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Gain Flattening and Noise Figure Analysis of a Dual Stage Bowtie WDM EDFA Configuration in C-Band

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Abstract— The paper presents an improved gain flattening and noise figure analysis in the C-band regime using an equalization filter of a dual stage single mode polarization maintaining bowtie erbium doped fiber amplifier. The configuration uses two in-line 980nm laser pumps. The gain and noise figure variation with fiber length, pump power and temperature of the system for C-band communication have been investigated. With equalization filter, a gain and noise figure flatness (p-p) of just 1.1dB and 2.3dB respectively, in 1530-1565 nm BW, for optimized 150 mW and 250 mW pump lasers was obtained. The gain has also shown temperature dependent variation, with minimum fluctuation of 0.71dB at 20^0C. Based on results, the system feasibility as in C-band communication has been discussed.

Index Terms— Erbium doped fiber amplifier, Bowtie polarization maintaining fiber, Giles model, McCumber's equations, C-band, Gain flattening, Noise figure, Equalization filter.

1 INTRODUCTION

The ever increasing demand for high speed data communication over long distances with minimal of losses have paved way for the erbium doped fiber amplifiers (EDFA) as in-line and pre-optical amplifiers and data carrying medium, hence becoming an obvious replacement for electronic regenerative repeaters for low amplified spontaneous noise (ASE) level. It has also shown wide bandwidths, lower noise figure and polarization insensitivity. The EDFA however has been successfully commercialized as a potential mean for data communication in conventional or C-band (1530-1565nm), long or L-band (1570-1620nm) region, and recently possibilities of short or S-band (1460-1530nm) as an effective communication channel have been explored [1, 2].

The introduction of wavelength division multiplexing (WDM) with rare earth doped amplifier such as EDFAs as power boosters and pre-amplifiers have increased the channel capacity to as high as 69.1 Tb/s over 240 km [3]. Figure 1 and 2 shows the standard co-directional EDFA pumped with 980nm laser and the EDFA gain spectrum obtained using EDFA GainMaster™ simulation tool, respectively. Such a wavelength selective variation of gain in case of a multiple wavelength input signal with same power would lead to large output power differences, giving poor signal to noise ratio (SNR) among various channels. This phenomenon gets particularly prominent during small signal analysis. Hence, this largely restricts EDFA application in a narrow band region which is undesirable for optical communication. It can be compensated with inclusion of equalization filters, fiber Bragg gratings (FBG) or Mach-Zehnder interferometer in the system [4]. Other approaches include inherent gain flattened EDFA such as asymmetric twin core (ATC) EDF which has a gain spectrum flattened within ±1 dB over 32 nm range [5].

In case of cascaded WDM systems, use of narrow band filters after each stage would increase ASE and saturate the subsequent amplifiers and hence reduce the gain in each stage. The noise associated with EDFA is due to ASE (forward and backward), which has a spectrum almost the same as the gain spectrum and needs to be reduced, especially the forward ASE, which propagates in the direction of the signal, to make EDFAs more incompatible for long haul communication. Figure 3 shows the noise figure (NF) associated with co-directional EDFA configuration as a function of wavelength.

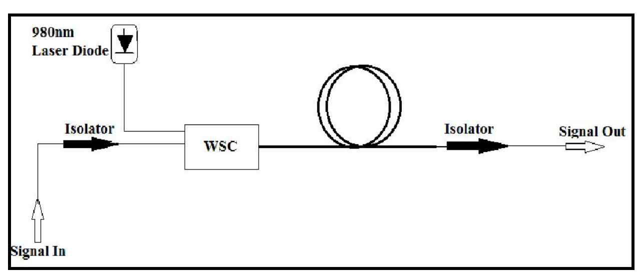

Fig.1. A standard co-directional 980nm pumped EDFA configuration.

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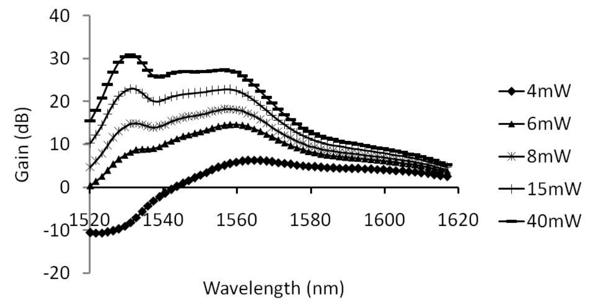

Fig.2. Gain (dB) vs wavelength (nm) for different pump powers in a co-directional 980nm pumped EDFA configuration.

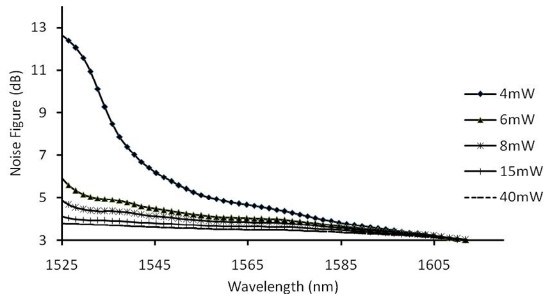

Fig.3. Noise Figure variation with signal wavelengths for different pump powers.

2 EDFA CHARACTERISTICS

Reduction of fiber losses and gain variation depends on the erbium doped fiber and its characteristics considerably. The dual stage configuration presented in this paper is based on specialty polarization maintaining (PM) bowtie single mode (SM) erbium fiber, shown in figure 4. Even though erbium doped fiber (EDF) are polarization independent, but some of the Er^{+3}dopant ions may have certain polarization, giving a polarization dependent gain (PDG). This is because there is a polarization offset between the input signal laser and the pump laser. Other such PM fibers include PANDA and elliptical jacket fiber.

First developed by Optical Fiber Group at University of Southampton in 1982 [6], the bowtie based PM induces birefringence when the fiber core experiences tension due to fiber drawing. This is because the core is guarded by boron-doped glass bow-ties which can shrink more compared to its silica based surrounding cladding. The birefringence produced, allows the incident light along the "slow axis" to travel at lower velocity compared to the light incident along the "fast axis". This velocity change along the two axes makes the cross-coupling of light difficult and rare, maintaining the polarization. Hence, greater is the stress applied; larger is the difference in the propagation constant. Both bowtie and PANDA today find extensive use in telecommunication industry as optical modulators, sensors, interferometers and gyroscopes.

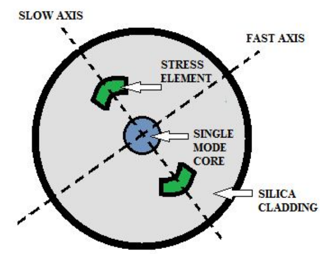

Fig.4. Cross-sectional view of a SM Bowtie EDF

The following table gives all the specifications associated with the bowtie EDF used for the analysis of dual stage gain flattened configuration.

TABLE 1.

BOWTIE EDFA SPECIFICATION

Parameters	Specifications*
Cut-off wavelength	860-960 nm
Numerical Aperature	0.22-0.26
Mode Field Diameter	3.5μm at 980nm 6.0μm at 1550 nm
Pump Absorption at 980 nm	10dB/m (minimum)
Signal Absoption at 1530 nm	12-27dB/m
Attenuation at 1200 nm	Less than 20 dB/m
Fiber Diameter	125μm approx.
Coating Diameter	245μm approx.
Coating Type	Dual Acrylate

Obtained from Fibercore DHB 1500 datasheet. nm = nanometer, μm = micrometer, dB = decibel, m = meter.*

3 EDFA MODELING FOR TWO LEVEL SYSTEM

Modeling of EDFA for simulation and performance analysis is largely based on the landmark work by C.R.Giles and E.Desurvire [7] in 1992. The EDFA model utilizes giles parameters which comprise of the wavelength dependent, absorption coefficient α (λλ) and gain coefficient $g^*(\lambda\lambda)$. The absorption coefficient is also dependent on the erbium ion concentration, and calculated with all laser active ions are in ground state. The gain coefficient or the emission spectra on the others hand is calculated with laser active ions in the excited level. Both α α(λλ) and $g^*(\lambda\lambda)$ are dependent on absorption cross section, $\sigma_a(\lambda\lambda)$ and emission cross-section , $\sigma\sigma_e(\lambda\lambda)$ respectively and given by the equation:

$$\alpha_k(\lambda_k) = \sigma_a(\lambda_k) \cdot \int_0^{2\pi}\int_0^{\infty} i_k(r,\phi) \cdot n_t(r,\phi,z).rdrd\phi \quad (1)$$

$$g_k(\lambda_k) = \sigma_e(\lambda_k) \cdot \int_0^{2\pi}\int_0^{\infty} i_k(r,\phi) \cdot n_t(r,\phi,z).rdrd\phi \quad (2)$$

$$\alpha_k(\lambda_k) = \Gamma(\lambda_k) \cdot \overline{n}_t \cdot \sigma_a(\lambda_k) \quad (3)$$

$$g_k(\lambda_k) = \Gamma(\lambda_k) \cdot \overline{n}_t \cdot \sigma_e(\lambda_k) \quad (4)$$

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Where Γ (λλ) is the overlap factor between the optical mode field and erbium ions (shown in fig.5), which results in stimulation absorption or emission from Er^{3+} transitions and η_t is the total Er^{3+} ion density, which can be measured experimentally using X-ray photoelectron spectroscopy (XPS), also known as electron spectroscopy for chemical analysis (ESCA) [8]. The overlap factor is a function of with □ and r in spherical coordinate system with □ as constant and 'b' is the radius of the Er^{3+} doped region.

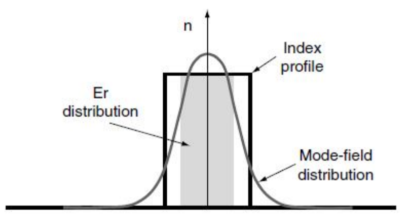
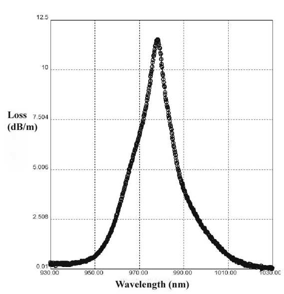
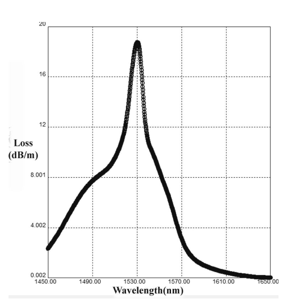


Fig.5. Interaction of Er^{3+} distribution with optical mode field.

These equations are however based on the assumption that parasitic losses such as scattering losses are minimal, Er^{3+} is uniformly distributed in the core and gain is dependent on laser transition only. Fig.6 (a), (b) and (c), shows the absorption parameter for both signal band and pump band, and gain parameter spectra of PM single mode (SM) bowtie EDF obtained from simulation. It is also assumed that no ion-ion interaction is present.



(a)



(b)

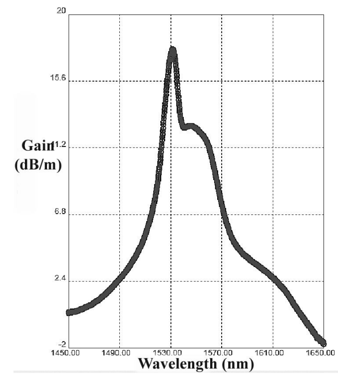


Fig.6. The absorption parameter spectra of (a) pump (b) signal band and (c) gain spectra of Bowtie PM SM EDFA.

The Giles algorithm solves the propagation equation (5) by integrating in both backward and forward direction in an iterative manner until the solution converges.

$$\frac{dp_k(z)}{dz} = u_k \cdot P_k(z) \cdot \left(g_k((\nu_k) + \alpha_k(\nu_k)) \cdot \frac{\overline{n}_2}{\overline{n}_t} - \alpha_k(\nu_k) - l_k \right) + u_k \cdot P_{ok} \cdot g_k(\nu_k) . \frac{\overline{n}_2}{\overline{n}_t} \quad (5)$$

Where, k signifies a definite signal, and u_k is the beam propagation direction with values 1 and -1 for forward and backward propagation and P_{ok} gives the contribution of the spontaneous emission form the local excited state population n_2 and is equal to $mh\nu_k\Delta\upsilon_k$, where m defines the number of polarization modes supported by the fiber.

The fiber saturation parameter ζ ($m^{-1}s^{-1}$) is measured by reducing the 980nm laser pump to the power where it reaches its saturation value. For an equivalent radius of doped region, b_{eff}, it is given by:

$$\zeta = \pi \cdot b_{eff}^2 \cdot n_t / \tau \quad (6)$$

Under steady state condition of the EDFA with uniform distribution for both upper and lower excited states, the steady state equation for population density at the upper level would be [7]:

$$\frac{\overline{n}_2}{\overline{n}_1}(z) = \frac{\sum_{k=1}^{n} \frac{P_k(z) \cdot \alpha_k \nu_k}{h \cdot \nu_k \cdot \zeta}}{1 + \sum_{k=1}^{n} \frac{P_k(z) \cdot (\alpha_k(\nu_k) + g_k(\nu_k))}{h\nu_k}} \quad (7)$$

The intrinsic fiber power saturation, P_{sat} (λ) is given by:

$$P_{sat}(\lambda) = \frac{h\nu A}{[\sigma_a(\lambda) + \sigma_e(\lambda)]\Gamma(\lambda)\tau} \quad (8)$$

Where, h is the Planck constant, ν is the frequency for the signal or the laser pump, A is the area of the doped region and τ is the lifetime of the metastable level.

The major source of noise in case of EDFA is the amplified spontaneous emission (ASE). During EDFA band transition, the stimulated photons are coherent in nature which contributes to amplification; however a photon in the excited state which is not stimulated within a lifetime of 10ms of the exited state contributes to spontaneous emission, which is incoherent in nature and is responsible for ASE noise (forward and backward). For a cascaded EDFA configuration, the ASE keeps on increasing at each successive step, hence reducing the overall gain of the system. This can be attenuated with the introduction of optical filters. But in long haul systems, with 200 amplifiers [9], the 1530nm have shown large attenuation whereas 1560nm peak have shown sharp rise. This shift in ASE power is attributed to wavelength-dependence nature of absorption and emission cross-sections, and saturations of the amplifier at each stage. Recent surveys have shown utilization of backward ASE power for simultaneous gain flattening at C and L-bands [10, 11].

4 RESULTS

The EDFA configuration (as shown in fig.7) under analysis had a multiple source with frequencies ranging from 1530nm to 1565nm with 15 channels of 0.01mW/channel simulated using EDFA GainMaster™. It was coupled with 980 nm pump laser by means of wavelength division multiplexing (WDM) with 200GHz spacings according to ITU standards, to PM SM bowtie EDFA. The output was again coupled to another 980nm pump laser using WDM and its output is filtered using an equalization filter to obtain a relatively flattened gain and NF. Optical isolators were used to avoid backward ASE power back into the source.

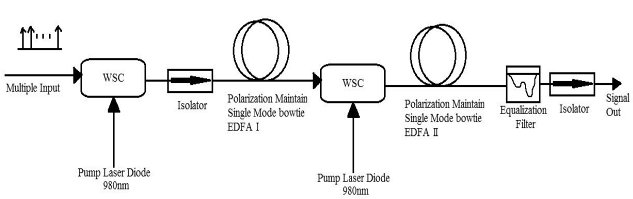


Fig.7. Schematic Diagram of a Dual Stage Gain Flattened EDFA configuration

4.1 Gain Flattened Curve

The gain spectrum for various combinations of pump powers for both the pump lasers was simulated and optimized (shown in Fig.13). It was found that with 150 mW, 250 mW pump power lasers I and II respectively with 5 m EDFA lengths, gave a flat gain spectrum variation of just 1.1dB for the entire C-band. As the pump power decreased, the gain spectrum showed larger variation in the C-band region. The table 2 gives the comparison of the gain variation for different pump powers. Such a flat gain system finds application in CATV and analog systems.

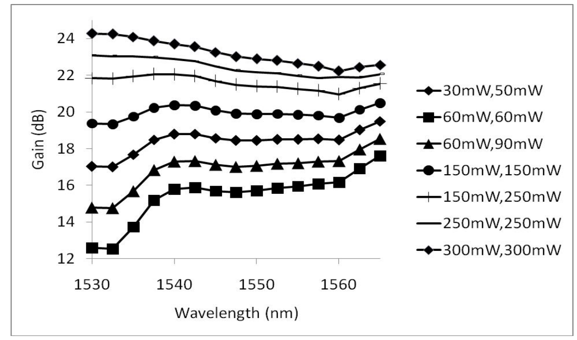


Fig.8. The gain flattened curve for various pump power combinations as a function of wavelength.

TABLE 2

GAIN CHARACTERISTICS FOR DIFFERENT PUMP POWERS

Sl. No.	980nm Pump Power (I)	980nm Pump Power (II)	Gain Flatness (p-p) in dB
1.	30 mW	50 mW	2.94
2.	60 mW	60 mW	5.0
3.	60 mW	90 mW	3.78
5.	150 mW	150 mW	1.14
6.	150 mW	250 mW	1.10
7.	250 mW	250 mW	1.17
8.	300 mW	300 mW	2.05

4.2 Noise Figure Analysis

The primary source of noise in any doped fiber amplifier (DFA) system is because of the presence of amplified spontaneous emission (ASE), which extends the entire gain spectrum. It was assumed in the simulation that ASE extends from 1520nm-1620nm. With the inclusion of an equalizer filter, the NF was found to be as low as 7.48dB which increased to 9.80dB over the entire C-band for gain-flattened optimized pump powers of 150mWand 250mW each (fig 9). This also indicates that for C plus L-band configuration would require two individual filters, since the NF increases as the wavelength approaches L-band regime. Comparison Table 3 gives the NF variation for different pump powers. For a cascaded system, the ASE accumulates at each stage reducing the overall gain at the output.

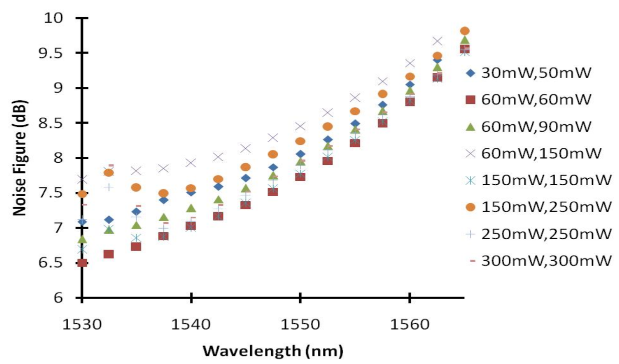


Fig.9. Schematic Diagram of a Dual Stage Gain Flattened EDFA configuration

TABLE 3

NOISE FIGURE CHARACTERISTICS FOR DIFFERENT PUMP POWERS

Sl. No.	980nm Pump Power (I)	980nm Pump Power (II)	NF Flatness (p-p) in dB
1.	30 mW	50 mW	2.73
2.	60 mW	60 mW	3.0
3.	60 mW	90 mW	2.86
5.	150 mW	150 mW	2.84
6.	150 mW	250 mW	2.30
7.	250 mW	250 mW	2.42

4.3 Equalization Filter Characteristics

The gain spectrum can be controlled either by changing fiber host properties, improving measurement techniques and employing new EDFA system designs. This paper uses a dual stage design, gain flattened by an optical filter. An optical gain equalization filter such as fiber grating filter is one of the most common ways to reduce the gain peaks to provide an equalized output. In the dual stage configuration under consideration, the primary peak obtained in the absence of filter for a 150 mW, 250 mW pumped laser and 5m EDF length is 24dB and, the secondary peak occurs at 30dB (fig 10). These peaks are reduced considerably in the presence of filter as shown in figure obtained from simulations. The transmission spectrum of the filter is shown in fig 11, which clearly indicates that the filter has spectrum inverse to that of the two stage EDFA system. The NF depends on the position of the filter in the system, and so the equalization filter was strategically chosen to be placed at the end of the second stage.

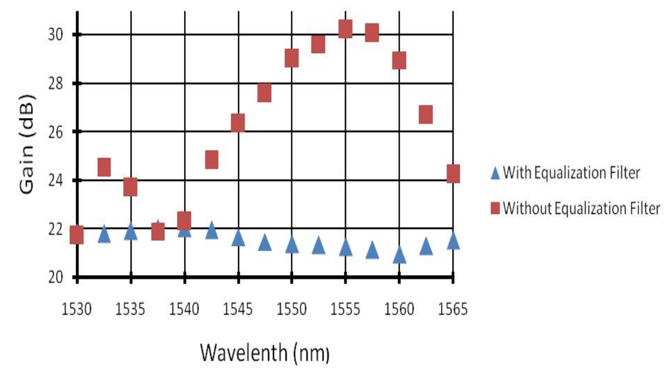


Fig.10. Schematic Diagram of a Dual Stage Gain Flattened EDFA configuration

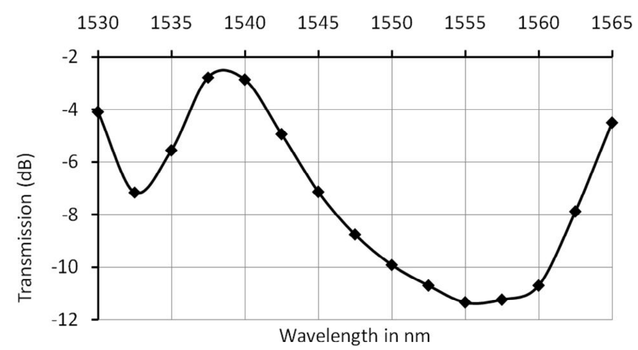


Fig.11.Equalization Filter transmission spectrum at 1530-1565nm regime.

4.4 Gain Dependence on EDF Length and Temperature

The EDFA gain is length dependent, for a given pump power, the gain reaches a maximum value before decreasing. This is because after propagating through a certain distance in the optical fiber, the pump power reduces due power absorption. Hence designing of an EDFA requires prior consideration of pump power and EDFA length. Fig 12 shows the gain dependence secondary EDFA for different channel wavelength. As seen from the graph, channels with higher frequency fall off quickly compared to channels with lower frequency. This becomes a limiting factor for WDM based optical communication.

The C-Band flattened gain undergoes temperature variation, according to the changes in ion energy levels in accordance to McCumbers equations [12]:

$$\frac{g^*(\lambda)}{\alpha(\lambda)} = exp\left[\frac{hc}{kT}\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)\right] \quad (9)$$

Where, k is boltzman's constant, h is Planck's conctant, T is temperature in degree kelvin and λ_0 is the cross-over wavelength. During the simulation, source and detector was considered to be temperature independent. Such temperature fluctuations have shown to have affected signal to noise ratio (SNR) and increased bit error rates (BER) for some channels compared to other [13]. The fig 13 shows the gain fluctuation over a temperature range of 0⁰C to 50⁰C over the C-band. The temperature coefficient of an EDFA is positive below 1540nm and negative above it. And for conventional equalization filters the temperature coefficient is positive below 1535 nm and negative above it. For an equalization filter based gain flattened EDFA configuration, above 1535nm the gain spectra of EDF and filter transmission spectra cancel out, whereas below this wavelength they reinforce, giving overall gain spectra as obtained in figure 18 from simulation. Table 4 shows the relative gain variations at different temperatures.

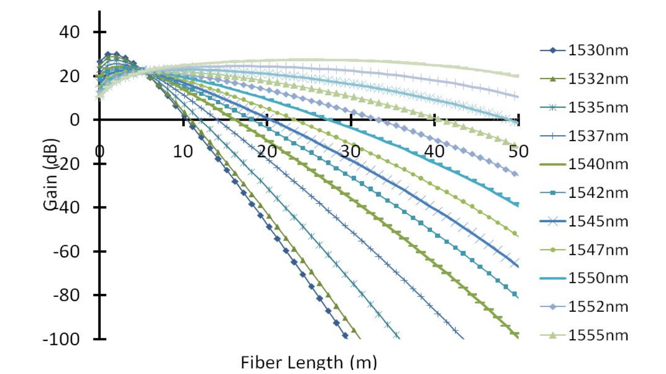


Fig.12. Gain variation with amplifier length for 14 different channels within 1530-1565nm

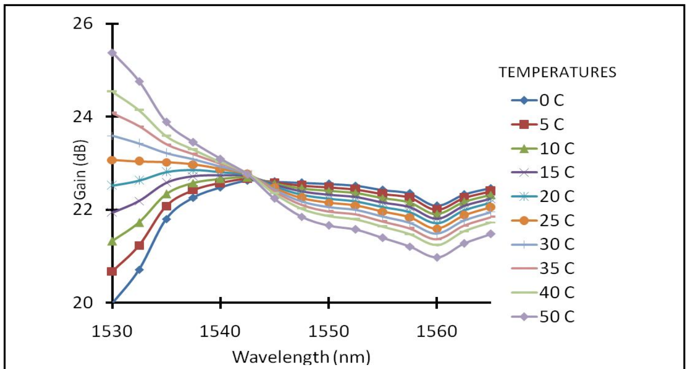


Fig.13. Effect of temperature on gain flattened curve within 1530-1565nm.

TABLE 3

GAIN VARIATION WITH TEMPERATURE

Sl. No.	Temperature in ^{0}C	Gain Variation (dB)
1.	0	2.65
2.	5	1.95
3.	10	1.37
4.	15	0.78
5.	20	0.71
6.	25	1.48
7.	30	2.10
8.	35	2.64
9.	40	3.30
10.	50	4.40

5 CONCLUSION

The Gain flattening and NF for a bowtie dual stage PM SM EDFA based system depends on pump power, EDF length and operating temperature. The paper has successfully presented the feasibility and limitations of using polarization maintaining single mode bowtie EDF in C-band communication. The strategically positioned equalization filter provided a peak to peak flatness of just 1.1dB and 2.3dB of gain and NF over 35nm range, respectively. However the system faces serious challenges with increasing length with restricted pump power. Temperature analysis of the system, the gain fluctuation has shown its dependence on temperature coefficient of the fiber. The minimum gain variation was obtained at 20⁰C operative temperature. It puts another limitation to the system, especially with its deployment in extreme geographical areas.

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