CHAPTER 4

HIGHLY NONLINEAR FIBER DESIGNS WITH INHERENTLY FLATTENED HIGH RAMAN GAIN AMPLIFIERS

In this chapter, we present two highly non-linear fiber (HNLF) designs for realizing discrete Raman amplifiers having high net gain (greater than 20 dB). The amplifier gain is inherently flattened by changing the spectral changes of distributed leakage losses to the basic mode, in the proposed fibers. Based on the proposed fibers, broadband, high Raman gain amplifiers have been designed and detailed amplifier characteristics have been modeled.

4.1 Introduction

A lot of interest is being developed by researchers in discrete Raman fiber amplifiers which are based on highly nonlinear fibers, having greater effective Raman gain coefficient (~ 6.7 W\(^{-1}\) per km) [39, 72], in contrast to about 0.6 W\(^{-1}\) km\(^{-1}\) in standard. Single mode fibers and approximately 2.5-3 W\(^{-1}\) per km in high Germania doped fibers like dispersion compensating fibers (DCF). The conventional HNLF\(_s\) fibers are generally based upon depressed clad (W shape) refractive index profile, that is fabricated for having less effective area (~10 \(\mu\)m\(^2\)), greater numerical aperture with having less background attenuation, resulting to high Raman gain. Because Raman gain is generally and spectrally non-flat, methods like multiple pumping [1] or spectrally broadband pumping along with gain equalizers [72] are applied for gain flatten. Multiple pumping method is not very suitable for getting gain flatten high Raman gain because the
spectral gain tilt is higher for higher gain, and therefore, the number of pumps needed for flattening high gain amplifiers is much larger than that required for flattening low gain amplifiers. The multiple pumping methods needs special design techniques for determining the suitable wavelengths and power levels to obtain a flatten spectra. This method is very costly and hence cannot be implemented. We have discussed a co-axial [66, 67] and an asymmetric double core fiber [27] design. In our proposal, the value of the effective Raman gain coefficient is very small (~1 W⁻¹ km⁻¹) doe to relatively high area and therefore, the proposal is unable to use for getting high gain in Raman fiber amplifiers. We have proposed the technique for obtaining inherently Raman gain flatten in high Raman gain W shape fiber [28], that is obtained when we use the wavelength based leakage loss of the basic modes.

In an ordinary fiber design, effective Raman gain γ_R is increased monotonically with wavelength when it does not reach to its maximum value. We have discussed detailed characteristics of the Raman amplifier based on the proposed fiber, and have shown that 21db gain with ± 1.4 db gain ripple for 25 nm band width can be obtained when we use only one pump at 1450 nm.

We also propose a segment claded fiber (SCF) design [29], that can further improve the Raman gain ripple to ± 0.5 dB for same magnitude of net gain. An SCF design is a modification of W-fiber and it provides additional degree of design freedom so that the loss and gain spectra can be better mtched, leading improved of leakage loss and promise to find applications in tunable wavelength filter, gain flattened S-band EDFAs (see Chapter 5) and L⁺- band thulium doped fiber amplifiers (see Chapter 6).
4.2 W-fiber design

4.2.1 Fiber profile and principle

Leaky modes are interesting for researchers who are working in the area of fiber optics, due to their detrimental effect [12, 71] based on working of depressed inner-claded single mode fibers (see Fig. 4.1), which provides excellent dispersion-compensating as well as dispersion-flattening properties.

![Refractive index of a W fiber design](image)

Fig. 4.1: Refractive index of a W fiber design

A W-fiber consists of a basic mode cut off wavelength, $\lambda_c$, over which the basic mode works such as a leakage mode and provides a distributed leakage loss. A few applications by utilizing leakage modes are shown and some of them, consider tailoring of transmission spectra having a long period grating by joining into leakage claded modes [60], getting assisted joiners use leakage modes [9].
and change the EDFA gain spectra to S band wavelength by drawing the basic mode to the C-band wavelengths [4].

The leakage loss obtained by the basic mode is increased firmly with increasing the wavelength and its spectral changing is obtained which is approximately linear [12]. The spectral changing in leakage loss is modified by varying the separation \( b - a \), in the core and outer cladding. Therefore, when fiber parameters are optimized, we obtain several spectral changes in the leakage losses over the operating wavelength regime \( \lambda > \lambda_c \) and therefore, the increment in the leakage loss corresponding to wavelength may be ordered to compensate for the large gain coefficient for longer wavelengths for achieving the inherent flatten gain. In this design, the presence of leakage loss does not change the model field confinement significantly, high Raman gain can be obtained along with inherent gain flattening. This is the main and fundamental law for the inherent gain flatten high gain, discrete Raman fiber amplifier.

4.2.2 Numerical modeling and result

Leakage modes are modeled using the analysis given in [65]. The optimum W profile for getting an inherent gain flatten, large gain Raman amplifier is provided by \( \Delta_1 = 2.1\% \), \( \Delta_2 = 0.43\% \), \( a = 1\mu m \) and \( b = 18.2 \mu m \), by which we ensure a cut-off wavelength of 1524 nm. Here, \( \Delta i \) is defined as \( (n_i^2 - n_3^2) / 2n_3^2 \), \( (i=1, 2) \); and \( n_3 \) is the refractive index of pure silica (calculated by using Sellemeir’s equation [21]). Figure 4.2 represents the leakage losses spectra of the proposed fiber.
The leakage loss in our design is finely tuned by changing the depressed clad region; in our design, the leakage losses generally change from 0.1 to 2.5 db/km for 1524-1545 nm.

Amplifier modeling is being done by following the analysis given in Chapter 2. In our proposed simulations, we include the effect of spectral changing of background attenuation for a high delta fiber and for the splice loss with standard transmission fiber (G.652). To decrease the device insertion loss, we consider the G.652 fiber, which is being tapered up to 40% and the W fiber is being tapered up to 45%, that provides excellent modal field overlapping.

The leakage loss affects the variation on net Raman gain spectrum, that can be understood from Fig. 4.4. obviously, the Raman gain spectra for various slope ($S$) of leakage losses spectrum, $S = 0$ describes the condition where leakage losses are not taken place, that is, the outer cladding is absent.
Different slopes of leakage loss spectra are obtained varying the distance $b - a$, all the other fiber parameters are kept as constant. The noise properties of proposed module is suppressed by using bi-directional pumping method [18], rather than using contra directional method. It is shown in figure 4.5, that the net gain, OSNR and NF spectrum, where the pump power is divided in a forward operated pump (100 mW) and a backward operated pump (220 mW) power. In figure, the dotted curve represents net gain of the bi directional orientation, that is approximately similar to the contra directional configuration.
4.2.3 Tolerance analysis: W-fiber design

We also do the tolerance analysis for our proposed module. It is clear that gain flattening is retained by slightly adjustments in input power with variations in fiber parameters. The gain fiber length is kept same in all orientations. Figure 4.6 and 4.7 explain the changing in gain spectra with changing in refractive index $n_1$ and the dimension $b$.

![Fig. 4.6: Net gain with a change in $n_1$](image1)

![Fig. 4.7: Net gain with a change in $b$](image2)

If we vary the core radius $a$ and refractive index $n_2$, we observe the same effect as because of $n_1$; for the fundamental mode, these changes basically cause to a shifting in cut off wavelength. Because the leakage losses of the basic mode are less than 2.5 db per km, the effective index of this mode is near to that of outside claded refractive index and in the core, the modal field is properly confined. Since the distance between the core and outer claded varies such that $b$
/ a~ 18, the induced loss effect corresponding to bend becomes negligible even if the bend radius is 6 cm. By using the analytical technique discussed in [35], we verify that if the bend radius becomes higher than or equal to 6 cm, the curve corresponding to leakage losses in the bent fiber are almost same to the leakage losses of the straight fiber.

4.3 Segmented-clad fiber design

The W-fiber design possesses an almost linear spectral variation of leakage loss, and its slope is adjusted by varying the parameter $b - a$. The spectrum of W-fiber design is translated on the wavelength scare by changing the cut off wavelength of the fiber (decided by $a, n_1, n_2$). The loss spectrum can not be well tuned to much the signal gain tilt exactly. For getting a fine matching between the leakage loss spectrum and the amplifier gain, we propose an innovative segment claded fiber (SCF) design, where the spectral changes corresponding to the leakage loss begin to non linear.

4.3.1 Fiber profile and basic principle

In figure 4.8 it is shown that the refractive index profile of the designed segmented-clad fiber with a three-segment cladding.

Fig. 4.8: Refractive index of SCF

Fig. 4.9: Leakage loss in W-fiber and SCF designs
The profile is accessed by two particular wavelengths \( \lambda_{c1} \) and \( \lambda_{c2} (> \lambda_{c1}) \), which is defined as following: at \( \lambda_{c1} \), the effective index of basic mode \( (n_{\text{eff}}) \) is equal to the outer side claded refractive index \( (n_4) \) and the basic mode begins to work as a leakage mode; at \( \lambda_{c2} \), the effective index is equal to inner side claded refractive index \( (n_3) \). Therefore, for the leaky mode, two particular wavelength regimes of operation:

\[
\lambda_{c1} < \lambda < \lambda_{c2} \quad \text{(where } n_3 < n_{\text{eff}} < n_4)\]

and

\[
\lambda > \lambda_{c2} \quad \text{(where } n_2 < n_{\text{eff}} < n_3)\]

Generally, the spectral changes of leakage loss is approximately linear in a leakage mode, and the variation slope is well controlled by the distance between core and greater indexed outer side cladding. Here, the greater is the distance, the less is the leakage loss, and vice versa take place. so that, in the designed SCF, in wavelength region \( \lambda_{c1} < \lambda < \lambda_{c2} \), the spectral changes in leakage loss is well controlled by the distance \( c-a \), and for \( \lambda < \lambda_{c2} \). By governing the dimensions of \( b \) and \( c \), the spectral changes corresponding to leakage losses in both particular wavelength regimes is finely tuned and independent. The selection of \( \lambda_{c1} \) and \( \lambda_{c2} \) is controlled by the wavelength range of required signal band; and choice of \( \lambda_{c1} \) and \( \lambda_{c2} \) ensures the refractive index of profile and core radius \( a \).

The parameter \( b \) and \( c \) are selected in such a way to obtain compensation for signal gain tilt correctly by desired leakage losses in given signal band. Higher degrees of design freedom provide an SCF profile allows almost exact matching between the leakage loss spectrum and the signal gain spectrum, for maximum tilt compensation. therefore, we draw different leakage losses spectrum (achieved
by changing fiber parameters), in an SCF profile and for an ordinary W-fiber profile in Fig. 4.9. An SCF profile is particularly useful in applications where drastically different leakage loss variations are required in different wavelength regions (S-band EDFA, discussed in Chapter 5).

4.3.2 Numerical modeling and result

The leakage loss, refractive indices and modal fields of the mode in the proposed SCF can be achieved by solving complex eigenvalue equation using matrices method [65]. The optimum SCF profile for getting inherent gain flatten Raman amplifier is realized by $\Delta_1 = 2.0\%$, $\Delta_2 = -0.2\%$, $\Delta_3 = -0.02\%$, $b/a = 16.8$ and $c/a = 27$, cause to $\lambda_{c1} = 1491$ nm and $\lambda_{c2} = 1512$ nm. Figure 4.10 describes the leakage loss spectrum of proposed fiber.

![Fig. 4.10: Leakage loss of SCF optimized for high gain discrete RA](image)
The leakage losses in the proposed fiber is finely tuned by changing the breadth of depress claded regime, and in optimum fabrication, the leakage loss changes from 0.04 - 3.3 db per km to 1491 – 1516 nm. Spectral variations of attenuation and splice loss are considered in the case of W-fiber design. To decrease the splice losses, we consider the G.652 fiber, which is being tapered upto 40% and the Segment claded fiber is being tapered upto 45%, that provides excellent modal field overlapping. The splice losses of the proposed module is obtained < 0.2 db for whole signal wavelength range.

The proposed high-gain Raman amplifier is a signal stage module which provides 19.8 km of segmented-clad fiber and 500 nW of pumping power at 1433 nm. Eight signal channels having equal spaced from 1488-1516 nm are taken in simulation. They provide total input power of 1-10 db.m, 20 db net gain with ± 0.5 db gain ripple is obtained for 28 nm band width (1488-1516). In figure 4.11, it is shown that the gain, OSNR and noise figure spectra for our module, with different input signal power circumstances.
The Raman gain spectrum in this case is shown in figure 4.12. It is obvious from the figure that the gain ripple (R) in every case is greater than ±0.7 db. $P_f$ and $P_b$ represent the forward side and backward side pumping power.

4.3.3 Tolerance analysis: SCF design

We also did tolerance analysis in detail, of the designed amplifier with changing the fiber parameters. The two representative results of this analysis are shown in figures 4.13 and 4.14.
Here L represents the optimum fiber length. ‘Dew’ represents the perturbation from standard fiber profile having its subscript refer to respective fiber parameter. In figure all parameters remain equal. We notice from the figure that gain flattening is effectively achieved when fluctuation takes place in fiber parameters, by re-optimizing to the fiber length.

4.4 Dispersion properties of the proposed module

The advantage of the proposed fiber (both W-fiber and SCF) is that they have a gradually changing negative dispersion coefficient having values from 83 to 84 ps per nm, for respective wavelength operating range. This indicates that the designed discrete amplifier module (e.g 13.6 km W-fiber) possesses a dispersion having values 1135.6 ps per nm and able to compensate the collective dispersion
of about 70 km of ideal transmission fiber (G.652) for full wavelength operating regime. The SCFs compensate partially for collective dispersion of 105 km of ideal transmission fiber (G.652) for full wavelength operating regime. In figure 4.15, it is shown that the residual dispersion spectra of transmission via 105 km of G.652 fiber and 19.8 km of proposed fiber.

![Residual dispersion with wavelength](image)

Fig. 4.15: Residual dispersion with wavelength

Therefore, the proposed modules are composite amplifiers and dispersed compensating unit over 25-30 nm band width in S-band, that is able to handle attenuation and dispersion of the length of G. 652 transmission. The designed modules are of low cost than the ordinary configuration
4.5 Conclusion

We propose here two highly non-linear fiber designs (W-fiber and segmented-clad fiber design), which are able to provide high net Raman gain (> 20 dB) with inherent gain flattening (< ± dB ripple) by using a signal pump. The amplifier gain is inherently flattened matching the spectral changes of leakage loss of the basic mode through the spectral changes of the amplifier gain, in our proposed fibers. Broadband amplification order of 30 nm gain-bandwidth can be achievable with S-band and the flattened gain-band can be transferred to any wavelength window by selecting the fiber parameters and pumping wavelength. The designed modules are able to partially compensate for accumulated dispersion during transmission for 70 to 100 km of ideal signal mode fiber (G.652). Therefore, the designs fibers are proposed to compensate the loss and attenuation of about a span of G.652 transmission.