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Gain Control Dynamics of Thulium-doped Fiber Amplifier at 2 µm

M. A. Khamis and K. Ennser
College of Engineering, Swansea University, Swansea, UK

ABSTRACT

This work is novel in that it explains the modeling and simulation of a thulium-doped fiber amplifier (TDFA) in a reconfigurable wavelength division multiplexing (WDM) system operating at 2 µm. We use the optical gain-clamping technique in order to control gain amplification and eliminate deleterious channel power fluctuations resulting from input power variation at the TDFA. The investigated system consists of 12 channels with -4 dBm total input power. Simulation results indicate that approximately1.5dB power excursion is produced after dropping 11 channels in unclamped-gain amplifier, and only 0.005 dB in a clamped-gain amplifier. Additionally, a clamped configuration brings the power excursion from 4.2 dB to under 0.08 dB, after adding 11 channels to the investigated system. Hence, optical gain-clamping is a simple and robust technique for controlling the power transient in amplifiers at 2 µm.

Keywords: Thulium-doped fiber amplifier, optical gain-clamping, power excursion, power transient

1. INTRODUCTION

As a result of the increase in communication traffic over the recent years, today's telecom networks have improved significantly. More efforts in research, with regard to increasing transmission capacity, have encouraged interest in radical new approaches to develop highly efficient data transmission[1]. One approach is to use the 2 µm wavelength region as a potential new transmission window for optical communications[2]. Communication over 2 µm offers several distinct advantages compared to the traditional 1.5 µm transmission window. Firstly, the use of a hollow-core photonic band gap fiber (HC-PBGF) produces an ultra-low loss window, at 2 µm, because it has the lowest latency as well as ultra low optical nonlinearity[3,4]. The availability of the high gain and low noise optical amplifier is another key requirement for optical transmission systems with a 2 µm transmission window[5]. More importantly, the thulium doped fiber amplifier (TDFA) is indicative of high gain and low noise amplification in this spectral window and therefore offers a route to significantly increasing amplification bandwidth around 2 µm[6]. TDFA produces an amplification bandwidth of approximately 30 THz (1700-2100 nm) at an emission spectrum of $^3F_4 - {}^3H_6$ transition in thulium-doped fiber, which is more than twice of the erbium-doped fiber amplifier (EDFA) at similar configuration and complexity[7].

Wavelength division multiplexing (WDM) technology is used in order to explore the large amplification bandwidth[8]. The input power in the amplifier is varied with time due to channel addition or dropping in the WDM system and therefore may cause dynamic gain transients in TDFA. These variations in TDFA gain can cause an increase in power excursion, which is defined by the ratio of the maximum power to the minimum power of the surviving channel[9]. The restriction in the WDM transmission distance causes problematic transients in the communication networks at 2 µm. As a result, the signal to noise ratio of the received channels degrades. This issue may occur when using cascade of optical amplifiers[10]. Thus, the future of WDM in optical communication networks needs to provide control of dynamic gain variation. Several methods have been developed in order to avoid this effect. Optical gain-clamping (OGC) is one well-known method to eliminate gain dynamic effects using a laser feedback signal for EDFAs[11,12]. Additionally, the OGC-TDFA in the S-band was investigated experimentally[13,14]. However, there is no investigation on the OGC-TDFA for communication at 2µm.

In this paper, the OGC-TDFA model is presented theoretically within the WDM reconfiguration network. The proposed model is based on a laser configuration within a two-level system. We use the optical gain-clamping technique to control gain amplification and eliminate deleterious channel power fluctuations resulting from input power variation in the amplifier. The simulation results of the numerical investigation indicates that the proposed model was able to suppress the power excursion to under 0.005 dB, even when 11 out of the 12 channels were dropped. Additionally, a clamped configuration is effective to reduce the power excursion from 4.2 dB to under 0.08 dB, after adding 11 channels to our system.

2. OGC-TDFA MODELING

The rate equations of thulium-doped fiber amplifier can be described as a model considering two energy level of thulium when it is pumped at 1.6 μm or called in band pump power[15,16]. The thulium-ions at the ground energy level $^3H_6$ are excited to higher energy level $^3H_4$ by the pumping photons. Based on the OGC modeling designed for two energy level[17,18], the rate equations of OGC-TDFA can be expressed as:

$$\begin{aligned}\frac{dN_2}{dt} = -\frac{N_2}{\tau_T} &+ \frac{1}{A_{eff}L}\left[(F_s(t)+F_{ASE}(t))(1-G_s(t))\right] + \frac{1}{A_{eff}L}\left[F_p(t)(1-G_p(t))\right] \\ &+ \frac{1}{A_{eff}L}\left[F_L(t)(1-G_L(t))\right]\end{aligned} \tag{1}$$

and

$$N_1(t) = N_T - N_2(t). \tag{2}$$

Here N_1 and N_2 represent the populations of energy level $^3H_6$ and $^3H_4$ respectively, N_T is the thulium concentration, A_{eff} is the effective area of thulium fiber core, L is the thulium-doped fiber length, τ_T is the fluorescence lifetime, G_s is the signal gain, G_p is the pump gain and G_L is the laser gain which are given by Eq. (3-5) respectively:

$$G_p = e^{\Gamma L(\sigma_{ep}N_2 - \sigma_{ap}N_1)} \tag{3}$$

$$G_s = e^{\Gamma L(\sigma_{es}N_2 - \sigma_{as}N_1)} \tag{4}$$

and

$$G_L = e^{\Gamma L(\sigma_{eL}N_2 - \sigma_{aL}N_1)}. \tag{5}$$

Where Γ represents the overlap factor, σ_{ap}, σ_{aL} and σ_{as} are the absorption cross-section of pump, signal and laser wavelengths, σ_{ep}, σ_{es} and σ_{eL} are the emission cross-section of pump, signal and laser wavelengths. Also in Eq. (1), F_{ASE} is the input photon flux of the amplified spontaneous emission on the signal wavelength, F_s is the signal flux F_p is the pump flux and F_L is the laser flux which are given in the steady state condition by:

$$F_p(t) = x\,F_{p,th} \tag{6}$$

and

$$F_L = \frac{\dfrac{N_2}{\tau_T} - \dfrac{1}{A_{eff}L}(F_s+F_{ASE})(1-G_s) - \dfrac{1}{A_{eff}L}F_p(1-G_p)}{\dfrac{1}{A_{eff}L}(1-G_L)} \tag{7}$$

Here x is the power factor which is set to unity at unclamped gain and greater than unity for clamped gain. Notes that at clamped case it is necessary to provide an extra pump power in order to effectively clamp the gain. $F_{p,th}$ is the pump flux at laser threshold which is given by Eq. (8):

$$F_{p,th} = \frac{\frac{N_2}{\tau_T} - \frac{1}{A_{eff}L}(F_s + F_{ASE})(1-G_s)}{\frac{1}{A_{eff}L}(1-G_p)} \tag{8}$$

Notes from Eq. (1) that the laser signal is added to the amplifier rate equations together with the input signal. The laser signal keeps the total power of the TDFA constant and consequently it clamps the amplifier gain. The flux equation of the laser signal varies with respect to the time and can be explained as:

$$\frac{dF_L}{dt} = \frac{F_L(t)(G_L(t)\alpha - 1)}{T} \tag{9}$$

Where T is the roundtrip time of the laser cavity and α is the laser loss. It can be observed from the OGC-TDFA model that the laser signal saturates thulium-doped fiber amplifier and fixes a fractional value of the populations by adding the feedback signal to the TDFA model.

3. RESULTS AND DISCUSSION

We developed a MATLAB program to study the dynamic behavior of the thulium-doped fiber amplifier (TDFA). Total input power was set at -4dBm for 12 channels (1900-1960 nm) with a channel spacing of 5 nm, and each channel has -14.8 dBm of power. The amplifier gain is assumed to be flat, in order to focus on the dynamics. The amplified spontaneous emission of the signal wavelength is ignored (i.e., F_{ASE}=0). Table 1 is used to describe the typical parameters of our proposed model[19,20].

Table 1. The typical parameters of the proposed model.

Symbol	**Quantity**	**Value**
N_T	Thulium concentration.	8.4×10^{25} ion/m^3
τ_T	Fluorescence life8ltime	650 nm
λ_p	Pump wavelength	1558 nm
λ_s	Surviving channel wavelength.	1940 nm
λ_L	Laser wavelength	1930 nm
σ_{ap}	Absorption cross-section at pump wavelength.	3.1×10^{-25} m^2
σ_{ep}	Emission cross-section at pump wavelength.	0.3×10^{-25} m^2
σ_{as}	Absorption cross-section at surviving channel wavelength.	0
σ_{es}	Emission cross-section at surviving channel wavelength.	2.1×10^{-25} m^2
σ_{aL}	Absorption cross-section at laser wavelength.	0
σ_{eL}	Emission cross-section at laser wavelength.	2.2×10^{-25} m^2

Γ	Overlap factor	0.7
n_f	Refractive index	1.456
A_{eff}	The effective area of thulium-fiber core	5×10^{-11} m^2

The dynamic behavior of the OGC-TDFA is investigated by studying power variation in the surviving channels after a perturbation. In our simulations, the perturbation was a change in the number of channels being amplified. After 11 channels are dropped or added to an unclamped-gain amplifier, power excursion of approximately 1.5 dB and 4.2 dB, respectively, occurred (Fig. 1). Using a clamped configuration effectively reduced the power excursion resulting from dropping or adding 11 channels to 0.005 dB and 0.08 dB, respectively (Fig. 3). Adding channels to the WDM system at an unclamped-gain amplifier clearly leads to an increase in the input signal power and a decrease in the output gain when the optical amplifier operates in a saturation regime, as illustrated in Fig. 2. Hence, the power excursion increases as the number of channels added to, or dropped from, the investigation system increases.

The gain dynamics of OGC-TDFA is shown in Fig. 4 for two different cases. When 11 of the 12 channels are dropped, the gain oscillates rapidly until t=0.8ms and the system reaches stability. In contrast, when 11 channels are added, the gain varies until t = 1.2 ms, after which it become constant. The number of channels added or dropped clearly influences dynamic behavior. Increasing the number of add/drop channels leads to high signal gain oscillation and low recovery time. For the unclamped-amplifier, the gain increases from 20 to 28 dB when 11 channels are dropped, whereas, the gain decreases when adding the same number of channels to approximately 7 dB.

A higher slope in the gain-saturation regime is produced as input power increases and therefore the system is unstable and requires more control, e.g., a higher pump factor (Fig. 2). The simulations reveal that adding or dropping channels has a large effect on power excursion of the surviving channels of the unclamped amplifier. In addition, our findings show that large power excursions can be avoided by using a feedback laser signal on the OGC-TDFA, as seen in Fig. 3.

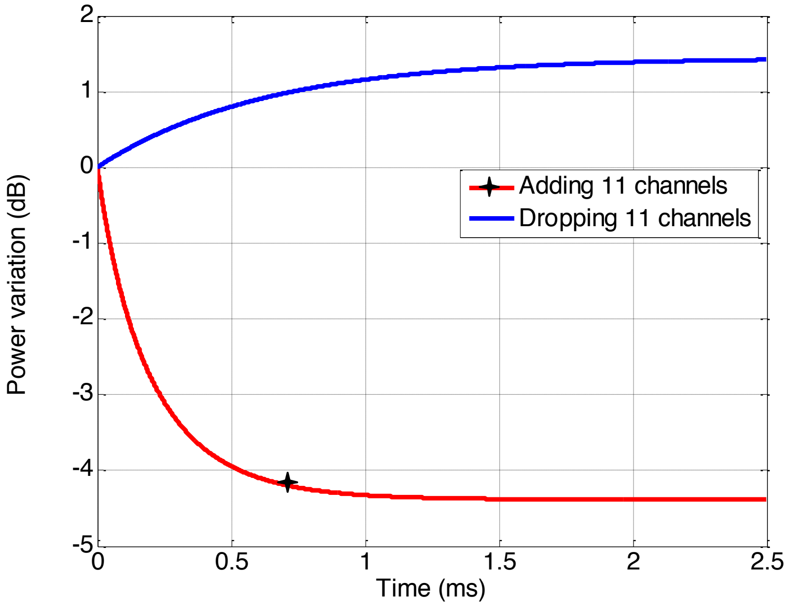

Figure 1. Power variation of the surviving channel after dropping and adding 11 channels from or to the 12 channels in unclamped TDFA.

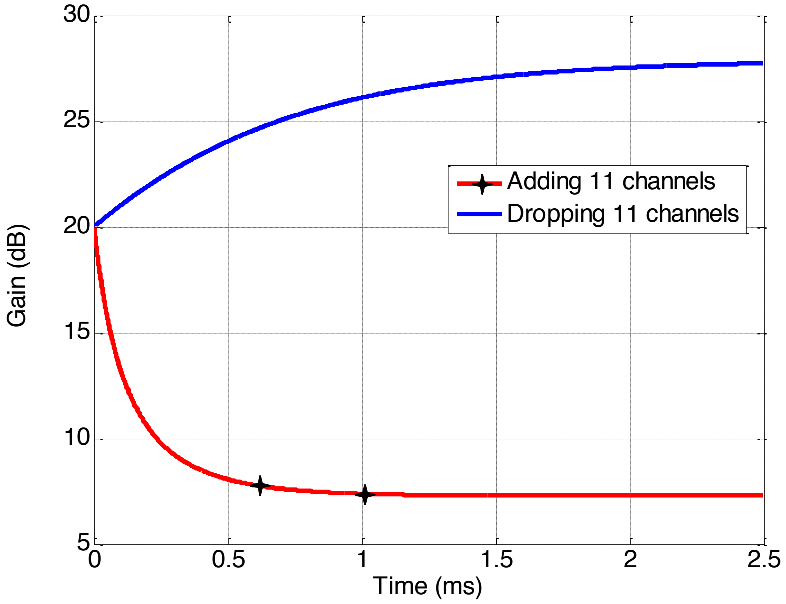

Figure 2. Gain variation after dropping and adding 11 channels from or to the 12 channels in unclamped TDFA.

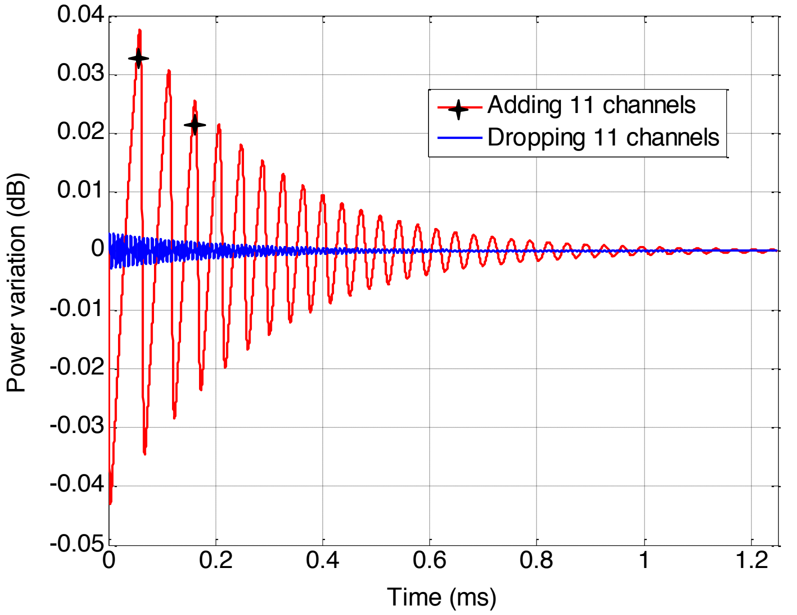

Figure 3. Power variation of the surviving channel after dropping and adding 11 channels from or to the 12 channels in OGC-TDFA.

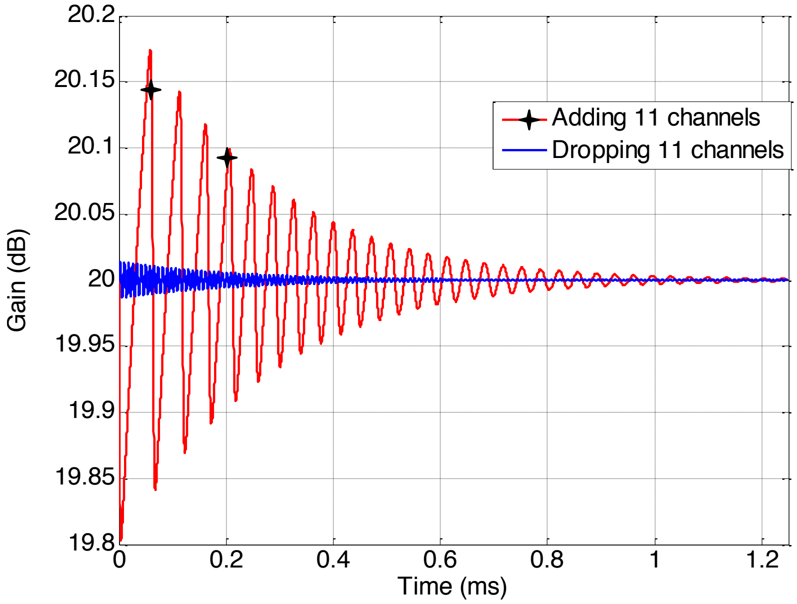

Figure 4. Gain variation after dropping and adding 11 channels from or to the 12 channels in OGC-TDFA.

4. CONCLUSION

In summary, we have thoroughly investigated the dynamic behavior of an OGC-TDFA operating at 2 µm under WDM channel reconfiguration. The simulations of the OGC-TDFA used a two-level thulium energy regime. The amplifier gain and surviving channel power were studied in a 12 WDM channels system by varying input signal power in the TDFA via adding and dropping channels. An approximately 1.5 dB power excursion was produced after dropping 11 out of 12 channels for an unclamped gain amplifier, and only 0.005 dB for a clamped gain amplifier. A clamped configuration was similarly effective in reducing the power excursion from 4.2 dB to under 0.08 dB after adding 11 channels. The simulations for unclamped TDFA show a relatively large power excursion and significant effects of dropping or adding channels on the power variation of the surviving channel. Moreover, the results reveal that the effects of power transients due to channel reconfigurations is reduced by a feedback laser signal. We thus conclude that optical gain-clamping is an effective technique to eliminate power excursions due to dynamic behavior of TDFA in an optical WDM transmission system at 2 µm. These findings may also be relevant for other applications where input power to a TDFA operating at 2 µm varies over time.

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