International Journal of Computer Applications (0975 – 8887)
National Conference on Structuring Innovation Through Quality "SITQ-2013"

Enhancing the Gain of TDFA with Optimizing Length of TDF in DWDM System

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Abstract

In this paper optimized gain of TDFA is achieved w.r.t. variation of length of TDF. Mathematical model using improved rate equations of TDFA has been implemented using MathCAD in this paper. An optimized gain of 27dB (without ASE) for 1460-1495nm wavelength range has been achieved when length of TDF is 7 m.

Keywords

DWDM, MathCAD, TDF, TDFA

1. Introduction

To increase the transmission capacity of a single fiber, DWDM is used. DWDM is a technology which combines large number of independent information carrying wavelengths onto the same fiber. A characteristic of DWDM is that the discrete wavelengths form an orthogonal set of carriers which can be separated, routed and switched without interfering with each other. This isolation between channels holds as long as the total optical power intensity is kept sufficiently low to prevent non linear effects e.g. Stimulated Brillion Scattering (SBS) and Four Wave Mixing processes (FWM) from degrading the link performance. The implementation of DWDM system requires a variety of passive and active devices to combine, distribute, isolate and amplify optical power at different wavelengths. Passive devices require no external control for their operation, so they are less flexible. The wavelength dependent performance of active devices can be controlled electronically, so they provide more flexibility to the network system. Optical amplifiers, tunable filters and tunable sources are integral part of any DWDM system [1-2]. The key component of DWDM system is optical amplifier. In the history of optical fiber communication systems, the advent of optical amplifier was an important milestone. Optical amplifiers can amplify the optical signals directly without requiring its conversion to the electric domain. The development of optical amplifiers started in early eighties and their use for long haul communication systems became widespread during late nineties. Optical amplifiers provided flexibility while upgrading the installed transmission links to higher bit rates. This flexibility of the bit rates allows overcoming the electrical bottleneck of an electric repeater, which was unable to transmit at high bit rates. It is clear that EDFAs are the best choice for optical amplification in present lightwave systems. Erbium (Er: 68) is used as dopant into glass host (fiber) and the 'doped fiber' is used as an amplifying medium. Er-doped fibers give an amplified output around 1550nm [3-7]. The EDFA is one of the key devices used for dense wavelength division multiplexed (DWDM) transmission systems. EDFAs are revolutionizing lightwave systems by reducing system costs and enhancing network performance. The main practical limitation of an EDFA stems from the spectral non-uniformity of the amplifier gain. As a result, different channels of a DWDM system are amplified by different amounts. These problems become quite severe in long-haul systems, employing cascaded chain of EDFAs. Secondly, for many EDFA deployments, automatic gain control (AGC) is used to ensure that the output signal power is proportional to the input power. However, there are times when a constant optical signal output, independent of input power, is more desirable, e.g., in an optical preamplifier at an optical receiver [8]. The figure 1[1-2] shows the gain spectrum of EDFA, from which it is clear that EDFA has peak gain at 1530nm, beyond which the gain reduces slightly and remains flat almost until 1550nm. After that, the gain reduces sharply.

In order to overcome this limitation of EDFA, different doping elements are coming into existence. One of such doping material is thulium and the doped fiber amplifier is known as Thulium Doped Fiber Amplifier (TDFA). TDFAs are highly viable alternative to meet out the limitations of EDFAs and have bright future prospects to be used in optical communication systems. The optical fiber can be doped with any of the rare earth element, such as Erbium (Er), Ytterbium (Yb), Neodymium (Nd) or Praseodymium (Pr), Thulium (Tm). The host fiber material can be either standard silica, a fluoride based glass or a multicomponent glass. The operating regions of these devices depend on the host material and the doping elements. Fluorozirconate glasses doped with Pr or Nd are used for operation in the 1300nm window, since neither of the ions can amplify 1300nm signals when embedded in silica glass. The next popular material for long haul telecommunication applications is a silica fiber doped with Thulium, which is known as Thulium Doped Fiber Amplifier (TDFA). In some cases as Yb is added to increase the pumping efficiency and the amplifier gain. The TDFA are used in S-band (1460-1530nm). The energy state diagram of Tm3+ is shown in figure 2 [9]. Tm+3 has three energy levels that are considered with respect to the Tm+3 populations. TDFA uses upconversion pumping method. The upconversion pumping consists of the two- step excitation of 3H6 to 3F4 and 3F4 to 3H4 with the same pump wavelength and this makes it possible to form a population inversion state between 3F4and 3H4. The gain and loss of TDFA in the 1460-1530nm wavelength region are determined not only by the excited state absorption (ESA) (3F4 to 3H4) and stimulated emission(SE) (3H4 to 3F4) but also by the ground state absorption (GSA) (3H6 to 3F4) .

2. Methodology and Analysis

When the TDF is pumped with 1050 nm laser, the ground state ions in the 3H6 energy level can be excited to the 3H5 energy level and then relaxed to the 3F4 energy level by non-radiative decay. The 1050nm is the most efficient wavelength for single-wavelength pumped TDFAs [10]. The impact 1050nm diode laser technology for the realization of a compact TDFA module is considered [11] for TDFA. In the rate equation models, the variables n0, n1, n2 and n3 are used to represent population density in the 3H6, 3F4, 3H5 and 3H4 energy levels respectively. According to the figure 2, the rate equations of population densities for each layer of TDFA can be modeled. The four population states of Tm+3 are state 0 with population density of n0, the state 1 with population density of n1 , state 2 with population density of n2 and excited state 3 with population density of n3 . The state 1 and state 2 are related with signal frequency and state 3 is related with pump frequency. Let P03 be the pumping rate from state 0 to excited state 3, P30 and P31 be the stimulated emission rate from excited state 3 to state 0 and state 1 respectively. It is assume that P30 is not considered as an important transition. There are two types of transitions that have been taken place from excited state 3, one is radiative transition and other is non-radiative transition. The radiative transition from excited state is further of two types i.e. state 1 and upto state 0 i.e. A31(r) and A30(r) respectively. It is also considered that the transition is mainly non- radiative, which implies that non-radiative transition (A31(nr)) » radiative transition(A31(r) , A30(r)). Let the rate of stimulated absorption and emission be S01 and S10 respectively. The rates of spontaneous emission from state 1 are also radiative and non-radiative in nature, at this level radiative transition (A10(r)) » non- radiative transition (A10(nr)). The non-radiative transition from excited state 3 and radiative transition from state 1 are considered as n3/τ’ and n1/τ respectively, where τ’ and τ are the respective transition rates.

So, the improved rate equations of the four states for the proposed model of TDFA are given in equation (1),

$$\frac{\delta n_0}{\delta t} = \Big(-P_{03}\ n_0\ - S_{01}\ n_0\ + S_{10}\, n_1 + n1\tau{+}P30n3\ \ {+}n3\tau',\ \ \delta n1\delta t{=}\ \ S01\ \ \ n0\ {-}S10\, n1{-}n1\tau{+}P31n3\ ,\delta n2\delta t{=}\ {-}A(nr)21\ n2\ \ {+}P32n3\ ,\delta n3\delta t{=}\ P03\ \ n0\ \ {-}P31\, n3\ {-}n1\tau{-}P30n3\ {-}n3\tau' \quad (1)$$

These rate equations involve several assumptions. Firstly, it has been assumed that any population in the 3H5 level will relax rapidly to the 3F4 level in a time scale which is short in comparison to the other decay times involved; thus the presence of the 3H5 level has been ignored. Secondly, by representing the ETU process we have ignored any energy migration processes, which is justifiable since this process occurs on a much smaller time scale (~10-10 s) [11]. Thirdly, it was assumed that ESA of the pump and signal photons can be ignored due to the relatively low ESA cross sections at the respective wavelengths. It has been estimated that the ESA cross section at the pump and signal wavelengths (1586 and 1800 nm) were to be ~ 3×10-31 and ~ 0 m2, respectively [12]. Although there is a relatively large error associated with these values, it suggests that ESA does not play a significant role in the upconversion process at these wavelengths. Algorithms (I) describes the mathematical modeling of TDFA. Algorithm I used for proposed mathematical model of TDFA is as follows:

Algorithm I:Algorithm_Sim_TDFA

Step I: Initialize n0, n1 and n3 (Tm+3 ion densities at ground, metastable and excied states),

doping concentration, I/P power, number of channels, spacing, A(area), L(length of Fiber),

Pp &Ps (Pump and Signal Power), λp & λs (Pump and Signal Wavelength), ASE power and I/P signal

Step II: n1, n1, n3, L and doping concentration = variable

Step III: Calculate optimum doping concentration for peak gain

Step IV: Calculate length for peak gain (without ASE)

Step V: Calculate length for peak gain (with ASE)

Step VI: Calculate optimum length

Step VII: Plot gain, NF for optimum length of TDF w.r.t.wavength

STEP VIII: Goal Achieved

3. Results

During the modeling of TDFA, the product of ppm and length of TDF is kept constant. Using Algorithm I, the model of TDFA shows the dependence of the TDFA gain spectra on Tm+3 Concentration. The Tm+3 concentrations varied from 1000 to 8000 ppm, and the fiber length was adjusted so that the product of Tm+3 concentration and fiber length was the same. The Table I shows the value of PPM, L and their product. The simulation results are shown in figure3. The TDF was forward pumped at a power of 200mW with the help of laser. As shown in Figure3, the gain peak shifted to a longer wavelength as Tm3+ concentration increased, which confirms the effectiveness of the high concentration doping technique.

Table I: Table shows the constant value of product of PPM and Length of TDFA

PPM	Length of TDF(in m) L	PPM X L
1000	40	4 X104
2000	20	4 X104
3000	13.3	4 X104
4000	10	4 X104
5000	8	4 X104
6000	6.7	4 X104
7000	5.7	4 X104
8000	5	4 X104

8000ppm Tm+3 concentrations with a fiber length of 5m can be considered as optimum values for maximum gain peak. So, operating pump power will be optimized with respect to the reference TDF length. If the reference TDF length is too short, the TDFA will be saturated at a very low pump power and this does not provide a high gain. Saturation takes place in TDFA due to the fixed thulium ion concentration and therefore after a certain amount of pump power, the N3 state population climbs to an almost constant level. In the case of a short TDF, the total population is very low and hence the TDF is fully inverted by a very low amount of pump power. If this low amount of pump power is selected as the operating pump power then the optimized TDF length with respect to this low amount of pump power is very short. On the other hand, if the length of TDF is longer than a greater pump power is required to invert the population of the entire TDF, especially toward the end of the TDF. In the optical network, an amplifier is mainly designed to obtain a gain as high as possible with a low noise figure using a minimum pump power. Optimization of the length of the thulium-doped fiber (TDF) used is one of the most important issues that need to be considered for designing a TDFA in order to obtain the best gain with the lowest noise figure. In the case of remote pumping, the location of the amplifiers is far away from the source and an optimized pump power is essential. The gain and noise figure of the TDFA are strongly dependent on the TDF length and the operating pump power. The optimum TDF length is also dependent on the operating pump power and therefore optimum TDF length is firstly determined in this work.

It is concluded that the gain gradually drops after the peak value as the TDF length increases. The modeled TDFA amplifies signal wavelengths spaced in the 1460nm to 1495 nm range. The spacing of 0.8nm is chosen as per ITU-T Recommendation G.694.1, which is specifically for DWDM system. The gain of TDFA versus amplifier length is plotted as shown in figure 3. 4. Conclusion:

It was considered that the optimum fiber length decreases when thulium ion concentration increases. So it is possible to design amplifiers with high gain for amplifier length as short as few meters by increasing thulium ion concentration and vice versa. According to the result at optimization TDFA can be designed by inserting optimum length with the value of thulium ion density in which gain is maximum at different pump powers. By implementing this model optimized gain of 27dB over 1460-1495nm for 8000ppm of Tm+3 for 7m long TDFA is achieved.

5. Figures

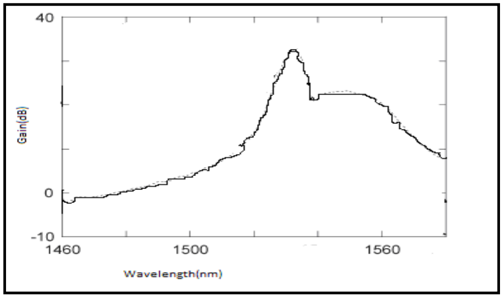

Figure 1:Gain Spectrum of EDFA [1-2]

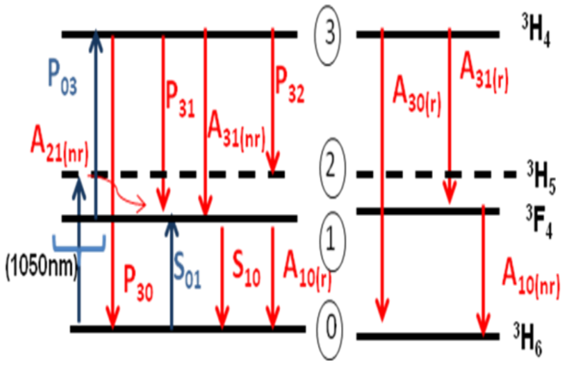

Figure 2: Energy Level Diagram of Tm3+ [8]

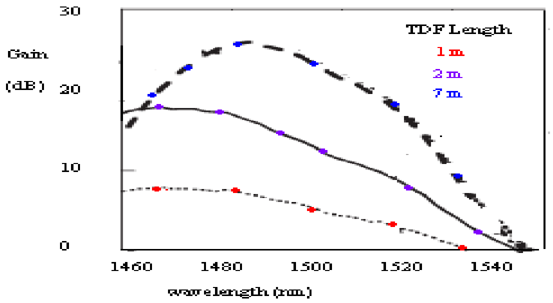

Figure3: Variation of gain of TDFA w.r.t. Length

4. Conclusion

It has been observed that the gain of TDFA is 27 dB(appox) for 1460-1490nm range. But as the length of TDF varies from 1 m to 7m the gain is also varied. An optimized gain of 27dB (appox)is achieved for 7m long TDF.

Acknowledgment

The authors would wish to acknowledge Optical Communication Laboratories of PEC, University of Technology, Chandigarh.

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