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A Dynamic Simulink Model For Erbium-Doped Fiber Amplifiers Overmodulation in Presence of Amplified Spontaneous Emission Effect

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ABSTRACT

This paper presented a method for investigating EDFA dynamics using the tools MATLAB and Simulink. We investigate the effect of ASE on the gain modulation in EDFAs. The gain modulation is the low-frequency (kHz) amplitude modulation of the EDFA pump and the communication signal used for propagating line monitoring Information. We develop, the previous models by including amplified spontaneous emission. The derivation of an analytical model for EDFA overmodulation response has been presented. This model provide analytic expressions for the pump and input signal overmodulation responses, respectively. These expressions describe the output signal modulation index amplitude and phase, assuming small sinusoidal steady-state oscillations of the mean pump or input signal power. In this paper We show that ASE have some effect on predictions in the high gain/low saturation regime.

KEYWORDS: ASE (amplified spontaneous emission) , Erbium-doped fiber amplifier (EDFA) , Gain modulation , Overmodulation .

I. INTRODUCTION

Erbium doped fiber amplifier (EDFA) is an imperative element in DWDM networks. This all-optical amplifier enables simultaneous amplification of multiple wavelengths in regard of electronic regeneration, direct optical amplific-ation using erbium-doped fiber amplifiers offers many advantages for long haul repeatered transmission. First, the repeater can be quite simply configured regardless of the line signal bit rate. This feature becomes more significant as the line signal bit rate exceeding 1 Tb/s at which speed electronic regeneration requires high-speed electronic circuits, thereby resulting in increase in hardware cost and power consumption. Therefore, optical amplifiers are particularly useful in submarine repeaters that have severe space and power constraints. Second, optical amplifiers are flexible as regard bit rate and modulation format, and support wavelength division multiplexed signal transmission. Infact Their deployment in WDM systems after 1995 revolutionized the field of fiber-optic communications [1],[2].

Standard EDFA models, which are typically static, are not well suited to investigating gain modulation, which is a dynamic effect. So we must use dynamic models.

Novak and Moesle [3] (2002) developed the perturbation concept of Freeman and Conradi (1993), using methods described by Bononi and Rusch (1998) for modeling transient effects in EDFAs, which are in turn based on the time-varying gain equation of Sun *et al.* (1996).Their model did not take into account amplifier spontaneous emission. In practice amplifier saturation has to be included in view of the competition between the amplified spontaneous emission (ASE) and the signal for the power available from the optical amplifiers.

In this paper, we develop the model of Novak and Moesle, by including amplified spontaneous emission (ASE) in the model.

II. BACKGROUND

The amplifier is modeled as a three-level system [4], having Three populations of erbium atoms are of interest here: 1) the ground state with population density n_1; 2) metastable level with population density n_2; and 3) pump level with population density n_3. In practice, transitions from 3 to 2 are much more likely than transitions back to the ground state (3 to 1) or the rate of spontaneous emission from state 2. Under these assumptions, $n_3 \approx 0$.The rate equations describing the effects of the pump (P_P),signal (P_S),and ASE (P_{ASE}) power reduces to the following for n_2:

$$\frac{\partial n_2(z,t)}{\partial t} = \frac{\Gamma_s \sigma_{12}}{h\upsilon_s A}\left(P_s + P_{ASE}^+ + P_{ASE}^-\right)n_1 - \frac{\Gamma_s \sigma_{21}}{h\upsilon_s A}\left(P_s + P_{ASE}^+ + P_{ASE}^-\right)n_2 - \frac{n_2}{\tau} - \frac{\Gamma_p \sigma_{13}}{h\upsilon_p A}\left(P_p^+ + P_p^-\right)n_2 \quad (1)$$

A is the effective cross-sectional area of the core. The σ 's are known absorption and emission cross-section data for the erbi-um fiber. The Γ 's are the mode confinement factors for the pump and signal waves. The superscript + designates pump and

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ASE copropagating with the signal , and - when they counterpr- opagate to the signal. In modern fibers we can neglect scattering and other losses ,so the convective equations describing the spatial development of the pump, signal and ASE in the fiber are[4]:

$$\frac{\partial P_S(z,t)}{\partial z} = P_P \Gamma_S (\sigma_{21} n_2 - \sigma_{12} n_1) \qquad \frac{\partial P_P^{\pm}(z,t)}{\partial z} = \pm P_P^{\pm} \Gamma_P (\sigma_{13} n_3)$$
$$\frac{\partial P_{ASE}^{\pm}(z,t)}{\partial z} = \pm P_{ASE}^{\pm} \Gamma_S (\sigma_{21} n_2 - \sigma_{12} n_1) \pm 2\sigma_{21} \Gamma_S h\upsilon_S \Delta\upsilon n_2. \quad (2)$$

Equations (1) and (2) are the basic equations describing an EDFA.

III. DYNAMICAL MODEL

For dynamical modelling , first (2) is substituted into (1) and then integrated over Z to remove the length dependence of erbium-doped fiber [5]. This results in a dynamic equation for the excited state population N_2, which in turn determines the dynamics of the output pump and communication signals.

$$\frac{\partial}{\partial t}(n_2 A) = -\frac{\partial P_S}{\partial z} - \frac{\partial P_P^+}{\partial z} - \frac{n_2 A}{\tau} - \frac{\partial P_{ASE}^+}{\partial z} + 2\sigma_{21}\Gamma_S h\upsilon_S n_2 \Delta\upsilon. \quad (3)$$

In equation (3) we include only copropagating pump and ASE. Integrating (3) over Z , we have

$$\frac{\partial}{\partial t} N_2 = P_S(0,t) - P_S(L,t) + P_P^+(0,t) - P_P^+(L,t) - \frac{N_2}{\tau} + P_{ASE}^+(0,t) - P_{ASE}^+(L,t) + 2\sigma_{21}\Gamma_S h\upsilon_S \Delta\upsilon \frac{N_2}{A}. \quad (4)$$

Where N_2 is the number of erbium ions in the excited state. *P*S (0,t) and *P*p(0,t) represent the time-dependent input powers for the pump and signal. The output powers *P*S (L,t) and *P*p(L,t) are explicit functions of N_2.

$$\frac{\partial}{\partial t} N_2 = P_S(0,t)\left[1-\exp\left(B_S N_2 - C_S\right)\right] + P_P^+(0,t)\left[1-\exp\left(B_P N_2 - C_P\right)\right] - \frac{N_2}{\tau} - 2h\upsilon_S n_{sp}\Delta\upsilon(G-1) + 2h\upsilon_S \frac{\beta_S}{\rho A}\Delta\upsilon N_2. \quad (5)$$

This is the key equation for considering dynamic gain effects in the EDFA including ASE. In equation (5) G is the gain, *βs* is the emission per unit length, Δ*v* and *v* refer to the wavelength deviation of the ASE power around *λ*, *h* is Plank's constant, and *nsp* is the population-inversion factor which is dimensionless [6]. In an EDFA, complete inversion can only be obtained when being pumped at 980 nm; at 980 nm *βP* = 0 and therefore *nsp* = 1. So a pump wavelength of 980 nm is assumed. The B and C are given in terms of the confinement factors Γ_S and Γ_P , the absorption and emission cross sections (σ_{12} , σ_{21} , and σ_{13}), the density of erbium atoms ρ , the length L, and the effective cross sectional area A of the erbium-doped fiber. *τ* is the rate of spontaneous emission, and *r* is the effective radius of the fiber core.

IV .GAIN MODULATION

To model the impact of modulation, we add perturbations to the pump and signal transition rates. Overmodulation is introduced as a sinusoidal time variation of the pump or signal power [3], described by

$$P_{P,S}(0,t) = P_{P,S}^0(0)\left(1 + m_{P,S}\cos\omega t\right) \quad (6)$$

Here, $P^0(0)$ is the mean power (pump or signal) at the input (z=0) and $m_{p,s}$ is the input modulation index. Note the overmodulation frequency is assumed small (~kHz) compared with the communications signal data rate (~Gb/s) and can be considered simply as an analog modulation imposed on the mean signal power power. The EDFA overmodulation behavior is then obtained by solving (5) with time-dependent inputs of the form of (6). As a first step, we expand N_2(t) about its mean (unmodulated) steady-state solution N_2^0:

$$N_2(t) = N_2^0\left(1 + \delta\cos(\omega t + \varphi)\right) \quad (7)$$

-Pump and signal Modulation

Using the method described by Novak and Mosle, the equations for the amplitude and phase of the pump-to-signal transfer function are given by

$$m'_P = \frac{m_P B_S\left[P_P^0(0) - P_P^0(L)\right]}{\sqrt{\omega^2 + \omega_{eff}^2}}$$

$$\tan\theta_P = -\frac{\omega}{\omega_{eff}} \qquad (8)$$

Where

$$\omega_{eff} = P_S^0(L) + P_P^0(L) + \frac{1}{\tau} + 2n_{sp}\Delta\upsilon G B_S - 2\Delta\upsilon\frac{\beta_S}{\rho A} \qquad (9)$$

And for the amplitude and phase of the signal-to-signal transfer function are given by

$$m'_S = \frac{m_S\sqrt{\omega^2 + \left(\omega_{eff} + K\right)^2}}{\sqrt{\omega^2 + \omega_{eff}^2}} \quad \text{with} \quad K = B_S\left[P_S^0(0) - P_S^0(L)\right] \quad \text{and} \quad \tan\theta_S = -\frac{\omega}{\omega_{eff} + \dfrac{\omega^2 + \omega_{eff}^2}{K}} \qquad (10)$$

These expressions describe the output signal modulation index amplitude and phase, assuming small sinusoidal steady-state oscillations of the mean pump or input signal power .

V. Simulink EDFA module for EDFA dynamics

The Simulink EDFA modules are shown in Figs. 1 to 3 by the numbers beside the block connecting lines. In this case there is one signal wavelength and one pump wavelength. The EDFA module in Fig. 1 is called from the main Simulink model where the input signal power is 57.8 mw.

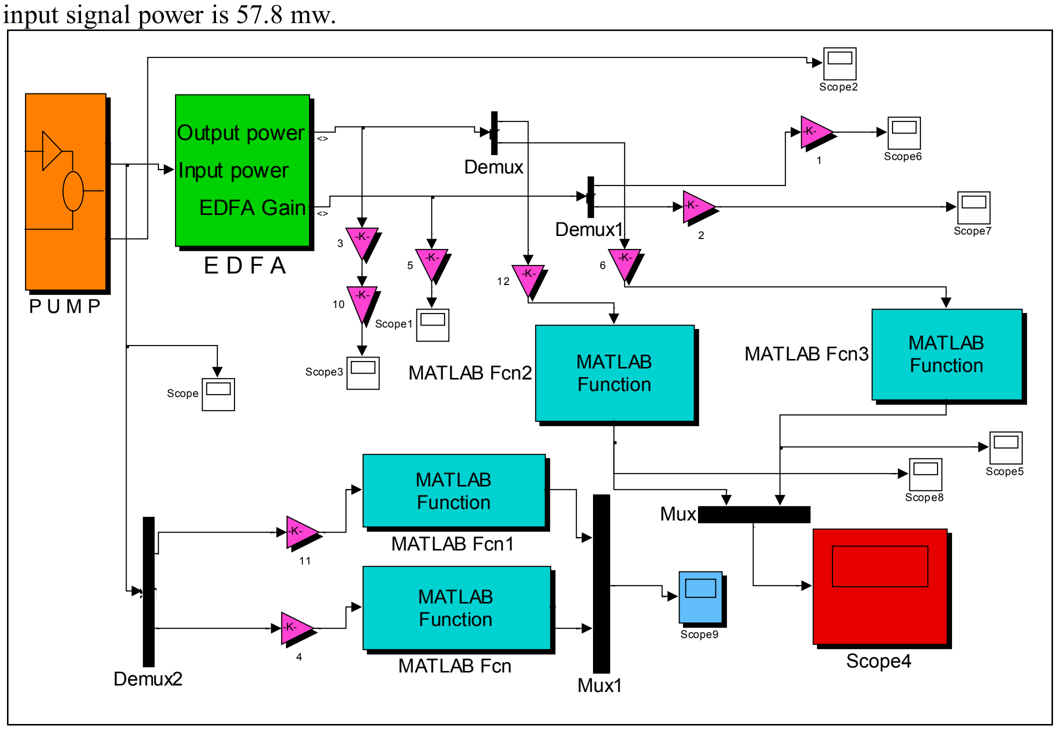

Fig.1. Overmodualtion module.

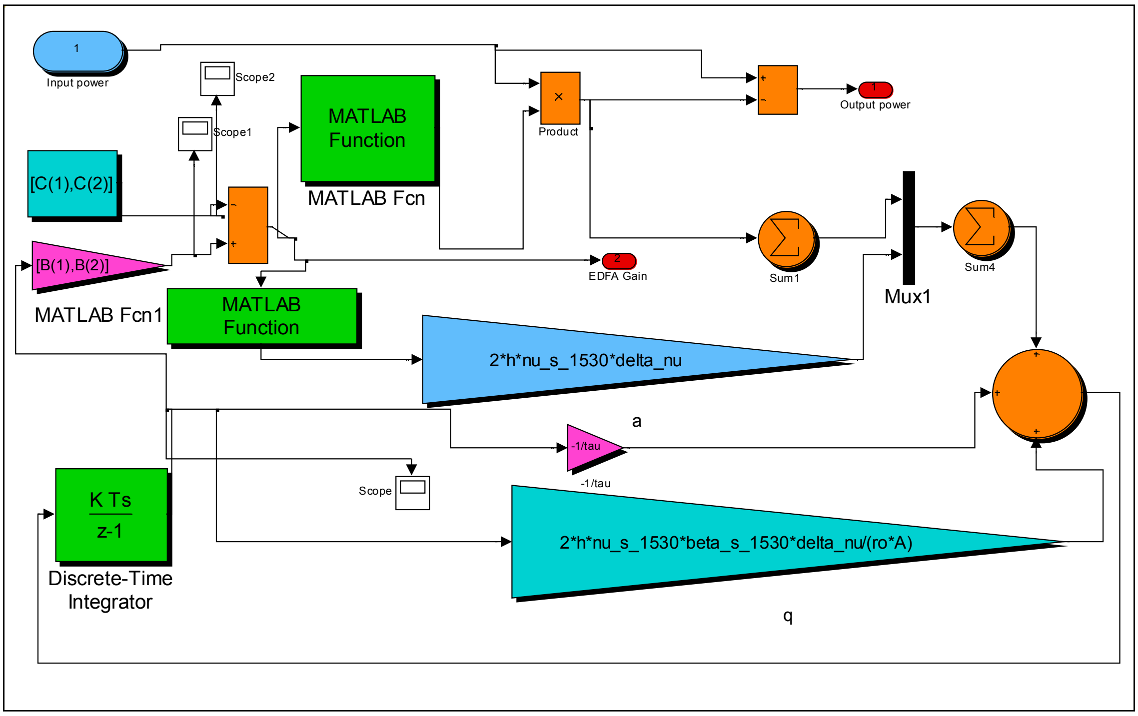

Fig.2 . Simulink EDFA module for EDFA dynamics

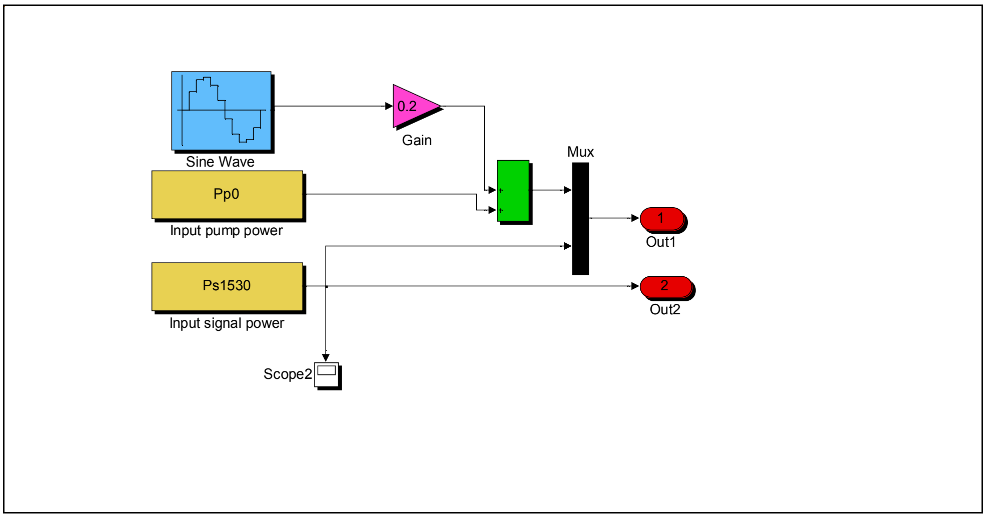

Fig.3. Pumping module.

VI. SIMULATION RESULTS

In this section, we compare our results from our expanded mo- del with the Novak and Moesle's model. The results are given in terms of the output signal modulation index amplitude and phase response caused by overmodulating the EDFA pump or input signal.The wavelength of pump and signal are 980 and 1530nm respectively.The necessary data are indicated in the table 1.

Table 1

$\alpha p = 3.31 dB/m$	$\tau = 10.5 ms$
$\alpha s = 4.19 dB/m$	$L = 10.5 m$
$\beta s = 4.04 dB/m$	$r = 1.2 \times 10^{-6} m$
$\rho = 6.3 \times 10^{24} m^{-3}$	$\Delta \upsilon = 3100 GHz (25 nm)$
input modulation index for both pump and signal = 5 %	
mean signal input powers = 57.8 mW	

-Effect of ASE and compression Level on output modulation indexes.

The *compression level* is defined to be the difference between the small signal gain and the gain at some specified signal power [3]. Fig. 4 shows the gain versus signal input behavior for the EDFA at the wavelength of 1530nm. The solid line are OASIX results. In Fig. 4, we also show the predictions of the Novak model (dashed line),which neglect ASE and our model (solid line) which include ASE. The three models agree at high compression .The Novak's model differ by 2 dB or less at low compression. But our model is match to the OASIX.

We now apply the analytic model to predict the overmodulation behavior for three saturation conditions at 1530 nm, corresponding to mean input signal power levels of - 30,-20, and -8 dBm (gain saturation levels ~ -1,-6,and -16dB). The pump overmodulation amplitude response is given in Fig. 5. In Figs. 6 and 7 we show the signal overmodulation amplitude and phase response , respectively. In the figures, the solid lines represent the model that we include ASE, and dotted lines represents tha results in wich, we neglect ASE.

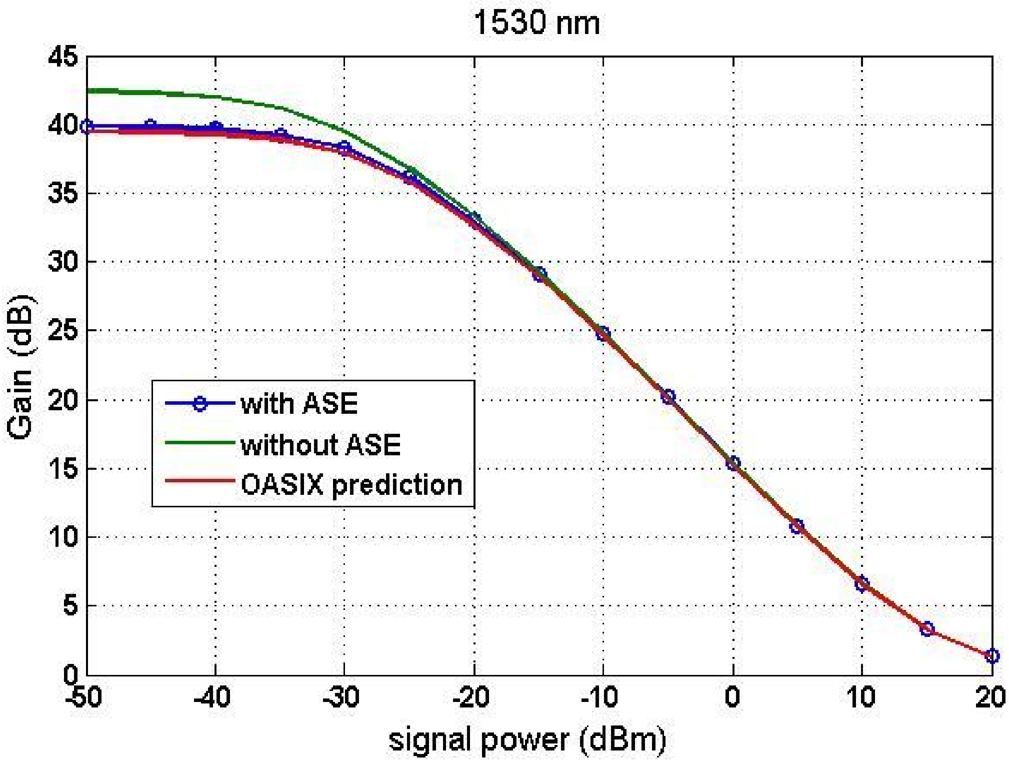

Fig. 4. Gain versus mean input signal power for the EDFA in Section VI.

OASIX predictions (red) including ASE are compared with Novak model predictions (green) and our model predictions (blue).

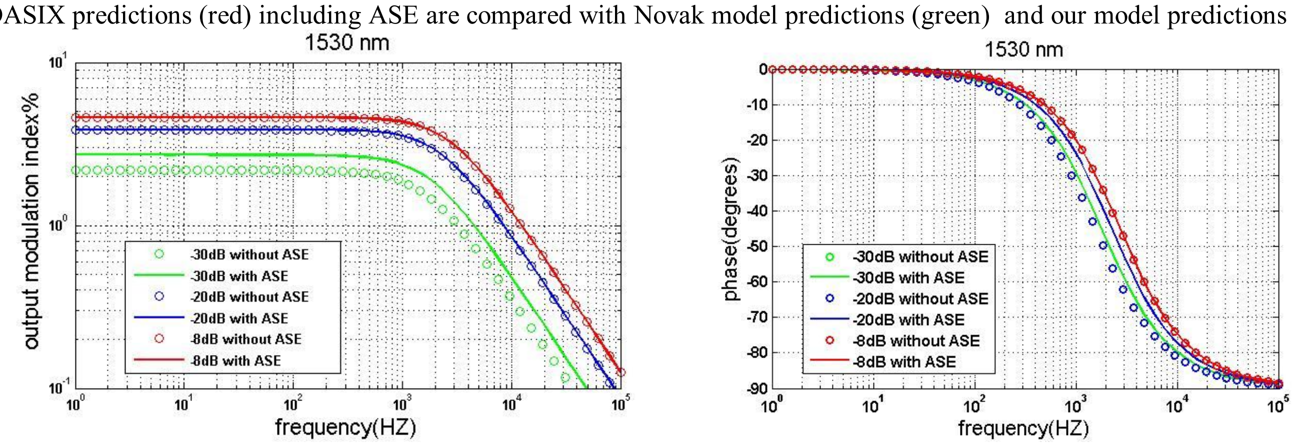

Fig. 5. Sensitivity of output modulation index amplitude and phase responses to pump overmodulation under no compression (-30dBm), 6-dB ompression (-20dBm), 16-dB compression (-8dBm),. Signal wavelength is 1530 nm. Comparison of including ASE (solid) with neglecting ASE (dotted).

In Fig. 5 for pump modulations, if mean input signal power is low (low compression) e.g. -30dBm including ASE make that output modulation index be more than the neglecting ASE condition. But if input signal power increase (high compression) e.g. -8dBm, including or excluding ASE have no effect on output modulation index.

Figs. 6 and 7 show the signal overmodulation amplitude and phase response, respectively. In the figures, the doted lines represent essentially no ASE and solid lines represent ASE take in to account. In Fig. 6 we show the output modulation index amplitude responses to signal overmodulation under no compression (-30dBm), -6dB compression (-20dBm), -16dB compression (-8dBm). If mean input signal power is low ,the result for including ASE is more than ,neglecting ASE. for the phase response (Fig. 7) if the compression level is low, the solid line (including ASE) is less than dotted line(neglecting ASE).For both figures(Figs.7,8) when compression level is high , two lines(solid and dotted) match together.

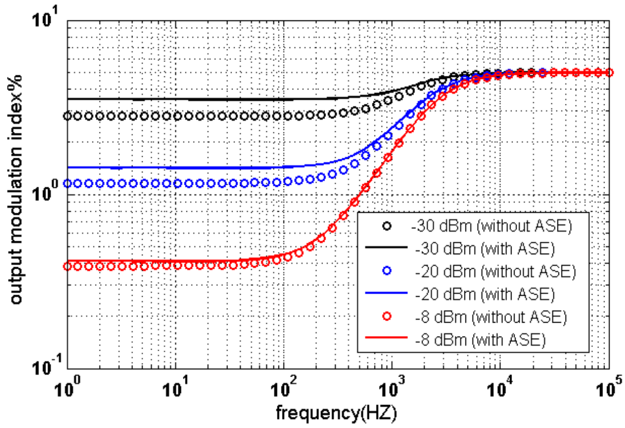

Fig. 6. Sensitivity of output modulation index amplitude responses to signal overmodulation under 3 input signal level at 1530 nm. Comparison of including ASE (solid) with neglecting ASE (dotted).

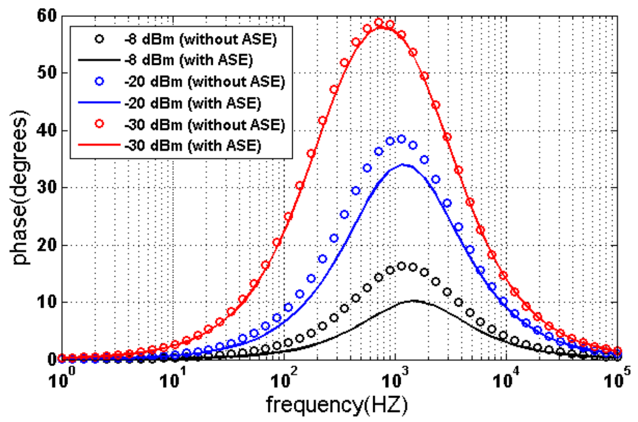

Fig. 7. Sensitivity of output modulation index phase responses to signal overm-
odulation under no compression (-30dBm), 6-dB ompression (-20dBm),
16-dB compression (-8dBm),. Signal wavelength is 1530 nm. Comparison
of including ASE (solid) with neglecing ASE (dotted).

In an effort to better understand the reversal and its dependence on compression levels, we looked at the pump and signal output modulation indexes at $\omega = 0$ as a function of mean input signal power. Results are shown in Fig. 8, where modulation indexes are normalized to their maximum values. The mean input signal powers at which reversal occurs for pump and signal overmodulation are very close. Fig .8-a shows that, normalized modulation indexes for the signal matches for both model. And , Fig .8-b shows that, normalized modulation indexes for the pump ,in solid line (including ASE) is more than doted line (neglecting ASE) by 0.4 at low compression and matches at high compressions.

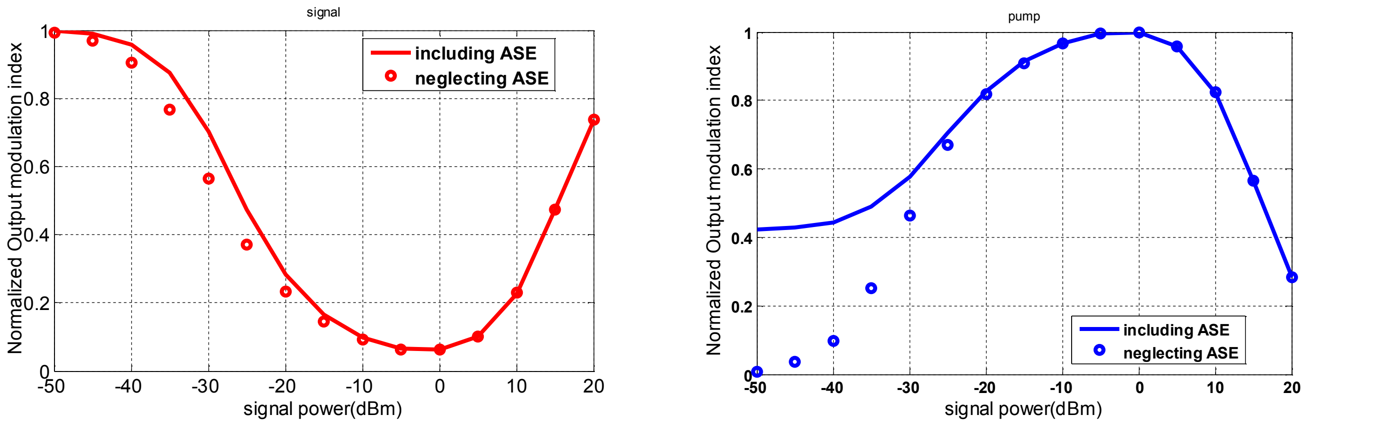

Fig. 8. Normalized output modulation index for: (a)signal and (b)pump ASE take in to account(solid lines),and ASE neglect (dotted lines).

ω_{eff} is an effective corner frequency [7], equation (9). Fig. 9, shows the ω_{eff} versus input signal power. The two models agree at high compression , but differ at low compression.

And finaly in Fig.10 the generated ASE power in dBm is indicated for wavelength range from 1520 nm to 1570nm. As shown in this figure , 1530 nm has the maximum ASE power.

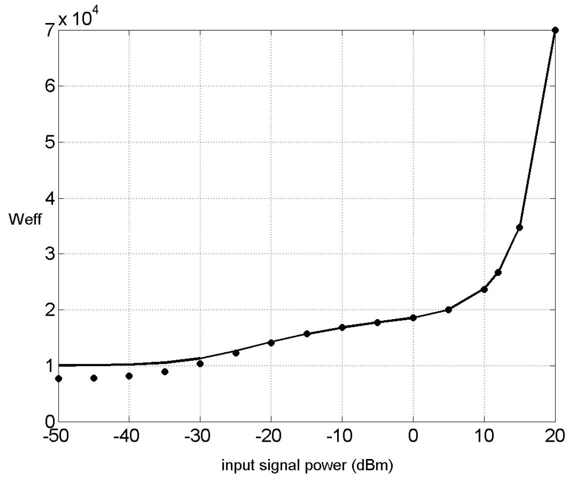

Fig. 9. sensitivity of ω_{eff} to mean input signal power.in solid line we includ ASE ,and in doted line we neglect ASE.

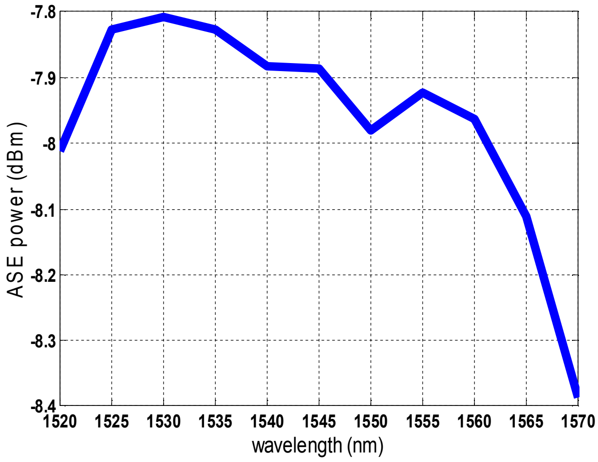

Fig.10 . ASE power to wavelength.

VII. SUMMARY AND CONCLUSIONS

The derivation of an analytical model for EDFA overmodulation response that include ASE, based on Novak model [3], and desurvire model [4], has been presented. Because of including ASE, our model agree at both low and high compression with OASIX but Novak's model differ at low compression because they neglect ASE. No other approximations are made and the model is believed to capture the overmodulation dynamics of an EDFA well as the saturation level is increased or decreased.

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