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PERFORMANCE ANALYSIS OF ERBIUM-DOPED FIBER AMPLIFIER IN FIBER OPTIC COMMUNICATION TECHNIQUE

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Performance Analysis of Erbium-Doped Fiber Amplifier in Fiber Optic Communication Technique

Avizit Basak^a, Mobasseer M. Hossain^σ & Md. Rakibul Islam^p

Abstract - Optical fiber communication is the best for transmitting data at a high rate, we are trying to push the data rate even higher. While the fiber channel may be capable of transmitting terabit-per-second data rates, no existing single communication system can make complete use of this speed. Adding more and more fibers to the system as a method of increasing speed is uneconomical as we know the global network is made of a large submarine cable networks that is expensive to modify.

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In this paper, performance analysis of EDFA technique was explored and different aspects of a system with fiber optic communication were discussed. EDFA helps to transfer data at higher rate and its pumping ability is higher than other amplifier. For EDFA, DWDM technique has the advantage of higher bit rates and is well equipped for long haul applications; however, this also imposes lower cost, low power consumption, desired noise level and also adds to the simplicity of system. EDFA also increases the operation flexibility and reduces different types of losses in fiber optic communication system.

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I. OPTICAL FIBER COMMUNICATION TECHNOLOGY

In optical communications system the transmitter is a light source whose output acts as the carrier wave. Although frequency division multiplexing (FDM),

techniques are used in longer broadcast systems most optical communication links use time division multiplexing (TDM) techniques. The easiest way to modulate a carrier wave with a digital signal is to turn it on and off, where that is called on-off keying, or amplitude shift keying. In optical systems this is commonly achieved by varying the source drive current directly, so causing a proportional change in optical power.

The components that are used to transmit or receive the optical signal are usually semiconductor devices. For transmission the most common light source used are laser diode (LD) and light emitting diode (LED) where they have different specification according to power spectrum and fabrication. At the receiving end of the optical link a PIN photodiode or Avalanche photodiode (APD), acts as a photo detector and converts the modulated light back into an electrical signal. The photodiode current is directly proportional to optical power.

II. WDM AND DWDM

Wavelength Division Multiplexing (WDM) is a technique of sending signals of several different wavelengths of Light into the Fiber simultaneously. In fiber optic communications, wavelength-division Multiplexing (WDM) is a technology which multiplexes multiple optical carrier signals on a single optical fiber by using different wavelengths (colors) of laser light to carry different signals. This allows for a multiplication in capacity, in addition to making it possible to perform Bidirectional communications over one strand of fiber.

Dense WDM (DWDM) uses the same 3rd transmission window (C-band) but with denser channel spacing. Common channel plans of DWDM vary, but a typical system would use 40 channels at 100 GHz spacing or 80 channels with 50 GHz spacing at distances of several thousand kilometers with amplification and regeneration along such a route. Some technologies are capable of 25 GHz spacing. DWDM using 25 GHz channel spacing is also sometimes called ultra-dense WDM. New amplification options (Raman amplification) enable the extension of the usable wavelengths to the L-band, more or less doubling number of channels. DWDM refers originally to

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optical signals multiplexed within the 1550-nm band to leverage the capabilities of Erbium Doped Fiber Amplifiers (EDFAs), which are effective for wavelengths between approximately 1525 nm – 1565 nm (C band), or 1570 nm - 1610 nm (L band)

III. ERBIUM-DOPED FIBER AMPLIFIERS (EDFA)

Erbium-doped fiber amplifiers are the by far most important-fiber amplifiers in the context of long-range optical fiber communications; they can efficiently amplify light in the 1500nm wavelength region, which coincides with the third transmission window of silica-based optical fiber, where telecom fibers have their loss minimum. A typical setup of a simple erbium-doped fiber amplifier (EDFA) is shown in Figure 2.21.

Its core is the erbium-doped optical fiber, which is typically a single-mode fiber. In the shown case, the active fiber is “pumped” with light from two laser diodes (bidirectional pumping), although unidirectional pumping in the forward or backward direction (co-directional and counter-directional pumping) is also very common. The pump light, which most often has a wavelength around 980nm and sometimes around 1450 nm, excites the erbium ions (Er^{3+}) into the $4I_{13/2}$ state (in the case of 980-nm pumping via $4I_{11/2}$), from where they can amplify light in the 1.5- μm wavelength region via stimulated emission back to the ground-state manifold $4I_{15/2}$. A particular attraction of EDFAs is their large gain bandwidth, which is typically tens of nanometers and thus actually more than enough to amplify data channels with the highest data rates without introducing any effects of gain narrowing. A single EDFA may be used for simultaneously amplifying many data channels at different wavelengths within the gain region; this technique is called wavelength division multiplexing. Before such fiber amplifiers were available, there was no practical method for amplifying all channels e.g. between long fiber spans of a fiber-optic link: one had to separate all data channels, detect and amplify them electronically, optically resubmit and again combine them. The introduction of fiber amplifiers thus brought an enormous reduction in the complexity, along with a corresponding increase in reliability. Very long lifetimes are possible by using redundant down-rated pump diodes.

Gain stage can be independently configured -1) Saturation output power up to 23dBm to support high capacity networks, 2) Gain flattening must less than 1dB in all conditions, 3) Proper signal control, 4) Accurate stage design for noise figure, 5) dynamic gain range selection, 6) Special monitoring process.

IV. CHROMATIC DISPERSION

The interaction between an electromagnetic wave and bound electrons of a dielectric medium is in general dependent on the optical frequency, ω , of the

signal. This property of optical transmission through a dielectric medium manifests itself in optical fiber primarily due to the frequency dependence of the refractive index of the core. It is referred to as chromatic dispersion.

Waveguide dispersion (D_w) depends on the fiber design parameters such as the core radius and the core-cladding index difference Δ . The contribution of D_w to β_2 is considered negligible except near the zero dispersion wavelength, where the two are comparable. The total dispersion is the mathematical addition of D_w and D_{mat}

$$D_{crom} = D_w + D_{mat}$$

Consequently it always results in shift of λ_0 and w to longer wavelengths because D_w and dD_w is negative through out the range of wavelength of interest.

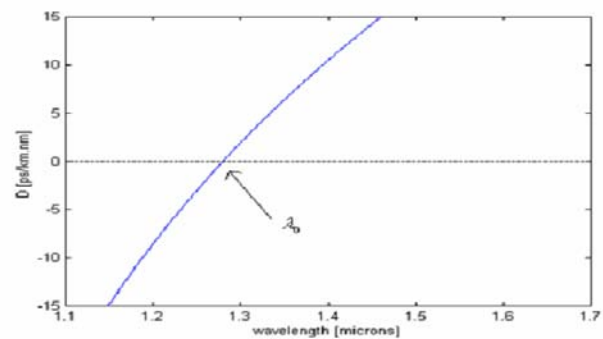


Figure 4.1 : Theoretical chromatic dispersion for fused silica fiber

V. FIBER NON-LINEAR CHARACTERISTIC

As the intensity of the electromagnetic wave increases, the response of the dielectric medium starts to exhibit non-linear behaviors. The origin of this non-linearity is related to the enharmonic motion of the bound electrons, when a high intensity field is applied. The relation between the induced polarization P and the electric field E is non-linear. A general relation between E and P is often satisfied by the following expression.

$$P_0 = \epsilon_0 (\chi^{(1)} \cdot E + \chi^{(2)} : EE + \chi^{(3)} : EEE + \dots)$$

Where ϵ_0 is the vacuum permittivity and $\chi^{(j)}$ is the j^{th} order susceptibility.

Most of the non-linear effects in optical fibers originate from the non-linear refractive index n_2 , which renders the total index of refraction intensity dependent, n_2 non-linear index coefficient, which is related to $\chi^{(3)}$ by,

$$n_2 = \frac{3}{8n} \text{Re}(\chi^{(3)})$$

The intensity dependence of the refractive index leads to a number of non-linear effects that inhibits the

performance of communication systems such as WDM. Some of the non-linear effects that are of great concern include self-phase modulation (SPM) and cross-phase modulation (XPM). These effects will be discussed in greater details later. The other phenomenon that contributes to the non-linear effect is caused by stimulated inelastic scattering in which energy is transferred from the optical signal to the non-linear medium. This transfer of energy causes vibrations in the silica molecules and manifests itself in one of two ways. The first is known as stimulated Raman scattering (SRS). The second effect is termed stimulated Brillouin scattering (SBS).

VI. BRAGG GRATING

An optical Bragg grating is a transparent device with a periodic variation of the refractive index, so that a large reflectivity may be reached in some wavelength range (bandwidth) around a certain wavelength which fulfills the Bragg condition.

$$\frac{2\pi}{\Lambda} = 2 \cdot \frac{2\pi n}{\lambda} \cos \theta$$

VII. GEOMETRIC DESCRIPTION OF BEAM PROPAGATION

The ray description of light propagation in fiber is based on the phenomenon of total internal reflection (TIR). The theory of TIR states that when a beam is incident at the boundary between two media where the incident medium is of a higher refractive index than the second medium and the angle of incidence exceeds a critical value θ_c , the light will be totally reflected. Beyond this angle light is no longer transmitted into the second medium, instead it is reflected into the original medium.

VIII. POLARIZATION-MODE DISPERSION

In a fiber that is perfectly cylindrical, there exist two orthogonally polarized degenerate modes. This fiber is considered to be ideal. However, in real fibers that have shape and stress variations, the symmetry between these orthogonal axes can be broken. At such points, the optical fiber typically exhibits a small difference in the refractive index for a particular pair of orthogonal polarization state. These factors remove the degeneracy of the fiber and result in one of the properties of optical fibers known as birefringence. The following relation is often used to measure the degree of birefringence.

IX. SCATTERING FOR AMPLIFICATION

When the intensity of the generated wave becomes sufficiently high, that wave may again act as the pump for a further Raman process. Apart from the mentioned stimulated Raman scattering effect, which

can be described with classical physics, there is also spontaneous Raman scattering, caused by quantum effects.

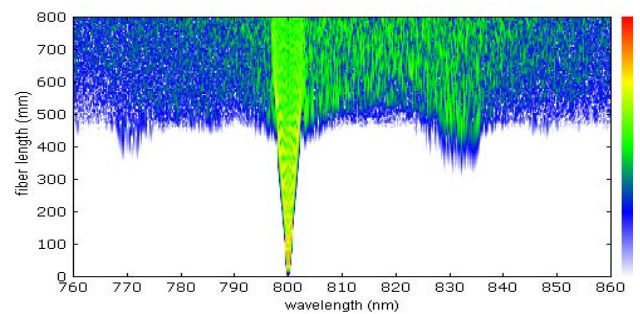


Figure 9.1 : Evolution of the optical spectrum of a 20-ps pulse with an initial peak power of 18kW in an optical fiber, shown with a logarithmic color scale for the power spectral density.

X. SYSTEM CROSSTALK

Crosstalk occurs in multi-channel optical transmission systems. There are two types of crosstalk noise discussed and analyzed in this work. First is the inter band crosstalk and it's a known also by "out of band" crosstalk. Second is intra band it's known by "inband". The use of the same wavelength in both directions causes these problems for Full Optical Duplex system. The effect of Crosstalk due to non-ideal circulator characteristics and the fiber Rayleigh backscattering is degrading to the transmitted data and raising the noise floor. It is known that when an optical signal enters a fiber strand of virtually infinite length it will experience back scattering effect due to the glass material itself and the light guiding properties of the fiber.

XI. SYSTEM POWER PENALTY

In optical communication the receiver sensitivity is defined with respect to the receiver noise for several basic detection scenarios. The highest sensitivity means the lowest value of the received optical power that is needed. The sensitivity of the photo detector of real receiver is degraded due to the impact of two principal noise contributions, the thermal noise (in PIN photo diodes) and quantum shot noise (in APD).

XII. SIMULATION DIAGRAM OF SYSTEM CROSSTALK AND POWER PENALTY

This topic is mainly concerned with the impairment caused by the optical crosstalk, the penalty can be regarded as the reduction of optical power level differences between the "one" and the "zero" states. In general terms, the spectral emission from a conventional LD conforms reasonably well to a Gaussian distribution, which then provides a simple analytical expression for use in any model. According to

Gaussian distribution in the mathematical model, the mean and variance for a random variable will be selected. The relationship between the power penalty and the crosstalk must be directly proportional to each other, and obviously that relationship between the signal power received and the power penalty is inversely proportional.

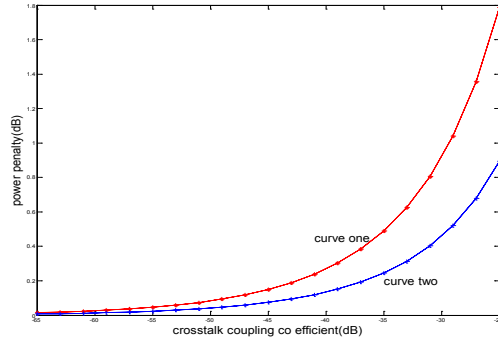


Figure 12.1 : Relation between power penalty and crosstalk coupling coefficient

XIII. DYNAMIC RESPONSE CHARACTERISTIC OF EDFA

In dynamic networks an additional major cause of transients is related to the actual add and drop event of channels. Therefore, transient suppression should be able to deal with events on a microsecond time-scale, ensuring compatibility with future switching technologies and applications. Furthermore, dynamic network are usually designed to cater for higher channel counts, up to 96 channels in the C-Band, meaning that changes in input power can be as high as 20 dB. The transient suppression time needs to be shorter, typically less 200 μ s. This type of performance is achieved using a proprietary digital feed-back control loop.

XIV. LINK POWER BUDGET FOR EDFA

Power budget considers the total allowed optical power loss PT between the source and the detector. The designer must account for losses due to fiber optic fiber attenuation, connectors, splices and allow for a "system margin" as a safety factor. The measure of the total power loss is given as,

$$P_{loss} = 10 \log_{10} \left(\frac{P_{out}}{P_{in}} \right)$$

The link power budget is determined by establishing the minimum power required to fall on the photodiode in order to ensure a certain BER. In light wave system a BER = 10^{-9} is considered acceptable. The light coupling efficiency of the transmitter, the loss of the fiber and the sequential loss contributions of each element in the link determine the power received at the detector. The power budget can be simply expressed as follows,

$$\bar{P}_{tr} = \bar{P}_{rec} + \bar{P}_{loss} + M_{sys}$$

Where $\bar{P}_{tr}$ is the average transmitted power, $\bar{P}_{rec}$ is the average received power. $\bar{P}_{loss}$ is the lost power and M_{sys} is the system margin.

The system margin is normally provided in the analysis to incorporate components ageing, temperature fluctuations and possible future addition of components in the system. A link margin of 6-8 dB is generally used for systems that might not require future additional components. The power loss is given as follows

$$\bar{P}_{loss} = \alpha_f L + \alpha_{con} + \alpha_{splice}$$

Where α_f is the attenuation of the fiber is dB/km, L is the fiber length in km, α_{con} the connector losses and α_{splice} is the splice losses.

XV. HIGH OUTPUT POWER WITH LASER SAFETY

High capacity reconfigurable networks require high output power in order to maintain acceptable levels of OSNR. On the other hand, a major requirement for optical networks is that they comply with relevant laser safety standards, such as IEC 60825 parts 1 and 2, ITU-T G.664, and CDRH 21 CFR §1040.10. The standards dictate a maximum safe level of laser radiation, known as the Class 1M hazard level, above which exposure to radiation can be potentially harmful to skin and eyes. For EDFA's operating in the C-Band, the Class 1M hazard level corresponds to a maximum theoretical output power of about 21.3 dBm. In practice however, the specified output power of a Class 1M EDFA should not exceed 20.5dBm, in order to take into account suitable safety margins. For an EDFA to provide output power above 20.5 dBm, and still retain a Class 1M safety classification, it is necessary to provide an automatic power reduction (APR) mechanism that ensures reduction of output power upon occurrence of any event which could potentially lead to exposure to radiation above the Class level.

XVI. PUMPED EDFA

Cladding-pumped EDFA have been identified as a solution for L-band amplification. , the noise performance of these devices is studied for both co- and counter-propagating pump schemes.

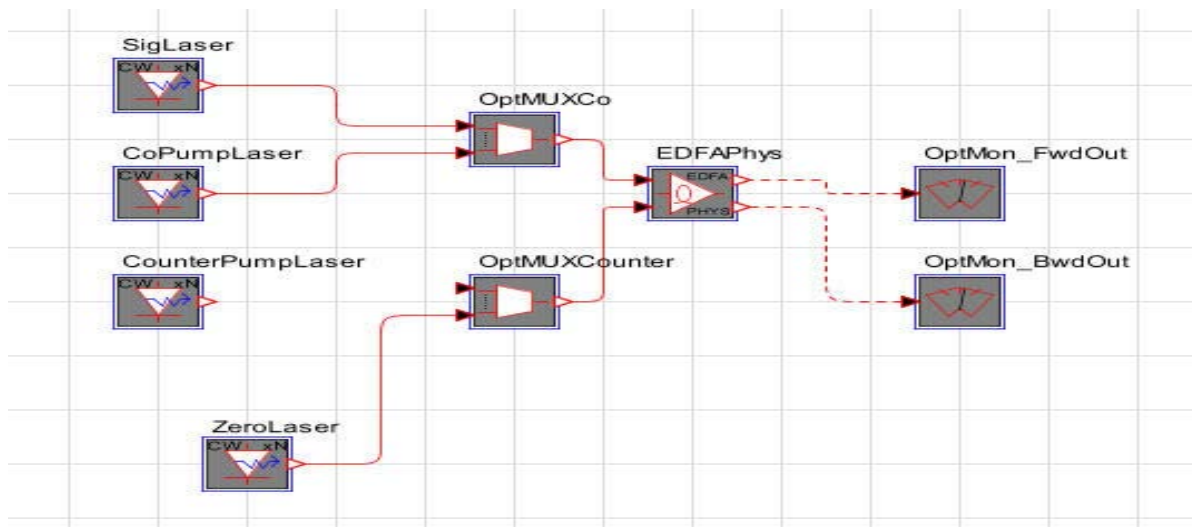


Figure16.1 : Network diagram of a pumped EDFA

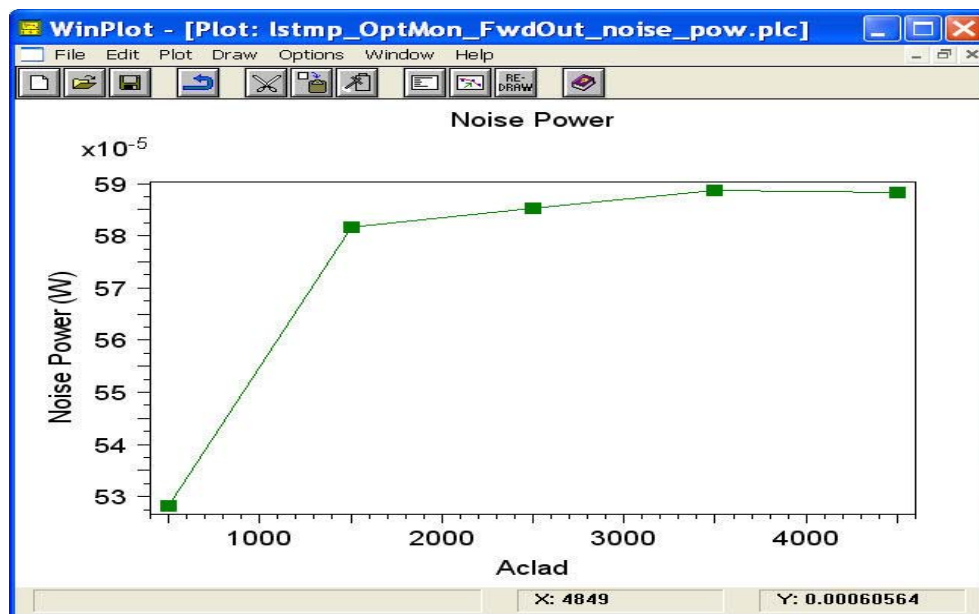


Figure16.2 : Output noise power of pumped EDFA

XVII. PROPER CALIBRATION PROCESS OF EDFA

Data from an integrated OCM can be used internally by the EDFA to optimize its gain and tilt settings to accommodate different channel loading conditions. While the benefits of integrating an OCM in the EDFA are clear, there are various technical complexities that need to be addressed. Calibration is achieved using an external referencing source, a solution which is expensive and impractical for an OCM integrated in an EDFA. Finisar's patent pending solution to this problem is to implement a sharp notch in the Gain Flattening Filter (GFF) of the EDFA. By placing this

notch outside of the transmission band, it only affects the amplified spontaneous emission (ASE) noise generated by the EDFA, creating a notch in the ASE spectrum which can be detected by the OCM, and thus used for referencing.

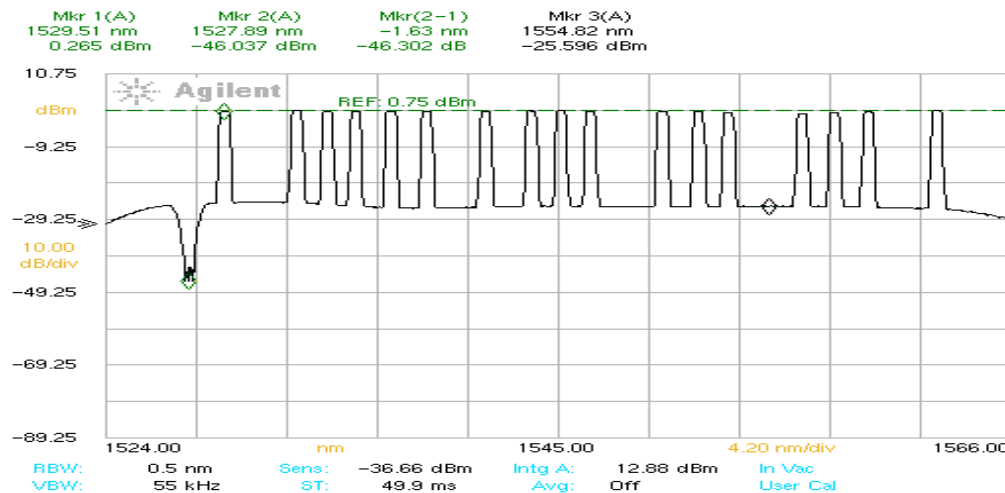


Figure 17.1 : An output spectrum of EDFA after calibration

XVIII. POWER TRANSIENTS IN EDFA

The 1550 nm signal is connected to an instance of the Transient Optical Switch model. The switch simulates adding and dropping of the signal at wavelength 1550 nm. The signal at 1556 nm is the

surviving channel. The attenuators simulate loss of the fibers. The optical multiplexers combine the signals, including the EDFA pump signals at 980 nm. The example demonstrates the effect of cross saturation in EDFA.

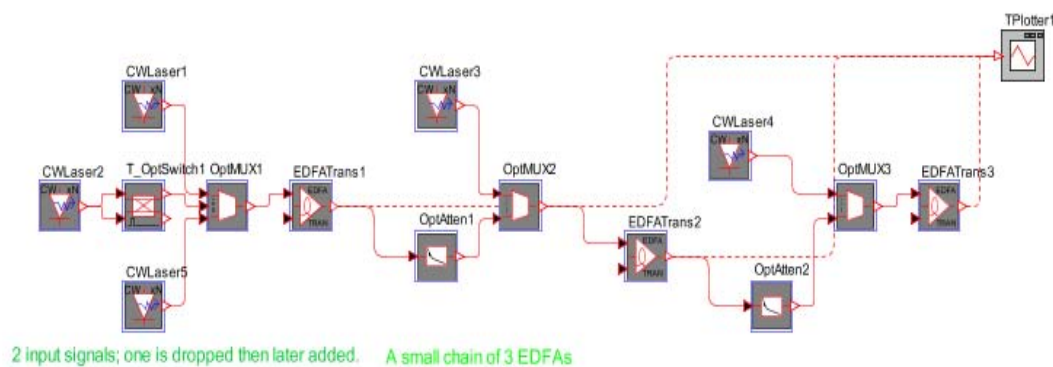


Figure 18.1 : Simple saturation operation of EDFA

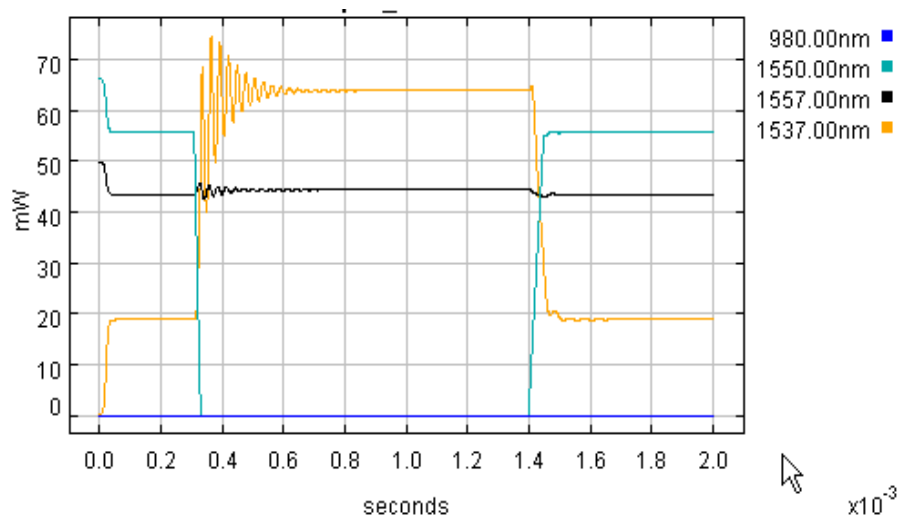


Figure 18.2 : Signal at the output after EDFA

XIX. TRANSFER FUNCTION OF EDFA

However, add and drop events are not the only concern in dynamic networks. Due to the existence of multiple active devices such as amplifiers and WSS's, complicated dynamics can evolve in long links and mesh networks which also include oscillations in the KHz and MHz frequency ranges, and not just sharp changes in the average optical powers. Such oscillations occurring at the input to an EDFA may cause unpredictable results in the EDFA gain response, especially since the EDFA "natural frequency" (dictated by the Er lifetime and saturation conditions) is often in the same frequency range. To reduce such effects and ensure a smooth gain response at all input frequencies, the EDFA control loop should be designed accordingly, and in particular be sufficiently fast to suppress deviations from a smooth frequency independent gain response. These effects can be characterized by the transfer function of the EDFA. This is typically generated using a network analyzer, and measures the change in amplitude and phase of the EDFA output as a function of the frequency of a pure sinusoidal input.

XX. ADVANTAGES OF EDFA

There are many advantages of EDFA. Such as-

- a. A high power efficiency can be achieved by in band pumping around 1450 nm. However, stimulated emission by pump light then limits the achievable excitation level, hence also the gain per unit length, and the maximum gain occurs at longer wavelengths.
- b. High output power with laser safety classification to support high capacity WDM and DWDM networks.
- c. The gain adjusts itself to the average signal power level.
- d. Relatively low-noise performance can be achieved by proper design.
- e. Provide maximum gain.
- f. Support for dynamic traffic routing in optical mesh networks by providing network management with data for optical path calculations.
- g. High laser cross section.
- h. Ultra-fast digital automatic gain control loop with smooth transfer function.
- i. Transient suppression compatible with network dynamics on a microsecond time-scale.
- j. Providing advanced wavelength and channel monitoring to support the dynamic functionality of the system.
- k. EDFA can work as a equipment for testing transmission hardware.
- l. Support for higher channel count and higher bit-rates required.
- m. Support advanced optical path calculations.
- n. Especially pertaining to Wavelength Selective Switch.

- o. Increasing network flexibility.
- p. Improving bandwidth utilization.
- q. Reducing operational complexity.
- r. EDFA are widely used in cable-TV systems and telecommunication for power of a data transmitter can be boosted easily by it.

XXI. CONCLUSION

Now- a- days, importance of data transmission via fiber optic communication is increased. EDFA provides the scope to transmit data at higher rates in fiber optic communication. There is possible to amplify high power pulses in the 1.5- μ m region to relatively high energies, using EDFA in the form of amplifier chains. One exploits the relatively high saturation energy of such amplifiers, particularly when using erbium-doped large mode area fibers. Integrated optical channel monitor with self calibration of wavelength measurement helps to transfer data with security. Erbium-doped double-clad fibers can be used for generating very high output power. EDFA makes it easier to pass more data over the different channel at a time in WDM in DWDM system with lower power loss. It also helps to clear the noise level. For variable Gain or fixed gain operation it provide more flexibility. Erbium-doped fiber amplifiers are an important component in the design of long-haul telecommunication links, and Physical EDFA model is a useful tool for studying the impact of EDFA gain and noise characteristics on a given link topology.

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