CHAPTER 6

GAIN-FLATTENED L⁺-BAND

THULIUM-DOPED FIBER AMPLIFIERS

The focus in this chapter is on the extension of conventional L-band of wavelengths (1580-1610 nm) by using thulium amplification in fluoride host. Two different fiber designs are discussed for getting efficient, inherent gain flattened L⁺ band with thulium doped fiber amplifier (TDFA). Gain in the L⁺ band is increased by removing the unwanted longer wavelength ASE by using distributed leakage losses in segmented-clad fiber (SCF) design and an optimum bend induced losses in the W-fiber design. It is an innovative and first time to the best of our knowledge that high gain thulium amplification is achieved in this wavelength region.

6.1 Introduction

In literature a lot of activities are studied for realizing dominated L band erbium doped fiber amplifier (EDFA) [42] and to extend the amplifier band width over ordinary L band. In ordinary L EDFA, the band width of operating wavelength is limited below 1610 nm and therefore, many techniques are discussed for extending the band width of L band amplifiers. A few of them comprise the application of antimony silicate glass host in place of Al / Si [17] or the application of Raman amplifier [11]. We discuss two novel designs which are related to a segment claded fiber and a bent W-fiber for getting inherent gain
flatten, fluoride based thulium doped fiber amplifiers (TDFA) having 20 db gain with 40 nm wide bandwidth in the L^+ band (1600 nm to 1640 nm).

Thulium is predominantly being used to get S band amplifiers [2] which depend on the \(^3\text{H}_4^+ - \(^3\text{F}_4\) transition whose centre is around 1470 nm, and longer wavelength lasers [48] which depend on \(^3\text{F}_4^- - \(^3\text{H}_6\) transition whose centre is around 1830 nm (fig. 6.1).

![Energy levels of Tm\(^{3+}\) ions](image1)

![Emission and absorption cross section of Tm\(^{3+}\) ions](image2)

The \(^3\text{F}_4^- - \(^3\text{H}_6\) transition consists of an emission tail upto 1600 nm (fig. 6.2), and therefore, the transition is being used to obtain L^+ band (from 1600 to 1640 nm) fiber amplifiers. Dominating L^+ band TDFA, is not obtained by ordinary fiber modules because the larger wavelength amplified spontaneous emission will decrease the population inversion process for the amplifier and it is practically not possible to enhance L band signal. Therefore, to obtain gain at lower side of
wavelengths, we have to remove the collection of higher wavelength ASE in the direction of the entire fiber length. A ZBLYAN based TDFA working on band width 1650 - 1670 nm has been previously discussed [55], where the longer wavelength amplified spontaneous emission is removed through doping of fiber with Terbium (Tb$^{3+}$) ions, that consists of a greater absorption cross section for wavelengths greater than 1750 nm. Here the usable amplifier band width varies from 1650 to 1670 nm, and the wavelength region is 1600-1650 nm cannot be exploited.

The removing of longer wavelength amplified spontaneous emission in a TDFA is allowed by using a proper wavelength based leakage losses of the basic mode in optimum segment claded fiber (SCF). The same principle is applied as in the S-band EDFA based on a SCF profile (refer to section 5.3). In literature, W-fiber designs have been discussed for removing C-band amplified spontaneous emission for gain increment in S-band EDFAs [4], and for filtering out strong four level amplified spontaneous emission transition and for enhancing three level transition in Neodymium and Ytterbium doped fibers [3, 58]. The main benefit of taking an segment claded fiber in place of ordinary W-fiber design is that along with using greater wavelength amplified spontaneous emission removal, an optimum SCF can make flattening the gain in signal band. Since the spectral changes in the leakage losses for an SCF is well tuned for compensating for spectral gain tilt, along with removing the problematic amplified spontaneous emission at greater wavelength. Therefore, we observe that the wavelengths greater than the signal band provide large leakage losses (greater than or equal to 70 db), where the signal operating range wavelengths provide less leakage losses (varies from 0
to 1.5 db per meter), for spectral changes proposed for compensating the signal gain tilt. therefore an SCF provides the dual purpose of longer wavelength ASE removing and inherent gain flattening. Simulations show that by using this design greater than 20 db net gain with ± 0.7 db ripple can be obtained for 40 nm wide band width between 1600 nm to 1640 nm, by using 180 mW of pump power at 1210 nm.

A properly proposed W-fiber design may be used to remove the unwanted and problematic longer wavelength ASE in an L⁺-band thulium-doped fiber amplifier, but here the signal gain is highly non-flat. For compensating this gain tilt, we propose to use an additional wavelength based bend induced leakage losses in signal operating range. Therefore, we propose an optimally bent W-fiber having a high leakage loss greater than 3 db per meter is applied to remove the greater wavelengths that are outside the signal band, so that a fine tuned bend induced leakage losses from 0 to 1 db per meter is given to the signal operating range wavelength for compensating the gain tilt. We prove that gain flattening up to ± 0.3 db consists of 32 nm band width existing in designed L⁺ band TDFA.

In our simulations, we consider fluoride hosts for getting gain flatten L⁺ band TDFA because it gives relatively high efficiency in terms of pumping power. This method is also used for other hosts, while the pumping powers needed in this case will be greater due to consisting less fluorescence lifetime (approximately 0.4 ms). We emphasize that in both the proposed designs the inherently gain flatten is obtained by removing the gain at relatively larger signal wavelengths and an increment in the gain at lesser wavelength signals by reshuffling of power in the signals channels. It is contradictory to make the gain
flattening with help of discrete filters, that is obtained by removing of gain for all the possible wavelengths. Therefore, the inherently gain flatten is more important than making flatten gain by using that of discrete filters. The gain and gain flattening in designed modules are examined for tolerance by changing fiber parameters and bend radius.

6.2 L⁺-band TDFA based on SCF profile

6.2.1 Basic principle

In an SCF, the spectral changes in leakage losses for the operating wavelength regime \( \lambda_{c1} < \lambda < \lambda_{c2} \) is basically controlled by changing the distance between c to a, and for \( \lambda > \lambda_{c2} \), that is controlled by changing the distance between b to a. Therefore, by changing the dimensions of b and c, the spectral changes of leakage losses in both wavelength regime is finely tuned and almost free. The selection of \( \lambda_{c1} \) and \( \lambda_{c2} \) is decided with help of the operating wavelength regime of the required signal band of 1600 - 1640 nm, and this selections sets the refractive indices of the core and radius a, we select \( \lambda_{c1} \) to be 1604 nm and \( \lambda_{c2} \) to be 1652 nm. The parameter b and c are selected such that the wavelengths which are larger than signal wavelengths (\( \lambda > \lambda_{c2} \)) experience a very high leakage losses, and the signal operating wavelengths \( \lambda_{c1} < \lambda < \lambda_{c2} \) experience less leakage losses over a spectral change that properly makes compensation for the gain tilt. The designed inherently gain-flatten L⁺ band TDFA works basically on this principle. The fiber parameters for the designed SCF profile are \( \Delta_1 = 0.7\% \), \( \Delta_2 = -0.2\% \), \( \Delta_3 = -0.02\% \), \( b/a = 8.15 \) and \( c/a = 15.35 \).

Leakage mode analysis is done by following the formalism developed in [65]. In figure 6.3, leakage loss spectrum of the designed fiber is shown.
Fig. 6.3: Leakage loss in the SCF

Fig. 6.4: L\textsuperscript{+} band TDFA gain spectrum

Fig. 6.3 tells that the different leakage losses spectrum is achieved for changing values of various fiber parameters. For compensating any such variation, the amplifier design has to be re-optimized by adjusting the concentration of thulium ion which is used in the manufacturing process, and the length of fiber which is used in the fiber amplifier. The methodology for finding the fiber length and ion concentration for re-optimizing is based on the principle of proper compensation of spectral gain tilt to obtain inherently gain flattened. Since, the longer wavelength ASE is sufficiently removed, so that, the quantity and spectral changes in leakage losses outside from the signal band is not significant. Because the spectral variation of signal gain (and hence the desired spectral changes in leakage losses) in an L TDFA is almost well linear, the amplifying fiber length needed to obtain the gain flattening should chosen such that the value of total leakage loss (dB) at a certain signal wavelength is approximately
equal to the case of ideal profile (see Fig. 6.3). A longer length of fiber is required in the case of leakage loss being smaller than that in the ideal profile and vice-versa. To obtain maximum gain, the product of fiber length and ion concentration for a certain pump power is constant. Thus, if the fiber length is selected, the desired ion concentration is determined by its inverse proportionality to the fiber length. The obtained set of values for leakage loss, fiber length ion concentration makes support to the gain flattened operation.

6.2.2 Numerical results and discussion

The proposed $L^+$ band TDFA having 32 meters of designed SCF, which is pumped by 180 mW power at 1210 nM. This pump is used to make transition of atoms into ($^3\text{H}_5$) level, and from where, they begin to decay non-radiatively to the upper lasing level ($^3\text{F}_4$), and therefore, the system works as a three level system. We use 800 nm band pump for obtaining populations inversion from $^3\text{F}_4$ to $^3\text{H}_6$ levels. The core region ($r < a$) of the proposed SCF is doped with thulium, having the concentration of $1.8 \times 10^{25}$ m$^{-3}$. For analyzing amplification in designed fiber, we use three level rate equation model as the standard model in case of EDFA (see section 2.2). The 1210 nm pumping scheme has greater efficiency than that of 800 nm pumping. To determine the leakage losses of the basic mode, an extra loss term is added in the propagation equations ved as signal and amplified spontaneous emission. The cross section data for emission and absorption using Tm$^{3+}$ ions as dopants in fluoride hosts are taken from Sakamoto et al. 1996. Because of the high leakage loss (greater than 10 db per meter) for wavelength greater than 1700 nm, the emission wavelength range over 1700 nm is not considered in simulation.
In fig. 6.4, the solid curve represents the gain spectrum of the proposed L⁺ band TDFAs; eleven equal distant signal channels from 1600 to 1640 nm are taken along with signal input power of 10 dbm. In fig., it is shown that for approximately 20 db gain is obtained with this design with a gain ripple of ± 0.7 db. The noise figure in our designed module exists below 7.5 db for total wavelengths, and changes from 3 db to 7.5 db with 1600 nm to 1640 nm. The main benefit of the designed plan is that the gain flattening amplification is moved towards higher wavelengths side by a proper selection of \( \lambda c_1 \) and \( \lambda c_2 \).

To discuss the importance of the proposed SCF based design, we simulate the functioning of an L⁺ band TDFA for cases as following:

1) For an ordinary step index fiber (SIF) which has no leakage loss.

2) In an ordinary W fiber, as discussed in [3], where the higher wavelength amplified spontaneous emission is removed by a proper selection cut-off for fundamental mode but leakage loss in signal band taken place is zero.

3) For a W fiber module, where along with removal of higher wavelength amplified spontaneous emission, a few signal wavelengths experience leakage losses to obtain maximum gain flattening.

4) In the designed step indexed fiber, the leakage losses spectra is well tuned for matching the spectrum gain tilt to obtain inherently gain flattening.

The step indexed fiber is simulated by putting \( n_3 = n_4 = n_2 \) and \( C = b = a \) in the designed SCF. The W Fiber is being simulated by putting \( n_4 = n_3 \) and \( c = b \) in the designed SCF. This provides the basic mode cut-off in W Fiber equal to around 1652 nm, therefore, the problematic greater wavelength amplified spontaneous emission is removed. The core parameters in all four cases are
selected equal, therefore, the mode field is overlapped (and hence the gain coefficient) in the thulium-doped region is identical for all four devices. The fiber length is made optimum in every case to obtain highest gain. Comparing with SCF, the fundamental fabrication restriction in a W II fiber due to the fact that the spectral changes for leakage losses in a W fiber is approximate linear and therefore the leakage losses spectra in both sides the signal band is not independently governed. This implies that if we try for matching the slope of the spectral changes of leakage loss with the signal gain tilt (approximately 0.035 dB / m), along with providing small magnitudes of leakage loss for the signal wavelengths (to ensure high gain), then the unwanted longer wavelength ASE experience very small leakage losses (less than 5 dB / m), resulting to large ASE build up and a subsequent pump depletion. Therefore, we find that for a W II– fiber, highest gain flattened along with a high signal, a high signal gain is obtained where the cut off wavelength is selected to lie at the centre of the signal band, therefore, half of the signal wavelength do not experience any leakage loss, where the other half experience higher leakage losses and the amplified spontaneous emission wavelength are also totally removed. The optimum thulium concentration and length for the optimized W II fiber are $2 \times 10^{25}$ m$^{-3}$ and 27 m respectively. In figure 6.4, the gain spectrum for all the four conditions are shown.

We observe that the L$^+$ frequency band operation is impossible in an ordinary fiber (shown by the dash-dot curve in Fig. 6.4). A W II fiber increases the L$^+$ band gain by removing of higher wavelength amplified spontaneous emission, but the band gain is little changed with wavelength (shown by the dashed curve in the
fig. 6.4). Here the gain for small wavelengths is not become high further by enhancing the pumping power, because higher wavelengths are further amplified, resulting with increment in gain tilt.

We provide a tolerance analysis for the working of amplifier by changing the various fiber parameters. The change in fiber parameters results to a deviation in the leakage loss spectrum from the ideal case (as shown in fig. 6.3) and this effect is made compensating for optimum the concentration of thulium ion which is used in the manufacturing process and the length of fiber used in the Raman amplifier. To observe the fiber dimensions by setting the pulling speed in the fiber designing process gives an extra tool for obtaining required values of cut off wavelength when we change the core parameters. The working of the proposed module is examined for the values of parameter $a \pm 1 \times 10^{-4}$ changing in value of refractive indices and $\pm 0.5 \, \mu m$ variation in fiber dimensions $b$ and $c$, and gain flatten operation (whose ripple is less than $\pm 1 \, \text{db}$ and gain is greater than $20 \, \text{db}$) is obtained in all conditions by using the equal pumping power like in the standard condition.

6.3 $L^+$ band TDFA based on bent W-fiber

Generally, It is observed that the spectral changes of leakage losses of the basic mode in a W-fiber is very near to linear. In applications like inherent gain flatten $L^+$ band TDFA, we obtain a strong difference between the leakage losses variation inside and outside the operating wavelength range. The leakage losses towards outside the signal band must be high enough (greater than $5 \, \text{db} / \text{m}$) to completely remove the adding of greater wavelength amplified spontaneous emission, and the leakage losses inside the operating wavelength range must be
small and sufficient enough for compensating signal gain tilt. Because the signal gain tilt $L^+$ band is nearly linear, so that the linear changes in the leakage losses for the operating signal band is sufficient to compensate for it. Therefore, we require to design different slopes of the spectral changes of leakage loss inside and outside the signal band. This is obtained by providing an additional degree of design freedom in the system by bending the W-fiber, that gives an additional bend induced leakage losses to basic mode.

The effect of bending a W-fiber is modeled by taking an equivalent refractive index profile (dashed curve in Fig. 6.5).

![Fig. 6.5: Refractive index profile of straight W-fiber](image)

By bending a W-fiber we can shift the cut off wavelength $\lambda_c$ to small wavelengths and therefore these wavelengths also provide leakage losses. This leakage loss can be governed by changing the radius of bend. If the bend radius has less value, the more is the blue-shifting of $\lambda_c$ is higher and the loss at a specific wavelength are also higher. Thus, to make distinction the act of signal
band wavelengths from that of unwanted and problematic ASE, we select the cut-off towards the straight W-fiber to be at the longer wavelength edge of signal band. By bending the fiber with a bend radius of 8 cm, the cut-off shifts towards the shorter edge of the signal band, that is, 1640 nm. Because of the leakage loss well induced by bending consists of a different spectral change (governed by bend radius $R$) than that of induced in a straight W-fiber, we propose to design the two wavelength bands (signal and longer wavelength ASE) which experience different amount of leakage loss, with different slopes of spectral changes. The superposing the leakage loss variation induced by bending and the leakage losses spectra of the straight fiber are equivalent.

6.3.1 Results and discussion
The bend sensitivity of the designed fiber is easily governed with the help of changing the fiber parameters. It means that to obtain same bend loss, fiber with smaller ratio of parameters $b$ and $a$ will need smaller bend radius than fibers with smaller $b/a$ ratio (the parameters of the core are same in both the cases). Bend induced leakage losses consist of an approximate linear spectrum changes with small wavelength range, and the slope of the change is finely tuned by changing the radius of bend. Therefore, an optimally selected bend radius effectively flattens the approximate gain tilt in an L$^+$ band TDFA. The fiber dimensions are selected such that the leakage losses in a straight W type fiber is enough (greater than 2.5 db per meter) to remove longer wavelength amplified spontaneous emission and the fiber is responsibly sensitive for bend induced leakage loss, that is why, a much less bend radius is not sufficient for achieving the required leakage losses in the operating signal band. The refractive index of the proposed W-fiber are
selected such that $\lambda_c = 1661$ nm, where the operating signal band varies from 1604 nm to 1636 nm. The core parameters $(\Delta_1, \Delta_2, a)$ basically ensure the fundamental mode cut-off wavelength ($\lambda_c$). For our design, the optimum fiber parameters are $\Delta_1 = 0.7\%$, $\Delta_2 = 0.2\%$ and $b/a = 8.25$. In figure 6.6, the leakage losses spectra in the with and without bend in the proposed fiber is shown.

![Image of spectral variation of leakage loss and gain and noise](image)

**Fig. 6.6**: Spectral variation of leakage loss  
**Fig. 6.7**: Spectral variation of gain and noise

In this case, the optimum bend radius is 8 cm. In fig. 6.6, the changes in leakage loss spectrum with a variation in bend radius are shown. When the bend is present, the shifts $\lambda_c$ from its initial value 1661 nm to 1604 nm in fiber amplifier. The proposed L$^+$ band TDFA has 32 meters of optimum W type fiber which is being pumped with help of 160 mW power at 1210 nm. The amplifier performance is modeled in the same manner as mentioned in section 6.2.2. In figure 6.7, the less signal gain and noise figure spectrum of the proposed L$^+$
band TDFA is shown. Here, 09 equally distant signal together channels with 1604-1636 nm are taken having a operating signal input power of 10 db.m. The figure illustrates that approximately 20 db gain consisting of gain ripple of ± 0.3 db is obtained with the design and the noise figure of the amplifier is maintained below 7 db for all wavelengths of signal.

The enhancement in amplification efficiency in L⁺ band through inherent gain flattening is explained by studying the spectral changes of forward sided amplified spontaneous emission power, for above discussed three conditions. The characteristics are shown in Fig. 6.8. We observe that leakage losses in a W type fiber moves the amplified spontaneous emission spectra towards the small wavelengths, and due to bend induced leakage losses it becomes flatten.

![Fig. 6.8: Spectral variation of forward ASE power](image1)
![Fig. 6.9: L⁺ band TDFA](image2)
The removing of longer wavelength amplified spontaneous emission results to a considerable increment in the population inversion process in the direction of the length of the fiber.

To discuss the importance of an optimum spectrum changes in leakage losses results to the inherently gain flattened, we simulate the working of an L$^+$ band TDFA for the following 03 conditions.

1) For an ordinary SIF leakage loss taken place is zero.

2) In a straight W type fiber, whereas the longer wavelength amplified spontaneous emission removed by a properly selected cut off for basic mode, but there no gain flattening takes place.

3) For an optimum bend W type fiber with removing of longer wavelength amplified spontaneous emission along with inherently gain flatten given by fine tuned spectral changes of leakage losses in operating signal band.

In fig. 6.9, the characteristics of all the above three conditions are shown. The pumping, signal power and ion concentration are identical to that of in Fig. 6.7. The fiber lengths are become optimum in each case to achieve maximum gain.

From Fig. 6.9, we observe that L$^+$ band operation is approximately impossible in an ordinary fiber (shown by dotted curve in the figure), where longer wavelength amplified spontaneous emission removal in a straight W type fiber dose increases the L$^+$ band gain but its gain is little changed with the wavelength (shown by dashed curve in the figure). If discrete filters at the both ends of the amplifier are applied to make flat the gain, so that, the gain of the amplifier is not achieve greater than 10 db for all possible wavelengths. The gain for small wavelengths is not enhanced considerable if we increase the pumping power.
because of the condition where the longer wavelengths are again amplified, resulting to an increment in the gain tilt. The gain in the bend W type fiber designed is shown by solid curve, where we observe that inherently gain flatten is obtained by redistribution of power in the direction of several signal channels. Therefore, high wavelength gain is removed and the smaller wavelength gain is increased, resulting to high total efficiency.

We provide a tolerance analysis for the fiber parameters, along with gain flattening in the designed $L^+$ band TDFA. This analysis results that in the overall leakage losses and its spectral changes, mainly controls the gain flatten in the proposed TDFA. We note that the variations in the losses spectra is properly made compensation by an optimum fiber length, pumping power and radius of bend.

The TDFA gain spectra consisting of various values of bend radius are shown in fig. 6.10, taking the fiber parameters and input operating power of signal, equal as in Fig. 6.7.

![Fig. 6.10: Spectral variations in gain for different values of bend radius](image-url)
$D_{Rb}$ denotes the shifting in bend radius from its optimum value, $P_P$ denotes the pumping power and $R$ denotes the gain ripple in every condition. The gain flattening changes from $\pm 0.3$ dB to $\pm 0.7$ dB for a $\pm 0.5$ cm change in bend radius. We also study tolerance of the design to fiber parameters $n_1$, $n_2$, a and b. Any change in the parameter of the core results to a change in cut-off wavelength. It is obvious that a re-optimum fiber length, ion concentration and bend radius restores the gain-flattened performance consisting of a gain ripple from $\pm 0.3$ dB to $0.5$ dB. For a $\pm 0.5$ μm change in b, the gain ripple changes from $\pm 0.3$ to $\pm 0.4$ dB.

**6.4 Conclusion**

We extract emission in fluoride based thulium doped fiber for getting inherently gain flattened amplification in L$^+$ band wavelength from 1600-1640 nm. The proposed designs are based on the theory of transferring of amplifier gain towards smaller wavelengths side by removing longer wavelength ASE by distributed leakage losses to the fundamental mode. For obtaining inherent gain flattening, extra optimized leakage loss is applied in the signal band. Two designs (Segmented clad fiber and a bent W fiber) are discussed to obtain the thulium-doped amplifier in L$^+$ band. Detailed modeling for amplifier characteristics is discussed and greater than 20 db gain with a gain ripple of $\pm 1$ dB to obtain for 32 nm band width from 1604-1636 nm, by using proper pump powers from 160-180 mW. We emphasize the inherent gain flattening which results to enhance overall efficiency because it is obtained by removing of gain at higher signal wavelength and an increment in gain at smaller signal wavelength. The violation of making gain flatten using discrete filters, that is obtained by removing the
gain at all possible wavelengths. The tolerance analysis of gain and gain flattened with varying fiber parameters etc., and it is confirmed that the required characteristics is retained by using re-optimum amplifier parameters.