Evaluation on the performance of Distributed Feedback Lasers (DFB) for Radio-Over-Fiber (RoF) Applications

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Abstract
The work in this paper regards the exploitation of a distributed feedback laser (DFB) on standard modulation schemes for radio-over-fiber applications. Specifically, the rate-equation model of the DFB laser is utilized in a number of simulations, concerning the case of intensity modulation by RF signals such as AM (Amplitude Modulation) and FM (frequency modulation), on the frequency band from 1 to 17GHz with special interest in the 2.4GHz, 5.7GHz regions due to standards for WLAN applications. Problems due to laser's intrinsic non-linearity are particularly addressed. The results show that apart from proper specifications on the laser's operating parameters also a suitable modulation scheme must be chosen.

Keywords
Distributed Feedback Laser (DFB), Radio-over-Fiber (RoF).

1. Introduction

Radio-over-fiber (RoF) systems provide a cost efficient solution for RF signal propagation in cellular radio and indoor wireless networks since they achieve low attenuation and high capacity (Baghersalimi 2003, Smyth 2004). With radio over fiber (RoF) links, once the multiplexed radio signal is modulated onto light, it is transmitted over a long distance through optical fiber. A simple RoF system consists of a Central Site (CS) and a Remote Site (RS) connected by an optical fiber link or network. For example, in WLANs, the CS would be the head-end while the Radio Access Point (RAP) would act as the RS. The frequencies of the radio signals distributed by RoF systems could span a wide range (usually in the GHz region) and depend on the nature of the applications. Besides transportation and mobility functions, RoF systems minimize the signal processing functions since they are performed at the central station (CS) resulting in the reduction of total network cost (Frigyes 2002). Better coverage and increased capacity, centralized upgrading and adaptation, higher reliability and lower maintenance costs, support for future broadband applications, and economic access to mobile broadband are among the most important advantages of RoF (Tonguz 1996).

Distribution of RF signals is achieved through Intensity Modulation – Direct Detection (IM-DD) that is, the laser is directly modulated using the appropriate RF signal. The advantage of the IM-DD method is its simplicity and low cost. Moreover, if low dispersion fiber is used in conjunction with an appropriate choice of the Laser's operating parameters the system becomes quasi linear. Consequently, the optical link acts only as an attenuator and is therefore transparent to the modulation format of the RF signal. Furthermore, unlike direct laser bias modulation, external modulators such as the Mach Zehnder Modulator (MZM) can be modulated with mmwave signals approaching 100 GHz, though this comes with a huge cost regarding power requirements. However, they require high drive voltages, which in turn lead to very costly drive amplifiers. Consequently, there is an increased interest in developing techniques and search for proper parameters so as to efficiently implement IM-DD for high frequency RF propagation.

Distributed Feedback (DFB) lasers are the proper light sources for analog transmission due to their single longitudinal mode, with side-mode suppression ratio (SMSR) in the order of 40dB, and stable operation with a narrow spectral width. However, they inherently have a serious problem of the modulation distortion caused by several factors; spatial-hole burning (SHB), leakage current, nonlinear interaction of carriers and photons, gain compression, nonlinear I-V characteristics in a pn heterojunction, and power dependent absorption. The SHB takes place due to nonuniform photon distribution along the cavity, which depends on both the coupling constant and the grating phase at laser facets, and can be eliminated by proper device design. The leakage current, which flows outside of an active layer, also causes the degradation of the L-I linearity. The distortion induced by the leakage current becomes remarkable at a high-power operation because the leakage current relatively increases in high-bias condition irrespective of the modulation frequency. Finally, the intrinsic nonlinear interaction drastically increases the harmonic or intermodulation distortion as the modulation frequency approaches the laser's resonance frequency. Multi-Quantum Well (MQW) DFB lasers enable high differential gain values thus increasing significantly the laser's resonance frequency (Vankwikelberge 1989).

The work in this paper examines the use of a distributed feedback laser (DFB) on several simulated case studies of propagation of RF signals applying IM-DD. In every case, the modulation scheme and the carrier frequency of the RF signal varies so as to evaluate the laser's performance not only in terms of intermodulation distortion due to non-linearities, but also on the impact and resilience capability on every modulation scheme. The rest of the paper is organized as follows. In section 2, the rate equations and the parameters that characterize the DFB laser are presented. In section 3, the deployment of several simulation experiments is shown while the achieved results are discussed. Finally, section 4 deals with conclusions and further work.

2. DFB Laser Model

The variation of the electric field E and the injected electron concentration n are described by a set of rate equations,

$$\frac{dE}{dt} = \tfrac{1}{2}(1+i\alpha)\left[G - \frac{1}{\tau_p}\right]E + F(t) \qquad (1)$$

$$\frac{dn}{dt} = \frac{I}{eV} - \frac{n}{\tau_s} - G|E|^2 \qquad (2)$$

where, V is the volume of the active region, G is the modal gain, n_0 is the carrier concentration at transparency, τ_p is the photon lifetime, e is the electron charge, τ_s is the carrier lifetime and α is the linewidth enhancement factor.

$$G = A\,(1 - s|E|^2) \qquad (3)$$

With A the linear gain coefficient and s the self gain saturation coefficient. The linear gain coefficient is calculated as,

$$A = v_g g(n - n_0) \qquad (4)$$

where g is the differential gain coefficient. Equations (1) – (4) are numerically integrated to simulate the laser operation. In the computation of laser dynamics, usual Langevin noise source is used represented by the term *F(t)* in (1).

Values for various parameters of a typical MQW DFB laser used in the simulations appear in Table 1. Apart from the intrinsic nonlinear interaction between carriers and photons, being the major nonlinearity, the model accounts for nonlinear gain compression.

TABLE 1

DFB laser parameters

Parameters	**Symbol**	**Value**
Differential gain coefficient	$g(cm^2)$	3.5×10^{-16}
Group index	n_g	3.5
Photon lifetime	$\tau_p(ps)$	0.5
Volume of active region	$V(\mu m^3)$	57.4
Carrier concentration at transparency	$n_0(cm^{-3})$	1.55×10^{18}
Linewidth enhancement factor	α	4.0
Nonlinear gain coefficient	$s(cm^3)$	1.0×10^{-17}
Carrier relaxation time	$\tau_{fc}(ns)$	1.0
Electron charge	$e(Cb)$	1.6×10^{-19}

Other nonlinear mechanisms like leakage current or SHB are assumed to be of minor importance for the current levels and DFB structure considered throughout this investigation.

3. Simulation results and discussion

This section describes the simulations performed by a numerical solution of the rate equations describing the behavior of the DFB laser. In the current work, the IM-DD scheme is used for transmission of several cases of RF signals. The latter are comprised of several schemes namely, standard AM, Double Side Band – Suppressed Carrier (DSB-SC), multiplexed AM and FM with

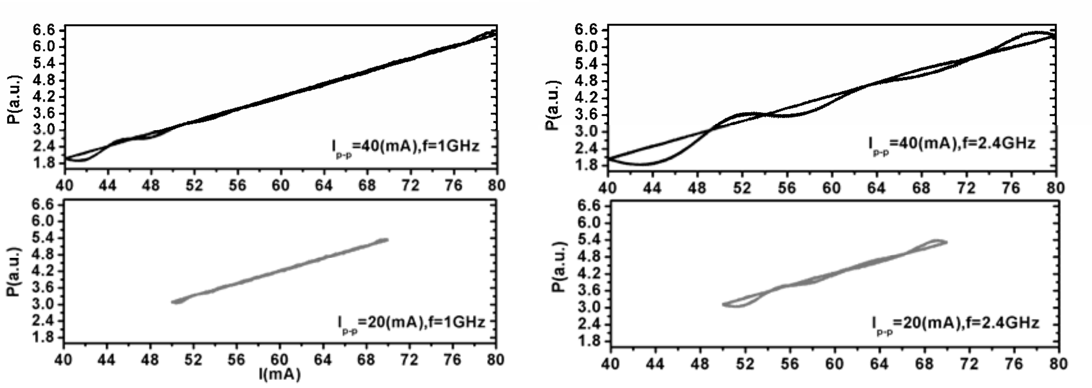


Figure 1: Dynamic Light – Current (L-I) characteristic of the DFB Laser at bias current I_b= 60 mA, and frequencies f=1GHz and f=2.4GHz.

various modulation indexes. In the following paragraphs, comparative graphs covering the above cases are provided. The frequencies of interest are in the range of 1GHz to 17GHz with particular emphasis on the bands of 2.4GHz and 5.7GHz since they are in use by many developed standards (IEEE 1999). The main consideration is the laser's non-linearity issues which are of great importance since they considerably degrade the performance of any such system. For example, the dynamic light-current characteristic for a bias current of 60mA and frequencies of 1GHz and 2.4GHz is illustrated in figure 1. The latter is obtained by solving numerically the rate equations using as input excitation a triangular pulse at frequencies 1GHz and 2.4GHz, respectively. It is evident that the linearity of the L-I curve is degraded if either the frequency or the dynamic range of the excitation signal increases. The DFB laser is well behaved (almost linearly) for bias

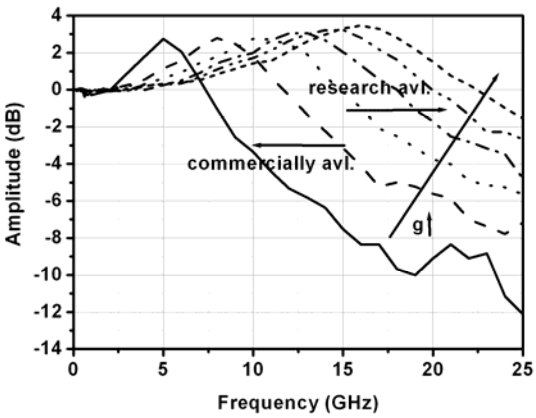


Figure 2: The frequency response of various DFB lasers.

currents up to 3 times the threshold current and signal amplitudes from about 0.2 to 0.9 times the threshold current as well. However, notice that although for lower signal amplitudes the linearity of the L-I curve is improved, the relative noise of the laser is increased. Eventually, the choice of the amplitude of the modulated RF signal or equivalently the modulation depth will be the result of a compromise between an acceptable signal distortion and signal to noise ratio (SNR). Another issue is the frequency response of the DFB laser. The frequency response of various DFB lasers is illustrated in figure 2. The response was evaluated through successive application of sinusoidal signals in the range of 1GHz to 25GHz. The bias current was set to 60mA. The DFB laser considered for this study has a 3dB intrinsic modulation bandwidth in the order of 20GHz.

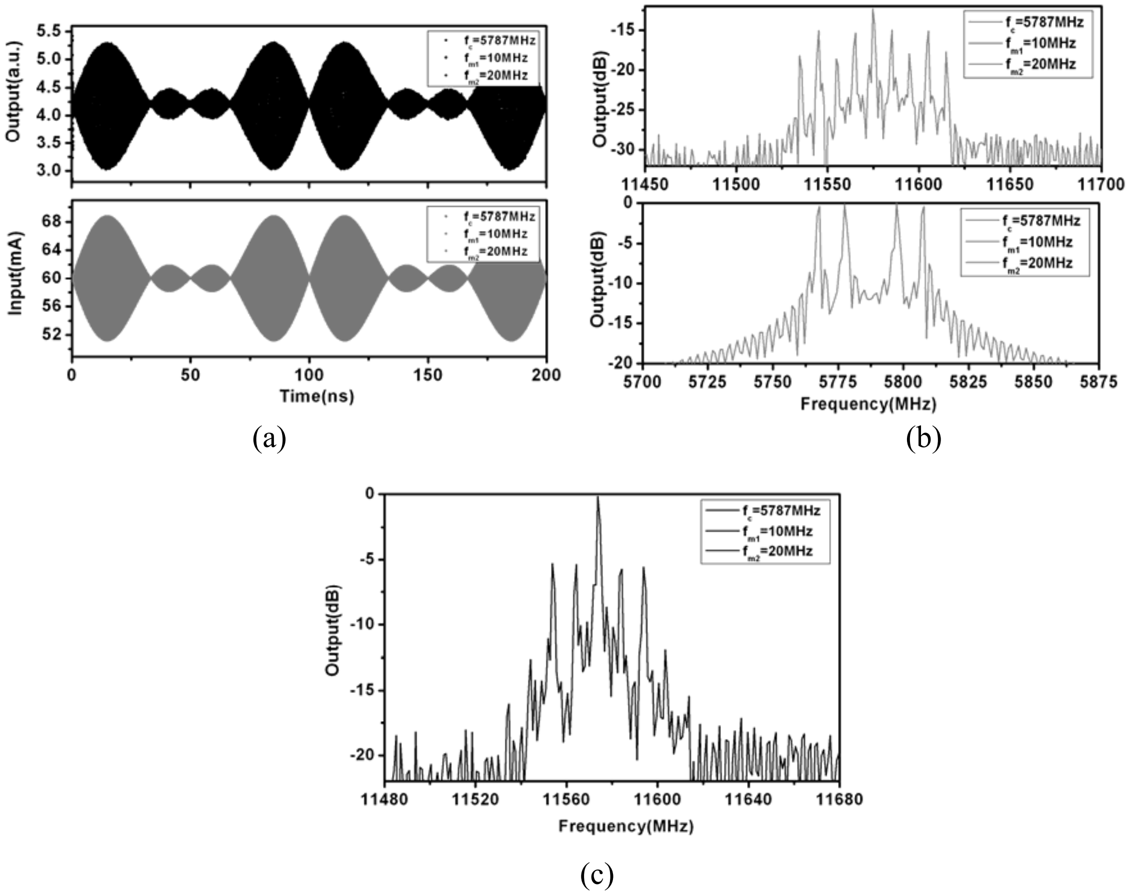


Figure 3: (a) Time domain input-output DSB-SC signal, (b) Output spectra for the DSB-SC and its 2[nd] harmonic, (c) Output spectra of the 2[nd] harmonic for the AM case.

The performance of the DFB laser in terms of spectral and intermodulation distortion can by understood by considering a direct modulation of the laser with a set of sinusoidal signals. In our case to ensure that a large number of mixing products were included in the selected example of 80MHz width band of interest, four-tone tests were performed for frequency arrangements of the type: $fc \pm fmi$ where f_c = 5.7GHz while f_{m1}= 10MHz and f_{m2}=20 MHz. In figure 3, output spectral is presented in the regions around the operating frequencies f_c and around $2f_c$ as well. As we can see, for DSB-SC (fig.3b) and AM (fig.3c), 2[nd] order harmonic distortion is evident. Furthermore, 3[rd] order intermodulation distortion strongly appears at the second harmonic for the DSB-SC

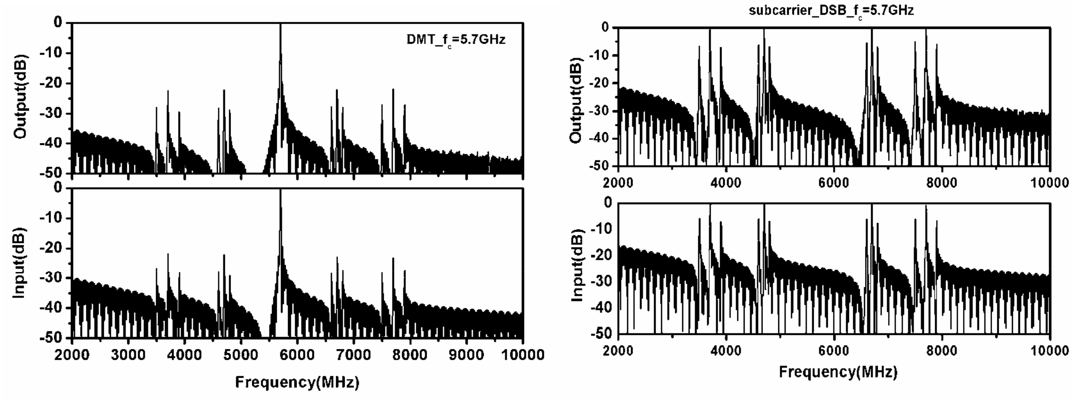


Figure 4: Multiplexed amplitude modulation for a 5.7GHz RF carrier, (a) case of AM. (b) case of DSB-SC. For both cases subcarriers are modulated.

case. Thus, AM is more resilient to spectral distortion due to laser's non-linearity.

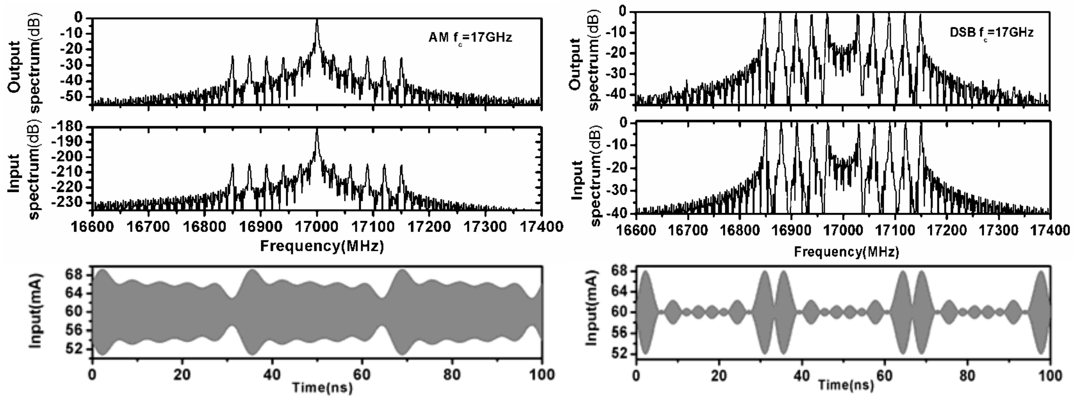
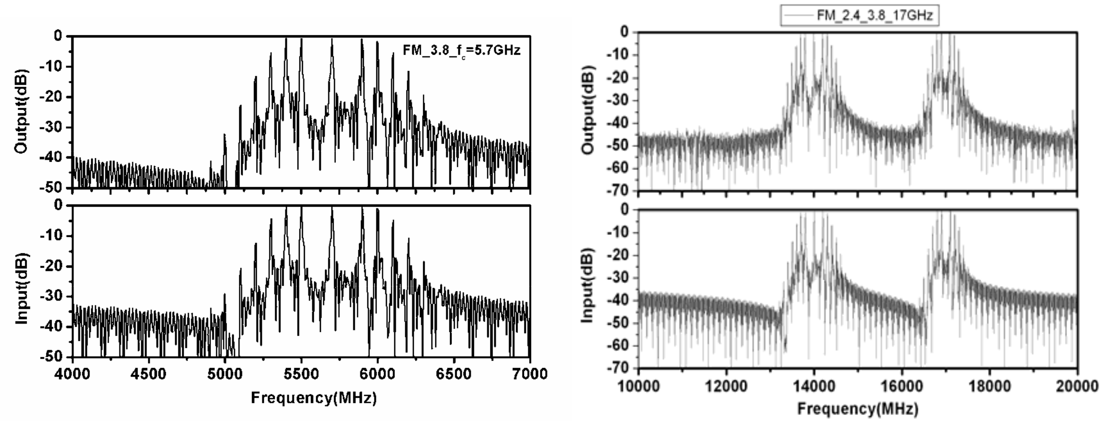


Figure 5: Multiplexed amplitude modulation for a 17GHz RF carrier, (a) case of five channels AM, (b) case of five channels DSB-SC.

Sequentially, we study the performance of IM-DD when multiplexed modulation schemes are applied. In all cases the dynamic current input range was selected to be 20mA (peak-to-peak input current). The case of AM and DSB-SC with subcarriers of 1GHz and 2GHz being modulated by tones of 100 and 200MHz respectively is presented in figure 4 where the input and output spectra is depicted. The RF carrier frequency was set to 5.7GHz. It is apparent that there is not considerable spectral distortion, even for the case of DSB-SC. A similar example is depicted in figure 5, where AM and DSB-SC were utilized for an RF carrier of 17GHz. Five subcarriers of frequencies 30MHz, 60MHz, 90MHz, 120MHz and 150MHz modulate the RF carrier. This case



(a) (b)

Figure 6: IM-DD using FM. (a) FM on an RF carrier of 5.7GHz with subcarrier frequency of 100MHz and m = 3.8, (b) multplexed FM on RF carriers of 14GHz and 17GHz with subcarriers of 100MHz and m = 2.4 and 3.8 respectively.

is analogous to orthogonal frequency division multiplexing (OFDM). As we can see, the effect of spectral distortion due to the laser's non-linearity is evident, in reduced degree, only for DSB-SC while for AM there is not considerable distortion if we compare the input-output spectra. Another point of interest is that in relation to the laser's frequency response (fig. 2), there is no significant spectral alteration if narrowband channels are used around the RF carrier frequency.

Concecutively, the case of IM-DD when frequency modulated RF signals, either single or multiplexed, are applied. Once again, the dynamic current input range was selected to be 20mA. The FM signal is described as,

$$E(t) = E_0 \cos[2\pi f_c t + m \cdot \sin(2\pi F t)] \qquad (5)$$

where, f_c is the carrier frequency, m is the modulation index and F is a tone or a subcarrier's frequency. The modulation index controls the amount of Bessel output spectral terms. In figure 6, the output frequency spectra for the directly modulated DFB laser for the case of FM is shown. In figure 6a, the carrier frequency is 5.7GHz while the subcarrier frequency is 100MHz with a modulation index of 3.8. The latter ensures that the carrier's adjacent spectral terms diminish. It is observed that the output spectrum is consistent to the input showing that no significant degradation is present.

In figure 6b, the output frequency spectra for the directly modulated DFB laser is shown when a multiplexed FM scheme is used. The first channel has a carrier frequency of 14GHz and the second 17GHz. In both channels the subcarrier frequency is 100MHz whereas the modulation index is 2.4 and 3.8 respectively. An index of 2.4 forces the carrier frequency to vanish.

Therefore, the selection of these indexes accounts for proper evaluation of intermodulation distortion if any. It is also observed that not important spectral distortion is present.
However, simulation results have shown that harmonic distortion due to laser's non-linearity is evident especially for the second case. The distortion follows a square law since the output spectrum appears not only at twice the original frequencies but also at 31GHz, which is the sum of the RF carriers.

4. Conclusions and further work

In this paper, the performance of a distributed feedback (DFB) laser for propagation of RF signals using IM-DD has been evaluated. Several standard RF modulation schemes were applied in order to investigate the laser's operational parameters and identify its limitations for the purpose of utilization in broadband RoF systems. Simulation results confirmed that an acceptable performance, in terms of spectral and intermodulation distortion, depends not only on DFB laser's non-linearity, carrier frequency and bias current level but also on the modulation scheme. Nevertheless, a proper adjustment of these parameters is crucial for feasibility of reliable IM-DD RoF systems. Further work involves the deployment of the most common digital modulation schemes either single carrier or multicarrier, which are currently used in broadband wireless applications.

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