Laser Innovations for Research and Applications

journal homepage: https://lira.journals.ekb.eg/

ISSN: Print 3009-6359 / Online 3009-6472

An overview of recent studies on the limitations of semiconductor lasers under direct modulation for use in analog RoF systems

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Abstract

Radio-over-fiber (RoF) systems have recently attracted a lot of attention as a way to integrate wireless and optical systems to enhance communication capacity and keep up with high-speed transmission services. Semiconductor lasers (SLs) play an important role in the development of analog RoF systems due to their high bandwidth. However, when the SL is directly modulated by RF signals simultaneously, the electron and photon densities in the active region are subject to nonlinear transfer characteristics. This generates undesirable distortion products and high-intensity noise in the modulated laser signal, which degrade the signal quality. The review introduces an overview of recent studies on the signal distortions and intensity noise induced by two-tone direct intensity modulation of a semiconductor laser for use in analog RoF systems.

Keywords: Semiconductor laser, Radio-over-fiber, Signal distortion, Intensity noise, Direct modulation

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1. Introduction

Optical communications started to revolutionize the industry of communication in the 1980s when low-loss optical fibers were introduced, which quickly became the favored medium for applications of high-capacity and long transmission lines (Sharma & Gupta). Recently, there has been a lot of interest in radio over fiber RoF technology as a way to merge wireless and optical systems to enhance communication bandwidth and keep up with integrated services (Llorente et al., 2011). The most common applications of wireless communications are the wireless local area networks (WLAN) and the distributed antenna systems (DAS) for in-building coverage in cellular systems (Wake, 2002), as well as satellite communication (Way et al., 1987). With the rapid development of these applications, there is increasing competition for transmission and distribution of microwave and millimeter-wave over long distances of optical fibers using simple and cost-effective techniques (Sharma et al., 2010; Wada, 2007). Nowadays, there are continuous developments in broadband distribution networks to keep up with the increasing demand for modern data transmission services at high speeds with large bandwidth. Multiplexing techniques like, wavelength division multiplexing (WDM), time-division multiplexing (TDM), optical code division multiplexing (OCDM), and subcarrier multiplexing (SCM) are used to achieve such optical broad-band transmissions (Koonen, 2006; Shumate, 2008). Such techniques are suitable for the 5th generation (5G) mobile networks, where high-frequency bands for 5G are mostly in the millimeter-wave (mm-wave) range of the electromagnetic spectrum (Rappaport et al., 2013). Subcarrier multiplexing (SCM) is a simple, versatile, and cost-effective technique that allows for the distribution of closely spaced radio frequency (RF) signals over several GHz on the optical spectrum. As a result, it is used to exploit the large bandwidth of optical fibers (Olshansky & Lanzisera, 1987; Olshansky et al., 1989; Yang, 2011).

The development of RoF systems is related to the performance of semiconductor lasers SLs due to their high-bandwidth advantage. Traditional LDs have bandwidth of several GHz (Agrawal, 2002), and recently has been enhanced to > 20 GHz with the innovation of multiple quantum well lasers (Sato et al., 2005). Direct intensity modulation-based SCM of SL is a simpler and less expensive method than that based on external modulation (Qazi et al., 2014). However, when the SL is directly modulated by RF signals simultaneously, the electron and photon densities in the active region are subject to nonlinear dynamics (K. Lau & A. Yariv, 1984). In addition to relaxation oscillations, these nonlinearities include spatial hole burning, gain suppression, and leakage currents (Morthier & Vankwikelberge, 2013; Odermatt, Witzigmann, & Schmithüsen, 2006). These inherent nonlinear transfer characteristics generate undesirable distortion products and high-intensity noise in the modulated laser signal, which degrade the signal quality (K. Lau & A. Yariv, 1984). The common distortion types associated with the modulated signals are harmonic distortions (HDs) and intermodulation distortions (IMDs) (Mahmoud et al., 2016). All these nonlinear distortion products become more significant when the frequency of the original signals approaches the frequency of the laser relaxation oscillation (f_r) (Bakry & Ahmed, 2013). Moreover, it is probable that intermodulation distortion products lie within the transmission range of the original tones and hence cannot be filtered out (Distortion, 2000). This problem is exacerbated in multi-tone SCM-RoF systems, where a large number of these nonlinear distortion products are generated in the laser output, resulting in extremely high levels of interference at particular original signals (Mahmoud et al., 2018). On the other hand, the laser output exhibits fluctuations in the intensity (known as intensity noise) due to the random recombination of electrons and photons within the active region (represents the fraction of spontaneous emission), which induces instantaneous time variations in photon density and output power. These intensity fluctuations are described by the frequency spectrum of relative intensity noise (RIN) (Chiddix et al., 1990; Westbergh et al., 2008a).

(1) Each application of SL has its own standard criteria (Distortion, 2000; Schuh et al., 2002; Schuh & Wake, 1999; Way, 1993), and all of them seek to keep a minimum level of distortion and noise of the device to ensure a high-quality service for users. Therefore, it is essential to investigate the dynamics of SL, as a nonlinear device, and determine the optimum modulation conditions that correspond to low distortion and noise. The modulation conditions include laser bias current, modulation depth, and modulation frequency. Gausia et al. (Qazi et al., 2014) and

Hung et al. (Lin & Kao, 1996) demonstrated that, within allowed current limits, high bias currents could be used to suppress all distortion products and improve the performance of the SCM systems. Safwat et al. (Mahmoud et al., 2016) showed that in CATV systems, the RIN is nearly constant at low modulation depth regardless of modulation frequency, whereas the high modulation depth causes degradation in noise levels. In addition, Bakry et al. (Ahmad Bakry & M Ahmed, 2016) confirmed that avoiding laser nonlinear distortions and noise necessitating limitation in both the modulation depth and modulation frequency. Yasmin et al. (El-Salam et al., 2022) shown that the nonlinear distortions increase as modulation depth increases. The highest distortion levels were observed when the modulation frequency approaches the laser relaxation frequency. At low modulation frequency f_{m1} (8 GHz) and intermediate value of m of 0.3, when I_b increases from 2 to $10I_{th}$, the modulated laser waveform improves from pulsing (high distortion) to sinusoidal (low distortion), respectively. The highest level of signal distortion is observed as irregular pulsing waveform as a route to chaos when increasing f_{m1} to 25 GHz at $I_b = 10I_{th}$ with $m = 0.6$. The distortion types (HD2, IMD2, and IMD3) increase as m increases regardless the values of I_b and/or f_{m1}. The highest signal distortions are simulated when $f_{m1} \approx f_r$ (i.e., $f_{m1} = 8$ GHz with $I_b = 2\ I_{th}$, and $f_{m1} = 25$ GHz with $I_b = 10\ I_{th}$). Over other modulation parameters, all distortion types reduce to lower values provided that $f_{m1} <$ f_3dB.

(2) The nonlinear intermodulation distortion together with the intensity noise of the SL determines the so-called "spurious-free dynamic range (SFDR)" that evaluates the dynamic range of the linearity of the laser and hence characterizes laser performance (Westbergh et al., 2008a). The authors in (Lin & Kao, 1996; Qazi et al., 2014) demonstrated that within allowed current limits, high bias currents could be used to suppress all distortion products and improve the performance of the SCM-RoF systems. Other studies showed that when the bias current is near the threshold with large

modulation depth, an increase in the distortion and noise levels is occurred due to the laser clipping effect (Leung, 2004; Qazi et al., 2014; Rainal, 1996). Laser clipping is a phenomenon that occurs when the modulation depth exceeds the laser threshold, where the valleys of the input current drop below the threshold current and hence, drop the gain below the threshold level, which results in nearly zero output power and shuts the laser off (Lai & Conradi, 1997). Mahmoud et al. (Mahmoud et al., 2016) showed that in CATV systems, the RIN is nearly constant at low modulation depth regardless of the modulation frequency, whereas the high modulation depth causes degradation in noise levels. In addition, Bakry et al. (A Bakry & M Ahmed, 2016) confirmed that avoiding laser nonlinear distortions and noise necessitate limitation in both the modulation depth and modulation frequency. The SFDR decreases with the increase of modulation frequency as reported in (Mahmoud et al., 2016). Related studies concerned with investigating distortions and determining SFDR could be found in (Jung & Han, 2002; K. Lau & A. Yariv, 1984; Westbergh et al., 2008a; Yamada et al., 1996). Despite these relevant previous studies, there is still room for more extensive investigation of the effect of laser modulation conditions on the modulated signal waveform and the corresponding spectral characteristics, especially at modulation frequencies in the GHz range. Yasmin et al. (El-Salam et al., 2022) shown that when increasing m up to 0.6 at $I_b = 10I_{th}$, a clipped continuous signal superposed by sub-peak is simulated which indicated an increase in the distortion level. When f_{m1} = 8 GHz and $I_b = 2I_{th}$ with $m = 0.3$, LF-RIN is low as ~ - 177 dBc/Hz and is slightly increases to ~ - 169 dBc/Hz when I_b increases to $10I_{th}$. Also, a significant increase in LF-RIN is predicte under strong modulation (m = 0.6) due to signal clipping. LF-RIN increased with the increase of m and/or I_b, and was minimum when f_{m1} = 8GHz, whereas it was maximum when f_{m1} = 25 GHz. This increase was more sensitive when $I_b = 10I_{th}$ and $m > 0.45$. SDFR have been calculated as 102 dB/Hz$^{2/3}$ when f_{m1} = 8GHz at $I_b = 2I_{th}$. A significant decreased in SDFR is recorded (= 52 dB/Hz$^{2/3}$) when f_{m1} increased to 25GHz at $I_b = 10I_{th}$, which indicated to low laser performance.

In this review, we present an overview of recent studies on the modulation parameters that affect the signal distortions and intensity noise induced by two-tone direct intensity modulation of SL for analog RoF systems. The review highlights the effects of modulation conditions, including laser bias current, modulation peak current, and modulation frequency, on the modulated laser signal output to evaluate the performance of SLs.

2. Analog SCM-RoF systems design

Subcarrier multiplexing SCM is a popular and economic multiplexing technique used for a wide range of analog services in optical access networks (Darcie et al., 1986). The attractive feature of the SCM system is that it is convenient, adaptable, simple, and does not need a multiplexer or de-multiplexer compared with the other techniques. In addition, it is a cost-effective approach that does not require complex optics (Bravi et al., 1997; Koonen, 2006; Shumate, 2008). SCM system allows for the transmission of closely spaced radio frequency (RF) signals (e.g. two or more channels) simultaneously and exploits the multi-gigahertz bandwidth potential of high-speed lasers (Olshansky et al., 1989). The two prominent applications that use SCM are the cable television (CATV) and the radio-over-fiber (RoF) systems (Tanaka, 2002). SCM-CATV systems are standards for analog TV video channel transmission and distribution with high reliability and low power budget (Darcie, 1990). SCM-RoF systems are used to effectively provide enhanced mobile wireless services, including distribution and subscriber access

with avoiding the use of high-power RF transmitters (Gowda et al., 2014; Thomas et al., 2015). The basic configuration of SCM systems is illustrated schematically in fig. (1-1). The RF carriers are mixed and modulated by using a semiconductor laser (transmitter) and then are delivered through an optical fiber to the receiver that transforms the optical signals into the electrical form (Pradeep & Vijayakumar, 2020).

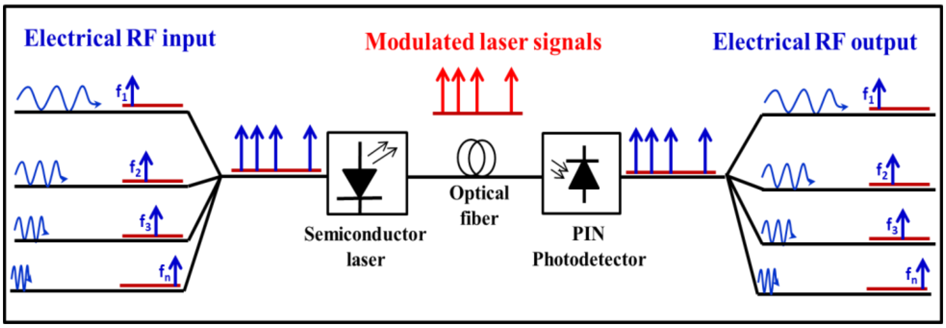

Fig. (1-1) Schematic diagram of SCM-RoF system

3. Limitations of direct modulation of SLs in SCM-RoF systems

The electrical RF signals are applied either directly to the SL or externally to an external modulator. The direct modulation is an attractive method due to its simplicity, compatibility with existing equipment, and is cost-effective solution for frequency distribution systems when compared with the external modulation method (Lipson et al., 1990). Direct modulation of SLs is accomplished by modulating the excitation current around a bias value, which causes corresponding change in the intensity of the laser optical output power (Pepeljugoski et al., 2003). For analog modulation of a single tone, the injection current $I(t)$ is represented as (Petermann, 1991):

$$I(t) = I_b + I_m[A\sin(2\pi f_m\, t)] \qquad (2\text{-}1)$$

where I_b represents the bias current, I_m is the modulation current, and $A\sin(2\pi f_m\, t)$ represents the form of the current signal, which is typically considered as a sinusoidal form at frequency f_m with amplitude A (Petermann, 1991). In the two–tone modulation, two sinusoidal carriers of frequencies f_{m1} and f_{m2} are considered, and the current signal is then given as:

$$I(t) = I_b + I_m[A\sin(2\pi f_{m1}\, t) + \sin(2\pi f_{m2}\, t)] \qquad (2\text{-}2)$$

In a laser-based systems, the "modulation depth (m)" is well known parameter that measure of how much the modulation signal impacts the light output, which is defined by as (Brillant, 2008):

$$m = \frac{A \times I_m}{I_b} \qquad (2\text{-}3)$$

Although using direct modulation of SLs provides several desired characteristics for SCM-RoF systems, it suffers from some factors that limit the system performance such as the nonlinear distortions and noise during laser operation.

3.1.Nonlinear distortions

Directly modulated LDs introduce nonlinear dynamics associated with the laser resonance, such as gain suppression and hole burning, which strongly affects the light-current linearity of the laser due to the inhomogeneous pinning of the electron density in the laser cavity (Odermatt, Witzigmann, Schmithüsen, et al., 2006). These nonlinear laser dynamics create undesired distortion products associated with the modulated laser signal, which degrades the transmission quality (K. Lau & A. J. A. P. L. Yariv, 1984). Typically, the nonlinear distortions associated with analog modulation of LDs are harmonic distortions (HDs) and intermodulation distortions (IMDs) (Gustavsson et al., 2003; Morton et al., 1989).

3.1.1. Harmonic distortions

When SLs are modulated with single analog RF signal f_m, the modulated laser signal output contains undesired components at harmonic frequencies of $2f_m$, $3f_m$, $4f_m$,…etc. This can be explained mathematically as follows. Typically, the nonlinear devices like SL is described by the nonlinear transfer function as follows:

$$\psi_{out} = K_0\psi_{in} + K_1\psi_{in}^2 + K_2\psi_{in}^3 + \cdots \quad (2\text{-}4)$$

where ψ_{out} is the output signal, ψ_{in} is the input signal and k_0, k_1, k_2, ,…. are coefficients. The expressions for the first, second, and third order distortions can be calculated using this formula as follows. Recalling equation (2-1) for single tone modulation, the input signal is in the form of $\psi_{in}(t) = A\sin(\omega_m t)$; $\omega_m = 2\pi f_m$, the resulting output ψ_{out} when inserted into equation (2-4) will be

$$\psi_{out} = K_0[A\sin(\omega_m t)] + K_1[A\sin(\omega_m t)]^2 + K_2[A\sin(\omega_m t)]^3 \quad (2\text{-}5)$$

Using trigonometric identities of power-reduction formula, this becomes

$$\psi_{out} = \frac{K_1A^2}{2} + \frac{4K_0A+3K_2A^3}{4}\sin(\omega_m t) - \frac{K_1A^2}{2}\cos 2(\omega_m t) + \frac{K_2A^3}{4}\sin 3(\omega_m t) \quad (2\text{-}6)$$

The first term in equation (2-6) is a DC term, the second term is the fundamental signal, the third is the second harmonic product (*2*f_m), and the fourth term is the third harmonic product (*3*f_m) (van de Water). The amplitude of the higher order harmonic distortion products (4th, 5th, ..., nth) are much lower than the amplitudes of the lower order harmonic products, and hence they have been ignored. Figure (2-2) shows a schematic diagram of the fast Fourier transform (FFT) power spectrum of the output power for single-tone modulation. The peaks shown in the figure indicate the fundamental and its harmonics whose powers are used to calculate the 2nd-order harmonic distortion (2HD) and 3rd-order harmonic distortion (3HD) for single-tone modulation. In general, the nth-order harmonic distortion (*n*HD) can be measured in decibels (dB) as the ratio of the power of the n$_{th}$-harmonic (P_n) to the power of the fundamental (P_1) as follows (Keiser, 1983):

$$n\text{HD} = 20 \log \frac{P_n}{P_1} \quad (dB) \tag{2-7}$$

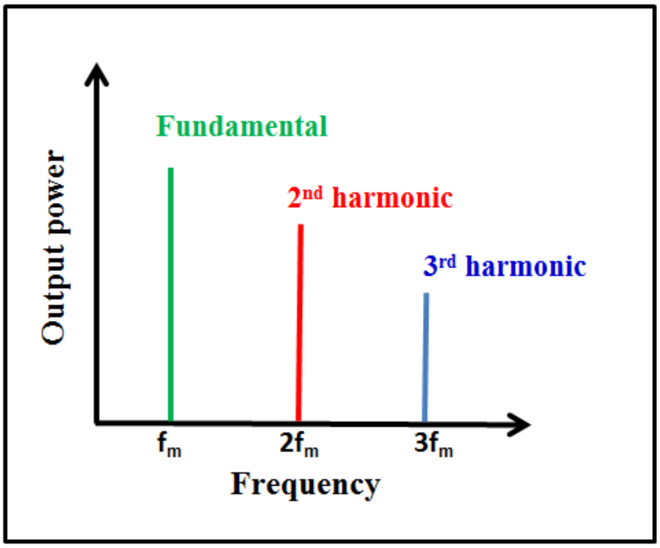

Fig. (2-2): A typical spectrum of the output power generated by single-tone direct modulation of SLs.

3.1.2. Intermodulation distortion

The most significant effect of SL nonlinearity in analog optical fiber applications is the IMD, which occurs when SLs are modulated with two or more analog RF signals (Hwang et al., 2005). For example, when SLs are modulated with two tones f_{m1} and f_{m2}, the modulated laser signal output contains undesired components at intermodulation frequencies of $f_{m1} \pm f_{m2}$, $2f_{m1} \pm f_{m2}$, $2f_{m2} \pm f_{m1}$, ….. etc., and can be explained mathematically as follows. Recalling equation (2-2) for two-tone modulation, the input signal is in the form of $\psi_{in}(t) = A\sin(2\pi f_{m1}\ t) + A\sin(2\pi f_{m2}\ t)$; $\omega_{m1} = 2\pi f_{m1}$ and $\omega_{m2} = 2\pi f_{m2}$, the resulting output ψout when inserted into equation (2-6) will be

$$\psi_{out} = K_0[\mathrm{A}\sin(\omega_{m1}t) + \mathrm{A}\sin(\omega_{m2}t)] + K_1[\mathrm{A}\sin(\omega_{m1}t) + \mathrm{A}\sin(\omega_{m2}t)]^2 + K_2[\mathrm{A}\sin(\omega_{m1}t) + \mathrm{A}\sin(\omega_{m2}t)]^3 \quad (2\text{-}8)$$

The quadratic term in equation (2-4) "$K_1[A\sin(\omega_{m1}t) + A\sin(\ \omega_{m2}t)]^2$ " generates the 2nd-order intermodulation distortion products, which can be extended using trigonometric identities of the power-reduction formula as:

$$= K_1A^2 + \frac{K_1A^2}{2}\cos 2(\omega_{m1}t) - \frac{K_1A^2}{2}\cos 2(\omega_{m2}t) + K_1A^2\cos[(\omega_{m2}t) - (\omega_{m1}t)] + K_1A^2\cos[(\omega_{m2}t) + (\omega_{m1}t)] \quad (2\text{-}9)$$

The biggest 2nd-order intermodulation distortion products are located at frequencies of $|f_{m2} \pm f_{m1}|$. The cube term in equation (2-4) "$K_2[A\sin(\omega_{m1}t) + \mathrm{A}\sin(\ \omega_{m2}t)]^3$" generates the 3rd-order intermodulation distortion products, which might be expanded into:

$$= \frac{9K_2A^3}{4}[\sin(\omega_{m1}t) + \sin(\omega_{m2}t)] + \frac{K_2A^3}{4}[\sin 3(\omega_{m1}t) + \sin 3(\omega_{m2}t)] - \frac{3K_2A^3}{4}[\sin[2(\omega_{m1}t) + (\omega_{m2}t)] - \sin[2(\omega_{m2}t) - (\omega_{m1}t)] + \sin[2(\omega_{m2}t) + (\omega_{m1}t)] - \sin[2(\omega_{m1}t) - (\omega_{m2}t)]] \quad (2\text{-}10)$$

The largest 3rd-order intermodulation distortion products can be found at the frequencies of $|2f_{m1} \pm f_{m2}|$ and $|2f_{m2} \pm f_{m1}|$. The schematic diagram of the FFT spectrum of the output power for simultaneous two-tone modulation is illustrated in figure (2-3). This figure illustrates the output power of two input signals (fundamentals) and various distortion products such as 2nd- and 3rd-order harmonic products, 2nd- and 3rd -order intermodulation products. The power difference between 2nd- and 3rd-order intermodulation distortion products and the fundamental signals is the IMD2 and IMD3, respectively.

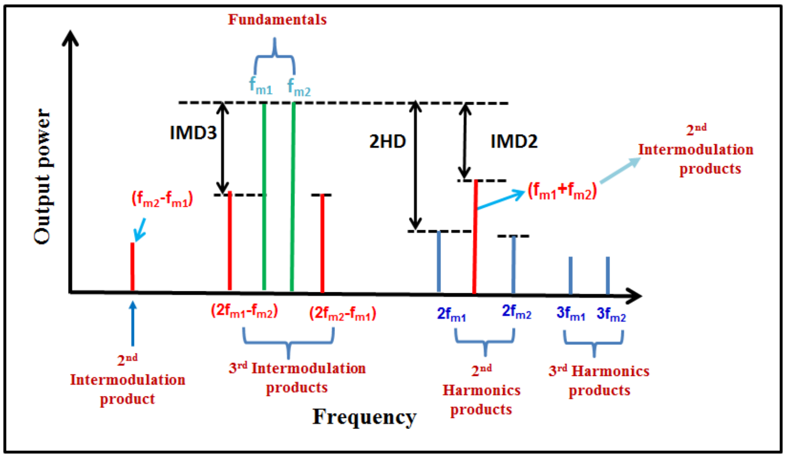

Fig. (2-3): Atypical distortion products produced by SLs when subjected to two-tone modulation.

The 2nd- and 3rd-higher intermodulation distortions (IMD2 and IMD3, respectively) can be measured in decibels (dB) as the ratio of powers of the 2nd and 3rd higher intermodulation products ($P_{fm1+fm2}$ or $P_{fm2-fm1}$) and ($P_{2fm1-fm2}$ or $P_{2fm2-fm1}$), respectively to the fundamental power (P_1) as follows (Westbergh et al., 2008b).

$$IMD2 = 20\log\left(\frac{P_{fm1\pm fm2}}{P_1}\right) \quad (dB) \tag{2-11}$$

$$IMD3 = 20\log\left(\frac{P_{2fm1\pm fm2}}{P_1}\right) \quad (dB) \tag{2-12}$$

3.2. Intensity noise

The laser output exhibits fluctuations in both the phase and intensity due to the random recombination of electrons and photons within the active region (represents the fraction of spontaneous emission), which induces instantaneous time variations in photon density and output power (Arnesson, 2012).The noise sources are represent white noise with Gaussian statistics and are δ-correlated (Ahmed et al., 2001).

The noise characteristics of the modulated signal are determined by RIN, which is calculated over a finite time period T as the Fourier transform of the auto-correlation function of the power fluctuation *δP(t)* as (Ahmed et al., 2001; Ahmed & Fields, 2004)

$$RIN = \frac{1}{\bar{P}^2}\left\{\frac{1}{T}\int_0^T\left[\int_0^\infty \delta P(t)\delta P(t+\tau)e^{j\omega t}d\tau\right]dt\right\}$$

$$RIN = \frac{1}{\bar{P}^2}\left\{\frac{1}{T}\left[\int_0^T \delta P(\tau)e^{-j\omega\tau}\,d\tau\right]^2\right\} \tag{2-13}$$

where $\delta P(t) = (P(t) - \bar{P})$ is the power fluctuations in *P(t)*, $\bar{P}$ is the time-average value, and ω is the Fourier angular frequency. The noise characteristics associated with the two-tone modulation are determined by the RIN frequency spectrum, which is calculated by applying FFT to equation (2-13) as (Ahmed & Fields, 2004),

$$RIN = \frac{1}{\bar{P}^2}\frac{\Delta t^2}{T}|FFT[\delta P(t)]|^2 \tag{2-14}$$

It is worth noting that the optical power fluctuation of the laser $\delta P(t)$ induces corresponding a fluctuation in the photo-detector current $\Re\delta P(t)$, where $\Re$ is the PIN photo-detector responsivity. Therefore, equation (2-14) can also be written as (Hui & O'Sullivan, 2009),

$$RIN = \frac{1}{\mathcal{R}^2\bar{P}^2}\frac{\Delta t^2}{T}|FFT[\mathcal{R}\delta P(t)]|^2 \tag{2-15}$$

where $\Re^2\bar{P}^2$ is the average signal electrical power. In fact, the noise sources of the PIN photodetector are disabled in this paper, as well as the responsivity does not affect the result of RIN measurement, because both the nominator and denominator of equation (2-15) are proportional to the responsivity.

3.3. Dynamic range

The dynamic range is one of the most essential parameters for describing the performance of analog optical links since it takes into account noise and nonlinear distortions (Marpaung, 2009). Distortions are below the noise floor at low modulation index m, while it rises above the noise floor when m increases. The maximum signal for which the output is distortion-free is the signal level at which distortion with amplitude equal to the noise floor. SFDR is the dynamic range of the laser when operating at the optimal modulation index m, and also known as the intermodulation-free dynamic range (Cox, 2002). Figure (2-4) illustrates the schematic plot used to calculate the SFDR .The figure shows the output power of the fundamental signal, the 3rd-order intermodulation distortion product, and the noise floor viruses the modulation index m in the logarithmic scale (Dalal, 1998). By extending the linear extrapolation, which is determined by the linear curve fit in the linear region, of the powers of the original signal, and 3rd-order intermodulation product, as well as the noise floor. SFDR is calculated as the power difference between the fundamental signal and the system noise floor at the point where the power of the 3rd-order intermodulation product equals the system noise floor, where the 3rd-order intermodulation product crosses the noise floor (Lee et al., 1999; Westbergh et al., 2008b).

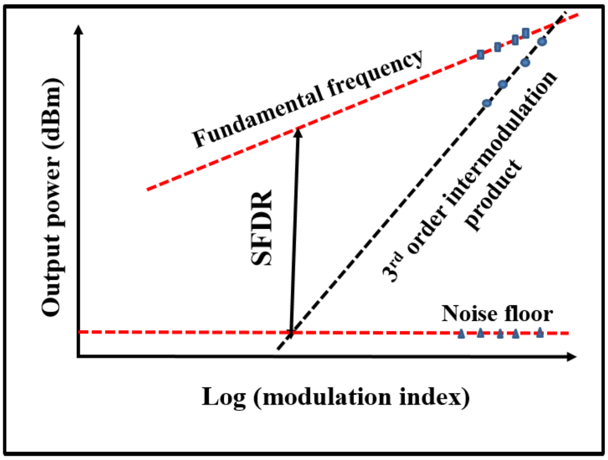

Fig. (2-4): Calculation of the SFDR. The powers of the fundamental signal, 3rd order intermodulation product and noise floor versus the modulation index.

4. Conclusion

We introduced an overview of recent studies on the signal distortions and intensity noise induced by two-tone direct intensity modulation of a semiconductor laser for use in analog RoF systems. We have explained a brief overview about an analog SCM-RoF systems design. Also we had shown the limitations of direct modulation of SLs in SCM-RoF systems including nonlinear distortion, harmonic distortion and intermodulation distortion, also intensity noise and dynamic range. In addition to we have been shown the effects of modulation conditions, including laser bias current, modulation peak current, and modulation frequency, on the modulated laser signal output to evaluate the performance of SLs. All distortion types increase as m increases regardless of the values of I_b and/or f_{m1}, also, the LF-RIN increase with m and/or I_b.

Funding This research received no external funding.
Data availability No datasets were generated or analysed during the current study.
Declarations

Conflict of interest The authors declare no conflict of interest.
Competing interests The authors declare no competing interests.

References

Agrawal, G. P. (2002). Fiber–Optic Communication System . New York: A John Wiley & Sons. *Inc. Publication*.

Ahmed, M., Yamada, M., & Saito, M. (2001). Numerical modeling of intensity and phase noise in semiconductor lasers. *IEEE Journal of Quantum Electronics, 37*(12), 1600-1610.

Ahmed, M. J. I. J. o. N. M. E. N., Devices, & Fields. (2004). Numerical approach to field fluctuations and spectral lineshape in InGaAsP laser diodes. *17*(2), 147-163.

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Bakry, A., & Ahmed, M. (2013). Influence of sinusoidal modulation on mode competition and signal distortion in multimode InGaAsP lasers. *Optics & Laser Technology*, *50*, 134-140.

Bakry, A., & Ahmed, M. (2016). Harmonic and intermodulation distortions and noise associated with two-tone modulation of high-speed semiconductor lasers. *Physics of Wave Phenomena, 24*, 64-72.

Bakry, A., & Ahmed, M. (2016). Harmonic and intermodulation distortions and noise associated with two-tone modulation of high-speed semiconductor lasers. *Physics of Wave Phenomena, 24*(1), 64-72.

Bravi, E., Casella, F., Iannone, E., & Sabella, R. (1997). Transmission of analog SCM signals through the transport network. Integrated Optics and Optical Fibre Communications, 11th International Conference on, and 23rd European Conference on Optical Communications (Conf. Publ. No.: 448),

Brillant, A. (2008). *Digital and analog fiber optic communications for CATV and FTTx applications* (Vol. 174). SPIE Press.

Chiddix, J. A., Laor, H., Pangrac, D. M., Williamson, L. D., & Wolfe, R. W. (1990). AM video on fiber in CATV systems: Need and implementation. *IEEE Journal on Selected Areas in Communications, 8*(7), 1229-1239.

Cox, C. J. R. P. T. i. O. F. L. (2002). Figures of merit and performance analysis of photonic. 1.

Dalal, R. V. (1998). *Investigation of high linearity DFB lasers for analog communications*.

Darcie, T., Dixon, M., Kasper, B., & Burrus, C. (1986). Lightwave system using microwave subcarrier multiplexing. *Electronics Letters, 22*(15), 774-775.

Darcie, T. E. J. I. J. o. s. a. i. C. (1990). Subcarrier multiplexing for lightwave networks and video distribution systems. *8*(7), 1240-1248.

Distortion, I. (2000). Measurements Using the 37300 Series Vector Network Analyzer. *Application Note/GIP-G, Anritsu*.

El-Salam, Y. A., Mohamed, T., & Mahmoud, A. (2022). Effects of two-tone intensity modulation on signal distortion and noise in a semiconductor laser for radio-over-fibre applications. *Pramana, 96*(3), 151.

Gowda, A. S., Dhaini, A. R., Kazovsky, L. G., Yang, H., Abraha, S. T., & Ng'oma, A. J. J. o. L. T. (2014). Towards green optical/wireless in-building networks: Radio-over-fiber. *32*(20), 3545-3556.

Gustavsson, J. S., Haglund, A., Carlsson, C., Bengtsson, J., & Larsson, A. J. I. j. o. q. e. (2003). Harmonic and intermodulation distortion in oxide-confined vertical-cavity surface-emitting lasers. *39*(8), 941-951.

Hui, R., & O'Sullivan, M. (2009). *Fiber optic measurement techniques*. Academic Press.

Hwang, S.-K., Tian, J.-M., & Lin, C.-F. (2005). Nonlinear distortion in directly modulated semiconductor lasers subject to external optical injection. IASTED International Conference on Optical Communication Systems and Networks, as part of the Fifth IASTED Int. Multi-Conference on Wireless and Optical Commun., OCSN 2005, Jung, H.-D., & Han, S.-K. (2002). Nonlinear distortion suppression in directly modulated DFB-LD by dual-parallel modulation. *IEEE Photonics Technology Letters, 14*(7), 980-982.

Keiser, G. (1983). *Optical fiber communications*. McGraw-Hill Science, Engineering & Mathematics.

Koonen, T. (2006). Fiber to the home/fiber to the premises: what, where, and when? *Proceedings of the IEEE, 94*(5), 911-934.

Lai, S., & Conradi, J. (1997). Theoretical and experimental analysis of clipping-induced impulsive noise in AM-VSB subcarrier multiplexed lightwave systems. *Journal of lightwave technology, 15*(1), 20-30.

Lau, K., & Yariv, A. (1984). Intermodulation distortion in a directly modulated semiconductor injection laser. *Applied Physics Letters, 45*(10), 1034-1036.

Lau, K., & Yariv, A. J. A. P. L. (1984). Intermodulation distortion in a directly modulated semiconductor injection laser. *45*(10), 1034-1036.

Lee, H., Dalal, R., Ram, R., & Choquette, K. J. I. P. T. L. (1999). Dynamic range of vertical-cavity surface-emitting lasers in multimode links. *11*(11), 1473-1475.

Leung, A. (2004). Performance analysis of SCM optical transmission link for fiber-to-the-home. *Master of Science Thesis, Department of Electrical Engineering & Computer Science, University of Kansas*.

Lin, H.-T., & Kao, Y.-H. (1996). Nonlinear distortions and compensations of DFB laser diode in AM-VSB lightwave CATV applications. *Journal of Lightwave Technology, 14*(11), 2567-2574.

Lipson, J., Upadhyayula, L., Huang, S.-Y., Roxlo, C. B., Flynn, E., Nitzsche, P., McGrath, C. J., Fenderson, G. L., Schaefer, M. S. J. I. t. o. m. t., & techniques. (1990). High-fidelity lightwave transmission of multiple AM-VSB NTSC signals. *38*(5), 483-493.

Llorente, R., Walker, S., Monroy, I. T., Beltrán, M., Morant, M., Quinlan, T., & Jensen, J. B. (2011). Triple-play and 60-GHz radio-over-fiber techniques for next-generation optical access networks. 2011 16th European Conference on Networks and Optical Communications,

Mahmoud, A., Ahmed, M., & Mahmoud, S. W. (2018). Optimum parameters controlling distortion and noise of semiconductor laser under analog multichannel modulation. *Pramana, 90*(5), 1-8.

Mahmoud, S. W., Mahmoud, A., & Ahmed, M. (2016). Noise performance and nonlinear distortion of semiconductor laser under two-tone modulation for use in analog CATV systems. *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields, 29*(2), 280-290.

Marpaung, D. A. I. J. U. o. T. (2009). High dynamic range analog photonic links design and implementation.

Morthier, G., & Vankwikelberge, P. (2013). *Handbook of distributed feedback laser diodes*. Artech House.

Morton, P. A., Ormondroyd, R., Bowers, J. E., & Demokan, M. J. I. J. o. Q. E. (1989). Large-signal harmonic and intermodulation distortions in wide-bandwidth GaInAsP semiconductor lasers. *25*(6), 1559-1567.

Odermatt, S., Witzigmann, B., & Schmithüsen, B. (2006). Harmonic balance analysis for semiconductor lasers under large-signal modulation. *Optical and Quantum Electronics, 38*(12), 1039-1044.

Odermatt, S., Witzigmann, B., Schmithüsen, B. J. O., & Electronics, Q. (2006). Harmonic balance analysis for semiconductor lasers under large-signal modulation. *38*(12), 1039-1044.

Olshansky, R., & Lanzisera, V. (1987). 60-channel FM video subcarrier multiplexed optical communication system. *Electronics Letters, 22*(23), 1196-1198.

Olshansky, R., Lanzisera, V. A., & Hill, P. M. (1989). Subcarrier multiplexed lightwave systems for broad-band distribution. *Journal of Lightwave Technology, 7*(9), 1329-1342.

Pepeljugoski, P. K., Kuchta, D. M. J. I. J. o. R., & Development. (2003). Design of optical communications data links. *47*(2.3), 223-237x.

Petermann, K. (1991). *Laser diode modulation and noise* (Vol. 3). Springer Science & Business Media.

Pradeep, R., & Vijayakumar, N. (2020). Subcarrier multiplexed radio over fiber system with optical single sideband modulation. *Journal of Optical Communications*.

Qazi, G., Sharma, A. K., & Uddin, M. (2014). Investigation on inter-modulation products (IMPs) for IM-DD SCM optical links. *Optik, 125*(5), 1629-1633.

Rainal, A. J. (1996). Limiting distortion of CATV lasers. *Journal of lightwave technology, 14*(3), 474-479.

Rappaport, T. S., Sun, S., Mayzus, R., Zhao, H., Azar, Y., Wang, K., Wong, G. N., Schulz, J. K., Samimi, M., & Gutierrez, F. (2013). Millimeter wave mobile communications for 5G cellular: It will work! *IEEE access, 1*, 335-349.

Sato, K., Kuwahara, S., & Miyamoto, Y. (2005). Chirp characteristics of 40-Gb/s directly modulated distributed-feedback laser diodes. *Journal of Lightwave technology, 23*(11), 3790.

Schuh, R., Wake, D., & Sundberg, E. (2002). A simple linearity analysis for active distributed antenna systems using W-CDMA signals. 2001 International Topical Meeting on Microwave Photonics. Technical Digest. MWP'01 (Cat. No. 01EX476),

Schuh, R. E., & Wake, D. (1999). Distortion of W-CDMA signals over optical fibre links. Int. Top. Meeting Microwave Photonics Tech. Dig.(MWP’99),

Sharma, V., & Gupta, N. OFDM Based Full Duplex Radio Over Fiber System.

Sharma, V., Singh, A., & Sharma, A. K. (2010). Simulative investigation of nonlinear distortion in single-and two-tone RoF systems using direct-and external-modulation techniques. *Optik, 121*(17), 1545-1549.

Shumate, P. W. (2008). Fiber-to-the-home: 1977–2007. *Journal of Lightwave Technology, 26*(9), 1093-1103.

Tanaka, Y. (2002). A study on optical wireless communication systems and their applications. *Keio University*.

Thomas, V. A., El-Hajjar, M., Hanzo, L. J. I. C. S., & Tutorials. (2015). Performance improvement and cost reduction techniques for radio over fiber communications. *17*(2), 627-670.

van de Water, M. Low-cost CATV Transmission in Fiber-to-the-Home Networks.

Wada, O. (2007). Quantum Dots and Semiconductor Nanostructures for Photonic Signal Processing Devices. Frontiers in Optics,

Wake, D. (2002). Trends and prospects for radio over fibre picocells. Proc. MWP,

Way, W., Krain, M., & Wolff, R. (1987). 1.3 micron 35 km fibre-optic microwave multicarrier transmission system for satellite earth stations. *Electronics Letters, 23*, 400-402.

Way, W. I. (1993). Optical fiber-based microcellular systems: An overview. *IEICE Transactions on Communications, 76*(9), 1091-1102.

Westbergh, P., Söderberg, E., Gustavsson, J. S., Larsson, A., Zhang, Z., Berggren, J., & Hammar, M. (2008a). Noise, distortion and dynamic range of single mode 1.3 µm InGaAs vertical cavity surface emitting lasers for radio-over-fibre links. *IET optoelectronics, 2*(2), 88-95.

Westbergh, P., Söderberg, E., Gustavsson, J. S., Larsson, A., Zhang, Z., Berggren, J., & Hammar, M. J. I. o. (2008b). Noise, distortion and dynamic range of single mode 1.3 µm InGaAs vertical cavity surface emitting lasers for radio-over-fibre links. *2*(2), 88-95.

Yamada, H., Okuda, T., Torikai, T., & Uji, T. (1996). Dynamic LI characteristics measurement of laser diodes for analyzing intermodulation distortion mechanism. Conference Digest. 15th IEEE International Semiconductor Laser Conference,

Yang, H. (2011). Optical techniques for broadband in-building networks. *Tech. Univ.*, 2-5.