Optik 124 (2013) 631–634

Contents lists available at SciVerse ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Intermodulation distortion analysis of feedforward linearised laser transmitter employing volterra series approach

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ARTICLE INFO

Article history:
Received 18 August 2011
Accepted 24 December 2011

Keywords:
Directly modulated semiconductor laser
Feedforward linearisation
Intermodulation distortion
Volterra series

ABSTRACT

This paper demonstrates intermodulation distortion (IMD) analysis of a feedforward linearisation technique in directly modulated semiconductor laser employing a Volterra series approach. Variations of IMD suppression with RF modulation frequency as well as modulation index are shown. The results show that the proposed system can reduce the third intermodulation distortion (IMD3) by more than 45 dB for the wide frequency range from 500 MHz to 10 GHz, 30 mA bias current and 0.1 modulation index. It is also shown that the IMD3 reductions remain constantly for variation of the index modulation from 0.1 to 0.9. Therefore the proposed system can reduce significantly IMD without influence of input power level.

1. Introduction

The drastic demands of subscribers for voice, data, and multimedia services give pressure on wireless communication systems to increase both their transmission capacity and coverage. However there is a trade off between coverage and capacity. The integration of optical networks and radio networks become the most attractive solutions to overcome that trade off and is known as Radio-over-Fibre (RoF) technology. With the high transmission capacity, comparatively low cost and low attenuation, optical fibre provides an ideal solution for accomplishing these interconnections. In addition, a radio system enables the significant mobility, flexibility and easy access. Therefore, RoF technology is suitable for the future high-speed broadband wireless communication [1,2].

An intensity modulation scheme employing direct modulation of a semiconductor laser is the most commonly used technique for the optical generation and distribution of the RF signal method due to simplicity, compactness, less expensive cost and efficient coupling of optical laser output to the fibre [2,3]. However, the nonlinearity of a laser diode is a significant cause of limitation on the performance of a multi-channel RoF system [2]. Therefore linearisation of the devices is very important to improve the system quality.

Many linearisation techniques have been proposed to suppress that nonlinearity [4–9], however each technique has some limitations. Predistortion technique might be a simpler approach but it has some restrictions since it exhibits device dependency and difficulty to suppress all order distortions simultaneously [4,5]. To overcome device dependency, feedback technique was proposed by some researchers. Besides being a promising approach due to its cost effectiveness and its simplicity, this technique is device-independent and it can operate smoothly regardless of various device parameters. However, the feedback linearisation technique exhibits limited operating bandwidth due to potential instability of the feedback loop at high frequency [6]. Likewise, the dual parallel modulation technique also suffers from narrow bandwidth [7]. Feed-forward linearisation technique offers a number of advantages compared to other techniques such as broadband distortion reduction at high frequency and reduction in all orders of distortion simultaneously [8,9].

The accurate model of optical feedforward transmitter is required for evaluation and optimisation of the system performance. Previously, a semiconductor laser nonlinearity has been modelled using Volterra series analysis [9–12]. In this paper, the Volterra series approach is used to provide a complete and accurate model for evaluation and optimisation of the proposed laser transmitter employing feedforward technique since we are dealing with a nonlinear system with memory. Variations of intermodulation distortion (IMD) suppression with RF modulation frequency as well as modulation index are shown. The analytical works show that the proposed system can reduce significantly IMD without influence of input power level. From the equation, it is also shown that distortion suppression is mainly influenced by the amplitude and phase imbalance in the second interference loop.

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0030-4026/$ – see front matter
doi:10.1016/j.ijleo.2011.12.041

2. Volterra transfer function of the semiconductor laser

Volterra series approach is suitable to represent nonlinear systems with memory and is very useful to calculate small distortions when the number of terms required in the Volterra series expansion is small. Semiconductor lasers have been modelled previously using Volterra series representation [9–12] and will be reviewed in this section.

Semiconductor lasers exhibit nonlinear behaviours that can be expressed by the laser rate equations. From the equations, it can be seen that the output photon density is related to the input injection current in term of the laser parameter. The output photon density can simply be omitted due to the spontaneous products being very small compared to the stimulated products in lasing condition. Furthermore, the two rate equations are combined to form the output to input equation [9,10]

$$I_a - I_{th} = \mathrm{eV}\left[\frac{1}{\Gamma}\cdot\frac{dQ}{dt} + \frac{1}{\Gamma\tau_p}\cdot Q - \frac{1}{\Gamma g}\right]\cdot\frac{d}{dt}\left[\frac{(dQ/dt)+(Q/\tau_p)}{(1-\varepsilon Q)Q}\right] \tag{1}$$

Semiconductor lasers need to be modelled in order to analyse the distortion products. From Eq. (1), one can see that the laser nonlinearity has a memory; hence the used of Volterra series representation to model the lasers. While the injection current is well above threshold, the lasers exhibit a weak non-linearity. Therefore the use of third order Volterra transfer function modelling is adequate. The first three Volterra transfer function of the laser system are denoted as H_1, H_2 and H_3 is given [9]

$$H_1(\omega_1) = \frac{1}{G_1(\omega_1)} \tag{2}$$

$$H_2(\omega_1,\omega_2) = \frac{1}{2}\cdot\frac{G_2(\omega_1,\omega_2)}{G_1(\omega_1)\cdot G_1(\omega_2)\cdot G_1(\omega_1+\omega_2)} \tag{3}$$

$$H_3(\omega_1,\omega_2,\omega_3) = \frac{1}{6}\cdot\frac{G_3(\omega_1,\omega_2,\omega_3)H_1(\omega_1)H_1(\omega_2)H_1(\omega_3) - G_2(\omega_1+\omega_2,\omega_3)Z}{G_1(\omega_1+\omega_2+\omega_3)} \tag{4}$$

$$Z = H_1(\omega_1)H_2(\omega_2,\omega_3) + H_1(\omega_2)H_2(\omega_1,\omega_3) + H_1(\omega_3)H_2(\omega_1,\omega_2) \tag{5}$$

Based on the Volterra transfer functions of semiconductor laser, the ratio of the third inter-modulation product with respect to the carrier is given in dB by [9]

$$\frac{\mathrm{IMD3}_{2\omega_1-\omega_2}}{C} = 20\log_{10}\left\{\frac{3}{4}\cdot\mathrm{m}^2\cdot(I_{dc}-I_{th})^2\cdot\frac{|H_3(\omega_1,\omega_1,-\omega_2)|\cdot|H_1(0)|^2}{|H_1(\omega_1)|^3}\right\} \tag{6}$$

3. Distortion analysis of the optical feedforward transmitter

In this section, the proposed feedforward laser transmitter will be modelled based on the semiconductor model from the previous section. The system is represented in Fig. 1, while its Volterra model counterpart is depicted in Fig. 2. Since it is assumed that the system requires less than octave bandwidth to operate, the distortion associated with second-degree terms will fall outside this band and will be neglected, thus only in-band distortion components produced by the third degree terms will be considered. In Fig. 1, the main semiconductor laser is represented by the first order and third order Volterra transfer functions $H_1(\omega)$ and $H_3(\omega_1, \omega_2, \omega_3)$, respectively, as defined in [9]. The second laser is assumed to be linear since it is modulated in a linear region and is represented by the first order Volterra transfer function $H_1'(\omega)$. The coupling coefficient of the first and second optical coupler is depicted by C_1 and C_2, respectively, and the complimentary coupling coefficients are

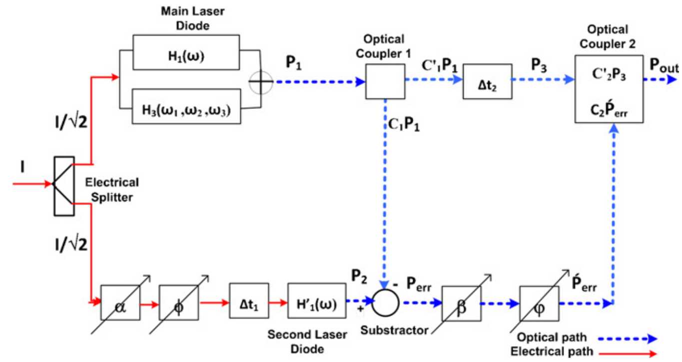

Fig. 1. System representation.

$$C_1' = 1 - C_1 \tag{7}$$

and

$$C_2' = 1 - C_2 \tag{8}$$

Δt_1 is taken to be the total delay introduced in the reference path of the signal cancellation loop and Δt_2 is the total delay introduced in the main path of the error cancellation loop.

Furthermore we assume to use a lossless 3 dB power splitter. Therefore the modulated current $I_m(t)$ is split into two identical signals by the electrical power splitter,

$$I_m(t) = \frac{I(t)}{\sqrt{2}} \tag{9}$$

The Volterra transfer functions of the proposed feedforward system are shown in Fig. 2. It is represented by $F_1(\omega)$ and $F_3(\omega_1,\omega_2,\omega_3)$ and will be derived in terms of system parameters. The input–output relation of the system is expressed by the equation

$$P_{out} = F(I) = C_2' T_2\left(C_1' H\left(\frac{I}{\sqrt{2}}\right)\right) + C_2\varphi\left(\beta\left[H_1'\left(T_1\left(\phi\left(\frac{\alpha I}{\sqrt{2}}\right)\right)\right) - C_1 H\left(\frac{I}{\sqrt{2}}\right)\right]\right) \tag{10}$$

where H, H', and F are the operators corresponding to the main laser, the second laser and the overall system respectively. T_1 and T_2 are the operators corresponding to the time delay in the first and second loops, respectively.

From Eq. (10), the Volterra transfer functions of the overall systems $F_1(\omega)$ and $F_3(\omega_1,\omega_2,\omega_3)$ are unknown and will be solved by replacing the first-degree and third-degree terms successively. By

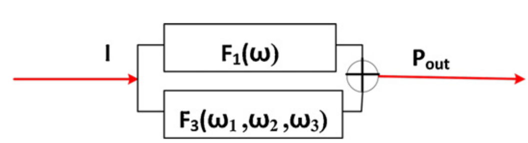

Fig. 2. Volterra transfer function of overall system.