Evaluation of Distributed Feedback (DFB) Laser Operating Parameters for Direct Modulation Schemes in IM-DD RoF Links.

S. Mikroulis, A. Chipouras, S. H. Karabetsos and A. A. Nassiopoulos
RDTL Laboratory, Department of Electronics, Technological Educational Institution of Athens, Egaleo - Greece

Abstract. **The increasing demand for high data rates in wireless networks indicates Radio-over-Fiber (RoF) systems as a good candidate for physical layer infrastructure in the development of future high-speed wireless communication systems. In this work, the performance of a distributed feedback (DFB) laser is evaluated in order to exploit its operational parameters and identify its limitations for the purpose of utilization in broadband RoF systems. It is shown that the laser's intrinsic non-linearity restrictions can be tolerated by appropriate adjustment of the operating parameters and choice of proper modulation schemes.**

Index Terms –Radio over Fiber (RoF), IM-DD RoF systems, intermodulation distortion, Distributed feedback (DFB) laser.

I. Introduction

WIRELESS local area networks (WLANs) are attractive since they combine high capacity and increased flexibility[1]. With fiber-optic radio links (RoF), once the radio signal is modulated onto light and multiplexed, it is transmitted over a long distance through optical fiber. A RoF system consists of a Central Site (CS) and a Remote Site (RS) connected by an optical fiber link or network. If the application area is in a Global Service Mobile (GSM) network, then the CS could be the Mobile Switching Centre (MSC) and the RS the Base Station (BS). For WLANs, the CS would be the headend while the Radio Access Point (RAP) would act as the RS. The frequencies of the radio signals distributed by RoF systems span a wide range (usually in the GHz region) and depend on the nature of the applications. The added value in using such a system lay in the capability to dynamically allocate capacity based on traffic demands. RoF systems of nowadays, are designed to perform added radio-system functionalities besides transportation and mobility functions. Hence, the electronic signal processing could be minimized as most of the signal processing functions could be performed at the central station (CS) resulting in the reduction of total network cost [2]. Better coverage and increased capacity, centralised 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 [3].

Among Several techniques for distributing and generating microwave signals [4], the Intensity Modulation – Direct Detection (IM-DD) is the most usable. The laser is directly modulated by using the appropriate RF signal.

The advantage of the IM-DD method is its simplicity and low cost. Secondly, if low dispersion fiber is used in conjunction with an appropriate choice of the Laser operating parameters the system becomes quasi linear. Consequently, the optical link acts only as an amplifier or attenuator and is therefore transparent to the modulation format of the RF signal. That is to say that both Amplitude Modulation (AM) based schemes and constant envelop based modulation schemes such as Phase Modulation (PM / QPSK) can be used. Such a system needs little or no upgrade whenever changes in the modulation format of the RF signal occur. Sub-Carrier Multiplexing (SCM) can also be used on such a system. Furthermore, unlike direct laser bias modulation, external modulators such as the Mach Zehnder Modulator (MZM) can be modulated with mm-wave signals approaching 100 GHz, though this comes with a huge cost regarding power requirements. Moreover, they require high drive voltages, which in turn lead to very costly drive amplifiers.

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.

In this work, the performance of a high-speed distributed feedback (DFB) laser is evaluated in order to exploit its operational parameters and identify its limitations for the purpose of utilization in future broadband RoF systems. It is shown that the laser's intrinsic non-linearity restrictions can be tolerated by appropriate adjustment of the operating parameters and choice of proper modulation schemes.

II. 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,

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

With *A* the linear gain coefficient and *s* the self gain saturation coefficient.

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

where *g* is the differential gain coefficient, 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, v_g is the group velocity, and α is the linewidth enhancement factor. 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 Eq. 1.

Values for various parameters of a high-speed MQW DFB laser used in the simulations appear in Table1. Apart from the intrinsic nonlinear interaction between carriers and photons, being the major nonlinearity, the model accounts for nonlinear gain compression, also.

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 assumed to be of minor importance for the current levels and DFB structure considered throughout this investigation.

III. RESULTS AND DISCUSSION

A. *Linearity of the DFB Laser*

This section describes the simulations performed by a numerical solution of the rate equations. The laser non-linearity may considerably degrade the performance of the RoF system. As it is shown in Figs. 1, 2 the laser exhibits a usual non-linear multistable behavior.

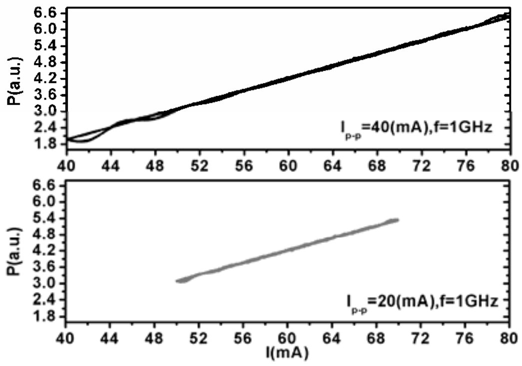

Fig.1 Dynamic Light – Current (L-I) characteristic of the DFB Laser at bias current I_b= 60 mA, f=1GHz

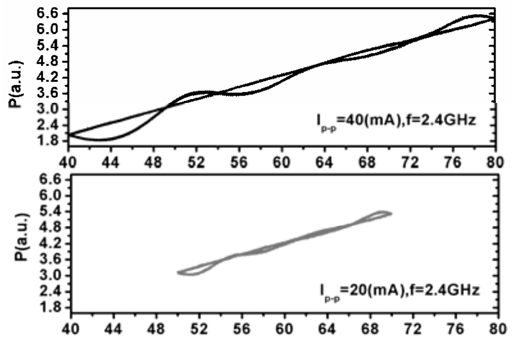

Fig.2 Dynamic Light – Current (L-I) characteristic of the DFB Laser at bias current I_b= 60 mA, f=2.4GHz

The dynamic light–current characteristic is obtained solving numerically the rate equations (Eqs.1-4) using as an input excitation a triangular pulse at frequencies 1 and 2.4 GHz, respectively. The degradation of the linearity of the L-I curve is enhanced by increasing the pulse amplitude and the frequency, as it is evident in Figs. 1, 2.

The small signal modulation response is calculated using the rate equations (1-4). For each frequency point, the rate equations are solved with an input sinusoid at that frequency. The small-signal amplitude (p-p) is 0.5 times the threshold current. In this example, an evaluation of different DFB lasers commercially/research available is presented with resonance frequencies ranging from 5 to 15 GHz which results in an equivalent intrinsic modulation bandwidth from 9 to 25GHz, at a current bias approx. $2.5I_{th}$, where I_{th} is the laser's threshold current. The calculated frequency response for g values from 1.0 to 5.0 x 10^{-16} cm^2 is shown in Fig 3.

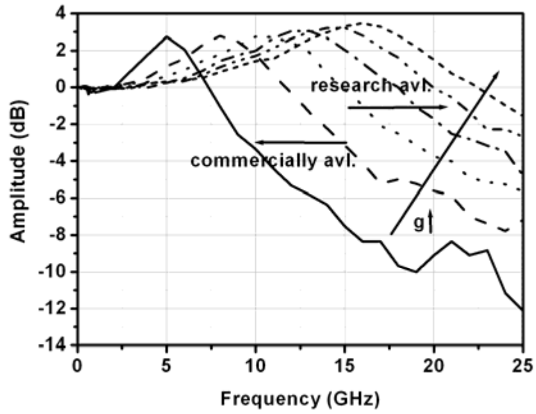

Fig.3 Frequency response of the DFB Laser for various differential gains

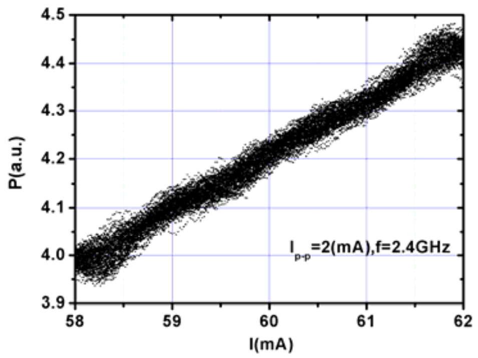

Fig.4 Dynamic Light – Current (L-I) characteristic of the transmitter Laser at bias current I_b= 60 mA, f=2.4GHz, Ip-p=2mA

The simulation results show that the DFB laser is well behaved (almost linearly) for bias currents up to 3 times the threshold current and signal amplitudes from about 0.2 to 0.9 times the threshold current as well. Thus, the RF signal will not experience significant distortion in the typical transmission band (well below the resonance frequency).

As expected for lower signal amplitudes the linearity of the L-I curve is improved but the relative noise of the laser is increased (Fig.4). Noise in lasers is mainly due to the amplified spontaneous emission (ASE) noise. The change in the photon population (or electric field, E) is usually associated with a noise term. This noise results in random fluctuations in the optical output signal and may significantly degrade the system's carrier-to-noise ratio (CNR). However the laser intensity noise (Relative Intensity Noise-RIN) is reduced for a higher optical power (higher injection levels).

The laser's RIN has its spectral maximum near the relaxation oscillation frequency (in the order of 12 GHz for our laser). The RIN is calculated to be in the order of -150dB/Hz, which is in agreement with published values for similar lasers [5]. Eventually the choice of the amplitude of the modulated RF signal or equivalently of the modulation depth will be the result of a compromise between an acceptable signal distortion and the minimum intensity noise. Moreover, noise figure (Fig.4) can be used to define appropriate levels for M-ASK/M-QAM modulation schemes.

B. Harmonic distortion analysis

Distortion in the laser can be analyzed by a numerical solution of the rate equations (Eqs. 1-4). A single tone inputs as a current modulation.

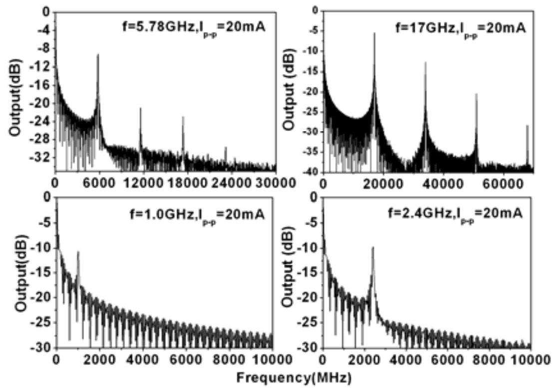

Fig 5 Frequency spectra of the optical output of directly modulated DFB laser with a single tone at 1, 2, 5.78 and 17 GHz.

The response of the laser is then Fourier-transformed, to yield the frequency information of the output light. The harmonic distortion power can be analyzed as a function of modulation frequency.

Because of the intrinsic non linearity of the transmitter the appearance of higher order harmonics is inevitable and as it is shown in Fig. 5 is more pronounced as the frequency increases. Using the simulation model, the ratio of high order distortion harmonics to carrier power, HMDn/C, is calculated. The ratios HMDn/C, where n=2,3, for the electric equivalent power spectra are in the order of –30dB increased with frequencies over 10 GHz. However, these harmonics are far enough over the concerned frequency band and can easily be removed using the appropriate filters. Consequently their existence is not crucial for the systems with operating frequencies in the order of 10 GHz).

C. Multichannel distortion noise

The performance of a direct IM-DD scheme is strongly influenced by the nonlinearity of the laser. When many RF subcarriers are multiplexed together and modulate the light source, harmonic distortions and intermodulation products are generated that influence negatively the quality of the signal at the receiver.

The origin of nonlinear distortion can be the carrier leakage, spatial hole burning and the nonlinear interaction between photons and electrons inside the laser cavity. When the laser is operated in multi-GHz range, it is the latter that dominates the nonlinear distortion. The distortion is especially prominent when the modulation frequency is in the proximity of the relaxation oscillation peak.

The impact of the multichannel distortion can by understood by considering a direct modulation of the laser with a set of N generic sinusoidal tones. The input current $i(t)$ to the direct modulated laser transmitter can be expressed as a

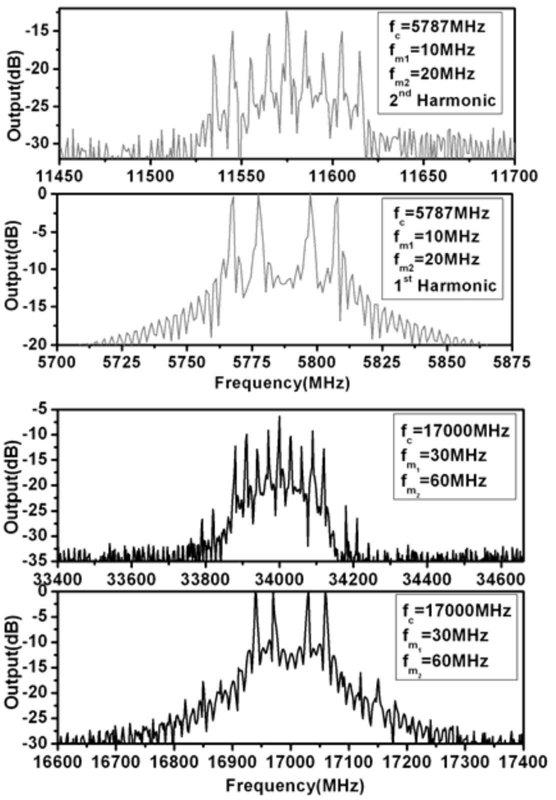

Fig.6 Frequency spectra of the optical output of directly modulated DFB laser with subcarrier multiplexing

sum of single tones ω_i with a modulation index m_i respectively,

$$i(t) = I_{bias}\left(1+\sum_{i=1}^{N} m_i \cos 2\pi f_i t\right) \quad (5a)$$

where I_{bias} is the applied bias current. Then the output optical signal expanded as a Taylor series is obtained as *P(t)*:

$$P(t) = a_0 i(t) + \sum_{1}^{\infty} \frac{1}{n!}\frac{\partial^n P(t)}{\partial^n [i(t)]}\frac{\partial^n [i(t)]}{\partial t^n} i(t)^n \quad (5b)$$

It is obvious that the output consists of the original sinusoidal signals at frequencies ω_i, with the addition of the following frequency components $m f_i \pm n f_j, \pm p f_k$ where *m*, *n* and *p* are integer numbers that can assume the values 0, 1, 2… If two of *m*, *n* and *p* are simultaneously null, the harmonic components of a tone are obtained; if at least two of them are different from zero, we talk of intermodulation products. The sum *m* + *n* + *p* defines the order of the harmonics and of the intermodulation products; So, the second-order harmonic distortion (HMD2) is identified as $2f_i$, $2f_j$, $2f_k$; the third order harmonic distortion (HMD3) as $3f_i$, $3f_j$, $3f_k$; second-order intermodulation (IMD2) as $f_i \pm f_j$; third order intermodulation (IMD3) as $2f_j \pm f_i$, $2f_i \pm f_j$, $f_i \pm f_j \pm f_k$ and so on. Some of these beats fall within the operational band where the original tones are allocated, thus yielding intraband distortion. It is important to note that in those RoF-systems, where a single wavelength is used to allocate several services, there can be an interband negative influence too, due to the harmonics or intermodulations that, generated in a certain band, fall within that dedicated to another service.

In our case to ensure that a large number of mixing products were included in the 80MHz width band of interest, four-tone tests were performed for frequency arrangements of the type: $f_c \pm f_{mi}$ where f_c = 5787 MHz and 17000 MHz while $f_{m2}=2f_{m1}$=20 MHz and 60 MHz respectively. In fig. 6 distortion products are presented in the regions around the operating frequencies f_c and around 2 f_c as well. As we can see, the dynamic nonlinearity of the laser results in the generation of sidebands around the original signal frequencies due to IMD3. In addition into the sidebands that are visible in the received spectrum, there are also IM2 products sitting on the $2f_c$ region that will affect the performance of these channels.

The ratios IMDn/C, *n* =2,3, for the electric equivalent power spectra are in the order of –30dB, increased with frequencies

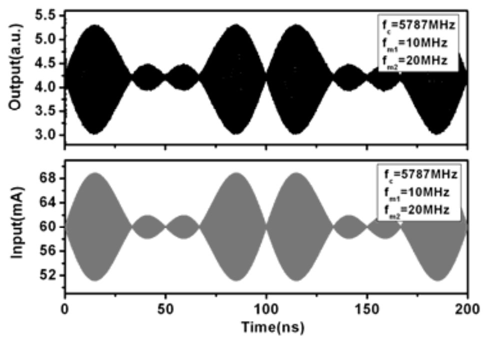

Fig.7 Input (electrical) and output (optical) signal for the case of f=5.787GHz carrier frequency with DSB-SC modulation.

over 10 GHz and modulation depth. It is noted that duplicating the modulation depth the ratios IMD2/C and IMD3/C, for the electric equivalent power spectra, are

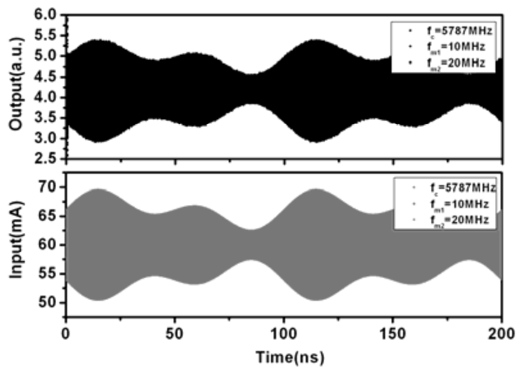

Fig.8 Input (electrical) and output (optical) signal for the case of f=5.787GHz carrier frequency with standard AM modulation.

increased about 3 dB and 9 dB respectively. Besides the asymmetry of the intermodulation products as they not have the same phase and magnitude due to the memory of the transmitting laser, must be noted. The IMDn products are

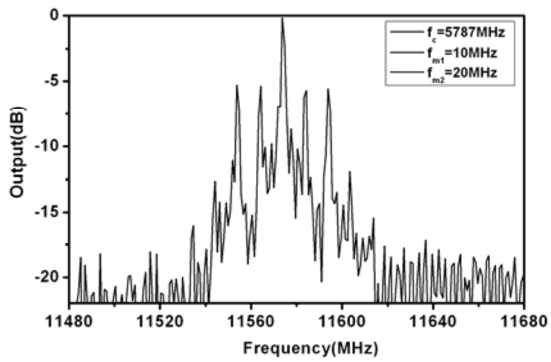

Fig.9 Frequency spectra of the optical output of directly modulated DFB laser with subcarrier multiplexing for the second harmonic.

reduced with increase in resonance frequency, because the resonance peak shifts to the higher frequency.

Therefore, a high resonance frequency, which can be achieved by MQW-DFB laser structure is indispensable to obtain low distortion. In addition, IMD3 decreases with increasing bias current, which is attributed to the increase of resonance frequency. In addition IMDns are noticeably decreased by increasing the bias current above 3.5 times the threshold current. However, at large bias levels the nonlinearity due to the leakage current limits the device's performance. Besides, low bias current is necessary to realize long-term reliability.

Furthermore, notice that Eq. 5a also expresses a Double Side Band – Suppressed Carrier (DSB-SC) modulation scheme having a carrier frequency of f_c. An example of the time domain input-output signal is depicted in Fig. 7. In contrast to this, the case of standard amplitude modulation (AM) using the same parameters is depicted in Fig. 8 while the frequency spectra of the optical output of the DFB laser for the second harmonic of the carrier frequency, is illustrated in Fig. 9. It is observed that the AM signal is more resilient to intermodulation distortion since intermodulation harmonics are suppressed compared to the DSB case (Fig. 6).

E. Calculation of the C/N for typical RoF link

A RoF system connects a Central Site (CS) to N Remote Sites (RS), supporting N radio channels connected by an optical fiber link. The current applied to the transmitter is the sum of N individuals channels with signal s(t):

$$i(t) = I_{bias}\left(1+\sum_{i=1}^{N} s(t)m_i \sin(2\pi f_i t+\phi_i)\right) \quad (6a)$$

For a large number of channels, by the central limit theorem, the input signal can be modeled as a Gaussian random variable with a standard variation of $m_{eff} I_{bias}$, where m_{eff} is the RMS modulation index:

$$m_{eff} = \sqrt{\frac{\sum_{i=1}^{N} m_i^2}{2}} \quad (6b)$$

Then the received CNR ratio to the most distant (RS) is given by [7]:

$$\left(\frac{C}{N}\right)_e = \frac{\left(m_{eff}\Re P_0 10^{-(aL+L_c)/10}\right)^2}{P_{thermal}+P_{shot}+P_{RIN}+P_{IMD3}} \quad (7)$$

Where $\Re$ is the detector responsivity, P_0 is the average transmitted optical power, L is the fiber length, L_c the coupler losses, and P_{shot}, $P_{Thermal}$, P_{RIN}, and P_{IM3} are the rms values of the noise currents associated with the shot noise, thermal noise, laser intensity noise, and distortion sources, respectively. The total IM power of the center channel on which the largest number of 3rd order intermodulation products will is [7]:

$$P_{IM3} = \frac{3(N^2-2N+1)}{8}(IMD3) \quad (8)$$

By calculating IM3 using the presented rate equations, the relation (7), and typical values of the relevant parameters, the CNR ratio can be calculated.

F. Conclusions

Through simulations, the performance of a distributed feedback (DFB) laser is evaluated in order to exploit its operational parameters and identify its limitations for the purpose of utilization in broadband RoF systems. The results showed a dependence of a possible RoF system's degradation, due to the DFB laser's nonlinearity, on bias current level, modulation depth, carrier frequency and modulation scheme. Nevertheless, a proper adjustment of these parameters is crucial for feasibility of IM-DD RoF systems with an acceptable performance.

References

[1] G. Baghersalimi, T. O'Farrell, V. Postoyalko, "*Modelling Laser-Diode Non-linearity in a Radio-over-Fibre Link*" Proceeding of London Communication Symposium, Pages: 321- 324, September 2003

[2] C. Harder, J. Katz, S. Margalit, J. Shacham, and A. Yariv, "Noise equivalent circuit of a semiconductor laser diode," *IEEE Journal of Quantum Electron*., vol. QE-18, pp. 333-337, 1982.

[3] I. Frigyes Basic Microwave Properties of Optical Links: Insertion Loss, Noise Figure, and Modulation Transfer" in *Radio over Fiber Technologies for Mobile Communications Networks"*, H. Al Raweshidy, and S. Komaki, ed. Artech House, Inc, USA, 2002

[4] P. Vankwikelberge *et al.*, "Analysis of the carrier-induced FM response of DFB lasers: Theoretical and experimental case studies," *IEEE J. Quantum Electron.*, vol. 25, pp. 2237–2254, Nov. 1989

[5] O. K. Tonguz and H. Jung, "Personal communications access networks using subcarrier multiplexed optical links," *IEEE J. Lightwave Technol.*, vol. 14, pp. 1400–1409, June 1996

[6] A.R. Shah and B. Jalali ,"Adaptive equalisation for broadband predistortion linearization of optical transmitters" IEE Proc.-Optoelectron., Vol. 152, No. 1, pp.16-34, February 2005

[7] H. Jung and O.K. Tonguz, "Comparison of fibre and coaxial link for access network in microcellular PCS", Electronc Letters, Vol. 32, No 5, pp. 425-426, Feb. 1996