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Performance Analysis of TDFA using 1050nm Pumping Power for 1479nm-1555nm Range

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Abstract: A model of TDFA has been proposed based on simulation after considering all the major parameters like pump and signal power, without considering ASE. Through this analysis of TDFA the optimum value of pump power and the range of fiber length (TDF) have been evaluated. In this section, an effort has further been made to use the least possible fiber length of TDF so as to maximum possible gain and in turn cheaper amplifier. The present research claims to support 96 DWDM channels across 1479nm-1555nm wavelength range with a channel spacing of 0.8nm. The optimum range of fiber length of TDFA has been evaluated between 8m-16m. The peak gain of ranging from 22 dB to 30.5dB has been attained for selected optimum fiber lengths ranging from 8m to 16m of TDF.

Keywords: ASE,DWDM, TDF, TDFA, Fiber length, Gain

1. Introduction

The present scenario of dense wavelength multiplexed system (DWDM) has lead to the demand of ever increasing bandwidth so as to accommodate more number of channels. To increase the transmission capacity of a single fiber, Dense Wavelength Division Multiplexing (DWDM) is one of the best possible solutions [1-5]. The implementation of DWDM system requires a variety of passive and active devices to combine, distribute, isolate and amplify optical power at different wavelengths. In DWDM system, it is desirable to set a very narrow grid of optical carriers in order to allow more channels in the same optical bandwidth. This not only demands an optical amplifier with high gain but also very broad and flat gain profile to ensure a nearly identical amplification factor in every channel. but also very broad and flat gain profile to ensure a nearly identical amplification factor in every channel.

The focus of the present research is to design improved doped amplifiers with broad and flat gain spectrum, so as to accommodate more number of channels in DWDM system. Thulium is the main dopant to be used for S-band doped fiber amplifiers. The performance of thulium doped fiber amplifier (TDFA) is dependent upon the doping level of thulium ions[7-18]. In the present work, the rate equations of TDFA have been thoroughly analyzed, remodeled and improvised without considering the effect of co-propagating Amplifier Spontaneous Emission (ASE). The fiber length is an important factor in determining the performance of amplifier as shorter the fiber length, lesser is the ASE and thence reduced noise and enhanced gain of the amplifier. Keeping this in consideration, the optimum length of fiber has been computed to consequently determine the gain by way of simulating rate equations without ASE noise.

The improvised rate equations have been designed and simulated using MATLAB for fiber lengths of Thulium doped fiber (TDF) ranging from 0-64m.

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2. Mathematical Modeling and Analysis of TDFA Without ASE

The initial steps in designing of thulium doped fiber amplifier have been started with finding the value of the appropriate pumping power and fiber length of TDF for TDFA. In this section, the modeling and analysis of TDFA has been carried out without considering the effect of ASE. In the present mathematical model of TDFA, ZBLAN fiber is considered as it has low photon energy. For complete utilization of S Band and C Band, 1479nm-1555nm operating wavelength range has been selected leaving the guard bands at both ends. For 96 channels the wavelength is considered from 1479nm to 1555nm (S Band + C Band) and the operating Bandwidth is 76nm. In this work, the rate equations without considering the effect of ASE are used to describe the TDFA. These improved rate equations describe the interaction between pump, signal and ASE in the TDFA. From the rate equations, the gain coefficient for signal light and absorption coefficient for pump light are defined by considering the absorption and stimulated emission cross sections [19]. To obtain the rate equations, an analysis of a four level energy system is discussed. Figure 1 shows the energy transitions of TDFA.

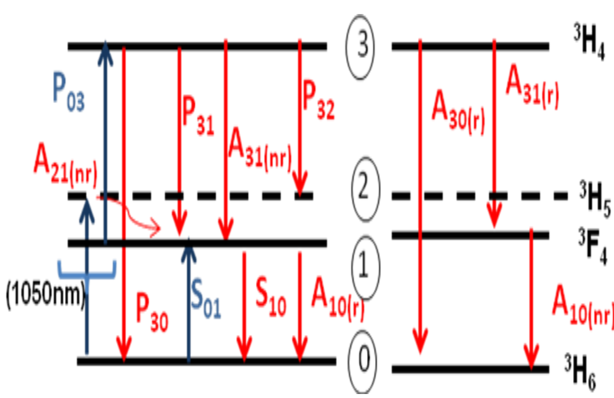

Figure 1: Energy Transitions in a Four Level TDFA

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 rate equations of the four states for the proposed model are given as:

$$\frac{\delta n_0}{\delta t} = \left(-P_{03}\ n_0\ - S_{01}\ n_0\ + S_{10}\ n_1 + \frac{n_1}{\tau} + P_{30}n_3 + \frac{n_3}{\tau'}\right) \quad (1)$$

$$\frac{\delta n_1}{\delta t} = \left(S_{01}\ n_0\ - S_{10}\ n_1 - \frac{n_1}{\tau} + P_{31}n_3\right) \quad (2)$$

$$\frac{\delta n_2}{\delta t} = \left(-A_{(nr)21}\ n_2\ + P_{32}n_3\right) \quad (3)$$

$$\frac{\delta n_3}{\delta t} = \left(P_{03}\ n_0\ - P_{31}\ n_3 - P_{30}n_3 - \frac{n_3}{\tau'}\right) \quad (4)$$

The presence of the 3H5 level has been ignored i.e. equation (3) has been ignored in the present work because population in the 3H5 level will relax rapidly to the 3F4 level. The total population of thulium ions at these three states is related with the population density (ρ) of thulium ions.

$$n_0 + n_1 + n_3 = \rho \quad (5)$$

Considering, the probability of occurrence of transition from state 3 to state 1 is more as compared either to that from state 3 to state 0 or from state 1 to state 0 and also, assuming total population inversion, the metastable population densities of thulium ion becomes:

$$\frac{\delta n_1}{\delta t} = \left(S_{01}\ n_0\ - S_{10}\ n_1 - \frac{n_1}{\tau} + P_{03}n_0\right) \quad (6)$$

The above equation shows that the rate equation of population density of state 1 mainly depends on the stimulated absorption and emission spectra of thulium ions, pumping rate from state 0 to state 3 and of course on the population density of thulium ions at state 0. S01, S10 represents the signal and pump rates which are dependent on cross-sectional area of core (A), absorption and emission cross section data (σ) of thulium fiber and confinement factors for pump and signal waves (Γ). The variation of pump and signal power with respect to linear distance l is given as:

$$\frac{\partial}{\partial l} P_P = -\Gamma_P \sigma_{03} n_0 P_P \qquad (7)$$

$$\frac{\partial}{\partial l} P_S = -\Gamma_s \sigma_{01} n_0 P_s + \Gamma_s \sigma_{10} n_1 P_s \qquad (8)$$

The above equations verify that rate of change of pump power as well as signal power are dependent on the respective confinement factors, population density at ground and metastable states. The pump power and signal power variations in terms of pump and signal rates become:

$$\frac{\partial}{\partial l} P_P = -A n_0 P_{03} \qquad (9)$$

$$\frac{\partial}{\partial l} P_S = -A\, S_{01} n_0 + A S_{10} n_1 P_s \qquad (10)$$

On multiplying equation (6) with A, area of cross section, we get

$$\frac{\delta n_1}{\delta t} A = \left(S_{01}\, n_0\, A - S_{10}\, n_1 A - \frac{n_1}{\tau} A + P_{03} n_0\, A\right) \qquad (11)$$

Using equations (9) & (10), the rate equation for the population (11) is written as:

$$\frac{\partial n_1}{\partial t} A = -\frac{\partial P_s}{\partial l} - \frac{\partial P_p}{\partial l} - \frac{n_1}{\tau} A \qquad (12)$$

The above equation is written as:

$$\frac{\partial N_1}{\partial t} = P_s(0,t) - P_s(L,t) + P_p(0,t) - P_p(L,t) - \frac{N_1}{\tau} \qquad (13)$$

Equation (13) represents the population density of TDF at metastable state (N1) as a function of position along the fiber without considering ASE. The above equation may be rewritten in terms of Bononi and Rusch's equations [20] as:

$$\frac{\partial N_1}{\partial t} = P_s(0,t)[1-\exp(K_S N_1 - I_S)] + P_p(0,t)[1-\exp(K_p N_1 - I_p)] - \frac{N_1}{\tau}] \qquad (14)$$

Where, Ps(0,t) and Pp(0,t) represent the time-dependent input powers for the pump and signal and the output powers Ps(L,t) and Pp(L,t) which are functions of N1 and the K and I (Kaur and Inder) are the terms of TDF related in terms of the confinement factors Γp and Γs, the absorption and emission cross sections (σ01, σ10 and σ03), the density of the thulium atoms ρ, the length L and the effective cross- sectional area A of the thulium doped fiber as defined for erbium doped fiber amplifiers[20].

2(a) Dependence of Constant related toPump (Ip) and Constant related to Signal (Is) on Length of TDF

It has been depicted from the equation (14) that the population density of metastable state is dependent upon pump power, signal power, constants related to pump (i.e. Kp and Ip), constants related to signal (i.e. Ks and Is), and emission and absorption coefficients. The dependence of Ip and Is on length of TDF has been shown in figure 2 and figure 3 respectively.

The dependence of Ip and Is on length of TDF can be tabulated as shown in Table I. This dependence will affect the metastable state population of TDFA and thence the gain of TDFA.

TABLE I. VARIATION OF IP & IS W.R.T LENGTH OF TDF

Length of Fiber(m)	Value of I_p	Value of I_s
0	0.000	0.000
8	220.110	114.609
16	440.220	229.217
24	660.330	343.826
32	880.440	458.434
40	1.101e3	573.043
48	1.321e3	687.651
56	1.541e3	802.260
64	1.761e3	916.869

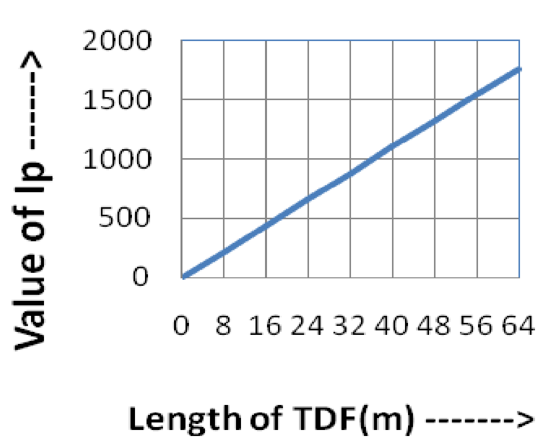

Figure 2: Variation of Ip w.r.t Length of TDF

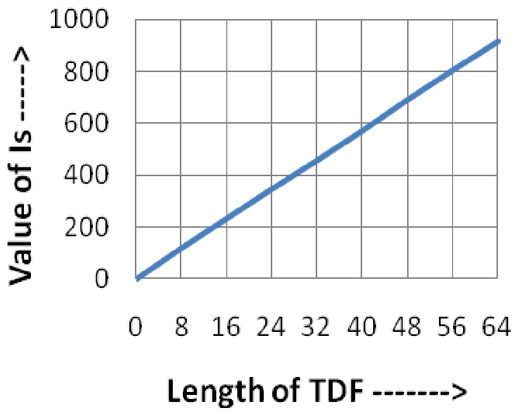

Figure 3: Variation of Is w.r.t Length of TDF

It is observed from Table I, Figure 2 and Figure 3 that as the length of TDF increases the values of Ip as well as Is also increases and hence metastable state population is varied. The next step for evaluating the performance of present TDFA model is the selection of range of fiber length of TDF.

2(b) Selection of Range of Length of TDF

It is well known fact that working principle of doped fiber amplifier (TDFA under consideration) is population inversion. The gain of TDFA depends on the metastable state ions. The gain of TDFA also depends on the fiber length. The maximum gain (G) in a three- level doped medium of length L, is given in equation 15.

$$G = \exp\left(\Gamma_S \rho \sigma_{03} L\right) \tag{15}$$

Also, the inversion level of TDFA is also dependent on the pump power. As the pump power decreases, the inversion level will reduce and thereby the gain of the amplifier will be reduced. The gain of TDFA can also be written in terms of input signal wavelength as shown in equation 16.

$$G = \frac{P_{s,out}}{P_{s,in}} \leq 1 + \frac{\lambda_P P_{P,in}}{\lambda_s P_{s,in}} \tag{16}$$

The peak gain is given by lowest of the two gain equations:

$$G_{TDFA} \leq \min\left\{\exp\left(\Gamma_S \rho \sigma_{03} L\right), 1 + \frac{\lambda_P P_{P,in}}{\lambda_s P_{s,in}}\right\} \tag{17}$$

For evaluating the range of fiber length of TDF, the gain of TDFA versus amplifier length has to be plotted using MATLAB.

The equation (17) specifies the dependence of gain of TDFA on fiber length of TDF as well on pump and signal power and wavelengths. So, it is inferred from above discussion that the gain of TDFA is dependent on metastable state population, which in turn depends on the fiber length of TDF. From Table III, it is cleared that fiber length of TDF is varied from 0-64m for further analysis.The standard data (or parameters) used for simulation is indicated in Table II has been taken from previous researches. Table III shows the parameters other than standard data used for simulation of present model.

TABLE II. STANDARD DATA (OR PARAMETERS) USED FOR TDFA MODEL

Parameter	Symbol	Value
Emission Coefficient (of Signal)	b	1.6dB/m
Absorption Coefficient of Pump	a_P	1.36 dB/m
Absorption Coefficient of Signal	a_S	0.15 dB/m
Population Density of Tm^{+3}	ρ	6000 ppm
Diameter of Core of Fiber	d	2.55×10^{-6}m
Transition Time	τ	9.0ms
Mean Pump Power	P_P	200mW
Mean Input Power	P_{in}	0.16mW
Confinement Factor of Pump	Γp	0.79
Confinement Factor of Signal	Γs	0.53
Pump Wavelength	λ_P	1050nm
Area of Core of Fiber	A	$5.10\ X10^{-12}\ m^2$
Cross Section Area of Excited State Absorption	σ_{03}	$6.2 \times 10^{-25}\ m^2$
Cross Section Area of Ground State Absorption	σ_{01}	$5.2 \times 10^{-25}\ m^2$
Cross Section Area of Emission	σ_{10}	$2 \times 10^{-26}\ m^2$

TABLE III. PARAMETERS (OTHER THAN STANDARD PARAMETERS) USED FOR SIMULATION OF PRESENT TDFA MODEL

Parameter	Symbol	Value
Length of Fiber	L	0-64m
Channel spacing	Δv	0.8nm
Signal Wavelength Range	λ	1479-1555nm
Signal Wavelength	λ_S	1530nm

Using Table II and Table III and equation (17), the gain of TDFA versus amplifier length is plotted as shown in figure 4. As discussed earlier that gain depends on the charge carriers of metastable population, so the gain attains its peak value as and when TDFA acquires sufficient number of charge carriers. The gain of TDFA versus amplifier length is plotted as shown in figure 4[21].

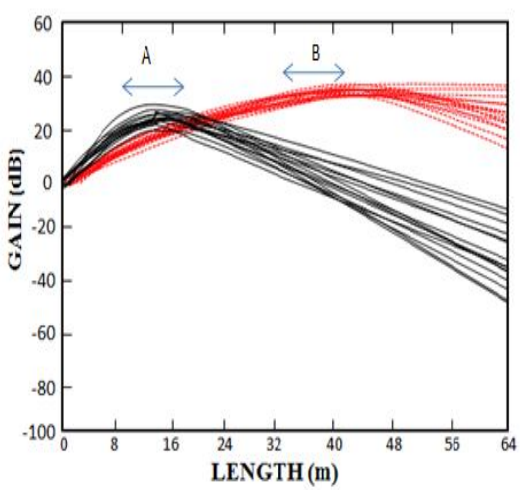

Figure 4: Variation of Gain of TDFA versus Length of TDF for 1479nm to 1555nm Range

This figure 4 depicts that the amplifier length at which maximum gain is obtained becomes more with increase in signal wavelength. It is also concluded that at a particular amplifier length, the TDFA will amplify each wavelength differently, which needs to be equalized for DWDM system. Figure 4 also shows that two maximum gain peaks which have been marked in figure 4 as 'A' and 'B'.

The peak 'A' is obtained at lengths of TDF ranging between 8m to16m and other peak 'B' is obtained at lengths of TDF ranging between 34m to 42m. This graph has been plotted for finding out peak gain at different wavelengths which are corresponding to different channels versus fiber lengths of TDF. So a range of 8m to 16m length of fiber has been selected for further analysis of performance of TDFA. The aim of the present work is to find the optimal length of TDF, so a graph is plotted for gain of TDFA versus wavelength for different lengths of TDF. The range of length of TDF is taken from 8m to 16m.

2(C) Selection of Pump Power

The next step in designing TDFA has been started with finding the value of the appropriate pumping power for TDFA [22]. To have complete population inversion at 1050nm pumping wavelength of TDFA, suitable pump power is required. The equation 14 shows the dependence of metastable state population of pump power. It implies suitable selection of pump power. Figure 5 shows the fractional amount of the metastable state population as a function of fiber length (TDF) pumped at 1050nm. It has been depicted from figure 5 that at low pump powers, most of the pump power is absorbed in the beginning of the fiber, thereby leaving most of the length of the fiber underpumped. In previous researches, pump power of 200mW has been already considered. In the present work, impact of lower pump powers on metastable population is also considered, so as to ensure that if TDFA can work satisfactorily for lesser pump powers. As the fiber length of TDF increases, more and more pump power is required to excite more photons for stimulated emission. The maximum metastable state population is obtained at pump power of 200mW. The peak in the population inversion for 200mW of pump at 1050nm, near 4m to 10 m is due to the fact that at this position the total ASE is the lowest .

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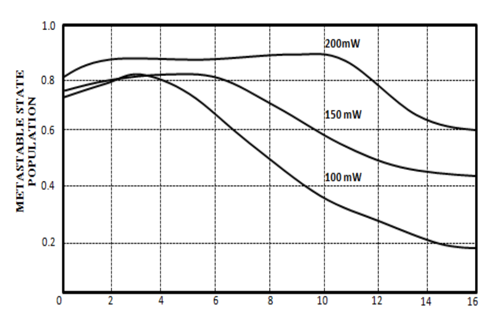

Figure 5: Variation of Population in Metastable State as a Function of Length of TDF

It has been depicted from figure 5 that at low pump powers, most of the pump power is absorbed in the beginning of the fiber, thereby leaving most of the length of the fiber underpumped. In previous researches, pump power of 200mW has been already considered. In the present work, impact of lower pump powers on metastable population is also considered, so as to ensure that if TDFA can work satisfactorily for lesser pump powers. As the fiber length of TDF increases, more and more pump power is required to excite more photons for stimulated emission. The maximum metastable state population is obtained at pump power of 200mW. The peak in the population inversion for 200mW of pump at 1050nm, near 4m to 10 m is due to the fact that at this position the total ASE is the lowest. It has been observed from figure 5 that after length of 10m metastable state population starts decreasing for pump power of 200mW. After analysis, inference can be made that for 200 mW pump power better metastable population has been achieved at lower fiber length of TDF. The rate equation of TDFA mentioned in equation (14) and gain equation mentioned in equation (15) further depicted that the metastable population and gain of TDFA are strongly dependent on operating pump power. So, gain versus length of TDF has been plotted for different pump powers is shown in figure 6.

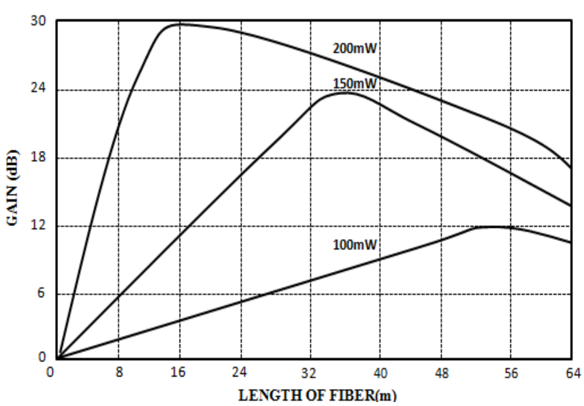

Figure 6: Variation of Gain versus Length of TDF for Different Pump Powers

It is observed from figure 6 that as the pump power increases, the length of TDF at which peak gain is achieved decreases. The maximum gain obtained is at 12dB, 24dB and 30 dB with the pump powers of 100mW, 150mW and 200mW at TDF lengths of 54m, 36m and 15m respectively.

Based upon the above analysis in sections, it is concluded that TDFA at pump power of 200mW and with fiber lengths of TDF ranging from 8m to 16m has been considered in the present work for further analysis. However, an effort has further been made to use the least possible fiber length of TDF so as to ensure least ASE noise for maximum possible gain and in turn cheaper amplifier.

2(d) Selection of Optimum Length of TDF

Based on the aforementioned equation (17), Table I, Figure 5 and Figure 6, it is very clear that the metastable population and thence the performance of TDFA is dependent on length of TDF. It implies that the population inversion can be controlled by proper choosing of fiber length and injected pump power to TDFA. (This characteristic is similar to that of EDFA, because both are doped fiber amplifiers). The pump power has been selected as 200mW (as mentioned in Table II) and range of length of fiber has been considered from 8m to 16m. So before performing the simulation for gain of TDFA, optimum length of the TDFA is to be evaluated so as to ensure that maximum possible gain has been achieved at least possible fiber length of TDF.

2(D) Variation of Gain versus Wavelength

The aim of the present work is to find the optimal length of TDF, so a graph is plotted for gain of TDFA versus wavelength for different lengths of TDF. The range of length of TDF is taken from 8m to 16m

The graph is plotted between gain and wavelength (without considering ASE) for TDF length ranges from 8m to 16m as shown in figure 7. This graph implies that the length 16m can be chosen as optimum length, because at this length, peak gain of 30.5dB is obtained while for 10m its value is 26dB and for 8m its value is 22dB.

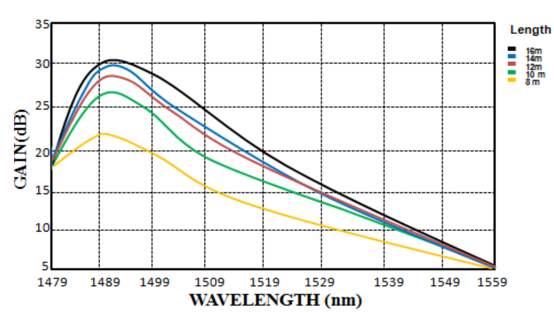

Figure 6: Gain versus Wavelength for Different Lengths of TDF without ASE

3. MODEL OF PROPOSED TDF

Simulink environment has been created by using equation (14) and is shown in figure 7a & 7b. The mathematical model shown in Simulink environment represents the interdependence of system parameters on the performance of TDFA. The mathematical model shown in figure 7a depicts that amplification of input signal depends on gain of TDFA, which in turn depends on Ip, Is (which are related to fiber lengths) and pump power. This diagram also represents the effect of ASE on metastable population

which in turn is related with performance of TDFA (i.e. gain and noise figure).
The block diagram of TDFA is shown in figure 7b.

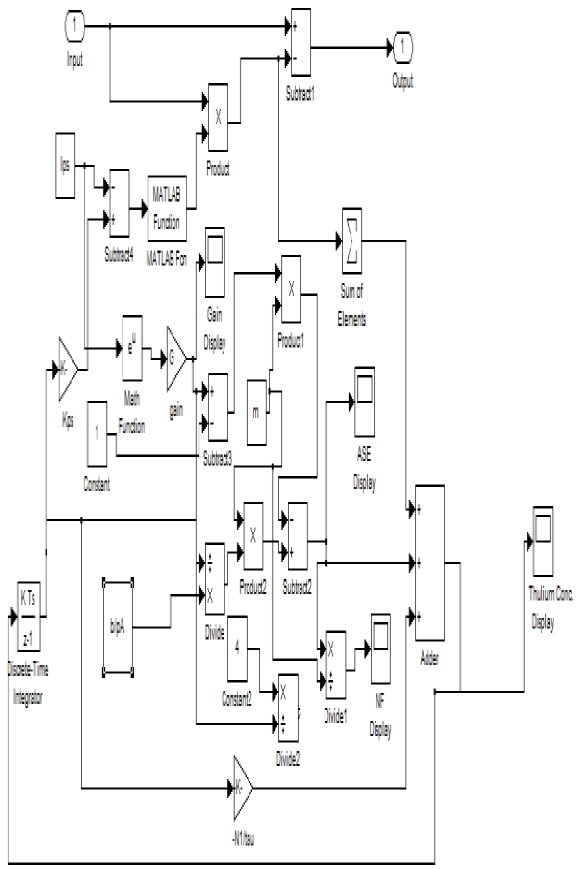

Figure 7a: Mathematical Model of TDFA

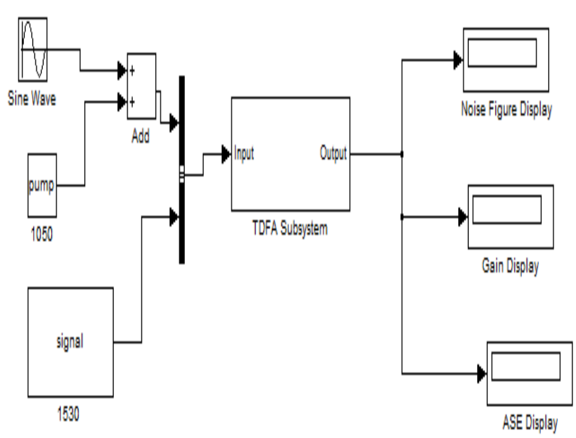

Figure 7b: Block diagram of TDFA

The Algorithm used for present model of TDFA is shown in Table IV.

TABLE IV. ALGORITHM_SIM_TDFA

STEP I: Initialize n_0, n_1 and n_3 (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), P_p &P_s (Pump and Signal Power),λ_p &λ_s (Pumpand Signal Wavelength) and I/P signal
STEP II: n_1, n_1 , n_3 and L = variable
STEP III: Calculate the range of lengths at which peak gain is achieved for different wavelengths(or channels)
STEP IV: Calculate effective pump power
STEP V: Calculate Gain with respect to Length of Fiber
STEP VI: Calculate Optimum Length of fiber for maximum gain
STEP VII: Plot gain for optimum length of TDF w.r.t.wavength.

The flowchart representing the modeling of TDFA using algorithm from Table IV is shown in Figure 8.

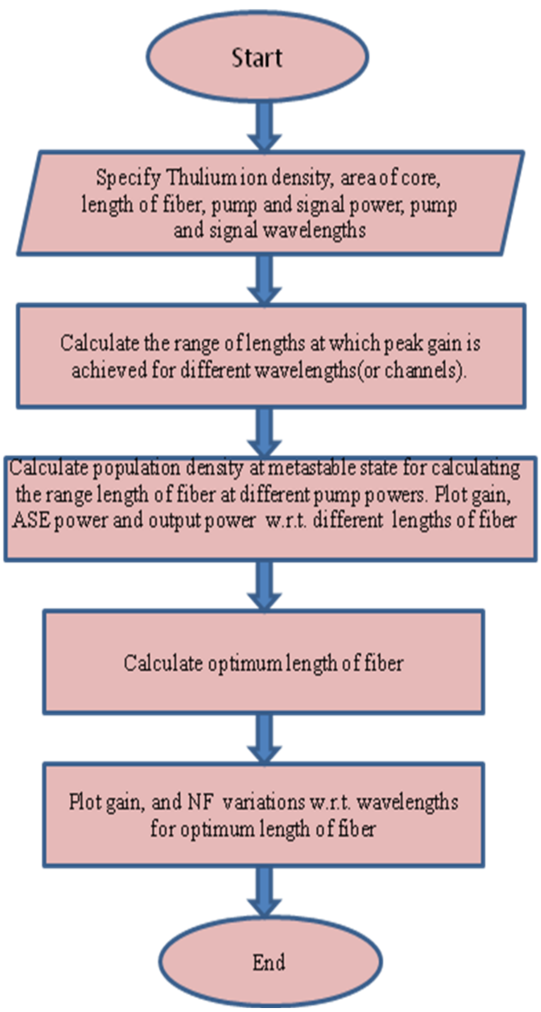

Figure 8: Flowchart Representing Dynamic Modeling of TDFA

4. RESULTS

A simulated model has been designed for investigating TDFA dynamics. The results have been shown in Table V and figure 9.

TABLE V. SUMMARIZED RESULTS OF TDFA

Without considering ASE	
Length(m)	Max. Gain(dB)
8	22
10	26
12	29
14	29.8
16	30.5

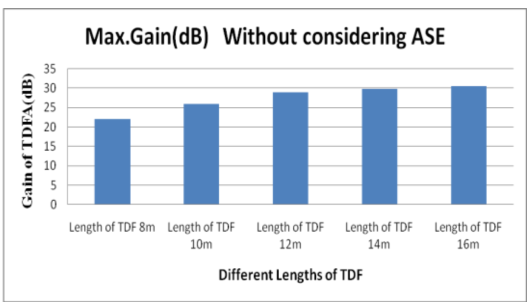

Figure 9: Gain (without ASE) at different lengths of TDF

5. CONCLUSION

A mathematical model of TDFA has been designed for investigating its dynamics. The model has been designed based on upconversion method. The results are given in terms of gain spectrum for optimal length of TDFA. The initial step in designing TDFA had been started with choosing the value of the appropriate pumping power as well as the optimum length of amplifier. Simulations have been carried out for gain (without ASE) versus signal wavelengths ranging from 1479nm to 1555nm for length of fiber ranging from 8m to 16m. The peak gain of ranging from 22 dB to 30.5dB has been attained for selected optimum fiber lengths ranging from 8m to 16m of TDF.

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