GAIN-FLATTENED S-BAND ERBIUM DOPED FIBER AMPLIFIERS

We present here two amplifier designs of inherently gain flatten S-band fiber amplifiers (EDFAs), which are erbium doped. S-band amplification by erbium ions requires the suppression of longer wavelength (C-band) amplified spontaneous emission (ASE), that we can obtain by distributed bend losses in a co-axial fiber design and distributed leakage loss in the segment claded fiber (SCF) design. Well removing of C-band ASE along with simultaneous gain flattening in S-band is obtained which provides a highly non-linear spectral variation of distributed losses in both designs and the flexibility is finely tune this spectral variation through optimum fiber parameters.

5.1 Introduction

For new wavelength bands of transmission (L-band and S-band) provides better to increase the capacity of wavelength division multiplex (WDM) systems. Presently, many researchers are working on S band amplifiers, and on various amplification methods related to Raman amplification [8], hybrid Raman EDFA [25] and thulium doped fluoride amplifiers [2] are used to amplify signal in the S band amplifiers, which consist of silica based (doped with erbium) fiber [43]. In figure 5.1, the emission and absorption spectra of Er$^{3+}$ ion in glass host are shown.
Fig. 5.1: Absorption and emission cross section spectra of Er$^{3+}$ ions

We note that in S-band wavelength region, the absorption cross-section is greater than the emission cross-section, that requires high population inversion for S-band amplification. The emission spectrum peaks at order of 1530 nm and the emission cross-section is greater than the absorption cross-section in the C-band of wavelengths, due to this, we can say that the C-band amplification more favourable. Therefore, the C-band ASE becomes S-band amplification in an S-band EDFA. It is obvious that effective S band EDFA needs high inversion levels in direction of the fiber and removing of C band ASE. We observe that the EDFA gain spectrum in S-band is clearly high non-linear and it is very tough to flatten it by using conventional techniques e.g. using discrete diluters or by employing fiber design which have a linear variation of distributed loss (W-fiber design).
Ono et al. (2003) have applied a nine-stage EDFA configuration having eight discrete amplified spontaneous emission filters, one fixed-loss gain-flattening fiber and one tunable gain-flattening fiber are used in between stages to obtain 21db gain with approximate ± 1db gain ripple. Arbore et al. (2003) have shown a two stages S band EDFA consisting of a W indexed fiber which has a basic mode cut-off at 1525 nm. The proposed W-fiber gives distributed losses to C-band amplified spontaneous emission and makes addition for S-band amplification. The obtained gain in S-band is highly non-flat (order of ± 10dB gain ripple). By comparing with multiple-stage configuration having discrete ASE filters, distributed amplified spontaneous emission filtering gives definite benefits in terms of less components, enhanced pumping effective and design simple.

We propose here an effective design for a single stage S band EDFA which is based upon a co-axial core fiber (section 3.2), whereas distributed amplified spontaneous emission filtration is obtained by windowing the fiber alongwith an optimum bend radius. Generally, Bend losses consist of a characteristic spectral changes depending on the change in modal field diameter with wavelengths. By Co-axial fiber design, additional degree of freedom is obtained because the MFD in a co-axial core fiber is fabricated to have strong spectral dependence, which is controlled by the fiber parameters.

Therefore, through optimizing the fiber parameters of a co-axial fiber and the bend radius, we obtain the wavelength below 1525 nm which suffer high bend loss greater than 6db/m, where the minimal loss is suffered by wavelength below 1525 nm. In designed fiber, bend losses at 1530 nm is hundred times larger than bend losses at 1490 nm, so that we get a greater gain in the S band.
proposed simulations, this is also shown that at ~ 25db gain with 30 nm band width (1495-1525 nm) is obtained by using the proposed module, with pumping power of 200 mW. By proper designing we obtain the gain ripple for the total 30 nm band width in order of ± 2.9dB.

An SCF design (see section 4.3) also provides high potential to get an inherently gain flattened S-band EDFA and it is shown that the performance of SCF-based S-EDFA obtained is far better than the one based on co-axial fiber design. The SCF is designed in such a way that the basic mode has leakage losses in C- and S-bands for the entire spectral changes of the losses which is slightly different in both the bands by proper selection of $\lambda_{c1}, \lambda_{c2}$ and the dimensions $b$ and $c$. C-band wavelength have been fabricated to have high leakage losses (the problematic amplified spontaneous emission is completely removed), where the signal wavelengths of S-band are proposed to have less leakage losses, that is just enough for compensating the signal gain tilt. We provide here, the characteristics of amplifier for the designed S-band EDFA, and in proposed simulation, it is shown that the 20db gain consisting of ± 0.9 db gain ripple with 30 nm band width in S band is obtained for the design.

5.2 Co-axial fiber design for S-EDFA

5.2.1 Fiber profile and basic principle

Co-axial fiber design is applied in many applications like dispersive compensation [69], intrinsic gain flattening of EDFA [68], intrinsic Raman gain flattening [66] etc, and also practically observed [5, 37]. The spectral changes of the modal field of the basic super mode is changed by fine tuning the phase matching wavelength (PMW) in a co-axial fiber, that is the wavelength for which the basic modes of
the each core is matched by phase one another. For wavelength below PMW, the mode field is well covered by the inner side core and as the wavelength reaches near to the PMW, the power in outer side core enhances, obtaining for slightly increasing the bend losses. Therefore, for optimum parameters of fiber and the bend radius, the spectral variation of the loss is under control and we can simultaneously obtain a high spectrally varying leakage loss for wavelength in C-band and a small leakage loss for S-band wavelength to the inherent flattening of the signal gain.

5.2.2 Numerical results

The parameters of the two individual cores of the designed co-axial fiber are selected such that each helps a signal azimuthally symmetric mode for the operating wavelength region. For obtaining an S-band EDFA in a co-axial fiber, we requires a strong distinction between the modal behaviour to compare and post PMW wavelengths, therefore, the S-band and C-band wavelength can possess different properties, as field confinement and susceptibility to bend loss. The distinction is obtained by designing the two individual cores which are very dissimilar to each other (in terms of core radius $a$ and numerical aperture, NA). The NA and $a$ combination shows variation of the mode in the $n_{eff}$versus wavelength; by narrowing the core, steeper is the spectral changes of $n_{eff}$ is obtained and vice-versa. For greatly dissimilar cores, the spectral changes of the effective refractive index of the two individual core modes cross each other by making large angles and because of the superstructure is strong between the behavior of pre- and post- PMW wavelengths. Therefore, we require that the inner core mode shows steepest spectral variation and the outer core mode shows
shallowest spectral variation. Thus, we desire the inner core to have a small $a$ and high NA and the outer core to have a large $a$ and small NA. However, there are few design constraints that need to be kept in mind while designing fiber parameters. One of these is the fabrication constraint; one cannot achieve arbitrarily small/large cores as well as numerical apertures. Second issue is that one must ensure signal-moded operation of both individual cores so that the resulting fiber has least number of modes. For EDFAs, one would like to have single mode-regime up to 980 nm (the pump wavelength). The inter-core separation $b-a$ also governs the curvature of the spectral variation of $n_{eff}$ of the supermodes and hence provides an additional degree of design freedom. We have optimized the fiber profile keeping all the afore-mentioned issues and constraints in mind, and the optimized fiber parameters are $a= 1.6 \ \mu m$, $b= 10.5 \ \mu m$, $c= 15.6 \ \mu m$, $\Delta_1= 1.2\%$ and $\Delta_2= 0.4\%$, by getting a PMW of order of 1525 nm. Figure 5.2 shows the spectral changes in effective indices of fundamental mode in the each core and in superstructure. The refractive indices and the modal field distributions are evaluated by using the standard matrix method.
Bend losses are determined by using the analysis which is given in [62]. It is shown in fig. 5.3 that the spectral changes of bend induced losses in proposed fiber, having a bend diameter equal to 3 cm, it possesses less bend losses below 1500 nm and a slight increment in the bend losses over 1525 nm. The other curves in the figure present typical bend loss variations that are simultaneously achieve low bend loss in S-band wavelength region along with a high bend loss in the C-band, using a standard SMF.

In designed fiber, we use the formulation shown in Chapter 2. To determine amplified simultaneous emission, 100 nm emission band width (1450 to 1550) nm, is splitted in 100 wavelength in which each slot having 1 nm width. Sixteen equal distant signal channels from width 1495-1525 nm are used in simulation. The proposed EDFA has a single stage amplifier having 4.7 m of co-axial core
EDF wounded 3 cm bend diameter. The inner side core region for which $0 < r < a$ is doped with Er$^{3+}$ in which concentration of ions is $1.7 \times 10^{25}$ m$^{-3}$. In fig. 5.4, the dashed curve represents the normalized forward side amplified simultaneous emission spectral density changes at the output of 4.7 meter long EDF, which is pumped by 200 mW pumping power at 980 nm, when there is no signal.

We observe that amplified simultaneous emission power is mainly concentrated around 1530 nm with negligible amplified simultaneous emission content in the S-band of wavelengths. The solid curve represents the amplified simultaneous emission spectral density for the same fiber wounded.

It is obvious from the figure that the amplified simultaneous emission spectrum is moved towards short wavelength side and a larger part of amplified simultaneous

![Graphs showing normalized forward ASE power and population inversion along the length of straight and bend co-axial fiber.](image)
emission power in the S-band. It is shown in figure 5.5 that the variation for population inversion \((N_2 - N_1) / N_1\) is in the direction of fiber length. The removal of C-band amplified simultaneous emission in a bent co-axial fiber increases the population inversion appreciable and aids in S-band amplification, it is because of saturation due to backward amplified simultaneous emission. In figure 5.6 the simulated gain spectra of proposed module is shown.

The solid curve represents the gain spectrum with the entire input power \(P_s\) (in) = -8 dBm having 200 mW pumping power at 980 nm. We observe gain of 25 dB consisting of \(\pm 2.9\) dB ripple is obtained with 30 nm band width in S-band. The dotted curve represents total signal input power -1 dbm in a 4 meter long EDF proposed, which is obtained by optimizing length for saturated gain region. The dashed curve represents the spectral changes of the noise, having range from 4.5 db 8 db with 1495 nm to 1525 nm. The splice losses of the module is obtained.
in order of 2.5 db. Since, the splice quality may be modified by tapering the fiber at both ends, therefore, at the joining of splices, the basic mode of the designed fiber by choice becomes appreciable because the splice losses are reduced.

When we change the radius of bend, results in changing of magnitude and the spectral changes of bend losses are obtained, so that the amplifier characteristics become modified. We maintain the bend diameter as constant and reduce the effects of bend induced birefringence are the main issues related to the designed amplifier configurations. These issues are well resolved through annealing process of the coiled fiber [63].

The sensitivity of amplifier working is determined toward accuracy in radius of bend. In figure 5.7, solid curve represents the simulated gain spectra of the designed module consisting of a constant bend diameter (3 cm) and the dotted curve concerning with half of the fiber length wounded over a bend whose diameter is of 2.9 cm and the rest half wounded with a bend whose diameter is of 3.1 cm. By changing the bend diameter to ± 1 mm, we observe that the gain of fiber amplifier is obtained very good. Tolerance with variations in fiber parameters is generally controlled by the effect on the PMW, since the working of the designed amplifier based on the PMW. A simple method to resolve the problem, is to characterize the working of fiber primarily and thereafter controlling the pulling speed of fiber showing to scale the parameters of fiber in such a way that required PMW is obtained [52].
5.3 Segmented clad fiber design for S-EDFA

5.3.1 Fiber profile and basic principle

The SCF design proposed in section 4.3 is able to provide sharply distinct spectral variations of leakage loss in two adjacent wavelength bands. The SCF profile is a modification of conventional W-fiber design and having an additional depressed clad layer by which the leakage loss of the fundamental mode is altered and additional tenability of the spectrum is provided. The profile is characterized by two particular wavelengths $\lambda_{c1}$ and $\lambda_{c2}$ ($>\lambda_{c1}$), and expressed as following: at $\lambda_{c1}$, effective index of basic mode ($n_{eff}$) begins to work in a leakage mode; at $\lambda_{c2}$, the effective index makes equal the inner side claded refractive index ($n_3$) (in Fig. 4.8). Therefore, we have two particular operating wavelength regimes in the leakage mode of wavelength $\lambda_{c1} < \lambda < \lambda_{c2}$ and $\lambda > \lambda_{c2}$ for which $n_2 < n_{eff} < n_3$.

For an EDFA depending on an SCF design, inherently gain flatten is obtained with distributed C band amplifier spontaneous emission filtration, the leakage losses are given to S band wavelengths, that is enough to compensate the spectral changes of gain in the S band. Since the spectral changes of the leakage losses taken place by the fundamental mode is well tuned by wavelengths of C-band and a small losses (0-5db/m) having an optimized spectral variation is given to the S-band wavelengths to get inherent gain flatten S band EDFA for the designed SCF, the fiber parameters are $\Delta_1 = 1.7\%$, $\Delta_2 = 0.2\%$, $\frac{b}{a} = 12.7$ and $\frac{c}{a} = 34$, results $\lambda_{c1} = 1497$ nm and $\lambda_{c2} = 1524$ nm. The distance between b to a and c to a is optimized in such a way that leakage losses in the S band ($\lambda_{c1} < \lambda < \lambda_{c2}$) is small and that is enough to make flat the gain and the leakage
losses in C-band ($\lambda < \lambda_{c2}$) is sufficient to filter out the C-band amplified spontaneous emission.

In figure 5.8, the leakage loss spectrum of the proposed fiber is shown. We observe the drastic change in slope of the losses curve for wavelengths whose values lie inside ($\lambda_{c1} < \lambda < \lambda_{c2}$) and outside ($\lambda_{c2} = 1524$ nm) the signal band.

![Fig. 5.8: Leakage loss of SCF optimized for S-Band EDFA](image)

![Fig. 5.9: Gain and Noise Figure of S-Band EDFA](image)

5.3.2 Numerical results and discussion

In figure 5.9, it is shown that the gain and noise spectra achieved with the designed S-band EDFA module in the situations of different input power. Sixteen equal distant altogether signal channel with 1495-1525 nm are included in our simulation. For input power of signal of $8$ db.m, approximately $20$ db gain consisting of a gain ripple of $\pm 0.9$ db is presented to obtain with our design with help of $125$ mW pumping power at $980$ nm. We observe that noise figure of the amplifier below $8$ db for entire operating signal wavelength region. In fig. 5.9, it is shown that gain flatten amplification is determined for different saturating circumstances by re-optimizing the length of fiber length and pumping
power in the proposed module. The designed amplifier requires to splice the ideal G.652 fiber, the insertion losses of device is calculated by the splice losses at the both end. To decrease the splice losses, we consider the G.652 fiber which is being tapered upto 45% and segment claded fiber being tapered upto 35%, to obtain excellent modal field overlapping. The determined splice losses of the proposed module is less than 1 db for total signal wavelength region. Gain flattening may be also maintained for a fluctuation in input pumping power. Simulations show that gain ripple changes from ± 0.9 db to ± 1 db, for a ± 25 mW variations in pumping power. We did a tolerance analysis for getting gain flatten in designed S band EDFA module, corresponding to different fiber parameters. The analysis elaborates that leakage losses and its spectral changes in the S-band that basically controls the flattening of gain in the proposed EDFA. If the distance between $b$ to $a$ is changed, the quantity of leakage loss per meter will be changed. So that the gain flattening is maintained by taking the optimum fiber length and pumping power. In figure 5.10 it is shown the EDFA gain spectra for SCF by applying different values of parameter $b$, while maintaining rest parameters as a constant as in Fig. 5.9. In the figures, ‘Dev’ denotes the shifting from standard fiber profile, having its subscript with respect to fiber parameters.
In figure the dashed and dotted curves explain $\pm$ 2% changes in value of parameter $b$ corresponding value in the ideal profile that is represented by solid curve. It is clear that the gain ripple ($R$) changes from $\pm$ 0.9 dB to $\pm$ 1.4 dB with parameter a $\pm$ 2% changes in parameter $b$. In every condition, the length (L) of fiber and pumping power ($P_p$) are optimized for obtaining maximum flatness in the gain. A similar procedure is performed for the parameter $c$ (see Fig. 5.11). Here, the gain flattening is changed from $\pm$ 0.8 dB to $\pm$ 1.1 dB with a $\pm$ 2% changes in value of parameter $c$. The changes in core parameters and refractive index results a change in $\lambda_{c1}$ and $\lambda_{c2}$ which modify the leakage losses spectra. The effect is properly compensated by optimum the erbium ion concentration which is used in manufacturing process and the pumping power and length of fiber is applied in the amplifier. The working of our proposed
module is examined with a ± 1 changes in refractive index ($n_1$ and $n_3$) and gain flattened operation is being hold good in all cases (in figs. 5.12 and 5.13.)

In both cases, the erbium ion concentration and the fiber length is re-optimized. The result of changing in refractive index $n_2$ and parameter $a$ is identical to that of $n_1$, so that it is applied in a similar way. We Scale the fiber dimensions and set the pulling speed in process of fiber drawing, which gives an extra tool to achieve required values of cut-off wavelengths in case where we change the values of parameters of the core ($a, n_1, n_2$).

5.4 Conclusion

We have discussed two novel amplifier designs for S-band amplification and a small wavelength dependent leakage loss to S-band wavelength (for compensation of signal gain tilt) to achieve efficient, inherent gain flatten S band erbium
doped fiber amplifier. This is an innovative result and first time in our knowledge that inherent gain flatten S band amplification is being achieved using erbium-doped fibers. The proposed designs are signal stage units and need only reasonable pump powers (approximately 100-300 mW) at standard 980 nm wavelength to provide gain greater than 20 db with less than \( \pm 1 \) db gain ripple for a 30 nm band width in S band.