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Simulative Extraction and Performance investigation of Improved Compensated DFB Laser for an IM-DD SCM Optical Link#

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Abstract: A variety of compensated Distributed feedback (DFB) lasers have been extracted by simulation using the laser rate equation description of a DFB laser. Here preselected desired system performance estimates are used as target measurements to extract physically realizable laser parameters for an intensity modulation direct detection (IM-DD) subcarrier multiplexing (SCM) optical link to offer a promising improved system performance. The resulting DFB laser models have favourably low threshold current and narrow line widths and have the capability of IMD and HD correction along with RIN and clipping distortion suppression.

Keywords: *Clipping, DFB laser, HD, IMD, Laser rate equation, RIN, SCM*

1. Introduction

SCM optical transmission systems efficiently synergize two communication domains and effectively combine the excellent properties of mature frequency division multiplexing (FDM) techniques in electrical domain with the wide bandwidth and low loss properties of an optical fiber [1]. SCM has been utilized in several applications involving access loops like hybrid fiber coaxial (HFC) based cable television (CATV), Radio over Fiber (RoF), subcarrier multiple access (SCMA) based fiber to the home (FTTH) and passive optical networks (PONs)[2, 3, 4] besides being used with wavelength division multiplexing (WDM) for enhancement of fiber transmission capacity [5, 6]. The SCM applications have been broadly realized by direct IM-DD scheme [4, 5], which is simpler and less complex to implement than IM-DD based on an external modulator [3]. However due to the inherent non-linear nature of the laser source impairments like harmonic distortion (HD), inter-modulation distortion (IMD), random intensity noise (RIN) and laser clipping distortion [2-7] cause performance degradation in IM-DD SCM systems. While intensity modulation of single subcarrier induces HD, however as the count of subcarriers increases, the multitude of products is compounded further causing IMD induced intermodulation products (IMPs). RIN is generated within the laser source due the spontaneous emission mechanism while the laser clipping distortion is generated when a laser diode threshold currents occur at high values close to the bias current [2, 4, 6].

Previous studies have reported several measures taken and solutions proposed to overcome the negative influence of the laser originating mechanism. These include feed-forward compensation and pre-distortion [3]; selection of octave transmission bandwidth [4, 9]; using an unequally spaced frequency plan [8] and adjustment of optical modulation depths (OMD) to suitable levels to make these systems clipping tolerant [2].A challenge among designers and manufacturers is to explore and improve these solutions further by exploiting the dependency of the laser non-linear characteristics and dynamic effects within the active layer on device processing, material and structural parameters [2, 4, 5].

This paper is organized as follows: In section 2 a theoretical description of DFB laser rate equation model [5, 10] provides an understanding of influence of these parameters on non-linear behaviour. This will help to identify the most appropriate target parameter values besides preferring low active layer volume, high carrier lifetime, and low laser threshold current and high bias current to allow suppression of the laser impairments [11-13] in an IM-DD SCM lightwave system. Section 3 of this paper describes simulative procedure involved in extraction of DFB laser followed by identifying a set of appropriate and physically reasonable DFB rate equation parameter values. Further in this section, a comparative study will be undertaken in case of the selected new DFB laser samples in an IM-DD SCM system. The results and discussion are highlighted in section 4 based on the performance and comparative study of the proposed compensated DFB laser in the basic IM-DD SCM system while the conclusion and future scope is presented in section 5.

2. Rate Equation Description of Distributed Feedback Laser

In DFB laser [5, 10] the optical feedback is distributed throughout the cavity length rather being localized [5], with the help of an in-built frequency selective reflector. In agreement with the broadly assumed single mode nature of a DFB laser, the single mode formulation of laser rate equations have been used to study its modulation dynamics [5,10,14]. The coupled rate equations which describe the operational characteristics of the single mode DFB laser is given by Equations (1a) and (1b) respectively.

$$\frac{dN(t)}{dt} = \frac{I(t)}{qV} - \frac{N(t)}{\tau_n} - g_0\frac{[N(t) - N_t]}{[1+\varepsilon S(t)]} \qquad 1(a)$$

$$\frac{dS(t)}{dt} = \Gamma\beta\frac{N(t)}{\tau_n} - \frac{S(t)}{\tau_p} + \Gamma g_0\frac{[N(t) - N_t]}{[1+\varepsilon S(t)]}S(t) \qquad 1(b)$$

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Here N(t) is the electrons carrier density (cm^{-3}); S(t) is the photon density (cm^{-3}); I(t)/qV is the total injected electron rate ; V is the active layer volume; τ_n is the Carrier life time; g_o is slope gain constant; N_t is carrier density at transparency; ϵ is the optical gain compression coefficient; Γ is the optical mode confinement factor; β is the probability of radiative spontaneous emission factor; τ_p is the photon life time and α is the linewidth enhancement factor.

The non-linear characteristic behaviour of the DFB laser can be suppressed through a proper selection of laser structural parameters and operational conditions. Γ, the optical mode confinement factor depends on the thickness of active region cavity. A high value of Γ is preferred in lasers to ensure a good optical mode confinement which will further assist in minimizing threshold current I_{th} of the laser. I(t) (amps), is the injected current or the modulating current into the laser. Minimization of laser threshold current I_{th} (amps), is one of the challenges in laser research and development and is greatly dependent on laser structural parameters [14]. It is low in laser designs with small active layer volume V, large Carrier life time τ_n,[10, 15], high differential gain, reduced cavity and mirror losses and in laser designs with heterojunctions. I_{bias} (amps), is the bias current of the laser device should be greater than I_{th} so as to avoid clipping and to allow large values of OMD. V(cm^3) is the active layer volume of the laser cavity. Small values of active layer volume lead to higher carrier density and are favoured till the optical mode is still sufficiently confined in it. η is the quantum efficiency and its indicates the fraction of the generated photons that manage to contribute to the output power of the laser. τ_p (s), the photon life time is the photon decay time and is associated with the cavity loss [14]. β is the probability of radiative spontaneous emission factor and accounts for the fraction of spontaneous emission incoherent photons coupled and confined to the lasing mode. N_t (cm^{-3}), is carrier density at transparency and the photons due to stimulated emission contribute to laser output only when N(t) is greater than N_t. g_o (cm^3/s) is the gain slope constant equal to the product $v_g a_o$ where v_g (cm/sec) is the group velocity of light in laser and a_o (cm^2) is differential gain coefficient. The differential gain coefficient should be large to achieve better performance. α is called the linewidth enhancement factor as it quantifies the enhancement in the spectral width of emission line of a single mode. Laser designs with small value of α are preferred so that both RIN mechanism and chirping will be suppressed. ϵ (cm^3), is the gain compression coefficient or factor and it is a non-linear gain parameter to account for slight reduction in gain as photon density S(t) increases. The reduction is attributed to several physical mechanisms such as spatial hole burning, carrier heating, and photon absorption

3. DFB Laser Modelling

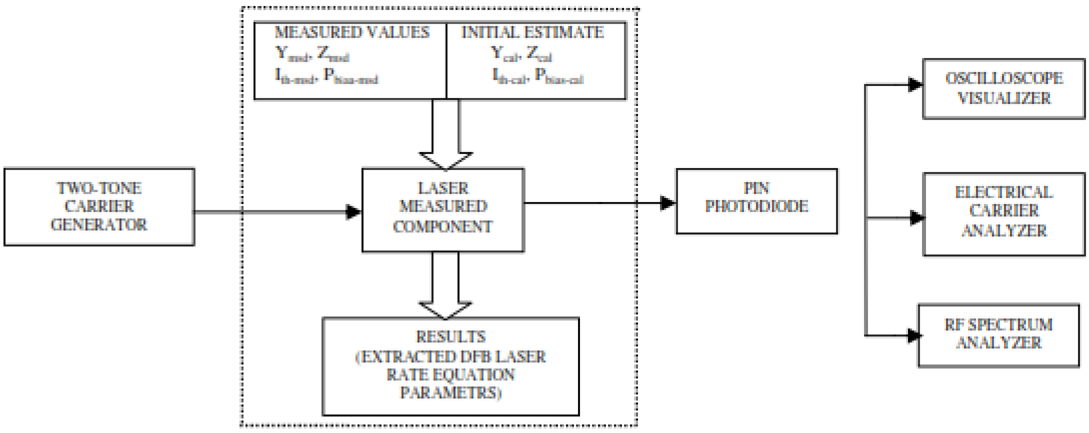
The IM-DD SCM systems for extraction and for performance evaluation have been implemented in an optical system design simulator [10], shown in Fig 1(a) and 1(b) respectively.

The DFB laser is characterized by extracted parameters of laser measured component in Fig 1(a) and by laser rate equation parameters in Fig 1(b) respectively. After intensity modulation of these lasers by subcarrier frequencies at $f_1$and f_2 equal to 500 and 525 MHz, the spectrum analyzer shows second-order IMD components at 1000, 1025 and 1050 MHz; two-tone third-order IMD components at 1525 and 1550 MHz; triple-beat third-order IMD components at 2025, 2050, and 2075 MHz and harmonics of 500 and 525 MHz Electrical carrier analyzers are tuned to the most significant distortion component appearing on the spectrum analyzer generated by the non-linear laser source.

3.1. RiskParameter Characterization of Reference DFB Laser Diode

A DFB laser diode (designated as Laser-1) has been chosen as the reference laser diode, whose performance has already been investigated in [11, 12, 13]. The parameter values of DFB Laser-1 are as illustrated in Table 1 (a)-(c). The value of slope efficiency (η_{slope}) and P_{bias} in Table 1(c) is calculated from output L-I curve while RIN spectrum specifications measurements are recorded from RF spectrum analyzer.

The values of I_{th} and P_{th} cannot be changed externally because their values are calculated within the simulator and depend on rate equation parameter of Table 1 [10, 14]. The functional dependence of I_{th} and P_{th} has been observed in case of active layer volume in Fig. 2(a) Fig.2 (b) when all other physical parameters listed in Table 1(a) are unchanged. Thus occurrence of low I_{th} can be realized in lasers with small active layer volume, although very small active layer volume may adversely cause reduction in Γ as well due to optical spill over.



Laser Measured Component Section

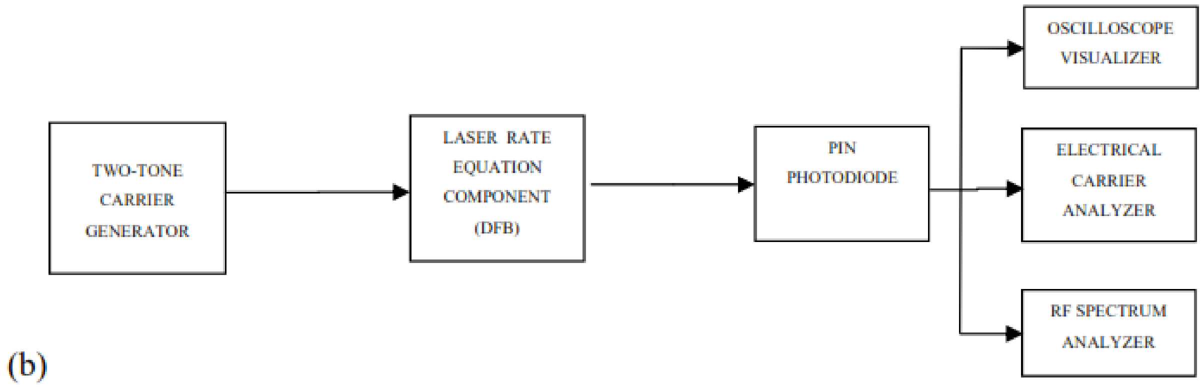


Figure 1: A schematic of IM-DD SCM based simulation setup (a) for extraction of DFB laser rate equation parameters using a laser measured component, (b) using laser rate equation component as DFB laser diode source

Table 1: DFB Laser-1 properties (a) Physical parameter characterization, (b) Main parameter values, (c) Slope efficiency of output L-I output, RIN peak power, peak position and spectral width.

1(a) Laser-1	
Physical parameter name	**Parameter value**
V(x 10^{-10} cm^3)	1.5
Γ	0.4
a_0 (x 10^{-15} cm^2)	0.25
η_o	0.4
ϵ (x 10^{-18} cm^3)	10
τ_p (ps)	3
τ_n(ns)	1
β (x 10^{-6})	30
N_t(x 10^{18} cm^{-3})	1
α	5
V_g (x 10^9 cm/s)	8.5

1(b) Laser-1	
Main Parameter	**Parameter value**
Frequency (THz)	193.1
I_{bias}(mA)	38
I_{pk} (mA)	3.8
I_{th}(mA)	33.4572
P_{th}(mW)	0.0155
1(c) Output L-I characteristics and RIN spectrum specifications	
η_{slope} (mW/mA)	0.1641
P_{bias}(mW)	0.7610
RIN peak power	-65.81dBm
RIN peak position	2.10 GHz
RIN spectral width	2.99 GHz

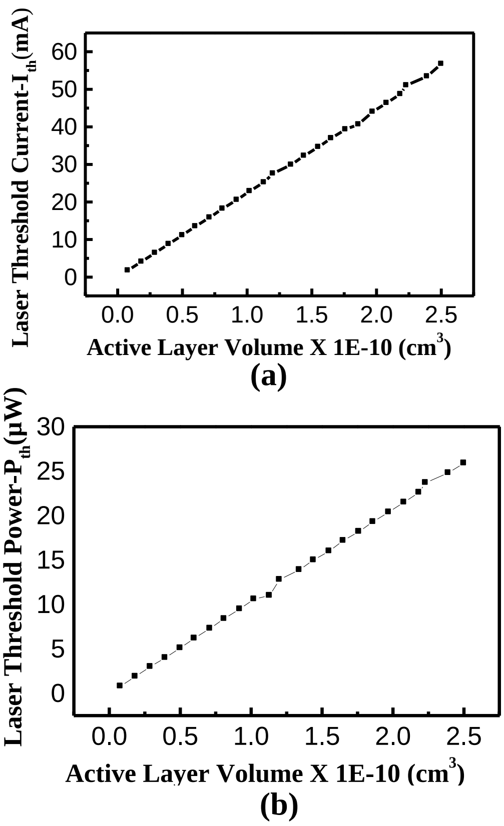


Figure 2: (a) Calculated I_{th}, and (b) P_{th}values with respective to active layer volume of Laser-1 changed from 0.078 E-10 cm^3 to 2.5 E-10 cm^3.

3.2. Simulative Parameter Extraction Procedure

The laser measured component used in the IM-DD SCM setup of Fig. 1(a) is based on a technique described in [14]. This component reproduces predefined measured results of threshold current (I_{th}), damping factor (Y), resonance frequency factor (Z) and bias power (P_{bias}), exploiting the fact that I_{th}, Y, Z and P_{bias} are functions of laser physical parameters [5, 10,14], involving minimization of sum of squared errors between their measured values (Y_{msd}, Z_{msd}, $I_{th\text{-}msd}$, $P_{bias\text{-}msd}$) and their calculated values (Y_{cal}, Z_{cal}, $I_{th\text{-}cal}$, $P_{bias\text{-}cal}$) which are obtained from initial estimates of rate equation parameters.
In the following section, the laser measured component has been used to perform various such minimization routines with the intension of producing new DFB laser samples or models with a promising low threshold current specification and with target DFB rate equation parameter measurements as close as possible to that of reference Laser-1. Table 2(a) to 2(c) illustrate the corresponding main parameter, measured parameters and initial

estimate setting respectively whereas Table 2(d) show the resulting output L-I and RIN characteristics of the laser. The extracted parameters shown in Table 2(e) will represent the rate equation description of a new DFB laser sample

The measured value of threshold current ($I_{th\text{-}msd}$), slope efficiency ($\eta_{slope.msd}$), and P_{ref} (P_{bias} of Laser-1) are set at 33.4572 mA, 0.1641 mW/mA and 0.7610 mW respectively in accordance to their values calibrated and obtained from output L-I characteristic of Laser-1. The measured damping factor (Y_{msd}) and measured defined resonance frequency factor (Z_{msd}) of the laser is fixed at 10.28 x 10^9 s^{-1} and 6.43 x 10^{20} Hz^2 respectively. These are the respective Y and Z values of small-signal IM frequency response as featured in [14]. Also the 2(d) section of this table gives the calculated values of Z_{res} (resonance frequency) and σ_λ (laser linewidth).

Subsequently the extraction procedure was repeated numerously in a similar fashion for reduced measured threshold currents from 32.4572 mA down to 20 mA and even at different slope efficiency settings. The resulting extracted samples showed varying range of laser properties. The intension was to identify and shortlist laser samples with overall suitable attributes. In this process two most seemingly suitable and compensated samples were shortlisted. These have been designated as Laser-2, and Laser-3. Their specifications and their rate equation parameter values have been listed in Table 3 with reference to Laser-1.

Table 2: Laser measured properties of extracted samples, where group velocity settings of v_g is 8.5x 10^9 (cm/s), I_{ref} is 38 mA, and $I_{th\text{-}msd}$ at 33.4572 mA. Sample-1 has been calculated on basis of $P_{ref\text{-}msd}$ equal 0.761 mW whereas remaining samples have been calculated on the basis of $\eta_{slope\text{-}msd}$ equal to 0.1641mW/mA.

2(a) Main parameters					
Frequency (THz)	193.1				
I_{bias}(mA)	38				
I_{pk} (mA)	3.8				
2(b) Measured parameters	**Values**	**2(e) Extracted results**			
		Sample-11	**Sample-12**	**Sample-13**	**Sample-14**
Y_{msd}(x10^9 s^{-1})	10.28	10.006	10.006	10.27	10.28
Z_{msd} (x10^{20} Hz^2)	6.43	6.25	6.25	6.429	6.43
$I_{th\text{-}msd}$(mA)	33.4572	32.8633	32.8631	33.4572	33.4571
$\eta_{slope\text{-}msd}$ (0.1641 mW/mA if T)	F/T	F	T	T	T
$\sigma_{\lambda\text{-}msd}$ (10 MHz if T)	F/T	F	F	T	T
Average RIN_{msd} (-140 dB/ Hz if T)	F/T	F	F	F	T
2(c) Initial estimate	**Value (Laser-1)**	**Sample-11**	**Sample-12**	**Sample-13**	**Sample-14**
V(x 10^{-10} cm^3)	1.5	1.466	1.466	2.419	2.302
Γ	0.4	1	1	0.994	0.99
a_0 (x 10^{-15} cm^2)	0.25	0.342	0.342	0.683	0.754
η	0.4	0.427	0.419	0.411	0.410
ϵ (x 10^{-18} cm^3)	10	25.10	25.01	43.43	41.13
τ_p (ps)	3	3.32	3.32	8.42	8.29
τ_n(ns)	1	0.381	0.381	27.32	22.79
β (x 10^{-6})	30	46.63	46.63	22.67	59.19
N_t(x 10^{18} cm^{-3})	1	0.429	0.429	23.56	20.65
α	5	5	5	2.310	1.1679
2(d) Output L-I and RIN characteristics		**Sample-11**	**Sample-12**	**Sample-13**	**Sample-14**
η_{slope} (mW/mA) (Laser-1 η_{slope} = 0.1641mW/mA)		0.1671	0.1637	0.1641	0.164
P_{bias} (mW) (Laser-1P_{bias}=0.7610 mW)		0.8587	0.8412	0.7454	0.7454
3dB bandwidth (GHz)		6.7554	6.755	6.846	6.846
Z_{res} (GHz)		3.817	3.817	3.866	3.866
σ_λ (MHz)		190.26	190.25	10	9.99
Average RIN (dB/Hz)		-137.63	-137.63	-144.26	-139

Table 3: Laser rate equation properties of Laser-1, -2, -3 and -4 based on extracted parameter values, where group velocity settings of V_G is 8.5x 10^9 (cm/s), I_{ref} is 38 mA.

Parameter Name	Parameter Value		
	Laser-1	Laser-2	Laser-3
v_g (cm/s)	8.5x 10^9	8.5x 10^9	8.5x 10^9
η	0.4	0.4	0.4
V(x 10^{-10} cm^3)	1.5	1.5086	1.5
τ_n(ns)	1	1.001	1.001
τ_p (ps)	3	3.001	3.001
β (x 10^{-6})	30	30	30
ϵ (x 10^{-18} cm^3)	10	10	10
N_t(x 10^{18} cm^{-3})	1	1	1
Γ	0.4	0.4	0.4
α	5	1.171	1.171
a_0 (x 10^{-15} cm^2)	0.25	0.271	0.271
I_{bia} (mA)	38	38	38
P_{th} (mw)	0.0155	0.0148	0.1476
I_{th} (mA)	33.4572	32.8787	32.6913
I_{pk} (mA)	3.8	3.8	3.8
(I_{bias}- I_{th}) mA	4.5428	5.122	5.308
η_{slope} (mW/mA)	0.1641	0.15773	0.1590
P_{bias} (mW)	0.7610	0.8227	0.8587
RIN peak power (dBm)	-65.81	-66.00	-64.88
RIN peak position (GHz)	2.10	2.139	2.262
RIN spectral width (GHz)	2.99	3.55	2.807
Clipping tolerant current range (I_{bias}- I_{th}) mA	4.54	5.122	5.308

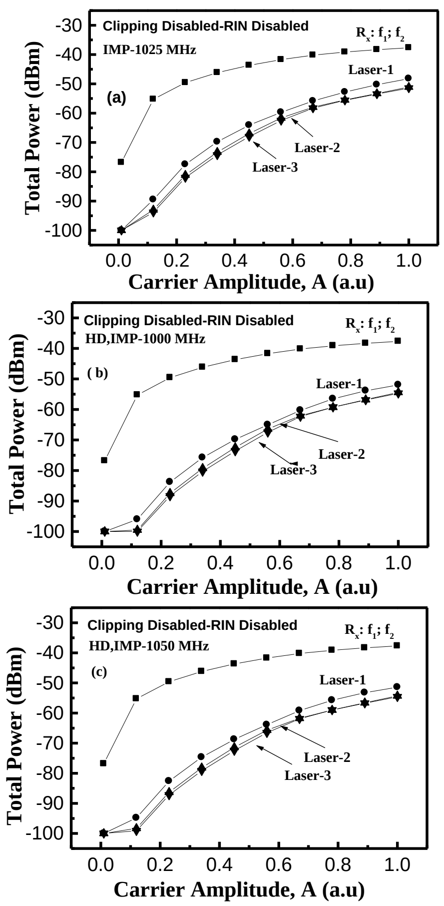


Figure 3: Response of DFB Laser-1, Laser-2 and Laser-3changes in carrier amplitude for (a) IMP-1025 Hz, (b) HD, IMP 1000 MHz, and (c) HD, IMP 1050 MHz, in a CD-RD IM-DD SCM system

3.3. Comparative study of proposed DFB laser samples in IM-DD SCM lightwave system

The suitability of the new proposed DFB Laser-2 and -3 lasers will be investigated and compared with reference to Laser-1 in case of a Clipping Disabled-RIN Disabled (CD-RD) based IM-DD SCM system model of [22]. This has been implemented in the simulative set up of Fig 1(b). Most significant distortion components which have been selected are designated as IMP-1025 MHz (f_3), HD, IMP-1000 MHz ($2f_1$, f_6) and HD, IMP-1050 MHz ($2f_2$, f_5) in the descending order of their significance. These are measured with respect to carrier amplitude within the clipping tolerant range of each laser and the results are henceforth shown in Fig. 3(a –c).

Overall comparison in case of the most dominant IMP-1025 MHz has been compiled in Table 4 in case of CD-RD IM-DD SCM system model.

4. Results and Discussion

An inspection of this table reveals that lasers Sample-11 and Sample-12, both show similar laser properties and extracted parameter values, whether these are calculated on the basis of $P_{ref-msd}$ of 0.761 mW as in former or on the basis of $\eta_{slope-msd}$ equal to 0.1641mW/mA as in case of latter. The extraction procedure in both these cases will be more relaxed since both laser linewidth data ($\sigma_{\lambda-msd}$) and average RIN data are set at false (F) implying that these parameters will not be part of the extraction procedure and hence extracted physical parameters of these samples approximate closely to the physical parameters of reference Laser-1, but at the cost of large linewidth and large RIN. On the contrary since in case of Sample-13, $\eta_{slope-msd}$, linewidth data are set true (T) thus these parameters are involved in the extraction procedure and hence extracted linewidth is 10 MHz and slope efficiency is 0.1641, but the extracted physical parameters assume different values from those of the reference Laser-1. In case of Sample-14, $\eta_{slope-msd}$, $\sigma_{\lambda-msd}$ and Average RIN_{msd} are all set at T and hence their extracted values of 0.1641 mW/mA, 10 MHz and -140 dB/Hz are very close to their measured values respectively, but the difference in extracted physical parameters of samples will differ from the reference Laser-1 physical parameter values.

The common trend which is exhibited is that the HD and IMD distortion power levels are the highest in case of Laser-1 and these distortion components are suppressed in case of Laser-2 and Laser-3. However Laser-2 and Laser-3 show comparable ability of distortion suppression, which can be justified due to their nearly same laser rate parameter values. The better performance of these lasers in comparison to the reference laser can be attributed to their low I_{th}, small α, and higher difference between threshold and bias current level, even when remaining parameters have nearly same values.

5. Conclusions

This paper explains the modelling and extraction of DFB laser rate parameters which suppresses its parasitic non-linear behaviour. It was observed that for an adequate IM-DD SCM system performance it is necessary to identify target rate equation parameters which can be physically realizable and which are used during the simulative extraction procedure. A laser with specifications like low threshold current, high bias current, small active layer volume with high mode confinement factor, high quantum efficiency, high carrier and photon life time, low spontaneous emission factor, small carrier density at transparency, high gain coefficient, and small linewidth enhancement factor showed improved performance in the CD-RD IM-DD SCM model. In future this work will be aimed at extracting parameters and modelling even lower threshold current DFB laser sources with higher distortion capability and which show improved performance in all the basic IM-DD SCM models.

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