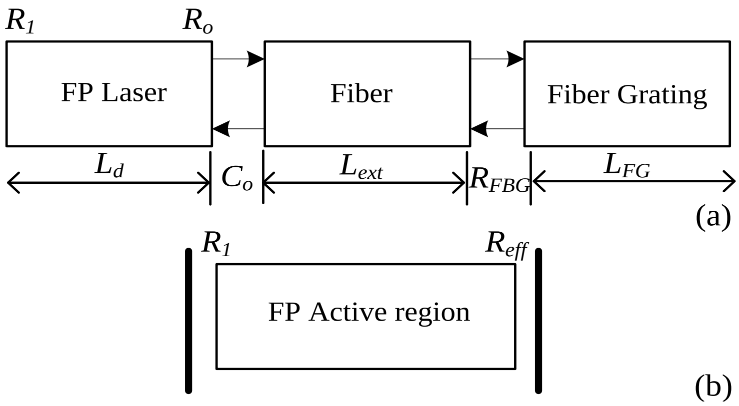

Fig. (1). (**a**) Schematic structure of FGFP laser and (**b**) Simplified configuration [11 - 14].

This configuration may be conveniently analyzed as a simple two-mirror laser structure (Fig. **1b**) by replacing the FP diode laser output facet reflectivity R_o by a complex-valued effective reflection coefficient R_{eff} [12 - 14].

$$R_{eff} = \frac{R_o^2 + R_{OFB}^2 + 2R_o R_{OFB}\cos(\omega\tau_e)}{1 + R_o^2 R_{OFB}^2 + 2R_o R_{OFB}\cos(\omega\tau_e)} \tag{1}$$

where $\omega\tau_e$ is the phase of the reflected light that travels through the external cavity and $\boldsymbol{\omega}$ is the laser angular frequency. In (1), $R_{OFB} = C_o\, R_{ext}$ is the amount of optical feedback reflection that coupled into FP laser diode, where C_o is the amplitude coupling coefficient between the FP laser diode and the grating fiber, and R_{ext} is the power reflectivity of FG defined as [15, 16]

$$R_{ext} = \left|R_{FBG}\right|^2 = \begin{cases} \dfrac{(kL_{FG})^2 \sinh^2(QL_{FG})}{(\Delta\beta L_{FG})^2 \sinh^2(QL_{FG}) + (QL_{FG})^2 \cosh^2(QL_{FG})} & f\,(kL_{FG})^2 \rangle (\Delta\beta L_{FG})^2 \\ \dfrac{(kL_{FG})^2 \sin^2(\Omega L_{FG})}{(\Delta\beta L_{FG})^2 - (kL_{FG})^2 \cos^2(\Omega L_{Fg})} & if\,(kL_{FG})^2 \langle (\Delta\beta L_{FG})^2 \end{cases} \quad \textbf{(2)}$$

where L_{FG} is the grating length, $\Delta\beta$ is the wavelength detuning, k is the coupling strength, $Q = \sqrt{k^2 - \Delta\beta^2}$, and $\Omega = iQ = \sqrt{\Delta\beta^2 - k^2}$. The phase coefficient for reflection light θ_{ref} is derived from the differential equations in [15] and is given by:

$$\theta_{ref} = \begin{cases} \tan^{-1}\left(\dfrac{Q\cosh(QL_{FG})}{\Delta\beta\sinh(QL_{FG})}\right), & \text{if} \quad (kL_{FG})^2 \rangle (\Delta\beta L_{FG})^2 \\ \tan^{-1}\left(\dfrac{\Omega\cos(\Omega L_{FG})}{\Delta\beta\sin(\Omega L_{FG})}\right), & \text{if} \quad (kL_{FG})^2 \langle (\Delta\beta L_{FG})^2 \end{cases} \quad \textbf{(3)}$$

By considering the phase change introduced by the optical filter in (1), R_{eff} can be rewritten as:

$$R_{eff} = \frac{R_o^2 + R_{OFB}^2 + 2R_oR_{OFB}\cos(\omega\tau_e - \theta_{ref})}{1 + R_o^2R_{OFB}^2 + 2R_oR_{OFB}\cos(\omega\tau_e - \theta_{ref})} \quad \textbf{(4)}$$

After modifying the well-known expressions for the FP laser [17] by taking into account the effect of FBGs reflectivity and coupling coefficient (C_o), the total cavity loss (α_{tot}) of FGFP laser model is given by:

$$\alpha_{tot} = \alpha_{\text{int}} + \frac{1}{2L_d}\ln\left(\frac{1}{R_1R_{eff}}\right) \quad \textbf{(5)}$$

Where α_{int} is the internal loss of the FP laser cavity.

3. RESULTS AND DISCUSSION

In this study, a FGFP laser with uniform FBG operating at 1550 nm wavelength is analyzed. The parameters of the laser model used in the analysis are L_d =400 µm, α_{int} = 1000 m^{-1}and R_1 = 0.9.

Fig. (**2**) shows the effective reflectivity (R_{eff}) of FGFP laser model function to the grating length coefficient (kL_{FG}) at different values of amplitude coupling coefficient (C_o). Stable fundamental lateral mode operation up to high power is required to achieve high laser-to-fiber coupling efficiency (C_o), so by increasing the gratings length (kL_{FG}) with increasing the coupling between the laser cavity and gratings fiber, the power reflectivity of FG (R_{ext}) will be increased due to increase in the reflective strength [16] then increasing R_{eff}; and this result seems to be consistent with what is given in Eqs. (2) and (4). In addition, result shows that for kL_{FG} > 2.5, the R_{eff} saturate approximately at its value with increasing C_o.

Fig. (**3**) shows the effective reflectivity (R_{eff}) of FGFP laser model function to the amplitude coupling coefficient (C_o) at different values of grating length coefficient (kL_{FG}) Since coupling loss occur twice during each reflection, thus the power coupling between the fiber gratins (FGs) and the active laser cavity is very important.

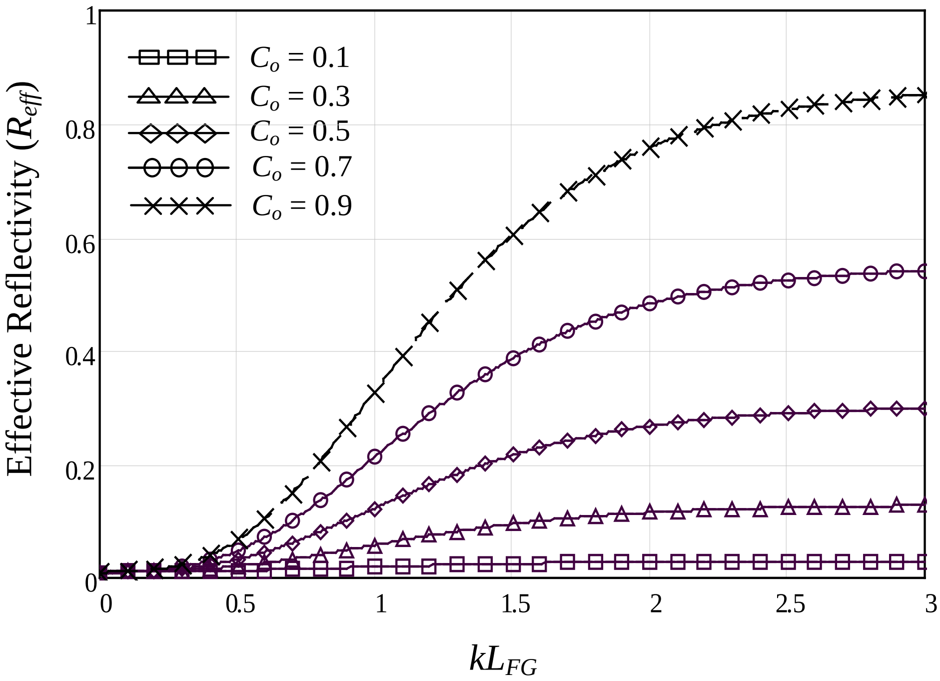

Fig. (2). Effective reflectivity (R_{eff}) of FGFP laser model function to the grating length coefficient (kL_{FG}) for different values of amplitude coupling coefficient.

Therefore, with increasing C_o, the optical coupling between the laser cavity and the FG will increase. This will reduce the output leakage from the laser cavity and also increase the incident light on the gratings fiber; and then increasing R_{eff}. The increasing of R_{eff} with increasing C_o is smoothly linear and R_{eff} is maximum if C_o is maximum. On the other hand, for $kL_{FG} > 2.5$ there is no significant impact on R_{eff} with increasing C_o.

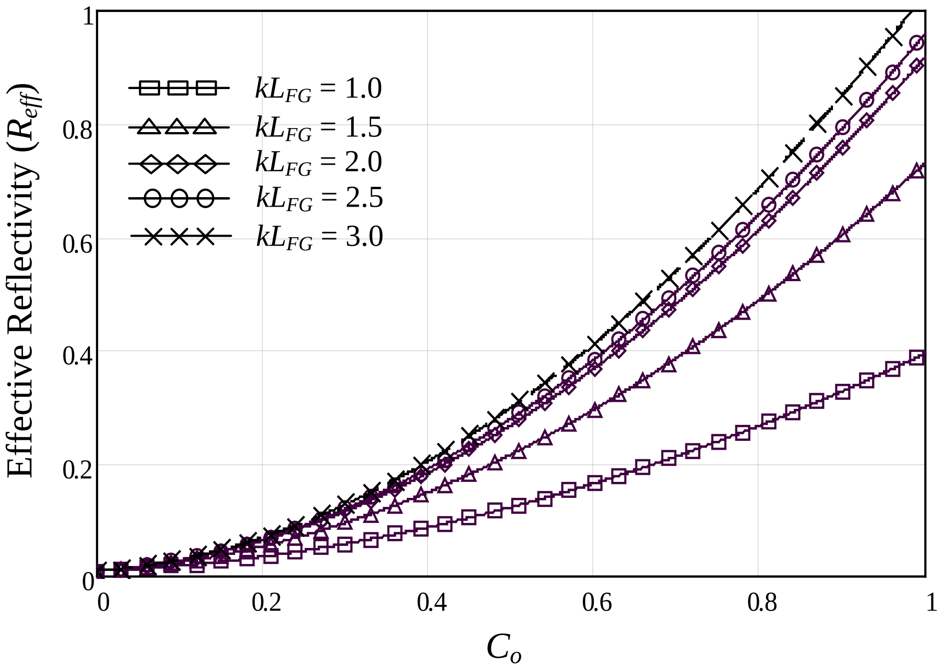

Fig. (3). The effective reflectivity (R_{eff}) of FGFP laser model function to the amplitude coupling coefficient (C_o) at different values of grating length coefficient (kL_{FG}).

Fig. (**4**) shows the total cavity loss (α_{tot}) of FGFP laser model function to the grating length coefficient (kL_{FG}) at different values of amplitude coupling coefficient (C_o). As shown, α_{tot} is relatively inversely proportional to increasing kL_{FG}. This decreasing is due to increasing R_{eff} as shown in Fig. (**2**); where with increasing the total reflectivity, the multi reflection inside the active region (as shown in Fig. **1b**) will increase and this leads to reduce in the mirror loss for the cavity and then reduce α_{tot}. This is because α_{tot}; as is well-known it relies heavily on mirror loss (as given in Eq. 5) and not on α_{int} [17]. Also, result shows that for kL_{FG} 1.5, α_{tot} is not significantly affected with increasing C_o. In addition, α_{tot} can reduce below 100/cm through operating with $C_o = 0.9$ and $kL_{FG} \geq 1.5$.

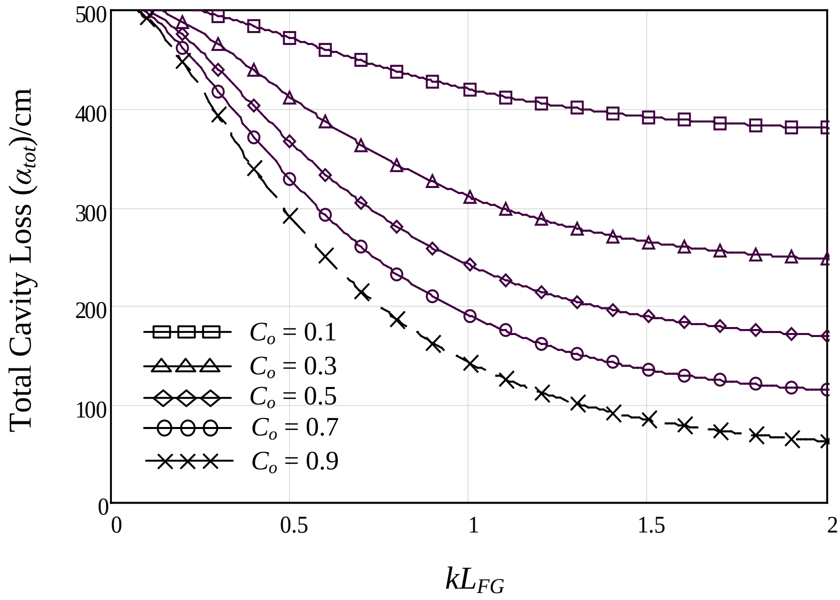

Fig. (4). Total cavity loss (α_{tot}) of FGFP laser model function to the grating length coefficient (kL_{FG}) at different values of amplitude coupling coefficient (C_o).

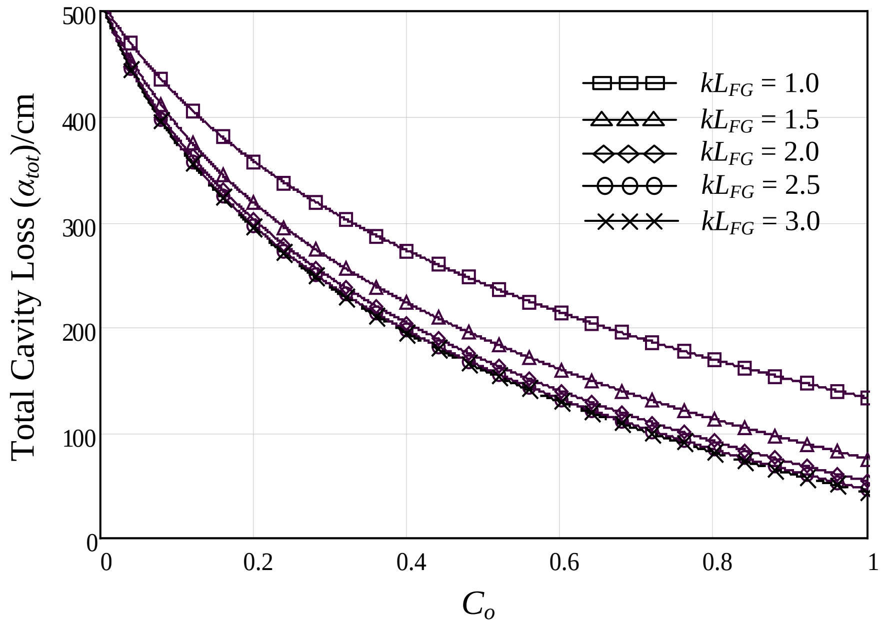

Fig. (5). Total cavity loss (α_{tot}) of FGFP laser model function to the amplitude coupling coefficient (C_o) for different values of grating length coefficient.

Fig. (**5**) shows the total cavity loss (α_{tot}) of FGFP laser model function to the amplitude coupling coefficient (C_o) at different values of grating length coefficient (kL_{FG}). As shown, with increasing C_o; the total loss is reduced obviously. In addition, when kL_{FG} is increased from 1 to 1.5, the reduction in the α_{tot} with increasing C_o is shown to be the maximum more than ever before. Also, result shows that the value of C_o on total loss reduction is somewhat ineffective with kL_{FG} >2.

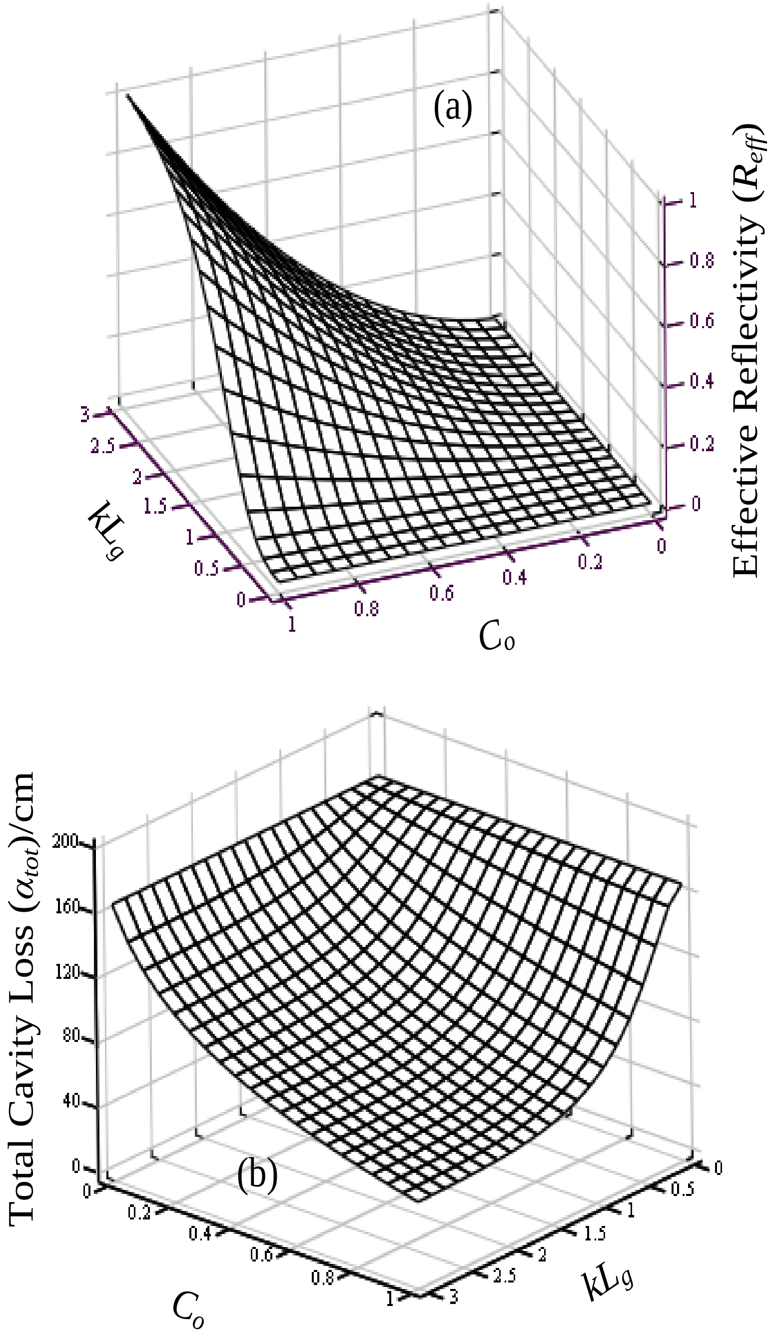

Fig. (6). Combine effect of amplitude coupling coefficient (C_o) and grating length coefficient (kL_g) on (**a**) Effective reflectivity (R_{eff}) and (**b**) Total cavity loss (α_{tot}) of FGFP laser model.

Finally, the combine effect of amplitude coupling coefficient (C_o) and grating length coefficient (kL_{FG}) on effective reflectivity (R_{eff}) and total cavity loss (α_{tot}) of FGFP laser model is shown in Fig. (**6**), respectively. As can be seen, a highly effective reflectivity and very low total cavity loss can be produced by increasing kL_{FG} and C_o. As a result, increasing the kL_{FG} and C_o leads to increase effective laser reflectivity and this leads to reduce the laser cavity loss. Fig. (**6**) shows that the designer can control the R_{eff} leads to increase effective laser reflectivity and this leads to reduce the laser cavity and α_{tot} values by optimizing the kL_{FG} and C_o, values. This can reduce the total cost due to reduction in the total design complexity.

CONCLUSION

A numerical study on the effects of gratings length (kL_{FG}) and amplitude coupling (C_o) coefficients on the effective reflectivity (R_{eff}) and the total cavity loss (α_{tot}) of a FGFP laser is successfully conducted. It has been shown, through simulation, R_{eff} and α_{tot} are extremely sensitive to the kL_{FG} and C_o coefficients. It has also been shown that for $kL_{FG}>2$, the value of C_o is somewhat ineffective on total loss reduction. In addition, by optimizing the kL_{FG} and C_o, α_{tot} can be reduced below 100/cm.

CONFLICT OF INTEREST

The author confirm that this article content has no conflict of interest.

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Declared none.

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