CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

Optical fiber communication has revolutionized the field of long-haul data communication by its immense information carrying and lower transmission losses as compared to its electrical counterpart-the coaxial cable. Since the carrier frequency in optical fiber communication lies in the optical domain, bit rates in excess of 10 Gigabits per second (Gbps) can be supported with a single wavelength, which is equivalent to sending 150,000 voice channels simultaneously through a single optical fiber. Information is sent through optical fibers via digital optical pulses and as these pulses are propagated along the fiber, they are attenuated. The present generation of optical fibers offer losses of ~0.25 Db/km around C-band of wavelengths (1530 to 1565 nm). For error free detection at the receiver end, the signal pulse power must be above a certain threshold level defined by the receiver sensitivity. Hence, during the course of transmission over long distances, the pulses need to be amplified at regular intervals. This can be done ether by electronic regeneration or by optical amplification. Optical amplification has advantages in terms of bit rate transparency, lower noise levels and lower insertion losses. Also, a wide range of wavelengths can be amplified simultaneously by the same optical amplifier, which makes optical amplifiers mostsuitable for WDM systems.

There are two classes of optical fiber amplifiers –doped fiber amplifiers (Erbium-doped, Thulium-doped, Praseodyium-doped etc) Nonlinear effects amplifiers (Raman, Brillouin-, Parametric-amplifiers etc.) In doped d fiber amplifiers, optical amplification
is done by the process of emission of photons (stimulated) by excited rare earth ions doped in silica fibers. Amplifiers based on nonlinearity, usually employ a high power pump light launched into the fiber, which gets frequency shifted to signal wavelengths (by the effect of different nonlinear phenomena) and thus causes signal amplification. Erbium doped fiber amplifiers (EDFA) [16] are the most popular optical amplifiers, which typically consist of a short lengths of erbium-doped fiber (∼ 20-30 meters) pumped with ∼50-100 mw of power at 980 or 1480 nm. Standard EDFAs can easily compensate for accumulated loss in one full span of the transmission (∼80 km length with loss ∼ 0.25 db / km). EDFAs are a well established technology now and are used invariably in all long distance optical fiber systems.

Raman fiber amplifier is one of the important fiber amplifiers [26]. RFA works on the theory of stimulated Raman scattering (SRS) in silica and Germania, which are the two main constituents of an optical fiber. In the process of SRS, an incoming photon undergoes inelastic scattering by phonons (vibrational quanta of energy) of the medium and as a result, it gets either downshifted in frequency (Stokes photon) or upshifted in frequency (Anti-Stokes photon). Thus, the incoming photon either gains energy from the phonons of the medium or loses energy to them. The Stokes process is more probable and is therefore utilized in realizing RFAs.

In a practical RFA, an incoming high power (> 200mw) pump waves is co-launched with signal waves into the optical fiber, which loses its energy to signal waves by the process of SRS. The Raman gain coefficient (RGC) provides information regarding material property of the medium, and its magnitude depends directly on the frequency shift in the pump and signal wave. Hence, We choose a
suitable pump wavelength and Raman amplification is obtained in any wavelength band. Since Raman amplification requires no special dopants, the normal transmission fiber can be taken as the gain medium and this configuration is known as distributed Raman amplifier (DRA). When special fibers are used as gain medium, the configuration is termed as discrete as Raman amplifier. In Chapter 2 of the thesis, we have reviewed the basic physics behind Raman fiber amplifiers and rare earth doped fiber amplifiers and have developed comprehensive models for simulating the performance of these amplifiers.

One of the important issues associated with optical fiber amplifiers used in wavelength division multiplexed (WDM) system is the gain is wavelength based, which leads to a discrepancy in optical powers of various channels, and thus, limits the amplifier bandwidth. Moreover, amplified spontaneous emission (ASE) at high gain wavelengths may cause gain saturation, which would further affect the performance of low gain channels. In amplifiers having spectrally narrow undesirable features (a peak or dip) in the best option for flattening the amplifier gain. An excellent example of this is the suppression of 1530-nm peak in the C-band gain spectrum using erbium doped fiber amplifier (EDFA) by using discrete filters like thin film interference filters, fiber gratings, Mach-Zhender filters (like L-and S-band EDFAs, Raman amplifiers etc.) distributed gain flattening techniques, which flatten the gain a distributed manner are more efficiently done than the use of discrete filters. Some of these distributed techniques are multiple pumping in Raman amplifiers [19], hybrid configurations of amplifiers [36, 59], changing the hosts in doped-fiber amplifiers [75, 76] or by modifying the fiber designs to alter the spectral evolution of gain along the fiber length [68, 69]. In
this thesis, we have explored novel fiber designs for inherently flattening the gain of optical fiber amplifiers, and we have applied these designs to RFAs as well as doped fiber amplifiers.

Various algorithms are present in literature to obtain a flatten gain spectra (~ 100 nm) [19]. In chapter 3 of this thesis, we investigate inherent gain flattening in Raman fiber amplifiers by tuning the spectral properties of fundamental mode field in the fiber. We have proposed a co-axial fiber profile and an asymmetrical twin core(ATC) fiber profile, which allow us to modify the spectral variation of effective area of Raman interaction in these fibers, leading to inherently flattened Raman gain. The proposed fibers also have high negative dispersion coefficient over large bandwidth; we have designed broadband, lossless dispersion by inherently gain-flattened Raman amplification. We compare the designs for lossless dispersion compensating modules with dispersion compensating Raman amplifier (DCRA) modules and we obtain that our modules are better and of low cost.

Recently, a lot of interest has been shown by researchers in discrete Raman amplifiers using nonlinear fibers, which are of high effective RGC (around 6.7 W$^{-1}$ km$^{-1}$ ) [39, 72], in contrast to around 0.6 w-1 km-1 in ideal single mode fiber and around 2.5-3 W$^{-1}$ km$^{-1}$ in high germania doped fibers like dispersion compensating fibers (DCF). As we know that the Raman gain is spectrally non-flat, therefore, the methods using multiple pumping [1] or spectrally broadened pump [72] are used for flattening the gain.

Multiple-pumping method is not very well suited for flattening Raman gain because the spectral gain tilt is much more in high gain amplifiers, and thus, the
number of pumps required for flattening high gain amplifiers is much larger than that required for flattening low gain amplifiers. In chapter 4 of this thesis, by using the wavelength dependent leakage loss of the fundamental mode we achieve the inherent Raman gain flattening. W-fibers are traditional candidates for highly non-linear fibers (HNLFs) because in these fibers, effective areas as small as 10-15µm2 are achievable. However, Raman amplifiers realized using such HNLFs still have a non-flat spectral variation of gain (∼ 4.5db over 25 nm bandwidth). In contrast to conventional W-fibers, we have designed the W-fiber in a manner that for most of the signal wavelengths, the fundamental mode works in leakage mode with a small, wavelength-dependent leakage loss, that is required for compensating the Raman gain tilt.

To further improve the Raman gain-flattening characteristics, By modifying W-fiber profile, we have proposed a segmented-clad fiber (SCF) design. An SCF profile contains an additional depressed cladding layer, which provides extra degree of design freedom to tune spectral variation loss. As a result, the loss spectrum could be matched more closely to the gain coefficient spectrum and gain flatness is improved to ± 0.5db. The advantage of both the fibers (W and SCF) is that they also have high dispersion coefficient and so, along with loss compensation, the accumulated dispersion can also be compensated by proposed discrete amplifier modules. The designed modules are thus proposed here as an amplifier and dispersive compensating units from 25 to 30 nm bandwidth in S band, that are able to control attenuation and dispersion of a signal.

This is observed that the emission spectra of various rare earth ions (e.g.,Er3+, Tm3+), used in doped-fiber amplifiers, extend over large bandwidth but the usable
gain-bandwidth is very narrow because the wavelengths around the transition peak (for which the gain is maximum) usually suppress the amplification of wavelengths with lower gain coefficient. Even if there are no signal channels corresponding to the peak gain wavelengths, the amplified spontaneous emission (ASE) at those wavelengths becomes strong enough to deplete the pump and forbid amplification of lower gain wavelengths. We have proposed fiber designs which have high distributed loss (due to leakage or bend) at the peak gain wavelengths so that the unwanted ASE gets suppressed along the fiber length and the amplification at shorter wavelengths get enhanced. In our proposed designs, a small distributed loss, with an optimized spectral variation, is given to the signal wavelengths, that is able to compensate for the spectral gain in the signal band. Our proposed designs give us the flexibility of having different loss variation in two adjacent wavelength bands (the signal band and the unwanted longer wavelength ASE band), which helped us in designing high efficient and inherently gain flatten S band EDFA.

In Chapter 5 of the thesis, we present here, two fibers for getting inherently gain flatten S-band EDFA. In literature, there are many phenomena take place in S-band amplifiers [8], hybrid Raman-EDFA configuration [25] and thulium-doped fluoride amplifiers [2] are studied for amplifying signals in the S band. S Band Amplifiers are consisting of silica based fibers doped with erbium are also discussed [4, 43] and it is proved that S band EDFAs need high population inversion levels with removing of C band amplified spontaneous emission, which prevents the process of population inversion. Ono et al. (2003) reported a 21-db gain in S-band by using discrete amplified spontaneous emission filters in each
stage. Arbore et al. (2003) have demonstrated a double stage S band EDFA, consisting of a W index fiber having basic mode cut-off at 1525 nm, that gives losses to C band amplified spontaneous emission. Distributed amplified spontaneous emission filtering provides great benefits by using less number of components involved, enhanced pumping efficiency and simply designed. We propose here an excellent design technique for getting a single stage S band EDFA on a suitably bent co-axial core fiber, so that the amplified spontaneous emission filtration is obtained by winding the fiber by best selecting the bend radius. Bend losses provide strong spectral changes because of changing the mode field diameter (MFD) with corresponding wavelength. Therefore, for optimum fiber parameters and bend radius, we ensure that the wavelengths greater than 1525 nm experience greater bend losses, whereas the wavelengths whose values are below 1525 nm experience minimum losses. In the optimized fiber, bend losses at 1530 nm are about 100 times greater than losses at 1490 nm, this results to a high gain in the S band. Simulations show that ~ at 25 db unsaturated gain for 30 nm bandwidth (1495-1525) nm can be obtained in this configuration, by using a nominal pumping power approximately 200 mw.

A segmented clad fiber (SCF) design also possesses high potential to ensure an inherently gain flatten S band EDFA because in this fiber, the spectral changes corresponding to leakage losses is quite different over two adjacent wavelength bands of operation by optimally choosing the parameters of the two depressed clad layers. We show in Chapter 5 that the performance of SCF-based is even better (gain flatness ~ ± 0.9db ) than one based on co-axial fiber design. The idea of removing longer wavelength ASE to enhance gain in the shorter
wavelength band has also been applied to thulium-doped fiber amplifiers (TDFA). Chapter 6 explores the possibility of L\(^+\) -band (1600-1640) nm TDFA utilizing the \(^3\)F\(_4\)\(^-\)\(^3\)H\(_6\) transition of researchers OF Tm\(^{3+}\) ion in silica, centered around 1830 nm. L-band amplifiers have been of interest to researchers (One et al. 1999) and efforts are done to extend the amplifier band width beyond traditional L-band of EDFA, that extends up to \(\sim\) 1610 nm \[11, 17\]. A TDFA consisting of ZBLYAN, is operated over 1650-1670 nm, has been previously reported \[55\] wherein longer wavelength (1750 to 2000 nm) amplified spontaneous emission was removed by doping the fiber through Terbium (Tb\(^{3+}\)) ions. We have proposed here two noel fiber design bent (W-fibe and SCF design) for realizing inherently gain flatten, floured-bad thulium doped fiber amplifier (TDFA), with over 2 db gain in the (1600 to 1640 nm) band. The inherent flattened amplification using thulium doping has been proposed in this wavelength band.

In all of our proposed designs the inherently gain flatten is obtained by minimizing of high signal wavelengths and simultaneously increment in gain at short signal wavelength by a redistribution of power in signal channels by detailed simulations. This is in contradictory to gain flattening through minimizing of gain at all the wavelengths. Therefore, the proposed designs work much efficiently than conventional designs using discrete filters. We have worked on long period fiber gratings (LPGs) which are important passive optical fiber devices, used in a variety of applications such as wavelength filters, dispersion compensators, sensors etc \[14, 73, 74\]. An LPG is periodic perturbation in the direction of optical fiber length that joins the power of two co-propagating fiber modes. Conventional LPGs joint light from the basic mode into claded modes.
that have 3 db band widths around 6 nm. Presently, an intense interest has been
developed in LPGs consisting of board transmission spectra and gratings and
gratings having band widths of around 63 nm are being reported [53], that finds
many applications in polarization based loss compensators and band selection
filters [14, 53]. We have proposed here an innovative staircase fiber design for
realizing broadband LPGs based on joining between LP$_{01}$ and LP$_{02}$ modes having
20-db band width.