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# Optimization of Gain Flattening Filter to Achieve Flat Gain of EDFA for DWDM Chaotic Communication

S. Maqsood[1], F. Qamar[2], M. Khawar[3], M. Zafrullah[4], A. Shahzad[5]

[1,2]*Telecommunication & Information Engineering Department, UET Taxila, 47050, Pakistan.*
[3]*Electrical Engineering Department, Taibah University, Al Madinah Al-Munawarah, K.S.A.*
[4]*Electrical Engineering Department, University of Lahore, Pakistan.*
[5]*Electrical Engineering Department, Federal Urdu University, Islamabad, Pakistan.*
[1]salehamaqsood07@yahoo.com

***Abstract-***In this paper the design of 8-channel Dense wavelength division multiplexing (DWDM) chaotic system is presented at frequencies ranging from 193.0 THz to 193.7 Thz. The chaotic signals are generated by using semiconductor laser and mathematically modeled by laser rate equation. The Gain flattening filter (GFF) is used with Erbium doped fiber amplifier (EDFA) in DWDM communication model for long distance transmission. The optimization of Gain flattening filter is done in chaotic environment to achieve the flattened gain profile of EDFA. The synchronization of chaos at transmitter and receiver is achieved to recover the received signal. Thus, our scheme combines two advantages i.e. efficient bandwidth utilization and security at the same time in DWDM communication model.

***Keywords-***Chaos, DWDM, Gain Flattening Filter, Chaos Synchronization, Chaotic Lasers, EDFA, Optisystem 14.0

## I. INTRODUCTION

Secure communication has become an emerging need of the next generation telecommunication networks. Message is encrypted at the physical layer to provide security. There are various methods to provide security in optical communication networks. Chaotic optical communication is one of the trending methods to improve security and privacy of critical information [i-iv]. In order to meet the more bandwidth demand chaotic signals are employed with WDM. EDFA is used to compensate for losses and to obtain amplified signals. As the EDFA gain is wavelength dependent, amplification of wavelengths varies from one another. In our work, EDFA gain is flattened using gain flattening filter so that these can be used to achieve longer distances while using with the multichannel transmission system. For this purpose, optimization of gain flattening filter is done to achieve flattened gain. The work is done for the first time on DWDM chaotic carriers to save the bandwidth in secure environment.

One of the property of chaotic pulses is that these are produced in random fashioni.e. the amplitude of each pulse is different from the other pulse. When these chaoticpulses with random amplitudes are passed through EDFA, these vary largely aftertheir amplification. If the output of EDFA is not flattened it will take extra bandwidthwhich is the drawback of DWDM communication model. On the other hand, if thesimple data pulses which are not chaotic in nature are passed through EDFA, thevariation in amplitude of pulses will not vary to that extant as in case of chaotic pulses. So, the response and optimization of filter will be different in both the cases. Although, different techniques are being used for the flattening of gain of EDFA, but this is the first time that we applied Gain flattening technique using filter on chaotic pulses in DWDM environment which is the significance of this work.

The idea of synchronization in chaotic optical secure communication has gained huge attention in the last few years. Optical communication employed with synchronized chaotic carriers can be used for providing security in digital communication systems [v]. Chaotic optical communication requires the synchronization of input and output chaos so that original message can be extracted from chaotic signal [vi-viii]. Athens and Greece experiments have first demonstrated the experimental implementation of chaos for security purposes. However, chaosis a stochastic process and has very unpredictable behavior and sensitive to initial condition. The disparity in transmitter and receiver chaotic signals causes poor synchronization and thus increases BER results [ix-xi].

Chaos generation techniques offer limited bandwidth so wavelength division multiplexing is the ultimate way to meet the bandwidth demand. Wavelength division multiplexing and dense wavelength division multiplexing technique have been extensively used for both security and bandwidth enhancement purposes [xii, xiii]. DWDM gives the maximum exploitation of available bandwidth as the channel spacing between channel is kept narrow i.e.100 GHz (0.8 nm). Erbium doped fiber amplifier has been extensively used in wavelength division multiplexing techniques to enhance data transmission rates and to improve BER [xiv-xvi]. As EDFA has wavelength dependent gain, few of the signals are amplified more than other, so to restore all the signals at approximately the same intensity various techniques have been reported [xvii-xx].

synchronization which is the key for retrieving original signal greatly depends upon methods of chaos generation, chaos control, effect of fiber transmission and effect of amplifier noise [xxi]. Chaos control and chaos synchronization are remarkable and important research fields aiming to affect the dynamics of chaotic systems in order to use them for different kinds of applications that can be examined within many different fields. In this paper, a new hybrid approach is proposed which is to achieve the flat gain of EDFA while taking signals in DWDM chaotic environment. The optimization of gain equalization is done to achieve the flattened gain of EDFA, synchronization of chaos at transmitter and receiver is achieved successfully to recover the original signals.

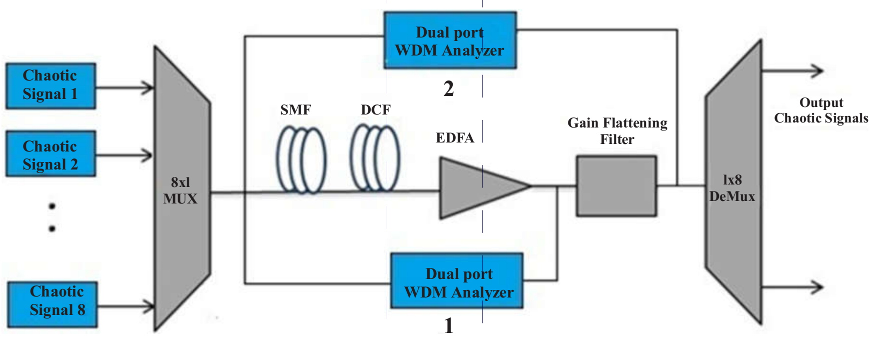


Fig. 1. 8-Channels DWDM chaotic communication model using GFF

This paper is arranged in following sections. section-I comprises of introduction of the paper, section-II covers the simulation setup whereas section-III is based on Mathematical model. Section-IV covers results and discussion and finally the paper is concluded in section-V.

## II. SIMULATION SETUP

The simulations are made over 8 chaotic channels, which are multiplexed in the wavelength range of 1548nm–1553nm with a channel spacing of 0.1 THz (0.8nm) as recommended by ITU for standard WDM system. Proposed 8-channel chaotic DWDM scheme is shown in Fig.1 whereas Table-I shows the parameters and their values used in this simulation model. In this scheme, sinusoidal direct modulation method of 8-individual laser diode is used to generate chaos. The input current of laser source is varied to control the degree of chaos. Data sources are directly modulated by using chaotic lasers so that the data appear as random noise like signal on single output multiplexed channel of 8×1 multiplexer. Chaotic signals are multiplexed and sent over 80 km of Single mode fiber (SMF) while 16 km Dispersion compensation fiber (DCF) is used in order to compensate for dispersion losses. An Isolator is used with EDFA, it improved the gain and noise figure of the EDFA. At the receiving side, after 1×8 demultiplexer retrieved signal is subtracted from same chaotic source to get the original data.

TABLE I
SIMULATION MODEL PARAMETERS

| Parameters | Values |
|---|---|
| Lasers power | 10dBm each |
| Lasers frequencies | 193.0 Thz – 193.7 Thz |
| Dispersion | 16.75ps/nm/km |
| Dispersion slope | 0.075 |
| Fiber length | 80km |
| Fiber attenuation | 0.2dB/km |

## III. MATHEMATICAL MODEL

The mathematical modeling of semiconductor laser diode is illustrated by following laser rate equation [xxii].

$$\frac{dN(t)}{dt} = \frac{I(t)}{q(V)} - G_o(N(t) - N_t)\frac{1}{1+\varepsilon S(t)}S(t) \quad (1)$$

$$\frac{dS(t)}{dt} = \Gamma G_o(N(t) - N_t)\frac{1}{1+\varepsilon S(t)}S(t) - \frac{S(t)}{\tau_p} \quad (2)$$

$$= \frac{\tau\beta N(t)}{\tau_p}, \quad (3)$$

$$\frac{d\emptyset}{dt} = \frac{1}{2}\alpha\left[\tau\, G_o(N(t) - N_t) - \frac{2}{\tau_p}\right] \quad (4)$$

$$G_o = v_g a_o \quad (5)$$

$$I_t = I_{DC} + I_{IN} I_{PK} \quad (6)$$

Where, 'N(t)' is the carrier density, 'S(t)' is the photon density, 'I' is the applied current, 'τ'is the confinement factor, '$\tau_n$' is the carrier life time, '$\tau_p$' is the

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carrier photon time, 'β' is the spontaneous emission factor, '$I_{DC}$' is the parameter bias current ($I_{DC} = 33mA$) and '$I_{PK}$' is the parameter modulation current ($I_{PK} = 10mA$). The values of laser parameters required for generating chaos are given in Table-II. Fig.1shows 8 chaotic signals fed into 8×1 multiplexer, each carrying data capacity of10Gbps with laser power adjusted as 10dBm. The fiber link comprises of standard telecommunication single mode fiber of 80 km with dispersion of 16ps/nm/km. DCF of 16km with dispersion value of -83.75ps/nm/km is used after SMF in our communication model. The signal from SMF and DCF is fed into EDFA for amplification and then passed through GFF. Parameters value set for EDFA are given in Table III.

TABLE II
PARAMETERS OF SEMICONDUCTOR LASER

| Symbol | Parameters | Value |
|---|---|---|
| $a_o$ | Active layer coefficient | $1.5 \times 10^{-10}$ |
| $v_g$ | Group velocity | $8.5 \times 10^{9}$ |
| ε | Gain compression factor | $1 \times 10^{-17}$ |
| $N_t$ | Carrier density at transparency | $1 \times 10^{18}$ |
| β | Fraction of spontaneous emission | $8 \times 10^{-7}$ |
| τ | Mode confinement factor | 0.4 |
| $V$ | Active layer volume | $1.5 \times 10^{-10}$ |
| $\tau_p$ | Photon lifetime | $3 \times 10^{12}$ |
| $\tau_n$ | Electron lifetime | $1 \times 10^{9}$ |
| Λ | Linewidth enhancement factor | 5 |

TABLE III
EDFA SIMULATION PARAMETERS

| Parameters | Values |
|---|---|
| Core radius | 2.2μm |
| Erdoping radius | 2.2 μm |
| Ermetastable lifetime | 10ms |
| Numerical aperture | 0.24 |
| Loss at 1550nm | 0.1dB/m |
| Length | 5m |

An isolator is used with EDFA to improve the gain and noise figure of amplifier. Isolator acts as the directive-selective filter i.e. the light propagating in the forward direction passes unaffected and the light propagating in the backward direction is attenuated [xxiii]. EDFA is an amplifier which uses erbium doped fiber as gain medium to amplify an optical signal. The core of EDFA is doped with trivalent erbium ions. They are efficiently pumped at wavelength of 980nm and 1480nm. The basic principle of EDFA involves the mixing of high power-driven beam of light with the input signal with the use of wavelength selective coupler. The mixed light is further fed into fiber core where erbium ions exist. In the fiber core the high powered optical beam excites the erbium ions to higher energy state.

The pump light emits the photons when it meets the excited erbium atoms, these atoms give up some of their energy back to signal and jump to lower energy state. EDFA's are designed by considering the numerical solutions of the rate and propagation equations under stationary conditions. Also, these amplifiers observe the amplified stimulated emission (ASE). In our setup, the population densities of EDFA at the ground and meta stable states are reasonable to calculate and are solved numerically by using the following rate and propagation equations [xxiv].

$$\frac{\partial N_b(z,t)}{\partial t} = -\frac{1}{A_{eff}}\sum_{n=1}^{N}\{\Gamma_n[\sigma_n^e + \sigma_n^a]\}[p_n^+(z,t) + p_n^-(z,t)] - \frac{N_b(z,t)}{\tau} \quad (7)$$

$$N_a + N_b = 1 \quad (8)$$

$$\frac{\partial p_n^{\pm}(z,t)}{\partial t} = u_n\{p_n\Gamma_n[(\sigma_n^e + \sigma_n^a)N_2(z,t) - \sigma_n^a - \alpha\}p_n^{\pm}(z,t) + 2\rho\Delta V N_b \tau_n \sigma_n^e \quad (9)$$

where, '$N_a$' and '$N_b$' are population density of meta stable and ground energy level respectively, 'τ' is the meta stable spontaneous emission lifetime, 'N' is the number of channels used for signals and pumps, 'ρ' is the active erbium ion's density, 'α' is the attenuation coefficient, '$A_{eff}$' f is the effective doped area and 'ΔV' is the frequency step. EDFA exhibits gain which changes with wavelength within the bandwidth so some signals are amplified more than others. Dynamic gain behavior of EDFA affects the system design and transmission performance. So that the gain variation can be controlled by making use of optical filters. Gain flattening filter is used to restore all wavelengths to exactly same intensity. In order to flatten the gain, a transfer function compliant with the gain spectrum of EDFA is used. This strict the gain variation of EDFA with wavelength. In Opti System 14.0, the optimization of GFF is done by targeting a gain ripple value of 0.07dB. The optimization is done by setting the minimum transmission value to -40 dB and maximum value to -0.1 dB from 1500 nm to 1600 nm. The transmission values of the filter are optimized against the frequencies of the 8 chaotic signals. The tolerance of the filter is set to 0.1dB. Fig. 2 shows input chaotic signals whereas Fig. 3 shows the output in the form of amplified chaotic signals.

## IV. RESULTS & DISCUSSION

Optimization of gain flattening filter is done to achieve the flattened gain profile for 8-DWDM chaotic signals. Improved gain ripple and output power level is achieved after optimization. Maximum gain of 9.28dB and minimum gain of 8.30dB was observed before optimization. The maximum gain of 10.23dB and minimum gain of10.20dB is obtained after optimization with gain ripple of 0.07 and maximum noise figure of 2.45dB. Fig. 4 shows the 8-chaotic signals ranging from 193.0THz to 193.7THz with equal power of 10dBm and channel spacing of 0.1THz (0.8 nm) according to ITU-T Standard G.692. Performance of DWDM channel can be determined from the gain and noise figure. Fiber impairments and EDFA parameters are controlled in parallel to achieve these results. Table-IV and Table-V shows the output of WDM analyzer in terms of gain and noise figure for each wavelength individually.

TABLE IV
WDM ANALYZER-1 OUTPUT AFTER EDFA WITHOUT USING GFF

| Frequency | Gain | Noise Figure |
|---|---|---|
| 193.0 | 08.30 | 04.83 |
| 193.1 | 08.46 | 04.85 |
| 193.2 | 08.62 | 04.88 |
| 193.3 | 08.78 | 04.90 |
| 193.4 | 08.87 | 04.91 |
| 193.5 | 09.00 | 04.93 |
| 193.6 | 09.13 | 04.96 |
| 193.7 | 09.28 | 04.98 |

TABLE V
WDM ANALYZER-2 OUTPUT USING GFF

| Frequency | Gain | Noise Figure |
|---|---|---|
| 193.0 | 10.23 | 02.40 |
| 193.1 | 10.22 | 02.42 |
| 193.2 | 10.23 | 02.41 |
| 193.3 | 10.22 | 02.43 |
| 193.4 | 10.22 | 02.42 |
| 193.5 | 10.23 | 02.44 |
| 193.6 | 10.20 | 02.45 |
| 193.7 | 10.23 | 02.44 |

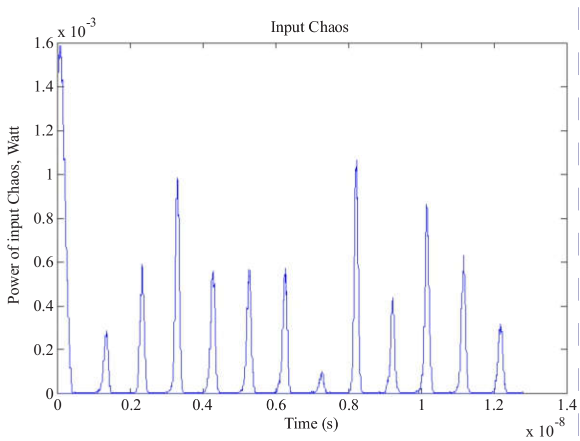


Fig. 2. Input chaos

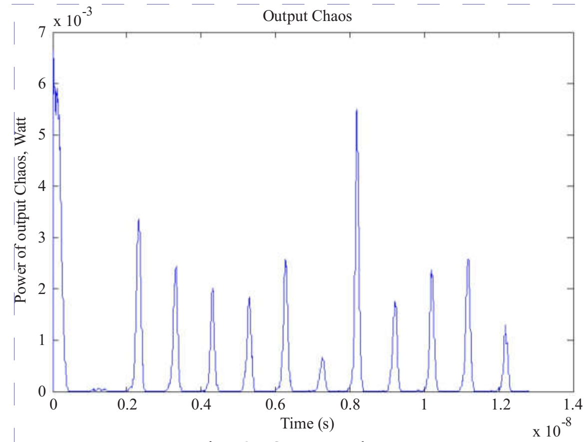


Fig. 3. Output chaos

Fig.4 shows the spectrum of 8-input chaotic pulses which are fed into multiplexer. Fig. 5 shows non-flat chaotic pulses after EDFA without optimization. These unoptimized chaotic signals are fed to GFF for optimization and produces flattened and higher power EDFA gain profile as shown in Fig. 6. Fig. 7 shows the gain profile comparison before and after optimization.

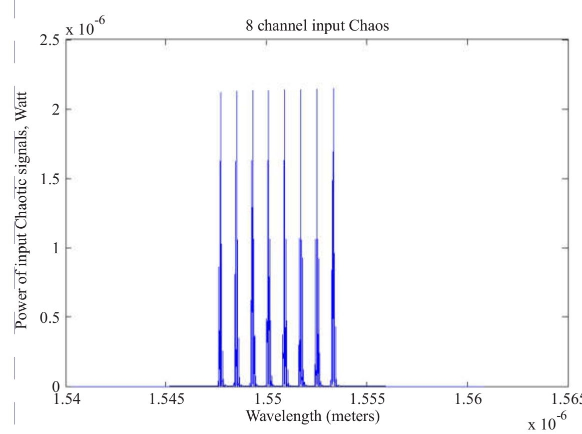


Fig. 4. 8-Input DWDM chaotic signals

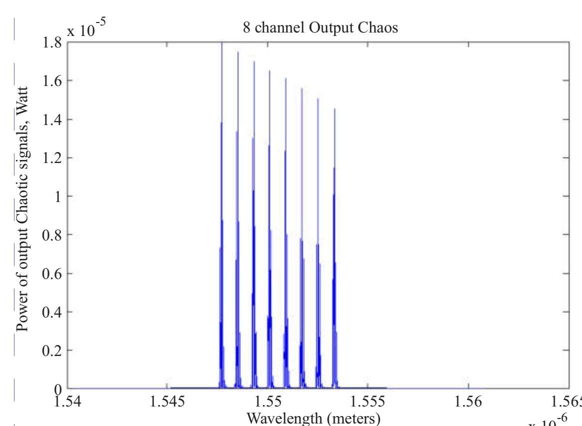


Fig. 5. Unoptimized 8-DWDM output chaotic signals

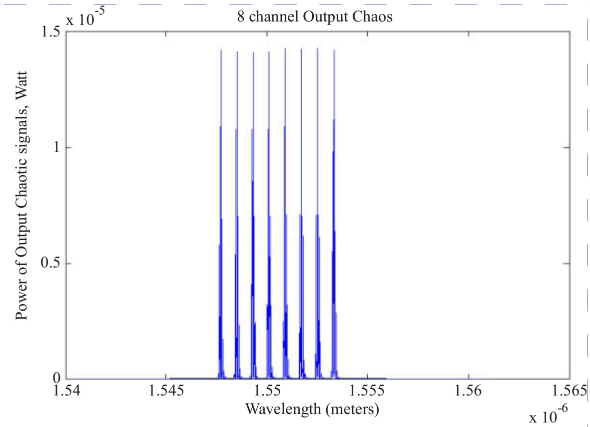


Fig. 6. Optimized output chaotic signals (After gain flattening filter)

The comparison clearly depicts that optimized gain plot is flat and improved whereas unoptimized gain plot is not flattened. Fig.8 shows the comparison of input chaos to output chaos for first two channels. It shows that input and output chaotic pulses are not perfectly synchronized. These two channels are lowest in frequencies and highest in wavelengths among the chosen channels. While Fig. 9 shows the chaos comparison for the remaining six channels. It shows approximately better synchronization of input and output chaotic pulses. The synchronization plots for all the 8-chaotic channels are also evaluated to clarify the deviation. Greater deviation in synchronization because of first two channels having frequencies 193.0 THz and 193.1 THz is clear in Fig. 10 while less deviation due to synchronization of rest of the six channels is shown in Fig. 11.

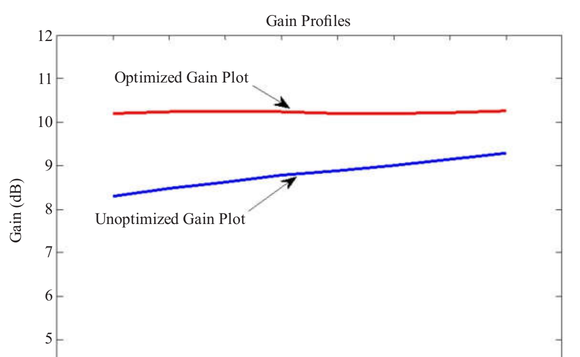


Fig. 7. Comparison of gain profiles of EDFA

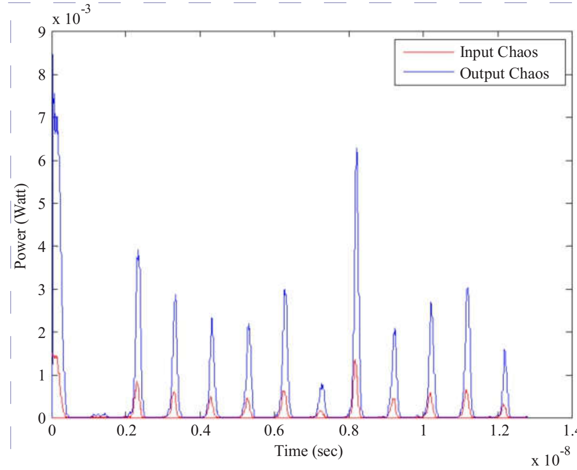


Fig. 8. Comparison of chaos at 193.0 THz to 193.1 THz

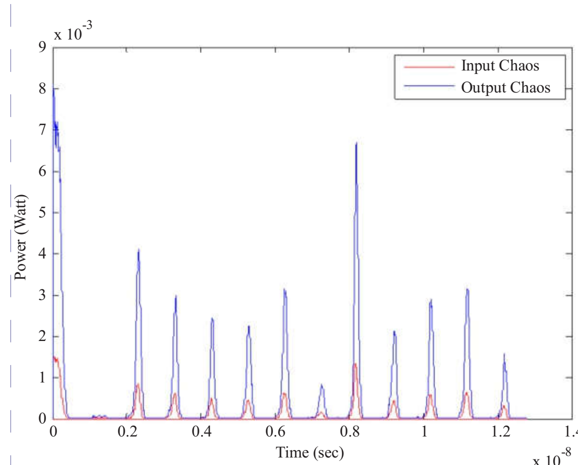


Fig.9. Comparison of chaos at 193.2 THz to 193.7 Thz

Fig. 10 clearly depicts that synchronization plot is worst for first two channels because their frequencies are lower among all the channels and reciprocally wavelengths are higher, resulted from transference of energy from the other six lowers wavelengths. This effect is due to Raman crosstalk.

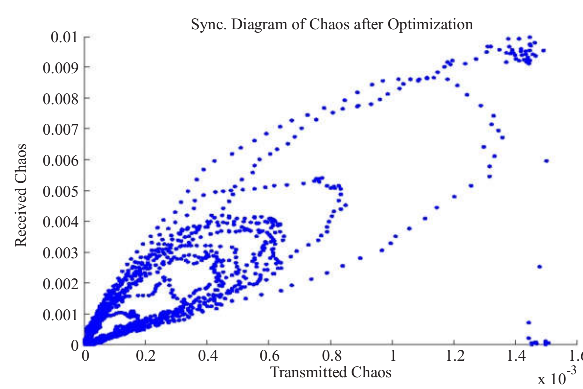


Fig.10. Synchronization diagram at 193.0THz and 193.1THz

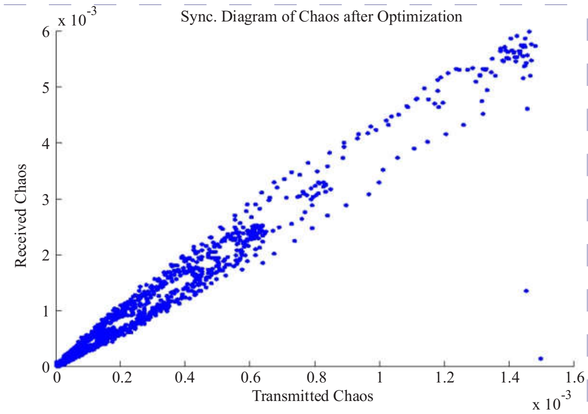


Fig. 11. Synchronization diagram at 193.2THz to 193.7 THz

## V. CONCLUSION

In this paper, chaotic communication system consisting of 8-chaotic channels with channel spacing according to international standard is proposed. The optimization of gain flattening filter is done to achieve the flat gain of EDFA, when chaotic signals are transmitted over the optical fiber channel. The fiber impairments like four-wave mixing and dispersion effects causes the mismatch of transmitter and receiver parameters. Crosstalk in DWDM channels due to these nonlinear effects disturbed the synchronization of input and output chaos. The most effected DWDM wavelengths are determined through synchronization plots. Chaotic synchronization is successfully achieved in our communication model to reconstruct the signal at receiver side. The optimization of GFF resulted in better and flat gain profile of EDFA by achieving the ripple gain of 0.07dB. Hence, bandwidth utilization is improved by flattening the gain of EDFA and the transmission is made secured by using chaotic semiconductor lasers in DWDM environment.

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