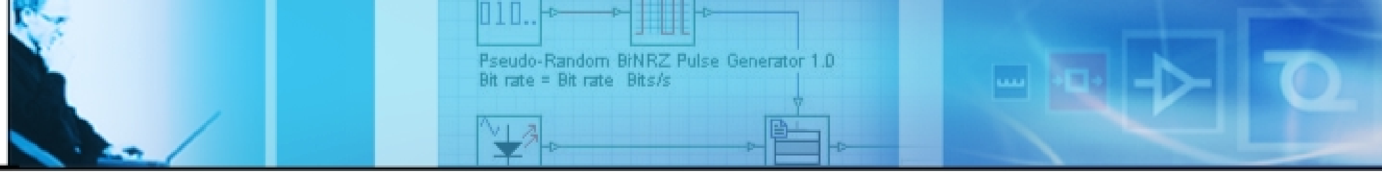
Erbium Doped Fiber Amplifiers



Part I – Gain Flattening EDFA Simulations

Part II – Designing L-Band Amplifiers in WDM Applications

Part III – EDFAs with Optical Automatic Control Simulations

Part IV- Gain-Clamped EDFAs Simulations

Part I – Gain Flattening EDFA Simulations

Outline

- Why Gain Flattening
  - Techniques to flatten the gain bandwidth
  - Typical configurations
- Key points in designing Gain Flattening amplifiers
  - Gain Flattening optimizations
  - Gain Flattening filters
- Simulating Gain Flattening Amplifiers
- Evaluating Gain-Flattened EDFA in a WDM system
- Conclusions

Why Gain Flattening

- Critical: gain bandwidth
- Enlarge and achieve a flat amplification bandwidth
- Increase the number of input channels / transmission capacity
- Operating band: C- and L-band amplifiers
- Applications:
  - WDM transmission systems
  - All-optical self-routed wavelength addressable networks

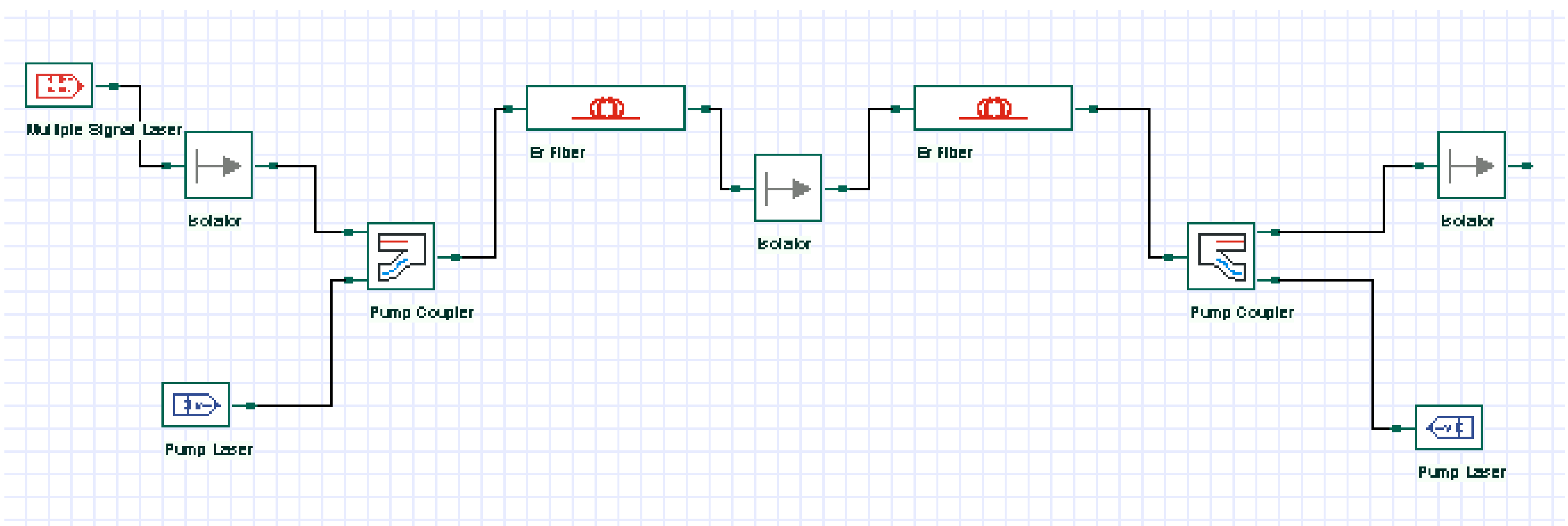
Techniques to Flatten the Gain Bandwidth

- Modifying the material composition in the EDF
  - silica with different co-dopants
  - fluoride
  - telluride
- Using optical filters to compensate for the variations in the gain spectrum – Gain equalizers
  - fiber Bragg gratings
  - fiber acousto-optic tunable filters
  - Mach-Zehnder filters
- Series/cascade and parallel configuration

Typical Configurations

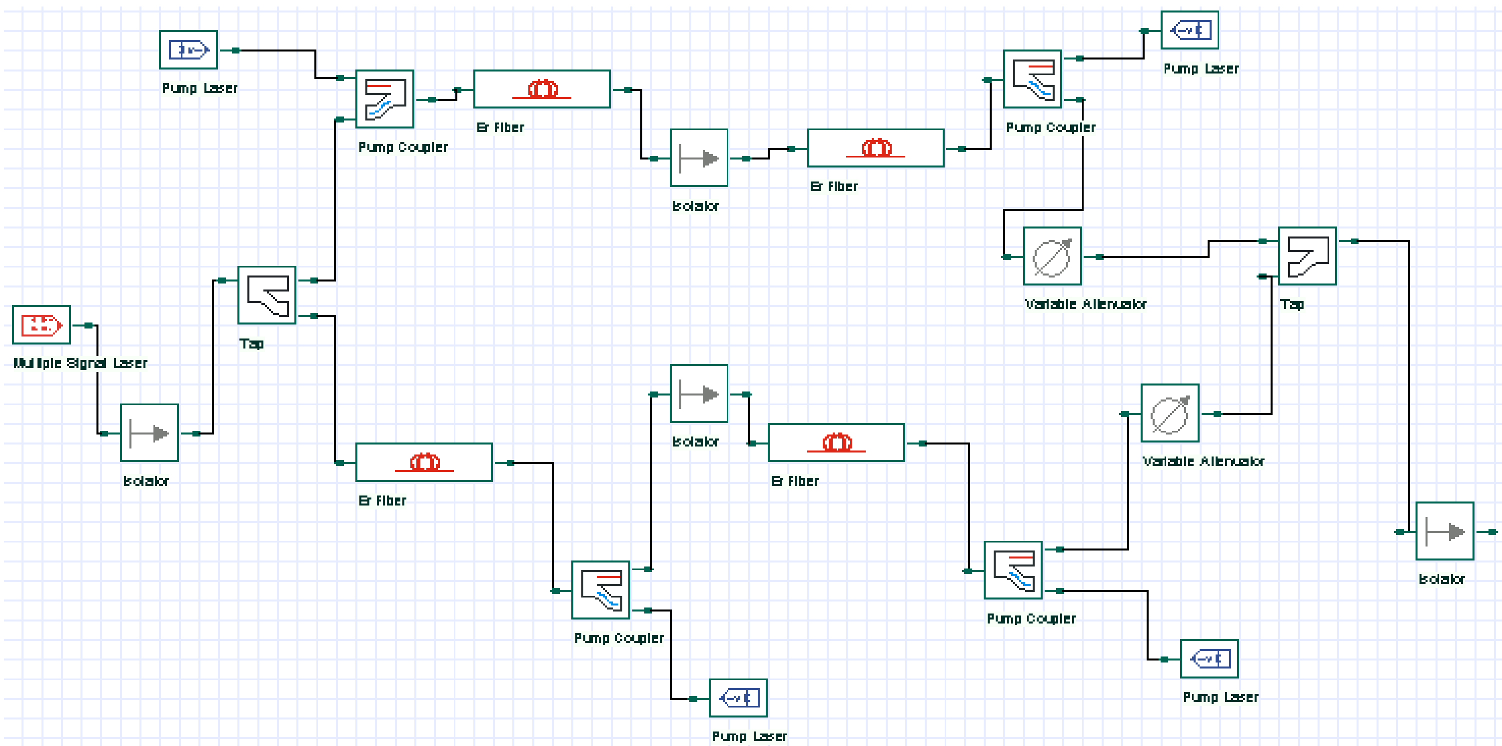
- Multiple fiber stages
- Element mid-stage: filter or isolator

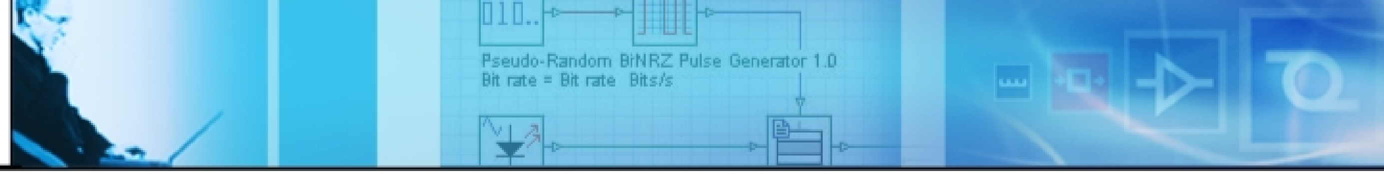
Series Configuration



Typical Configurations

Parallel Configuration





Key points in designing Gain Flattening Amplifiers

- Gain spectrum of a conventional EDFA is not constant over the bandwidth;
- Non-uniformity of gain in an EDFA is a critical limitation with multiple channels;
- If there are more than 16 channels, the gain spectra have to be flattened by external methods;
- Filters are designated to approximate the inverse profile of the gain spectrum.

Gain Flattening Optimizations

- Gain flattened filter allows the user to select two points in the layout with a filter between them.
- The optimization routine will try to find the optimum filter shape to obtain the gain flattening between these two points.
- In one simulation the user can select multiple optimizations; the user can also mix parameters iterations and optimizations.

Using Gain Flattening Filters

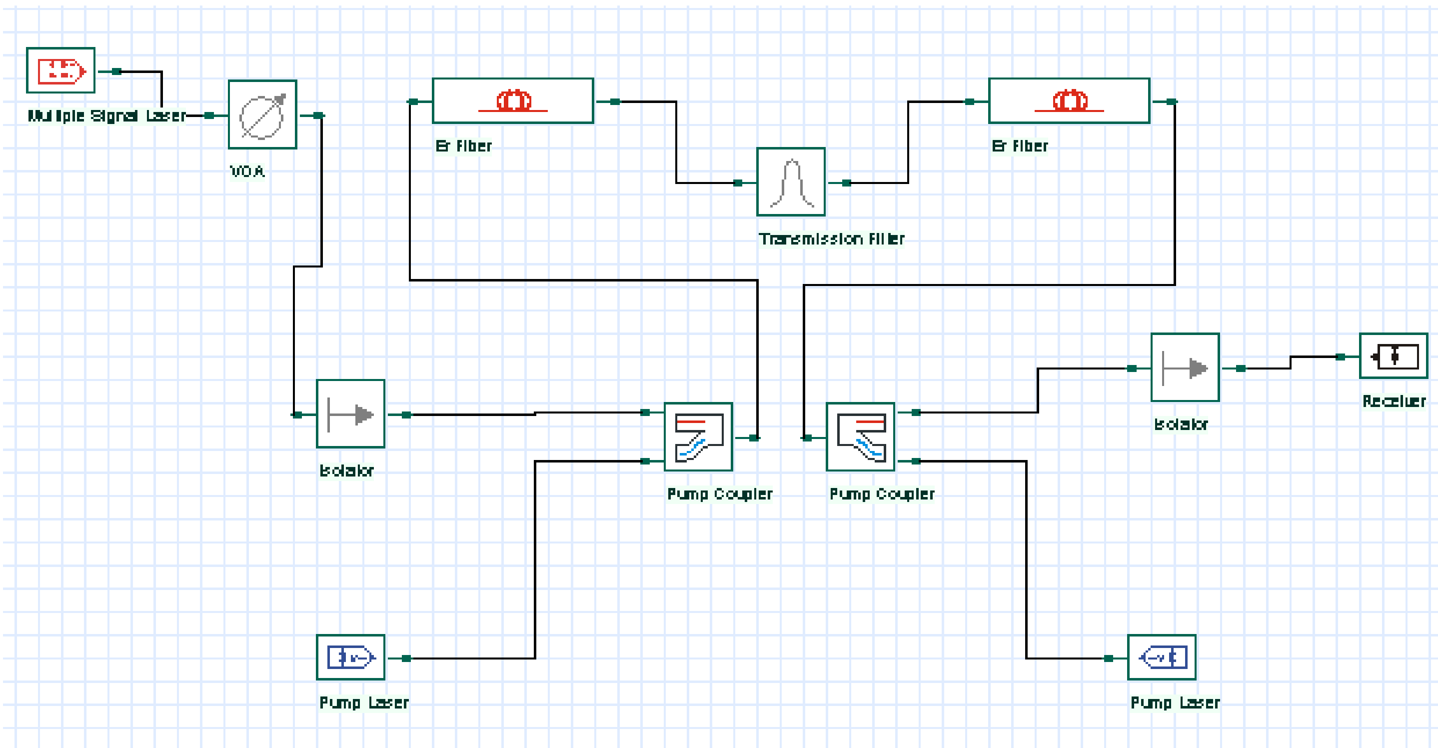
- Filters are designed to approximate the inverse profile of the gain spectrum;
- The gain flattened filter is usually placed between a multiple-stage amplifier (typically two-stages);
- Optimization is over at least 3 variables:
  - stage 1 of EDF;
  - stage 2 of EDF;
  - filter shape;
- Different filter optimizations can be accomplished.

Simulating Gain Flattening Amplifiers

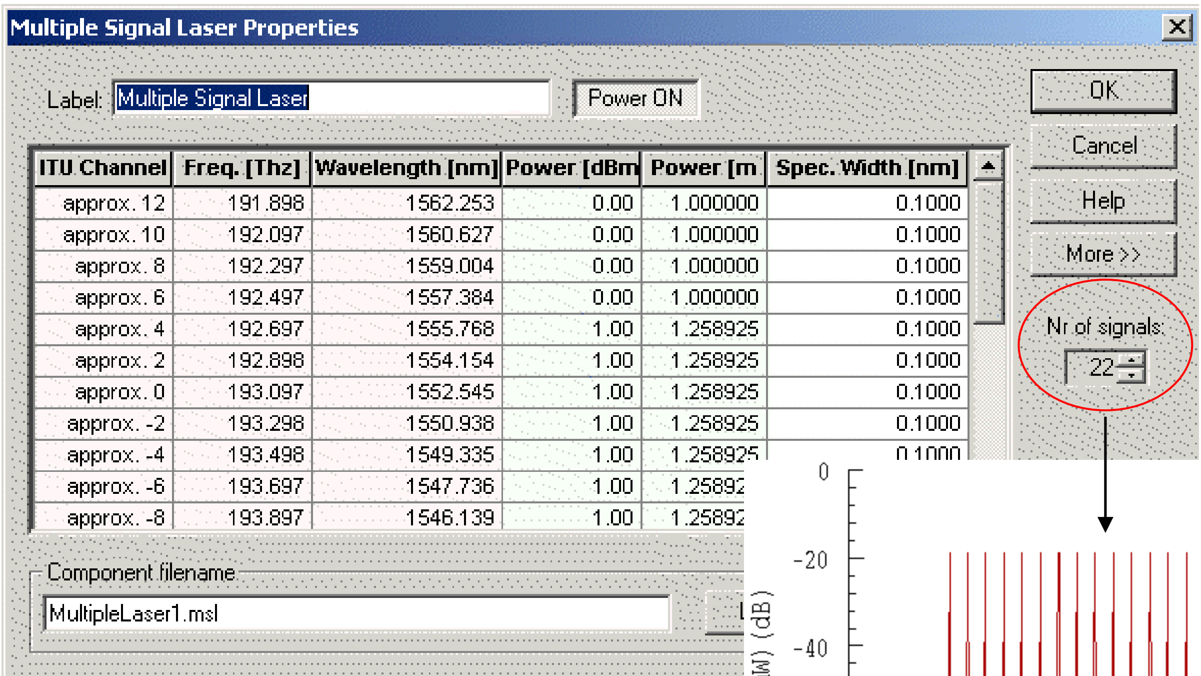
Main considerations

- Identifying the basic system parameters;
- Calculating fiber length and gain shape;
- Determining influence on system performance;
- Comparing amplifier's performance with and without the gain flattening filter.

Layout of two-fiber stages EDFA



Details of the Project – Signal Input



Multiple Signal Laser Properties

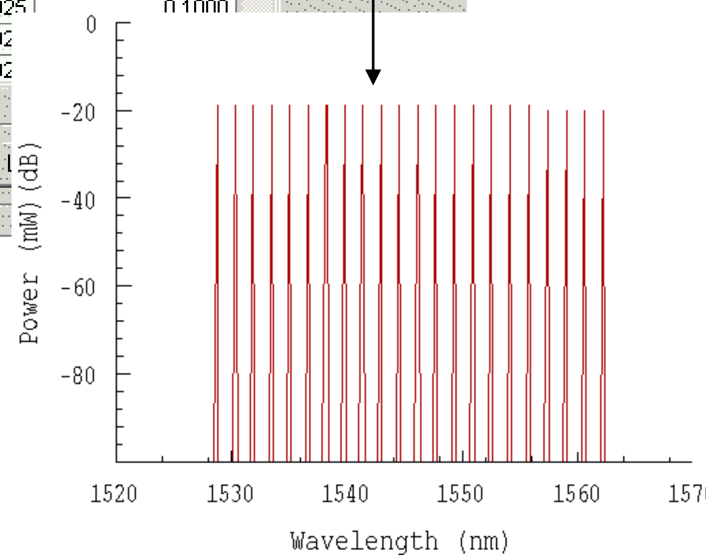
Label: Multiple Signal Laser | Power ON | OK | Cancel | Help | More >>

Nr of signals: 22

ITU Channel	Freq. [Thz]	Wavelength [nm]	Power [dBm	Power [m	Spec. Width [nm]
approx. 12	191.898	1562.253	0.00	1.000000	0.1000
approx. 10	192.097	1560.627	0.00	1.000000	0.1000
approx. 8	192.297	1559.004	0.00	1.000000	0.1000
approx. 6	192.497	1557.384	0.00	1.000000	0.1000
approx. 4	192.697	1555.768	1.00	1.258925	0.1000
approx. 2	192.898	1554.154	1.00	1.258925	0.1000
approx. 0	193.097	1552.545	1.00	1.258925	0.1000
approx. -2	193.298	1550.938	1.00	1.258925	0.1000
approx. -4	193.498	1549.335	1.00	1.258925	0.1000
approx. -6	193.697	1547.736	1.00	1.25892	
approx. -8	193.897	1546.139	1.00	1.25892	

Component filename: MultipleLaser1.msl

22 Signal Input Channels

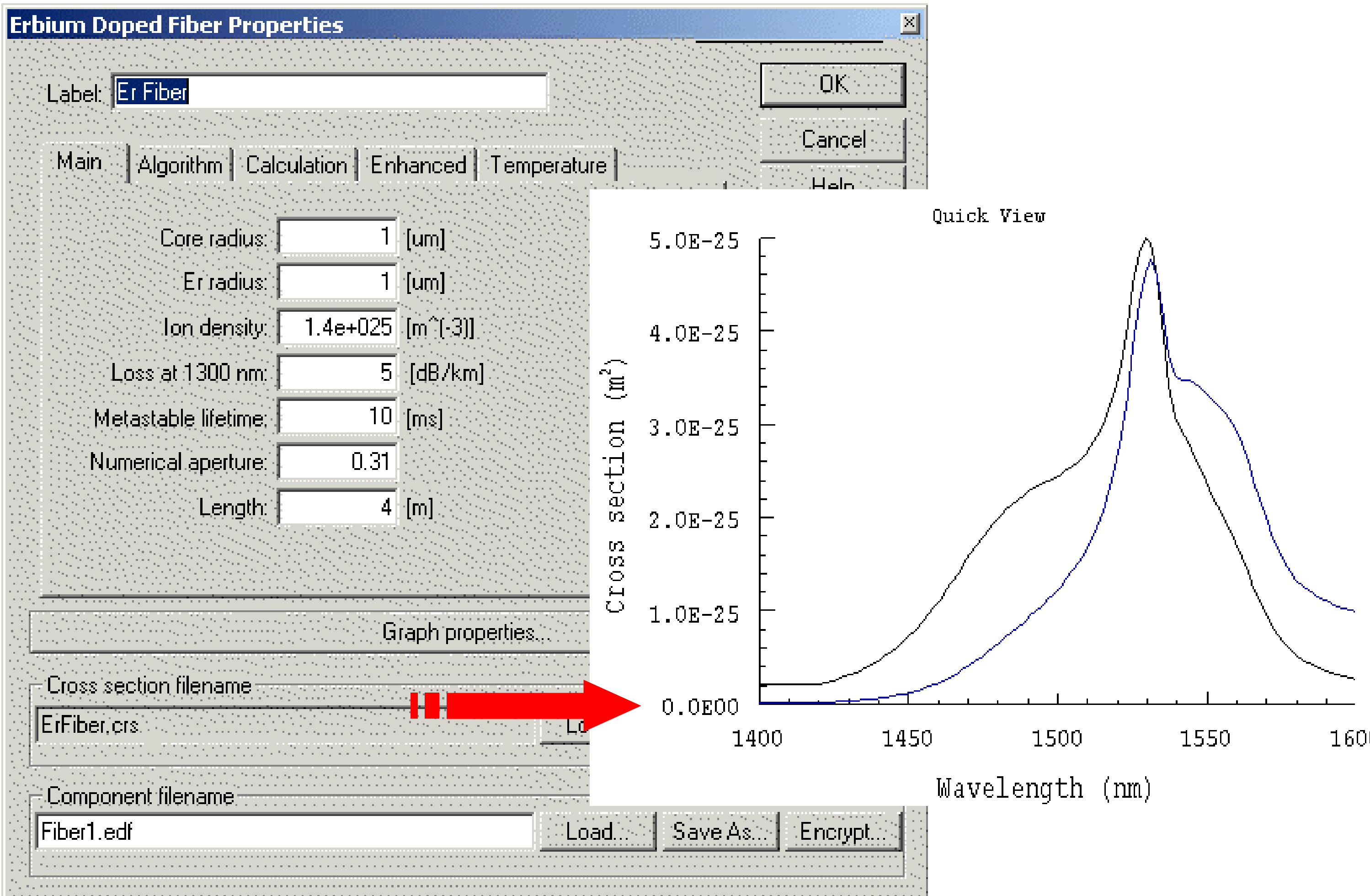


λ_s

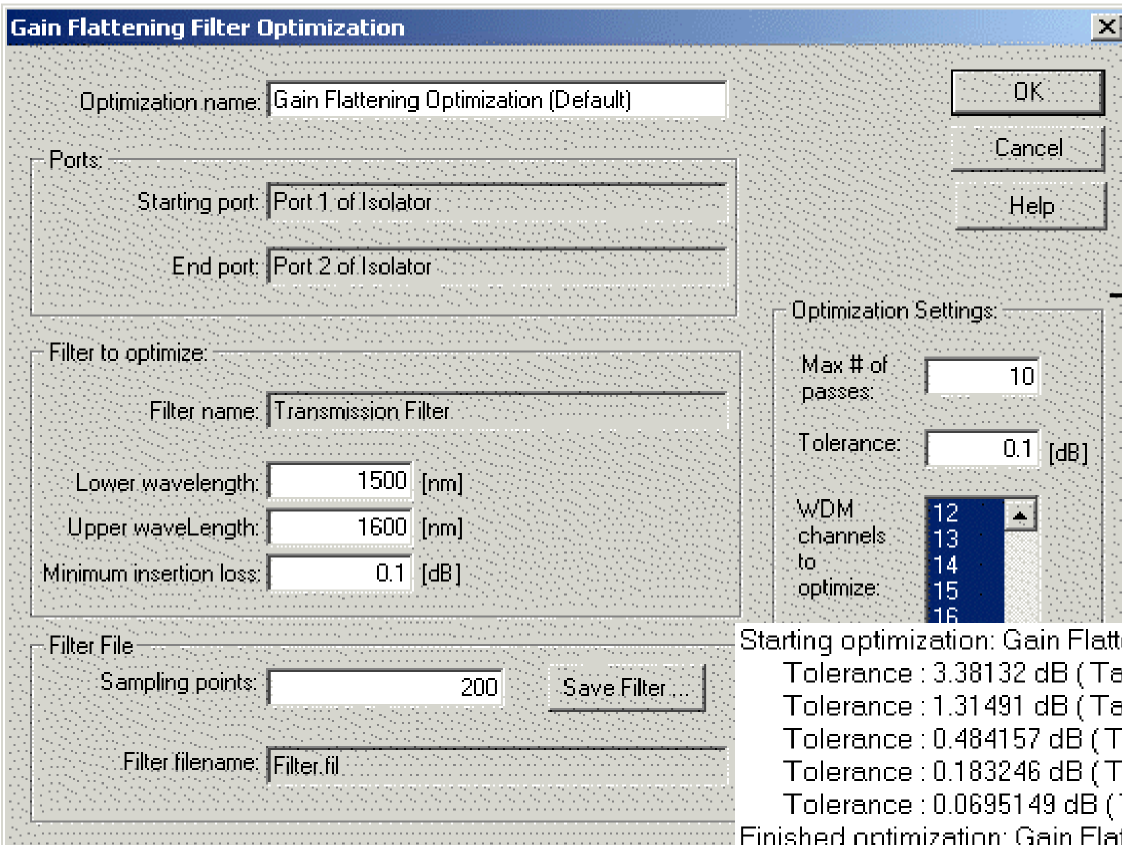
1528.79 nm to 1562.25 nm spaced by 1.56 nm

-20 dBm/channel

Details of the Project – EDF



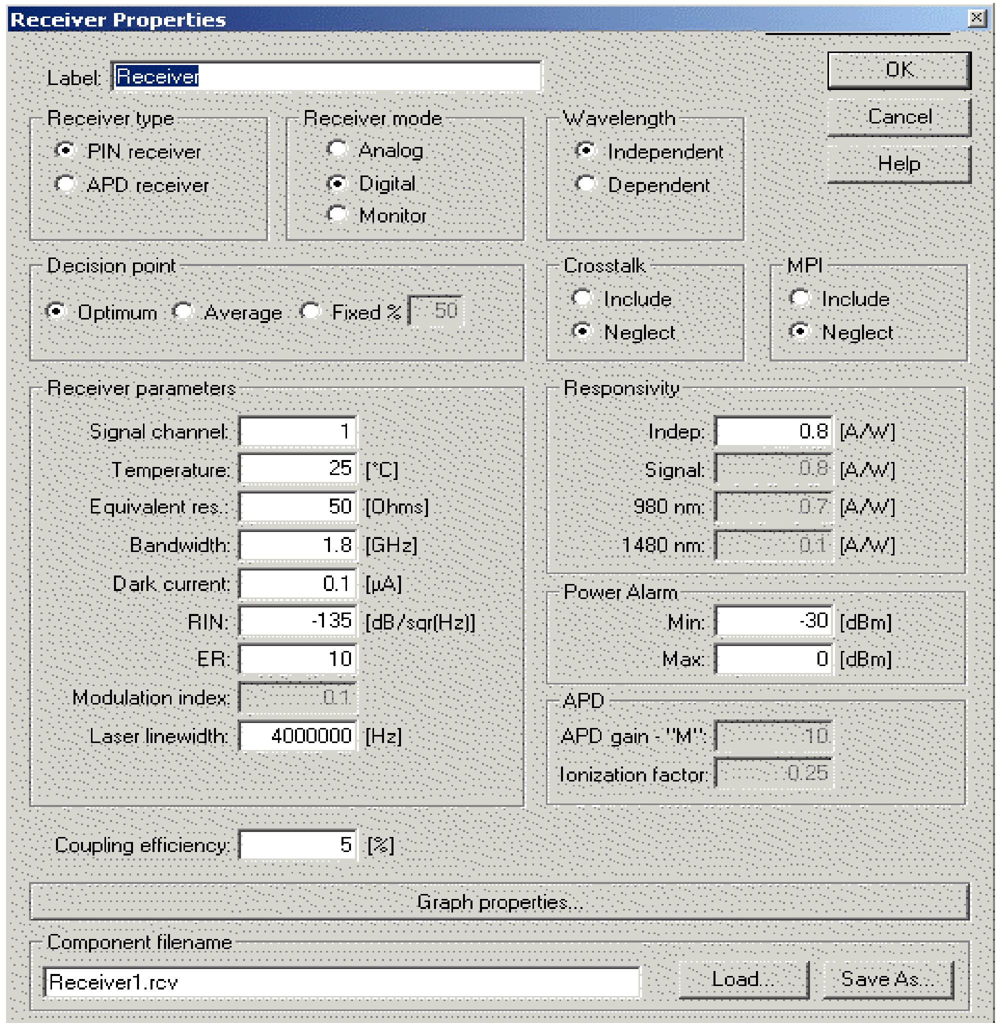
Details of the Project – Gain Flattening Filter



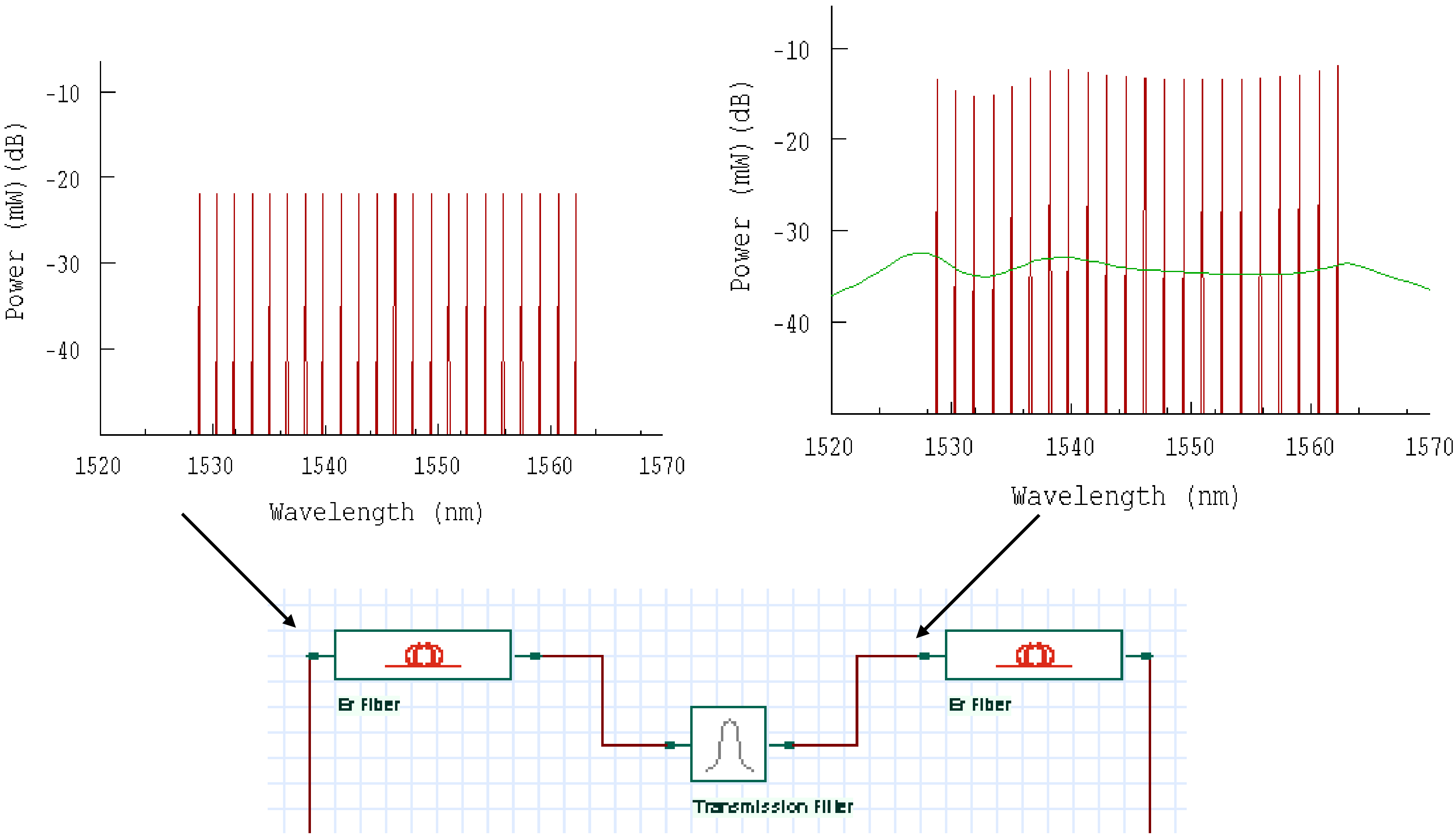
Tolerance specifies how flat the gain will be

Optiwave

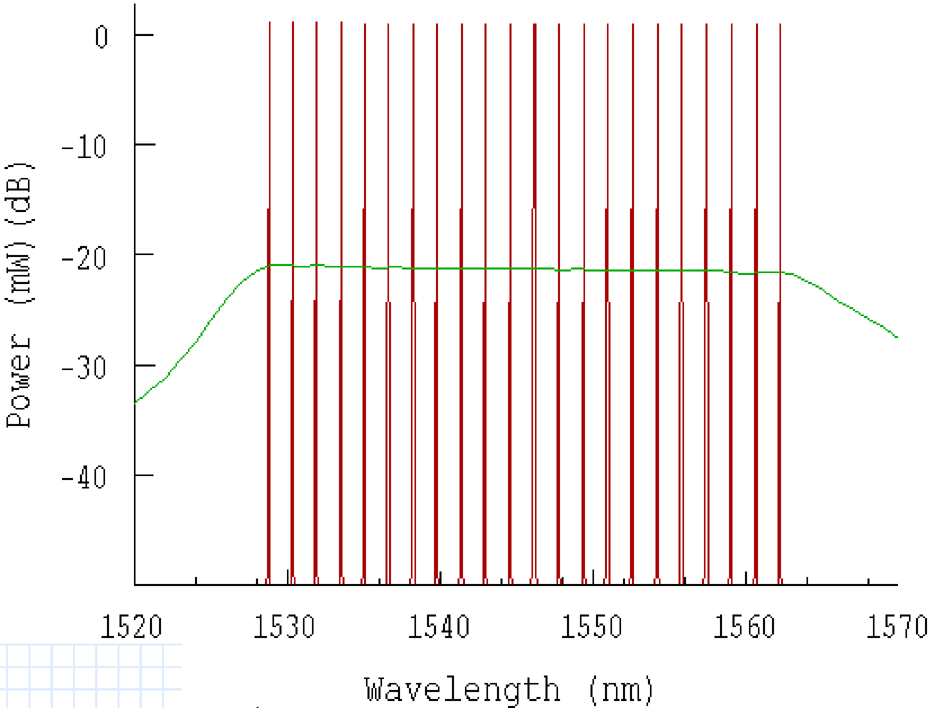
Details of the Project – Receiver

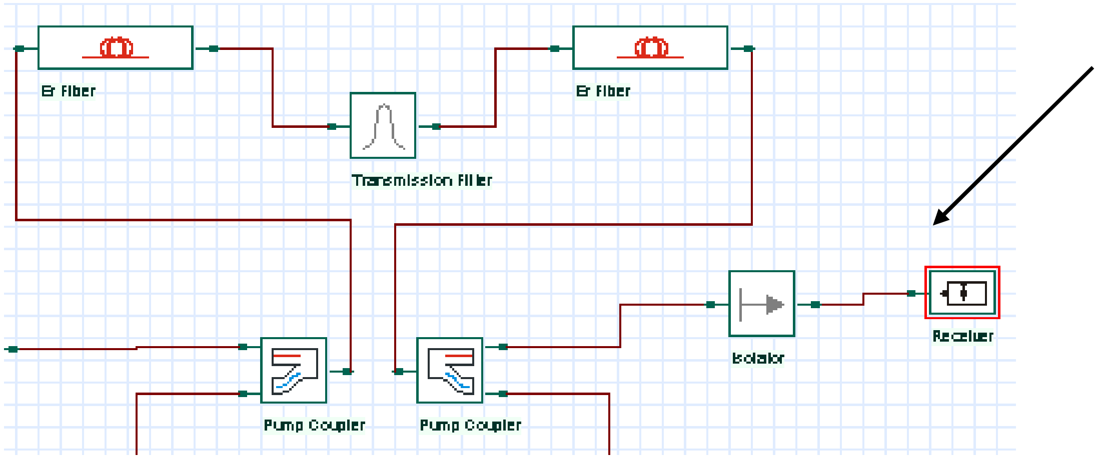


Simulation Results

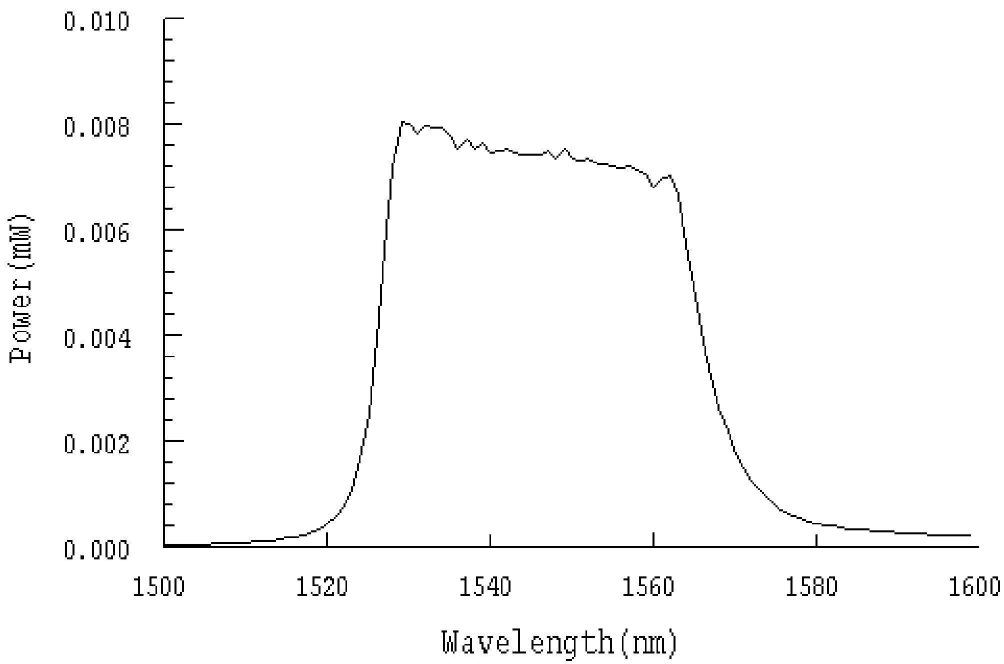


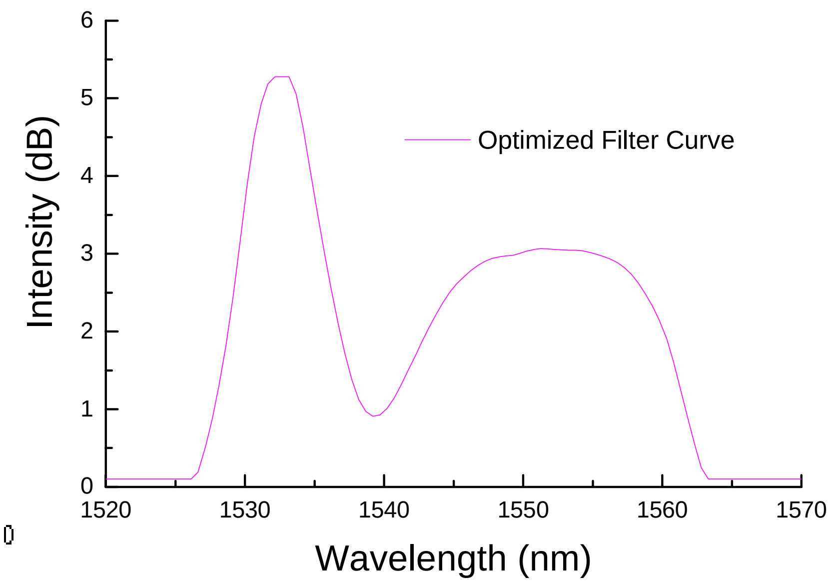
Flattened Amplifier Output



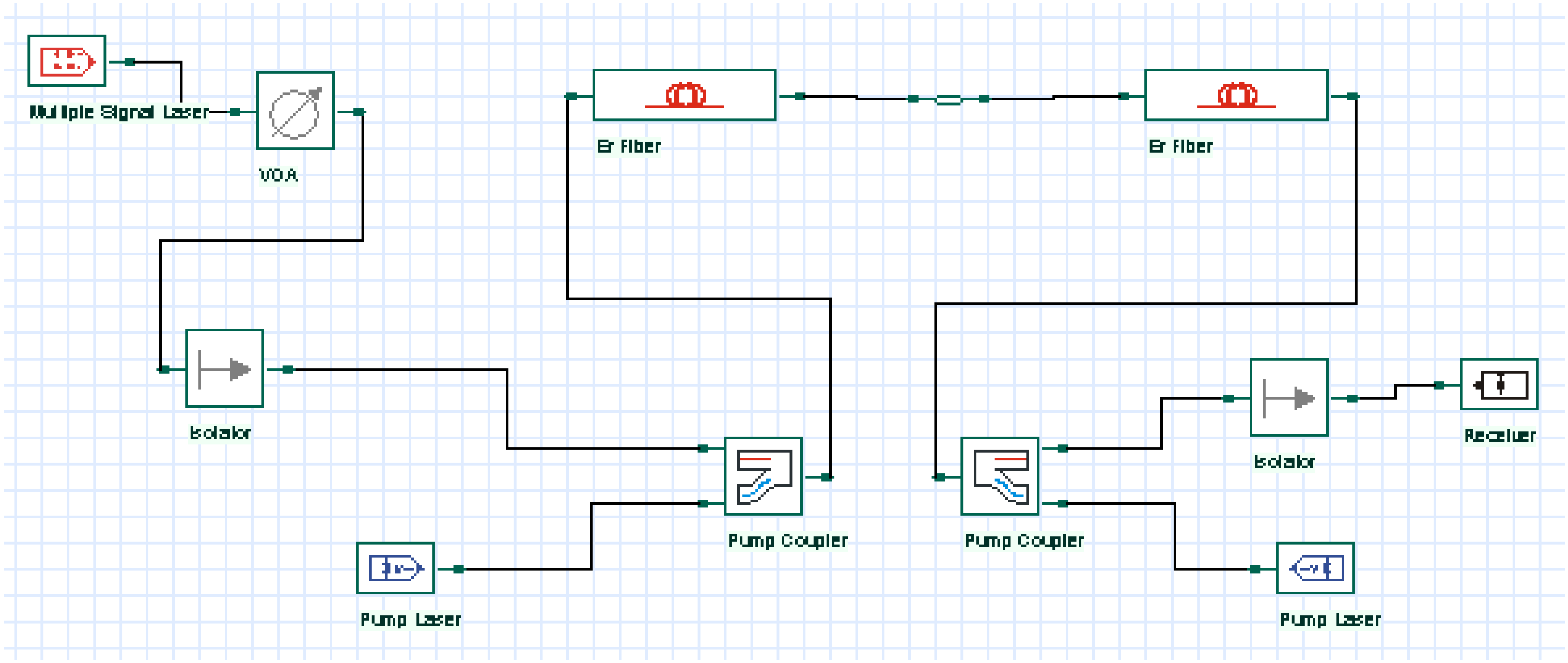


ASE Shape and Filter Curve

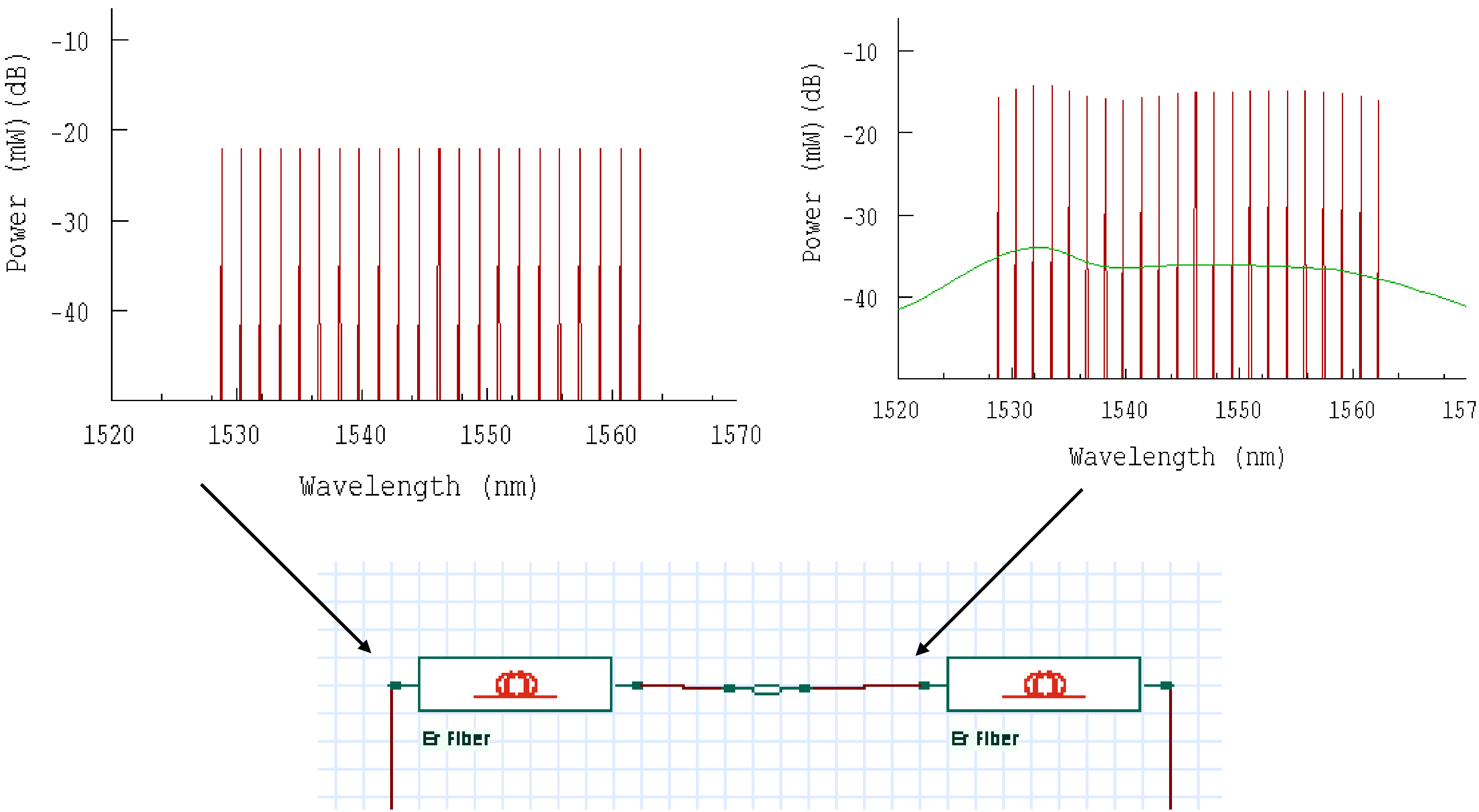




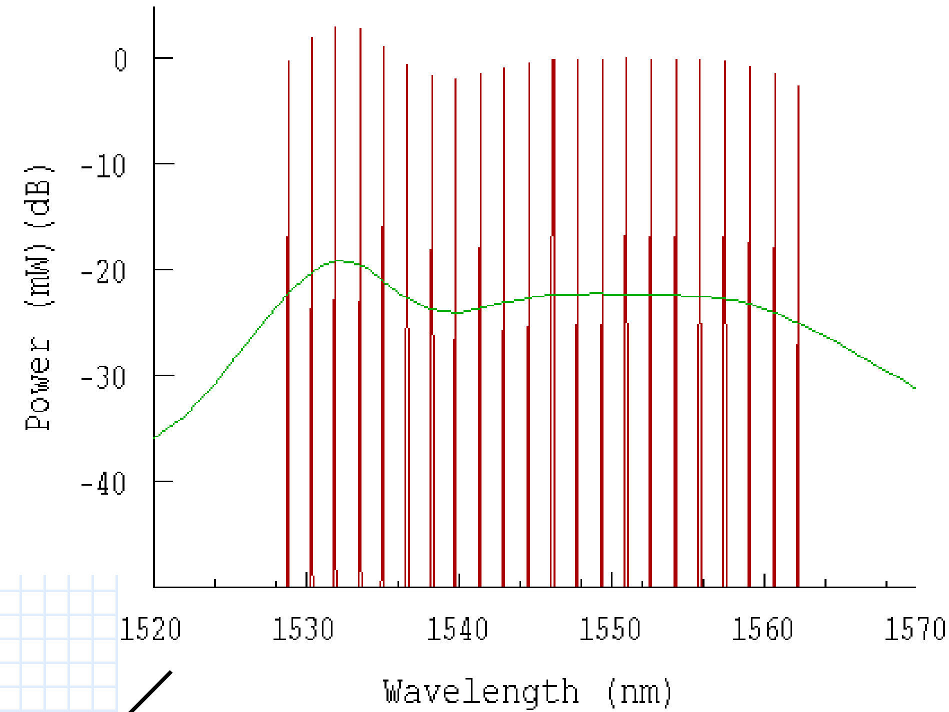
Layout with No Filter

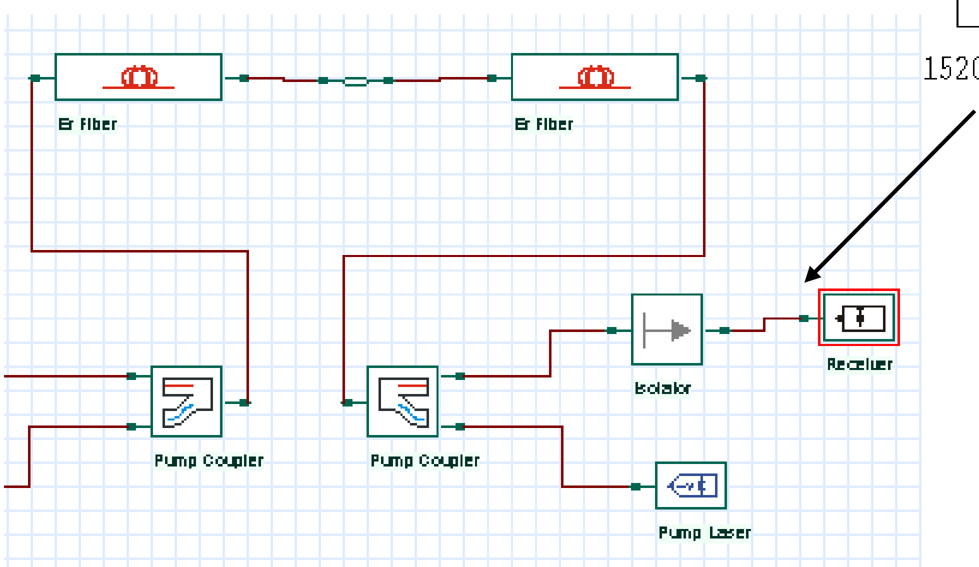


Simulation Results

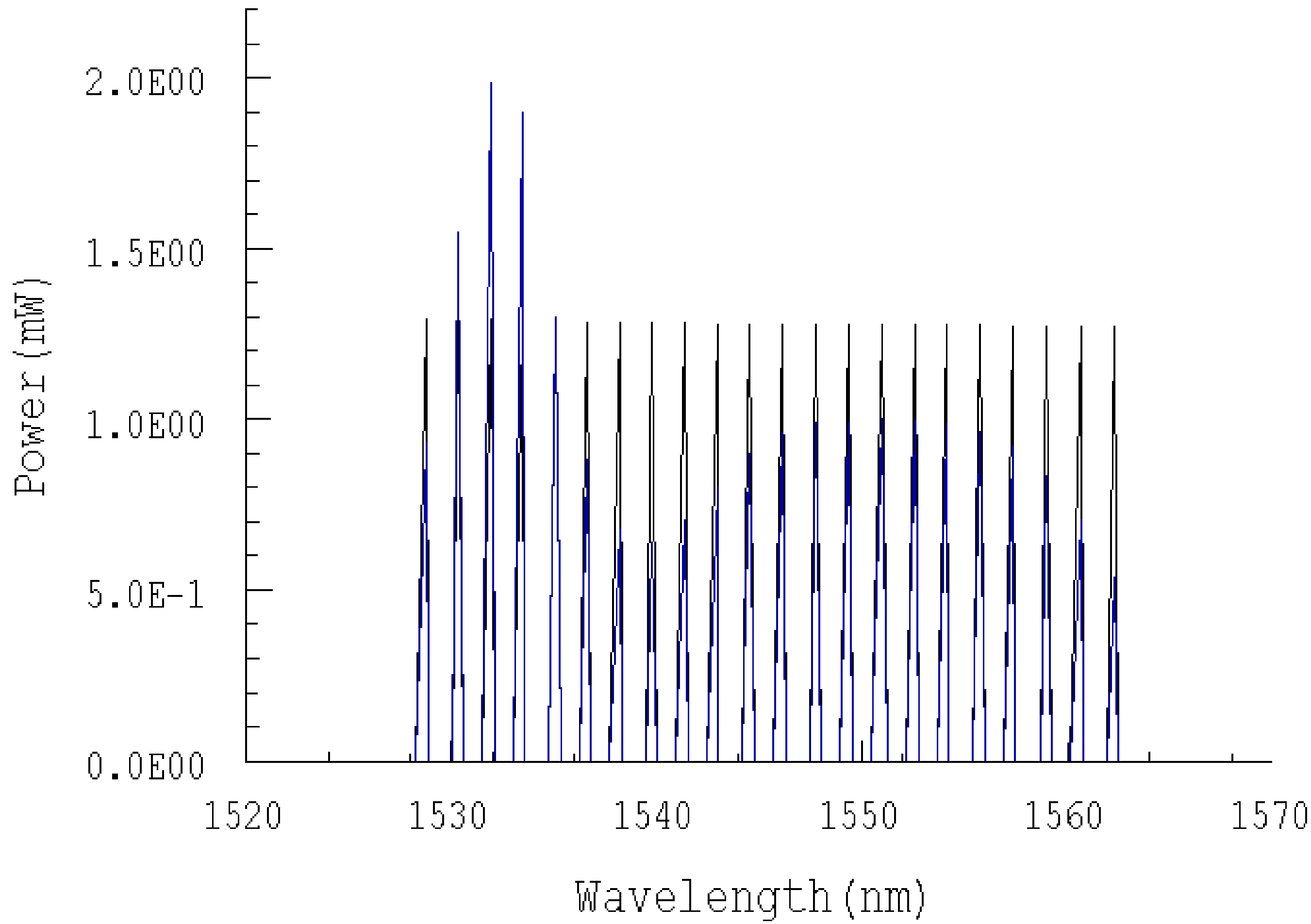


Signal Output at the Receiver



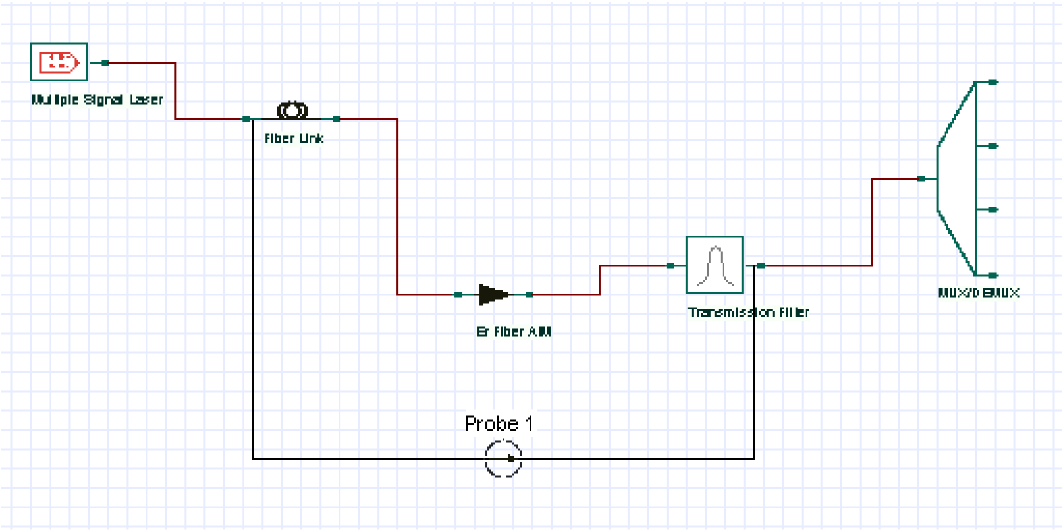


Comparing Results – With and Without Filter

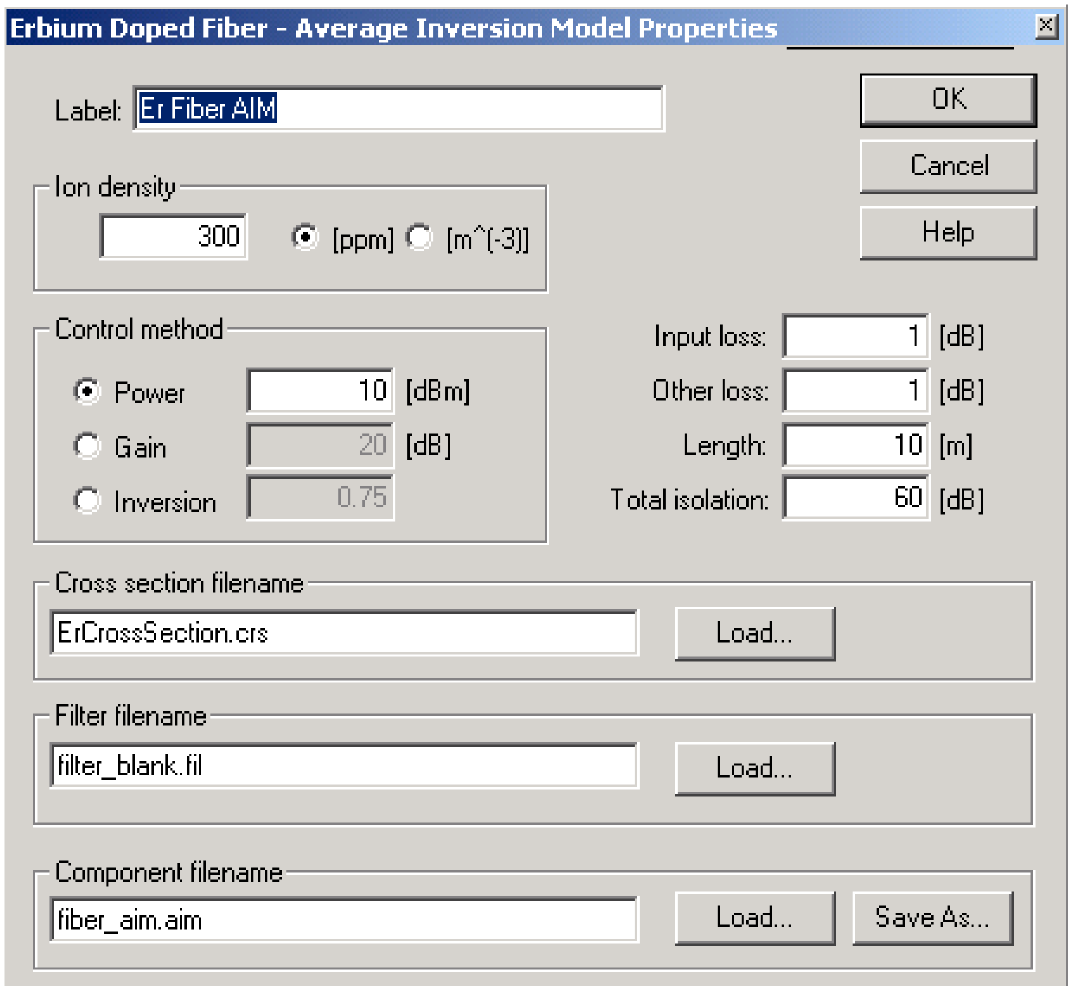


Evaluating Gain Flattened EDFA in a WDM system

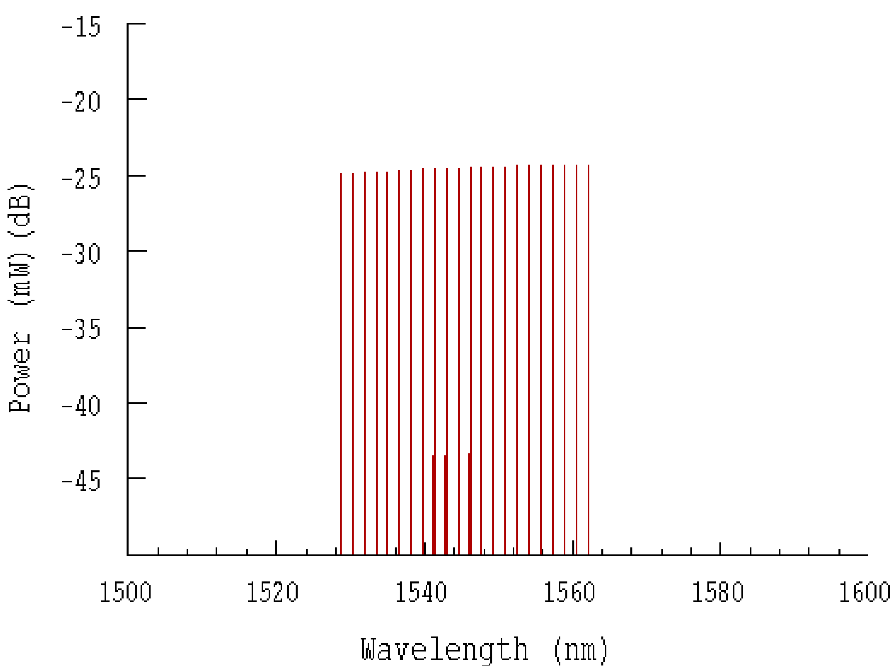
- Using a black-box model
- Evaluating a multi-span WDM system
- Using multiple signal input
- Gain flattening filter optimization

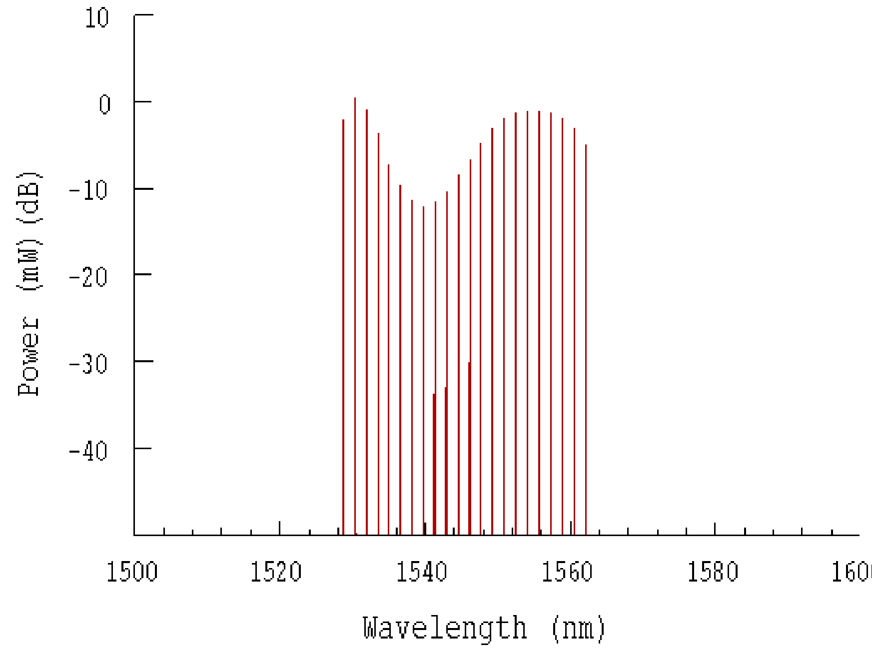


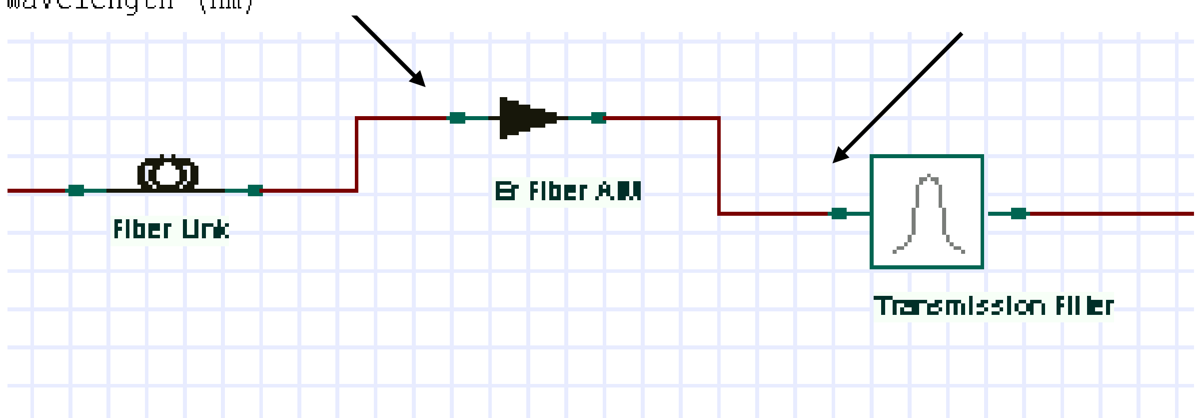
AIM – Black Box Component



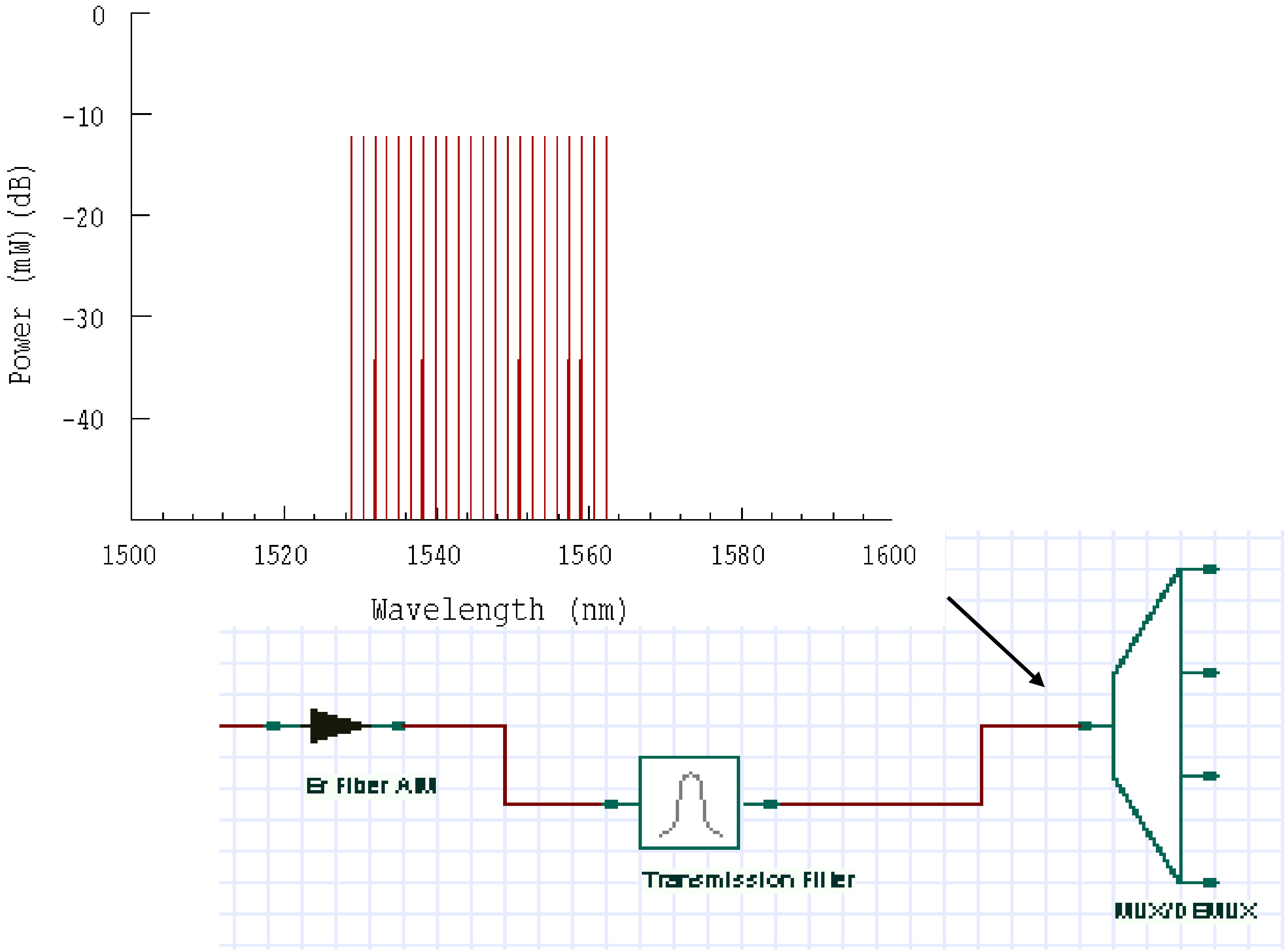
Signal Observed Along the System



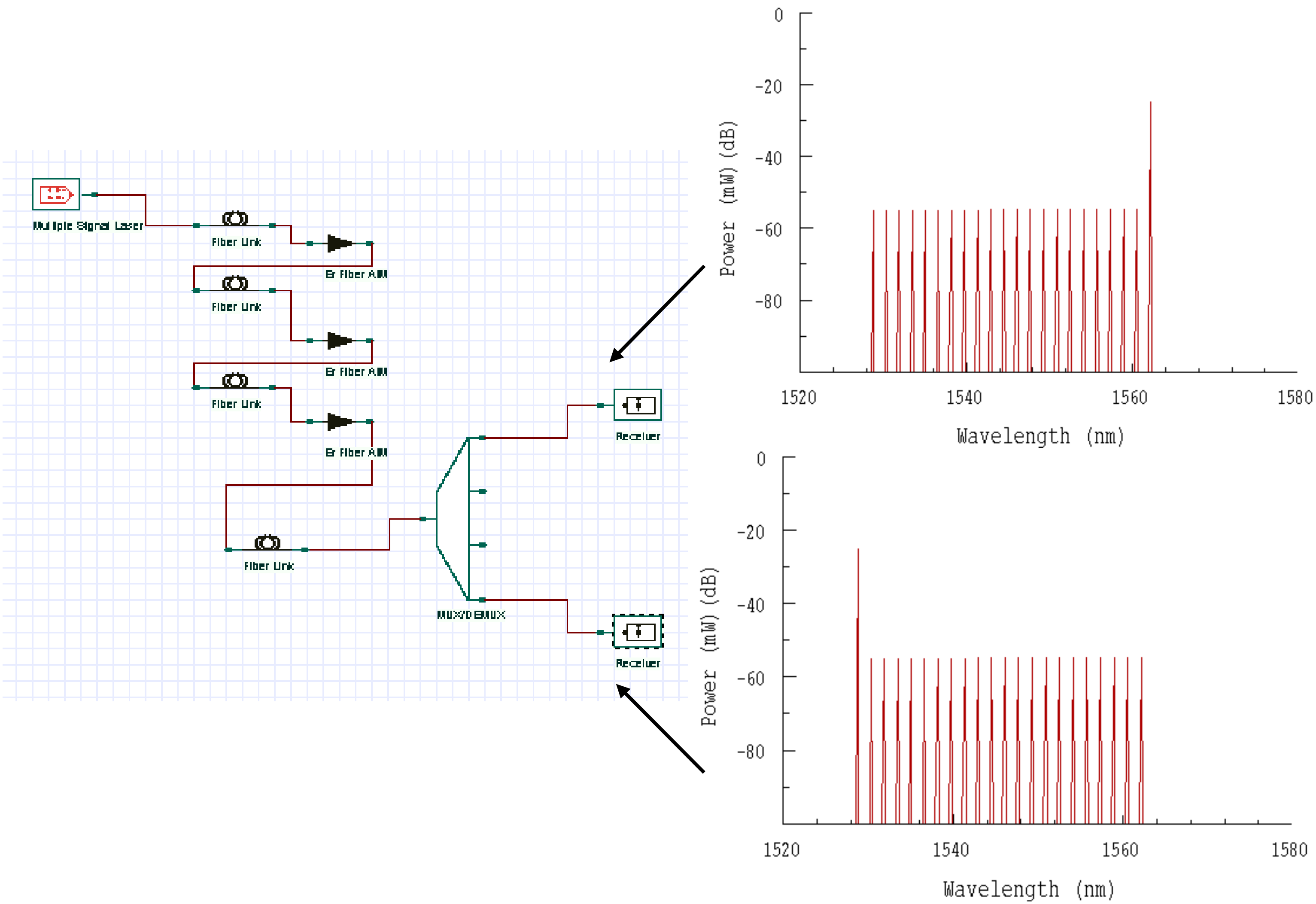




After Flattening the Gain



WDM Network



Multiple Signal Laser
Fiber Link
Er Fiber AM
Fiber Link
Er Fiber AM
Fiber Link
Er Fiber AM
Fiber Link
MUX/DEMUX
Receiver
Receiver
Power (mW) (dB)
0
-20
-40
-60
-80
1520
1540
1560
1580
Wavelength (nm)
Power (mW) (dB)
0
-20
-40
-60
-80
1520
1540
1560
1580
Wavelength (nm)

Conclusion

- Gain Flattened Amplifiers simulations
- Evaluation of the amplifier performance along the system including gain flattening filter optimization
- Flexibility to include different types of Er-doped fibers, different configurations

Part II -
Designing L-band Erbium Doped Fiber Amplifiers in WDM Applications

Outline

- Overview of basic characteristics of L-band EDFAs
- How to obtain long band amplification
- Simulating L-band amplifiers
- Fitting experimental results
- Facilities to split band selection
- Conclusions

Overview on Basic Characteristics of L-Band EDFAs

- Increasing interest in L-band amplifiers comes from the expanding demand for larger number of WDM channels

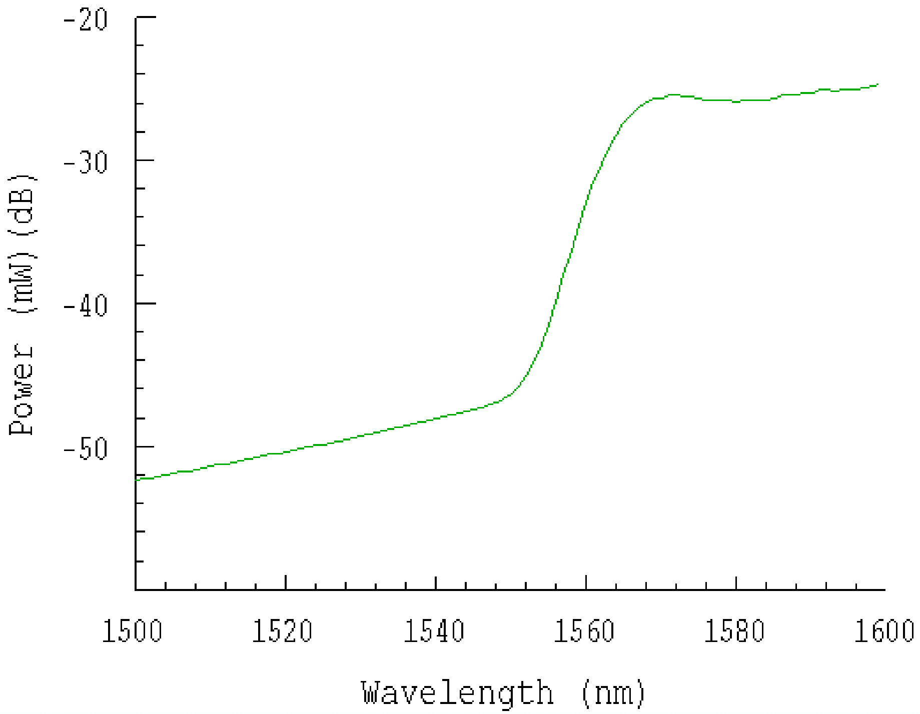
- Designing L-band (*1570 nm – 1610 nm*) fiber amplifiers is a simulation challenge

- Convergence of the numerical algorithms used to solve rate and propagation equations is slower and less stable than for C-band EDFAs (*1520 nm to 1570 nm*).

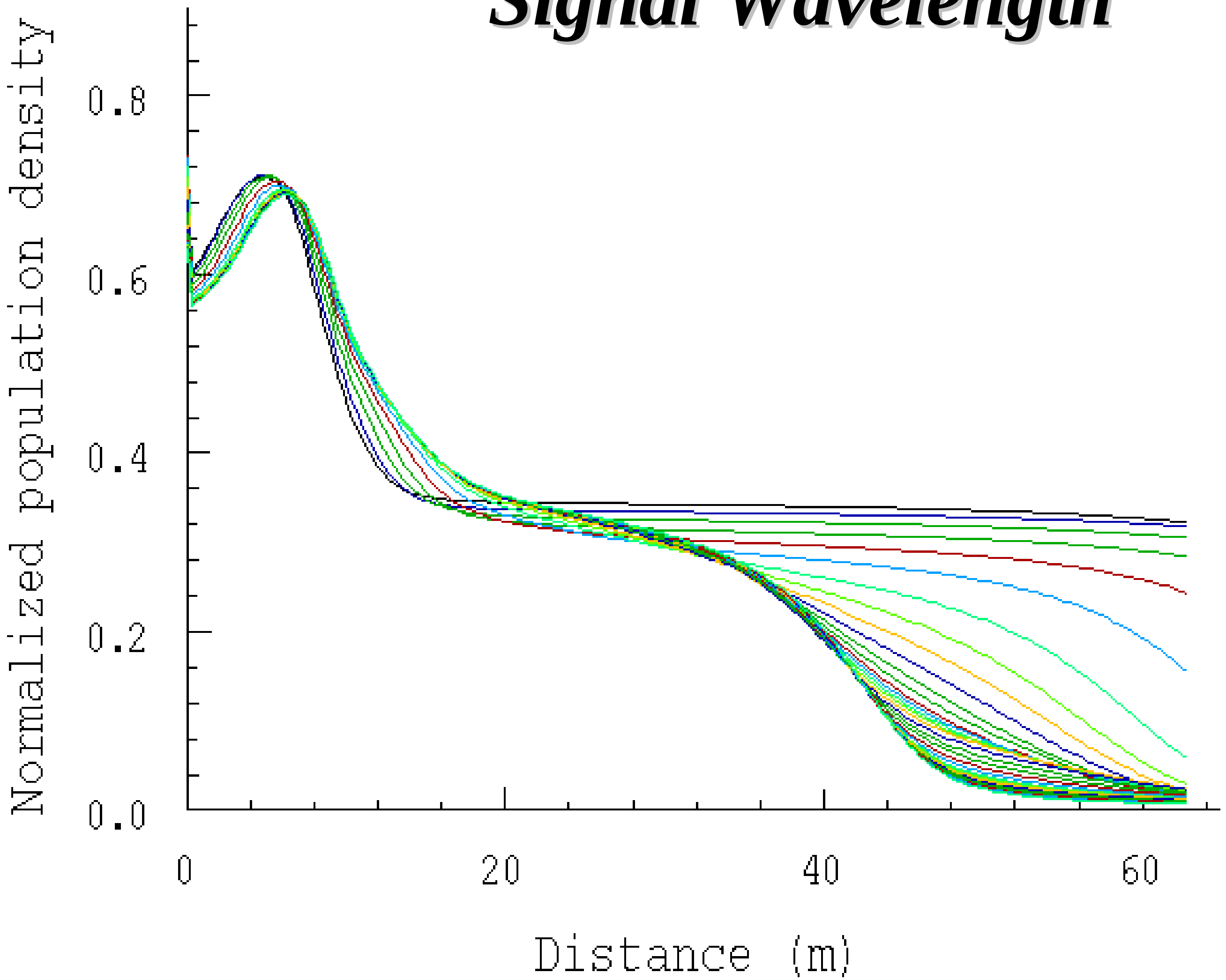
- Configurations: single and multiple Er-doped fiber stages

How to Obtain Long Band Amplification

- Main reason to extend the amplification to longer signal wavelengths: average inversion ~ 40 %
- Conventional band EDFAs: inversion > 70%



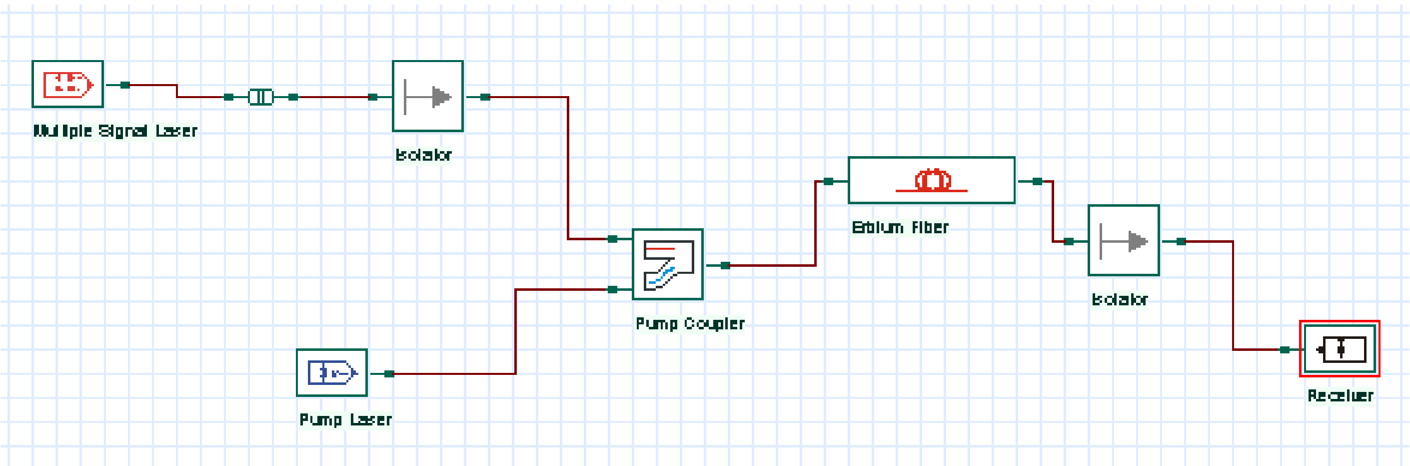
Average Inversion to Different Signal Wavelength



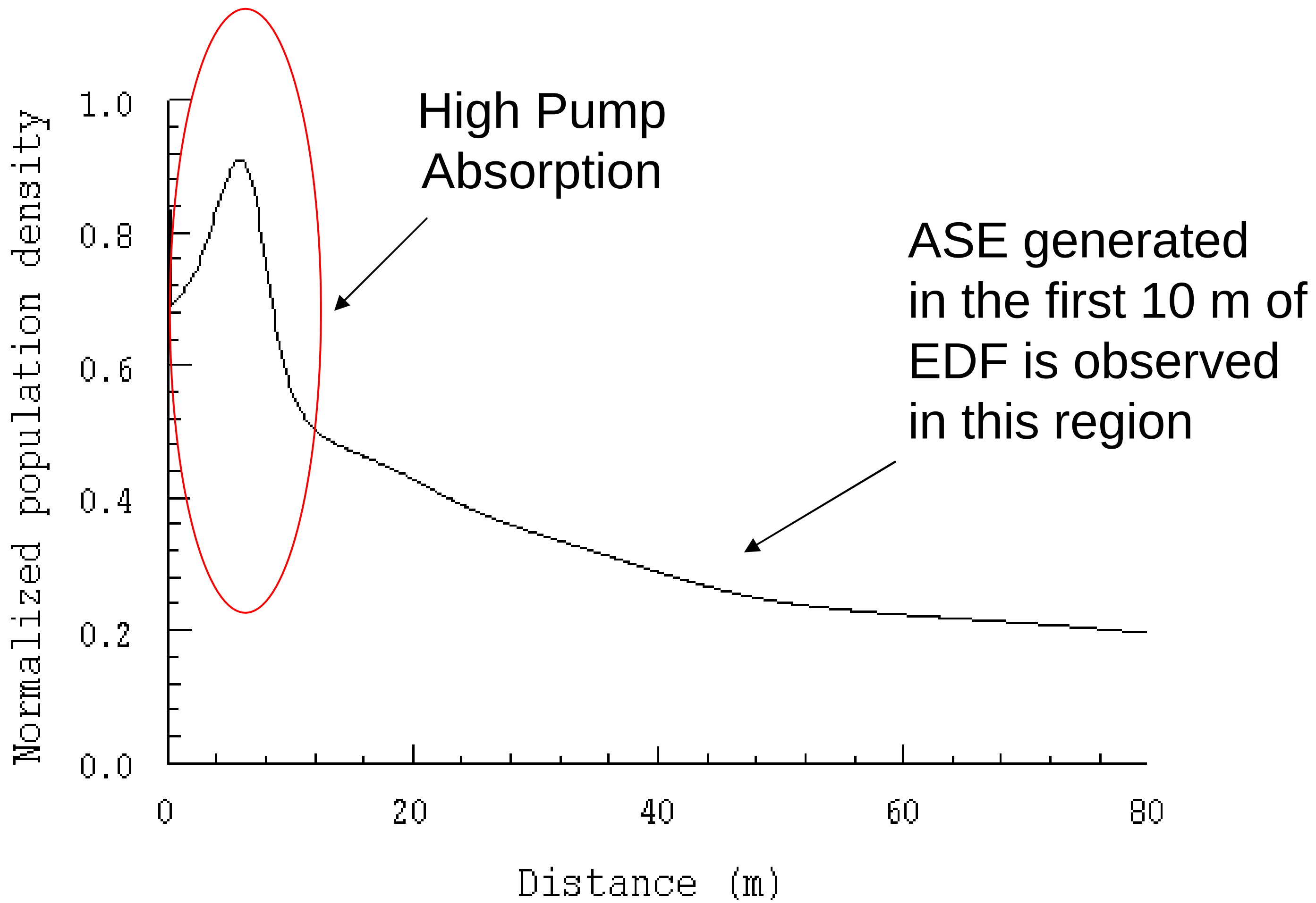
Simulating L-Band Amplifiers

- Designing amplifier including elements to be considered in a “possible” experimental evaluation
- Passive elements settings
- Choose to include wavelength dependence or not in the passive components settings

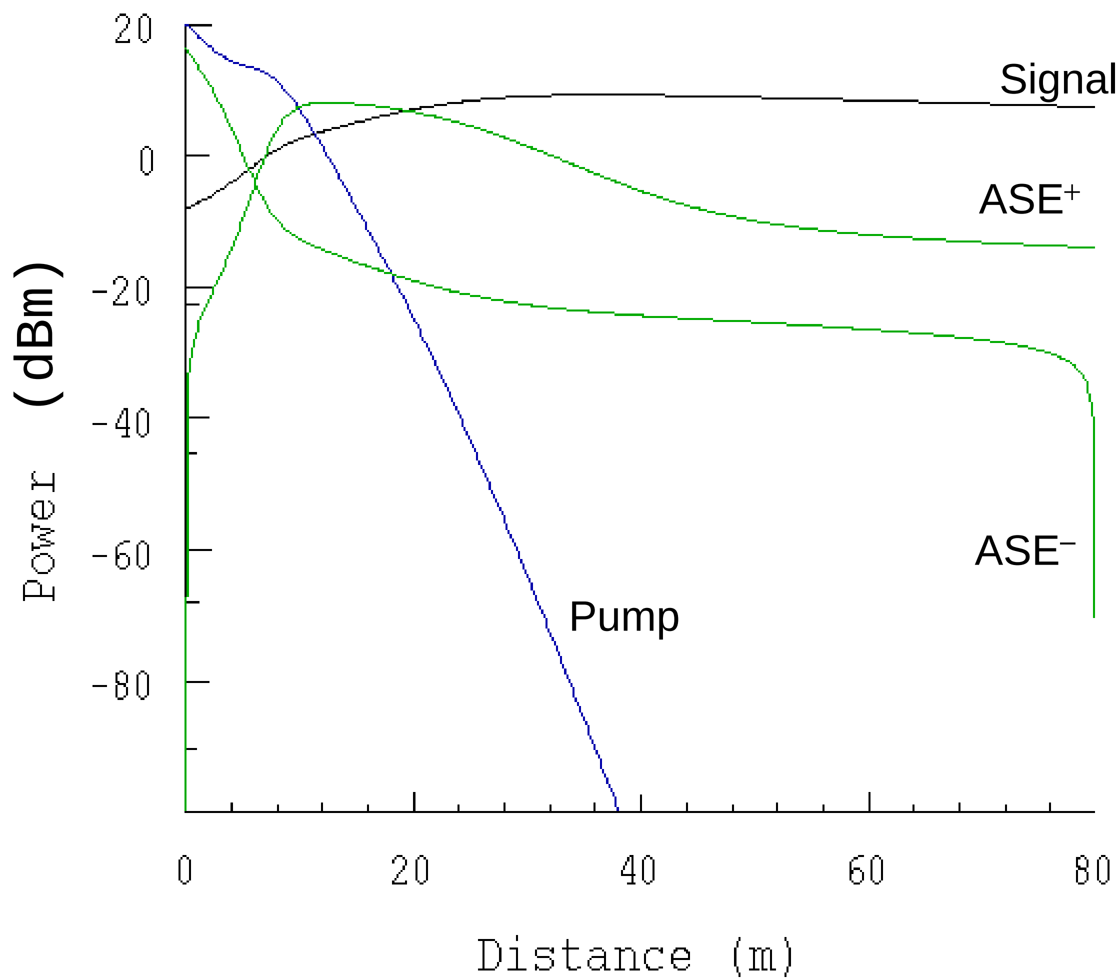
One-stage Configuration



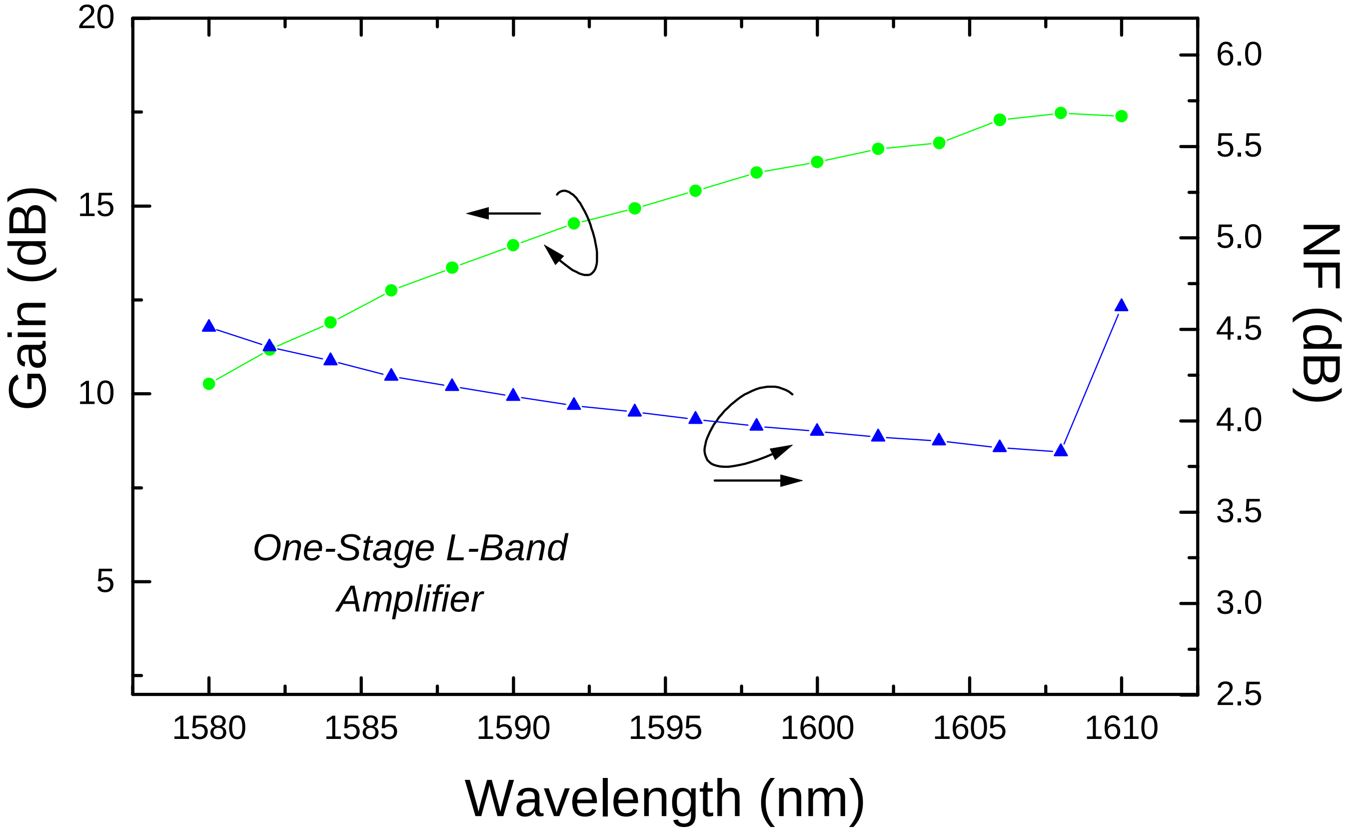
Inversion Along the EDF



Propagating Powers Along the EDF



Calculated Gain and NF



Fitting Experimental Results

• Adjustments performed to C-band amplifiers typically show an error rate of 5% or less when simulated results are compared with experimental data.

• If L-band amplifiers are considered, agreement between simulated results and experimental data is high. However, the error rate after comparing L-band simulated results with experimental data can be 3% higher than that observed for C-band amplifiers.

• Adjustments performed to L-band amplifiers that have component settings including wavelength dependence are critical to better match the experimental data.

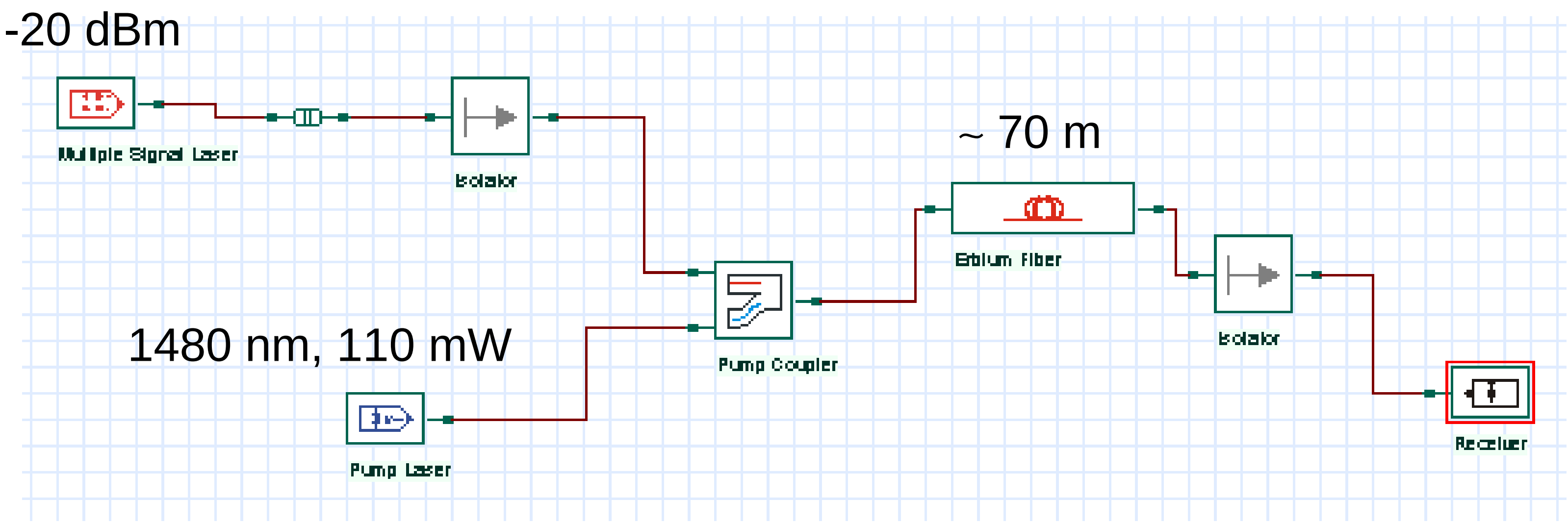
Critical Points in the Adjustments

1) Correct evaluation of the return loss of the components in the front end of the erbium fiber is fundamental to attempt correct predictions about the performance of the EDFA

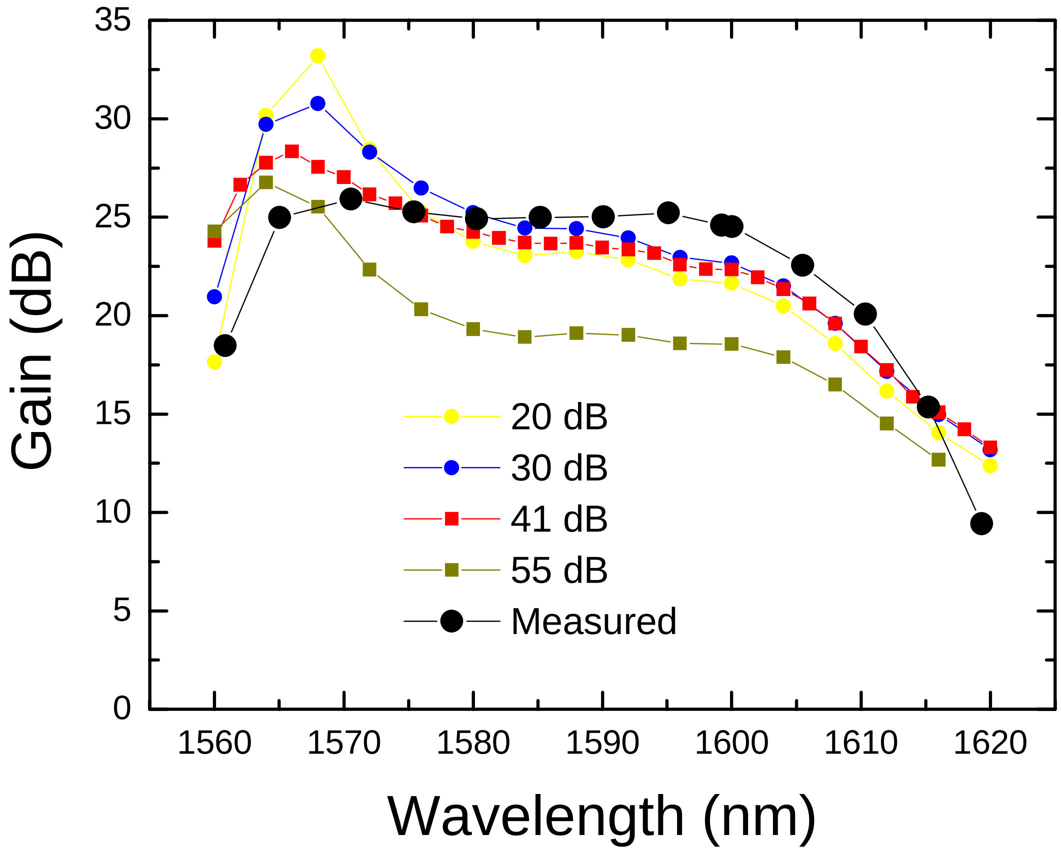
2) Inherent uncertainties due to the method used to measure cross sections can be prohibitive to running simulations with precision better than 5%

Experimental Data Adjustments

L-Band Amplifier Setup in One-EDF Stage

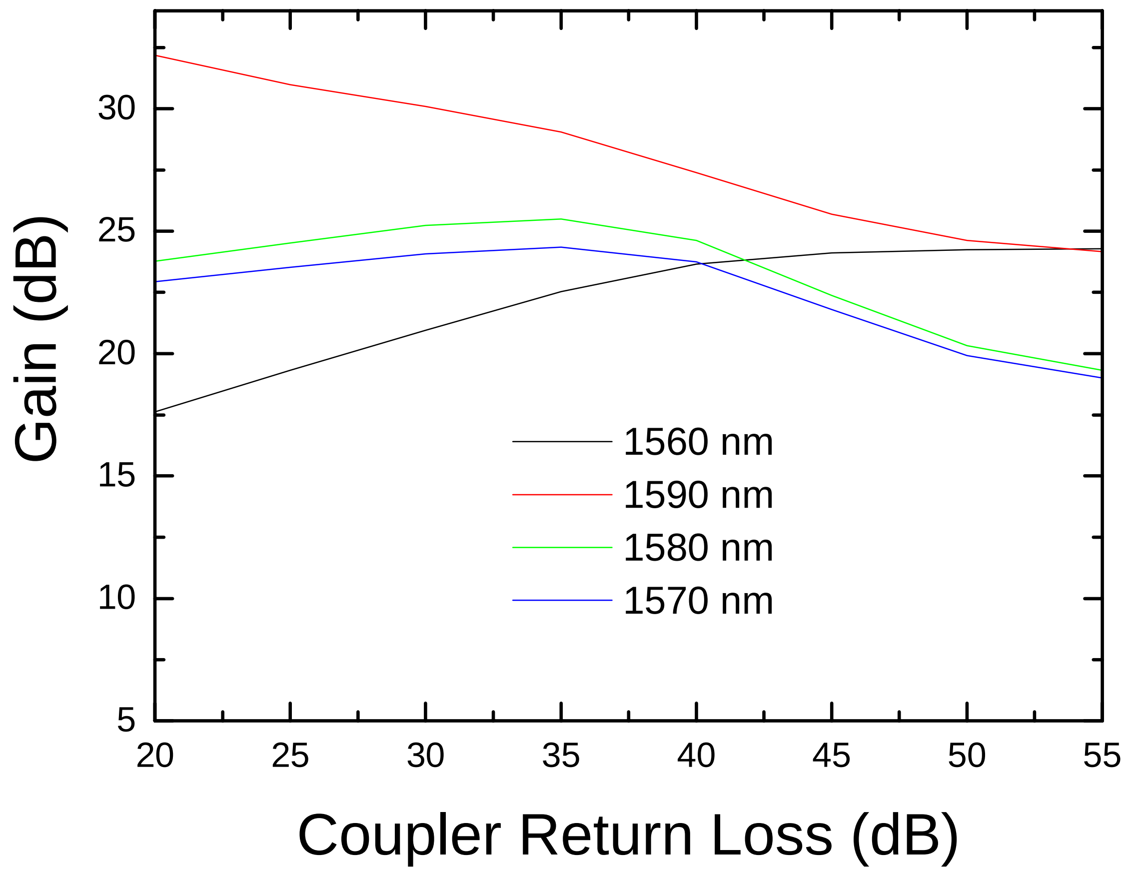


Setting Different Return Loss in the Coupler at the Fiber Input*

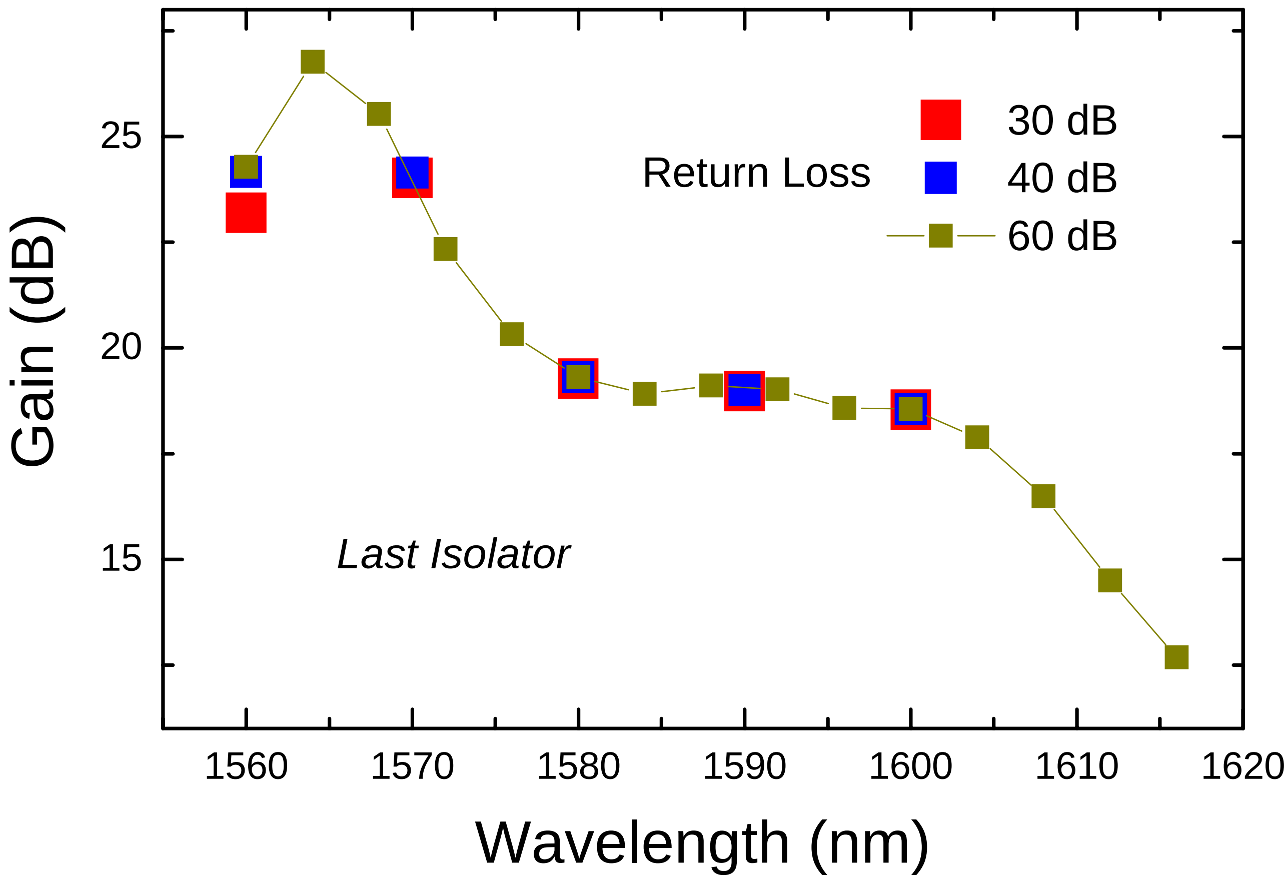


* *Nilsson et al., IEEE Photon. Techn. Lett. Vol. 10, No. 11, p. 1551, 1998.*

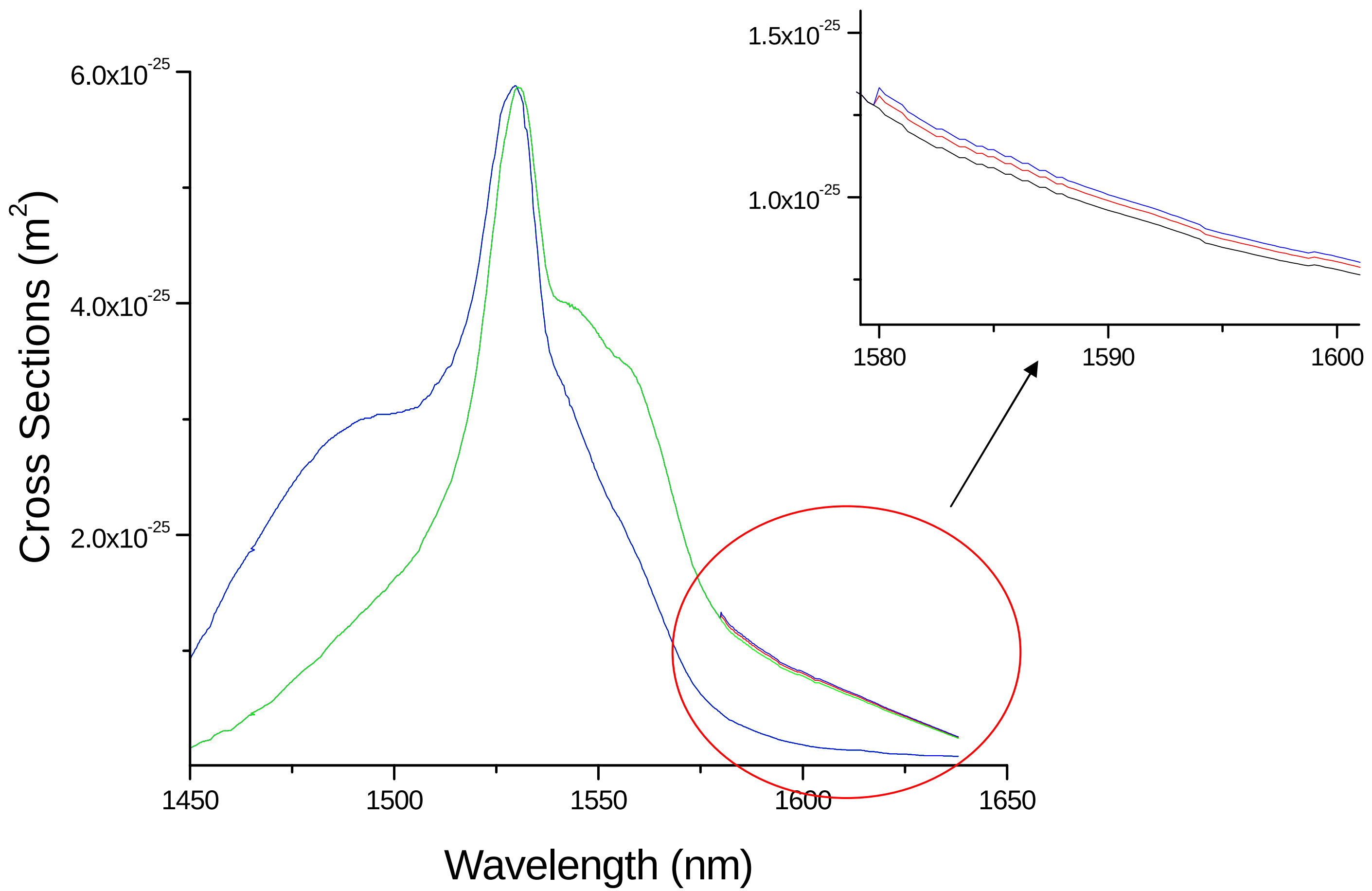
Gain versus Coupler Return Loss



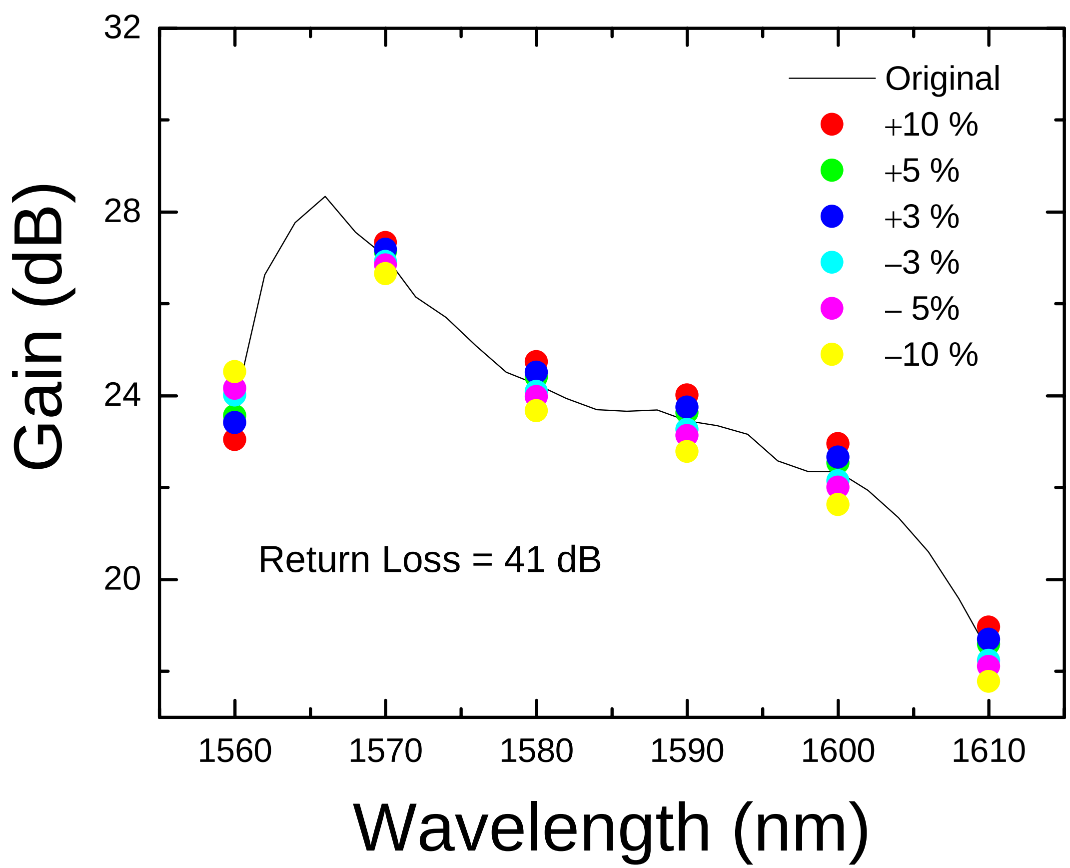
Changing RL in the 2nd Isolator



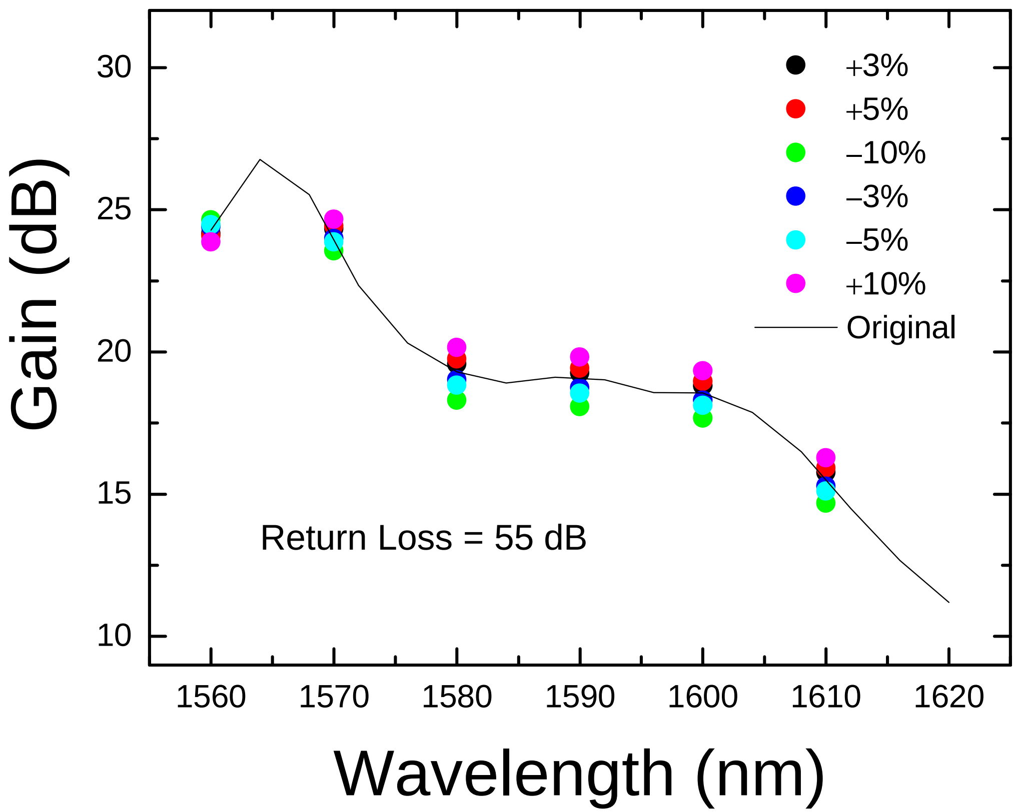
Cross-Section Spectra



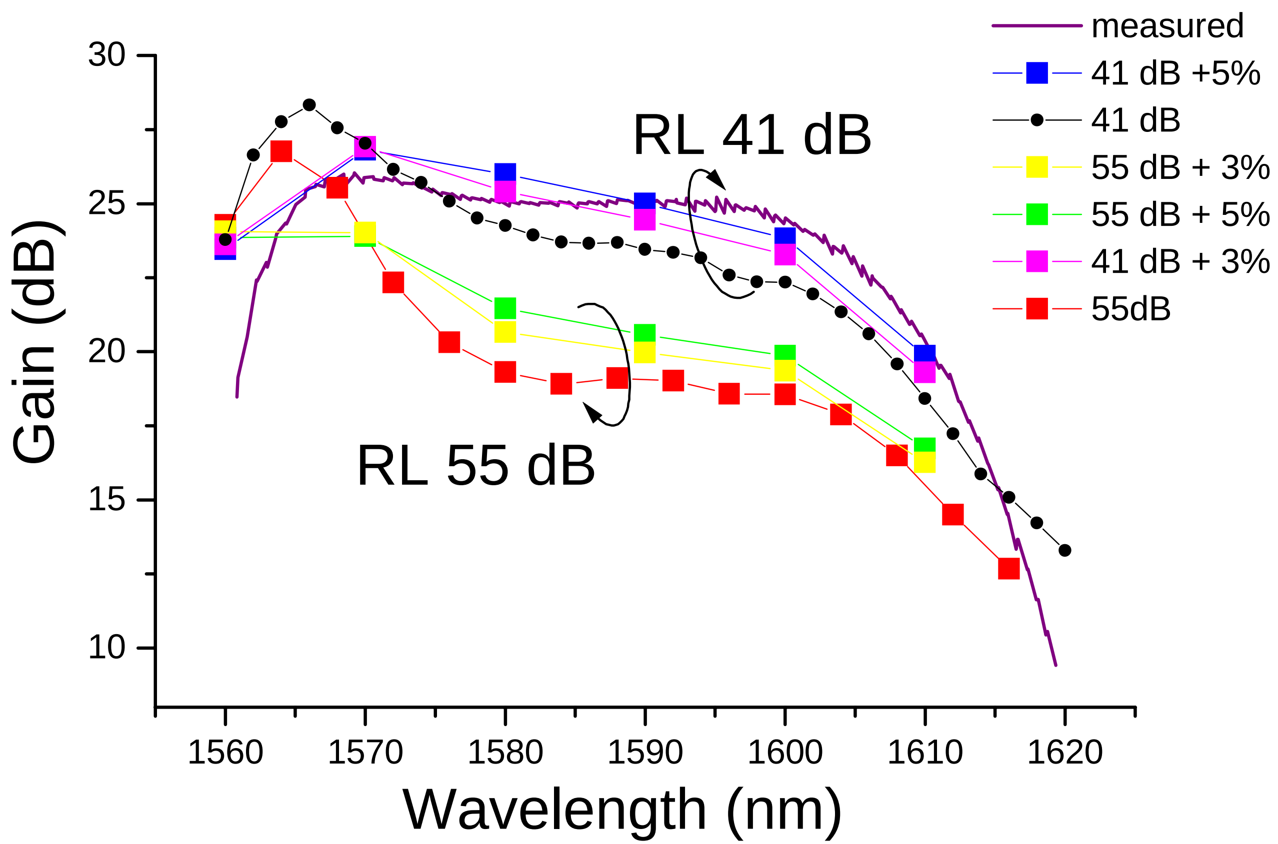
Testing Small Variations in the Cross-Section Values



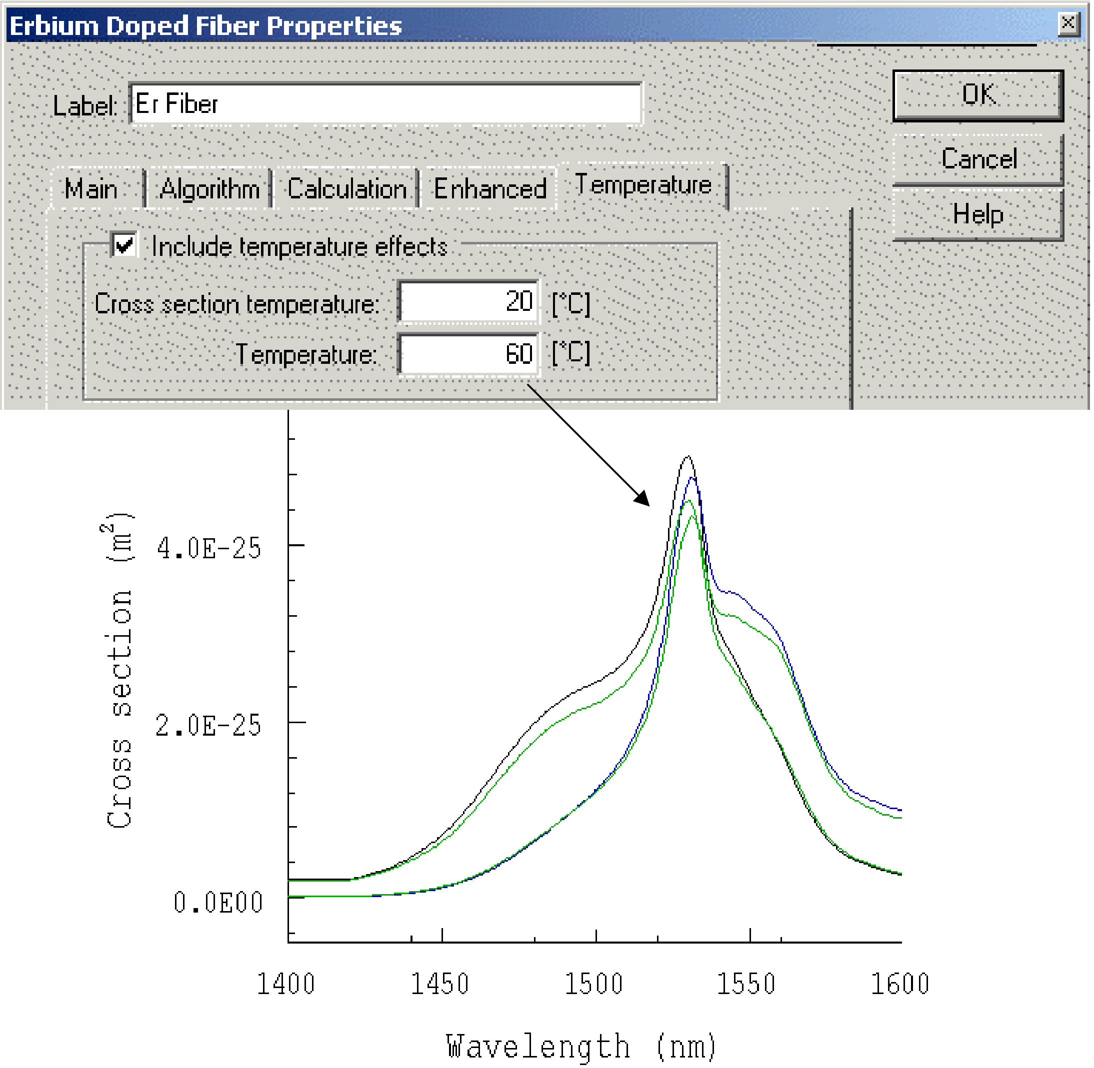
Testing Small Variations in the Cross-Section Values



Fitting Experimental Data with Modified Cross-Sections



Including Temperature Dependence

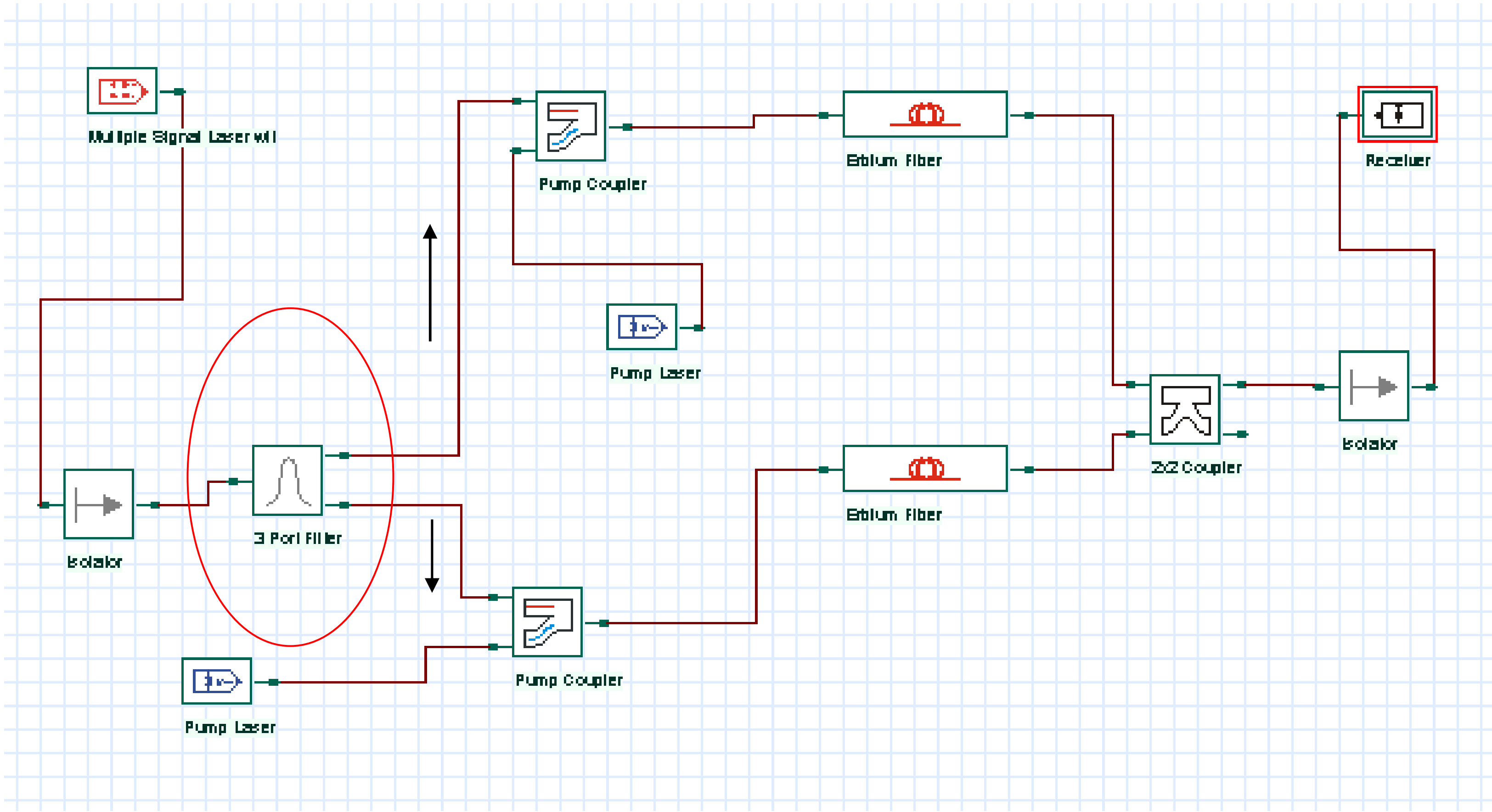


Optiwave

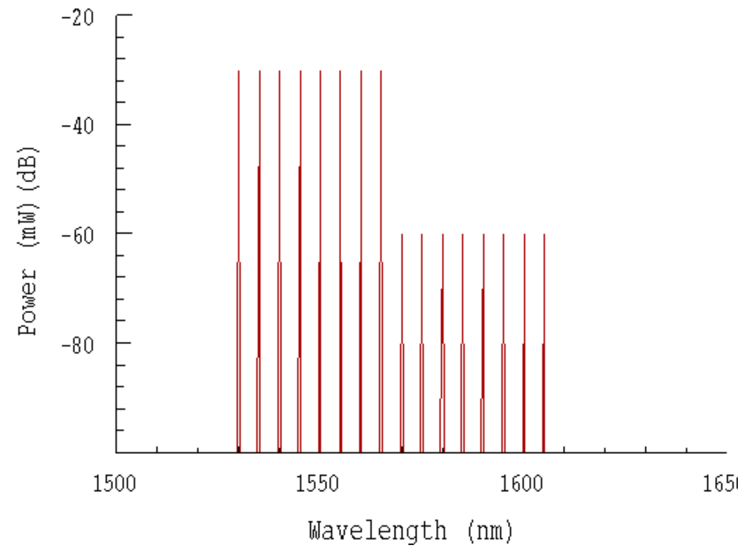
Facilities to Simulate L-Band Amplifiers

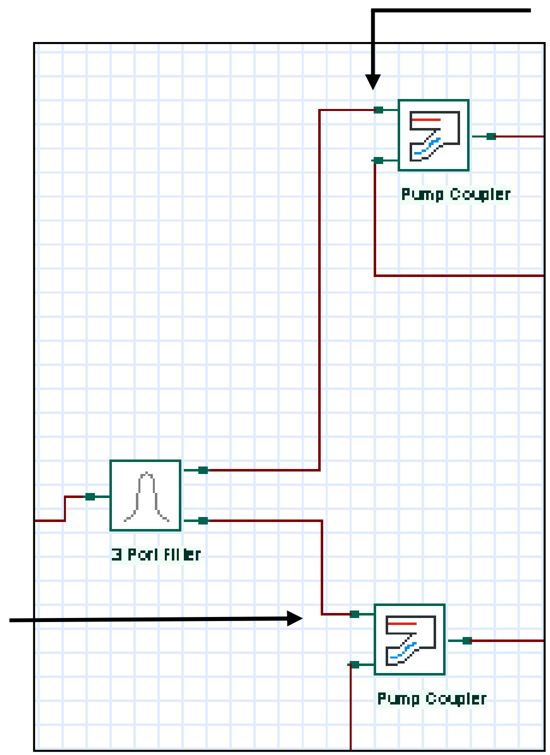
- Split band selection with optimization of the amplifier performed in two different regions separately in the same project (C-band and L-Band for example),
- Design of component to simulate this particular situation.

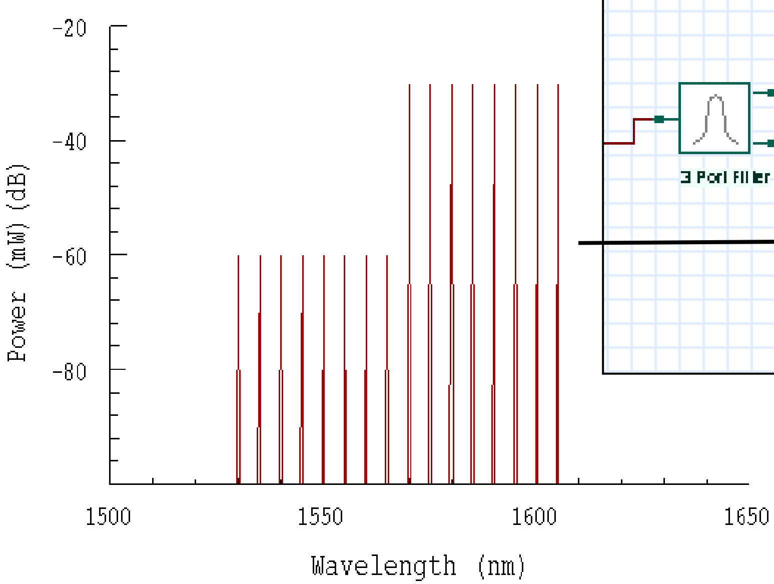
Splitting/Selecting C-Band and L-Band



Splitting Band







Conclusions

- Long band EDFAs design with a WDM signal source coupled to the amplifier is discussed;
- Simulating amplifiers with different configurations, considering L-band with clamped, automatic control, L-band with gain-flattening;
- Including the losses in the simulated layout is critical to adjusting the simulated results with experimental data;
- Cross-section input files;
- Temperature dependence;
- ESA effects.

Part III -
EDFAs with Optical Automatic Control Simulations

Outline

- Overview of Automatic Control Techniques
- Automatic Gain Control (AGC)
- Automatic Power Control (APC)
- Automatic Peak Power Control (APPC)
- Conclusions

Overview of Automatic Control Techniques

• Functionalities added to the EDFAs in order to achieve stable amplification for actual systems applications;

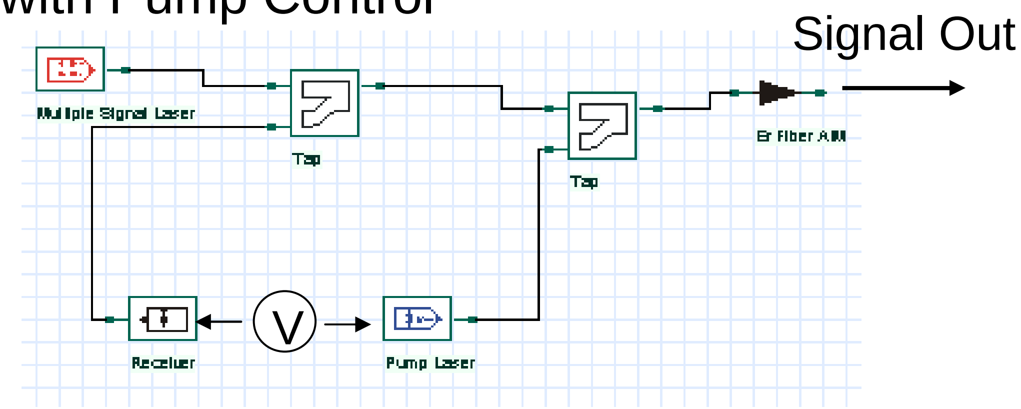
• Dynamic compensation of low frequency gain or output power fluctuations;

• Implementation: fully optical or electronic;

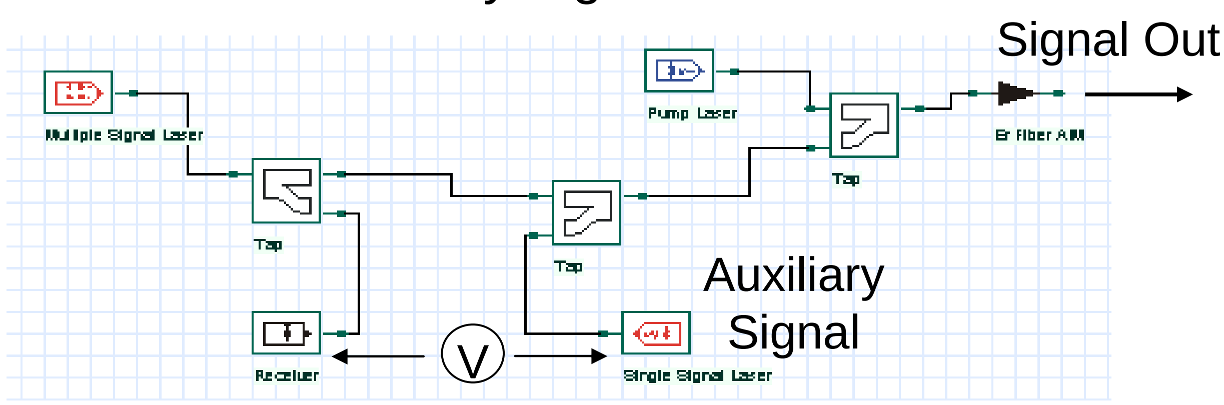
• Control fast power transients in optical networks.

Basic Configurations for AGC in EDFAs

1. Feedforward with Pump Control

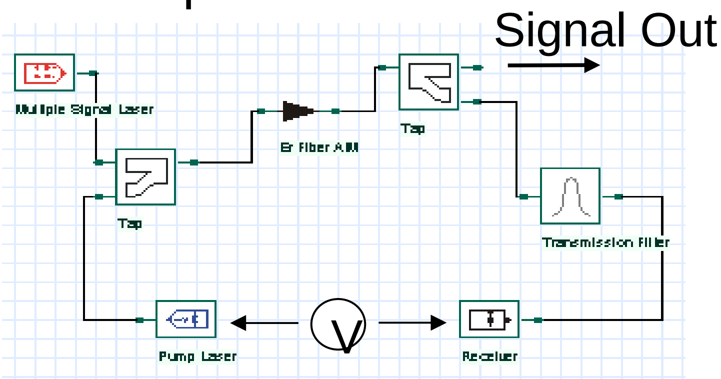


2. Feedforward with Auxiliary Signal Control

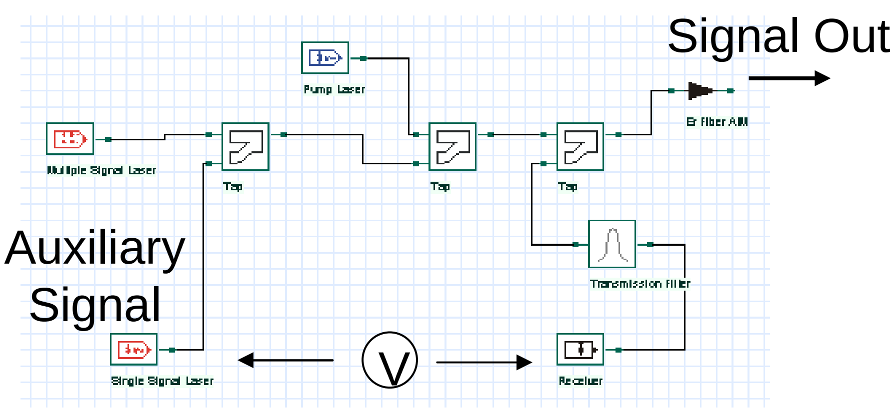


Basic Configurations for AGC in EDFAs

3. Feedback with Pump Control

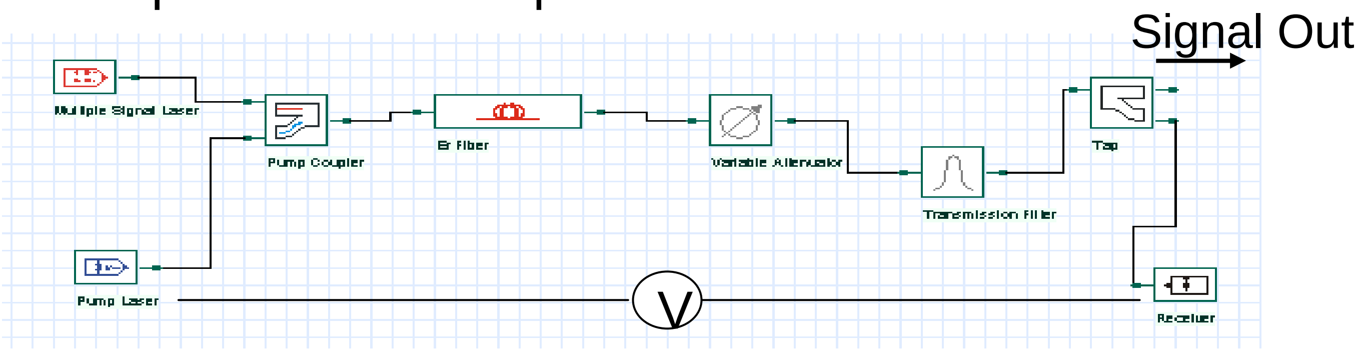


4. Feedback with Auxiliary Signal Control

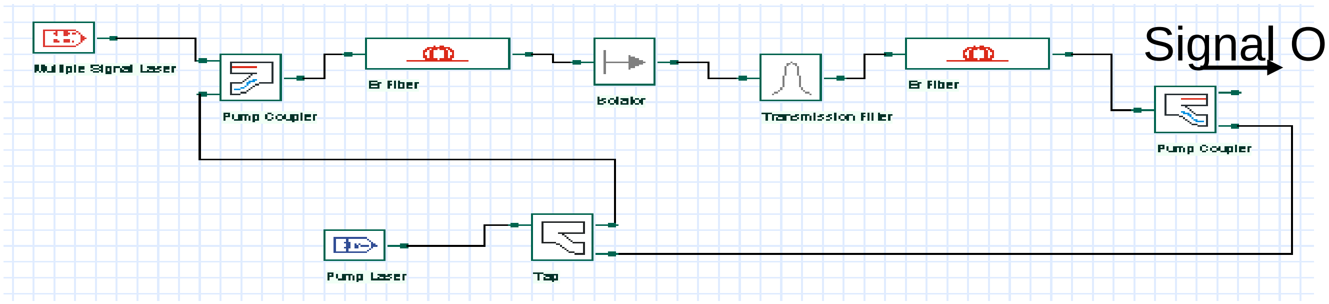


Basic Methods for Implementation of APC in EDFAs

1. Pump Feedback Loop

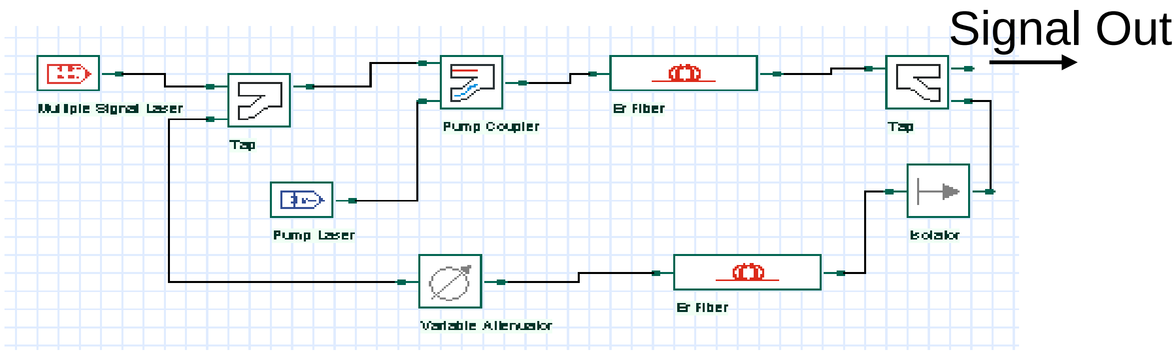


2. Tandem EDFAs

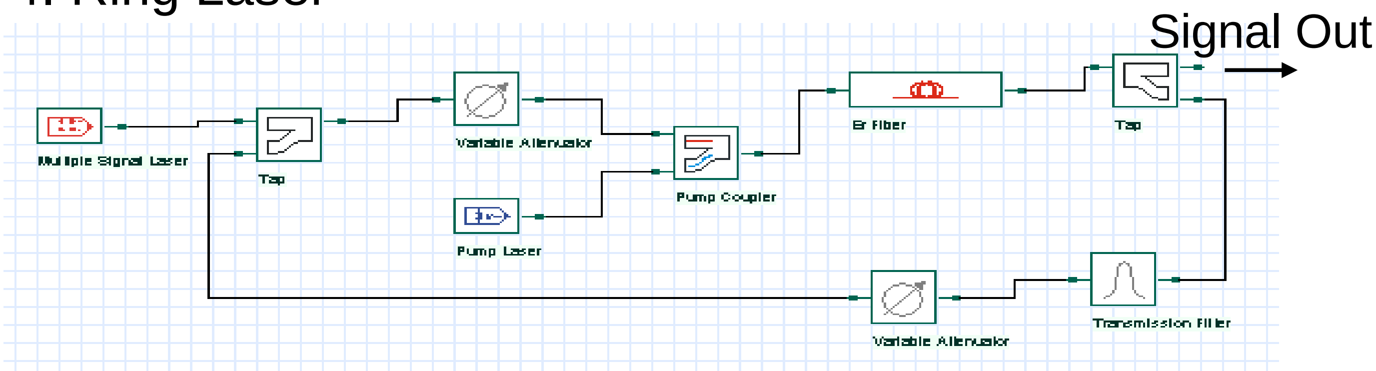


Basic Methods for Implementation of APC in EDFAs

3. Saturable Feedback



4. Ring Laser



Automatic Gain Control (AGC)

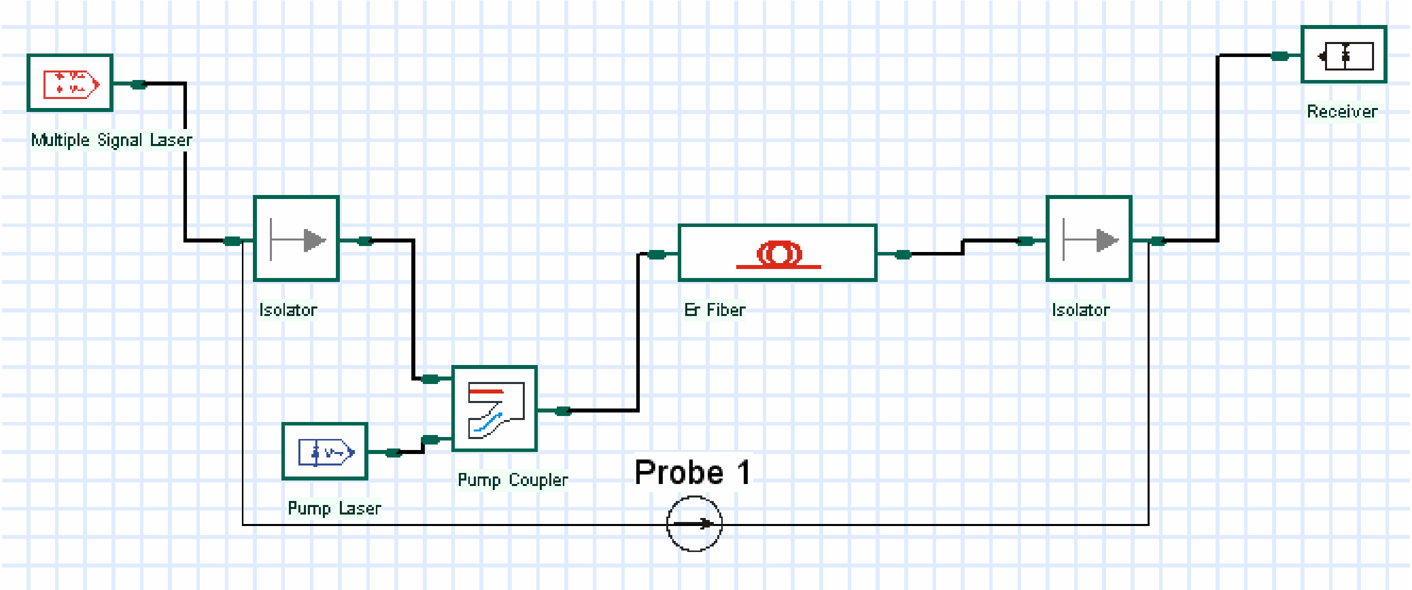
How to accomplish: Pump power varies to maintain the "approximately" constant gain

How to simulate AGC with steady-state solution:

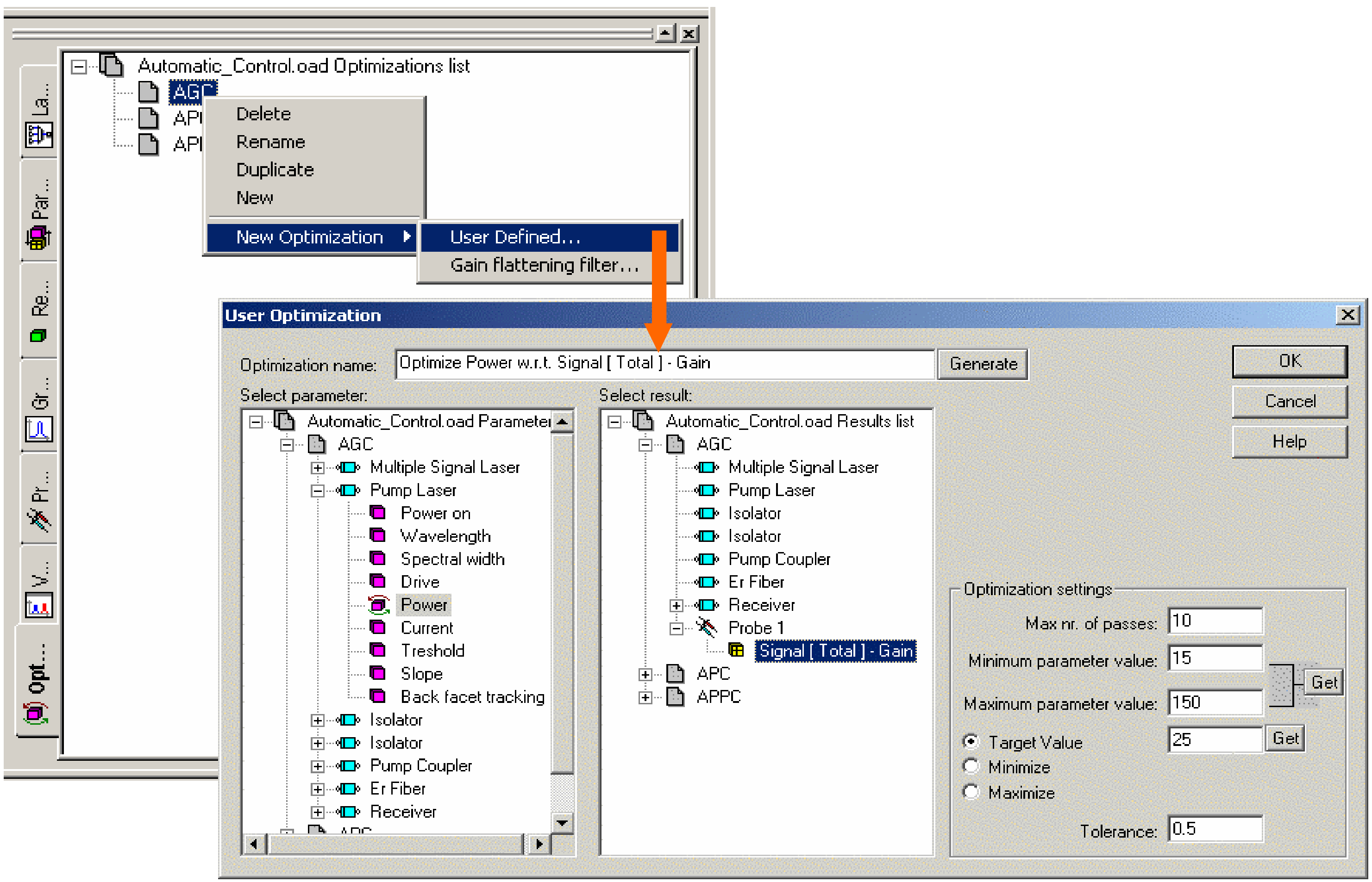
- Select a parameter and a result in user-defined optimizations;
- The parameter is changed through a number of iterations to hit the target value of the result – the ***target gain*** or ***output power***.

Amplifier with Automatic Gain Control

- Keep the total gain constant thereby controlling the pump power.
- The probe calculates the gain and an optimization to determine the pump power necessary to achieve this gain.
- Changing the pump power and controlling the gain between the two isolators.

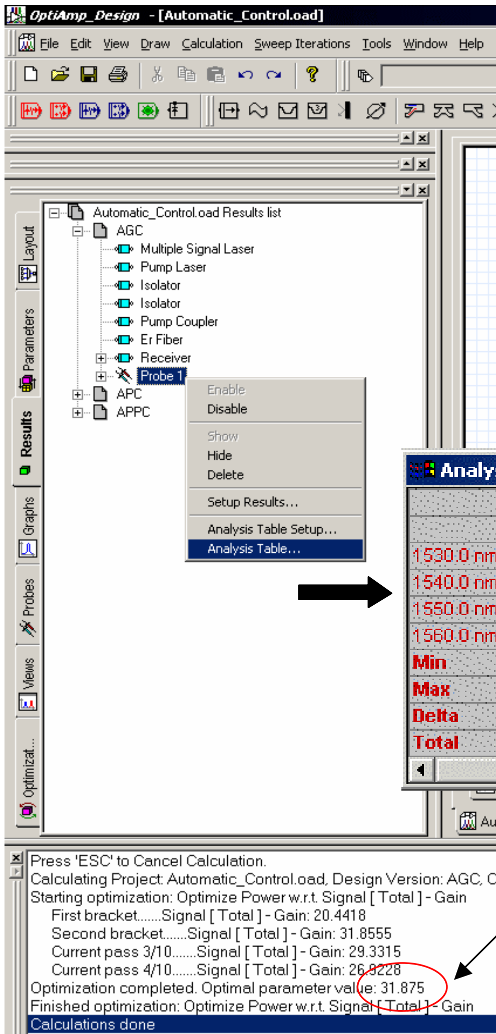


What is important to specify when starting calculations



Optimized Pump Power

Total signal input power : –13.98 dBm
Gain : 24.84 dB
Pump power : 31.875 mW

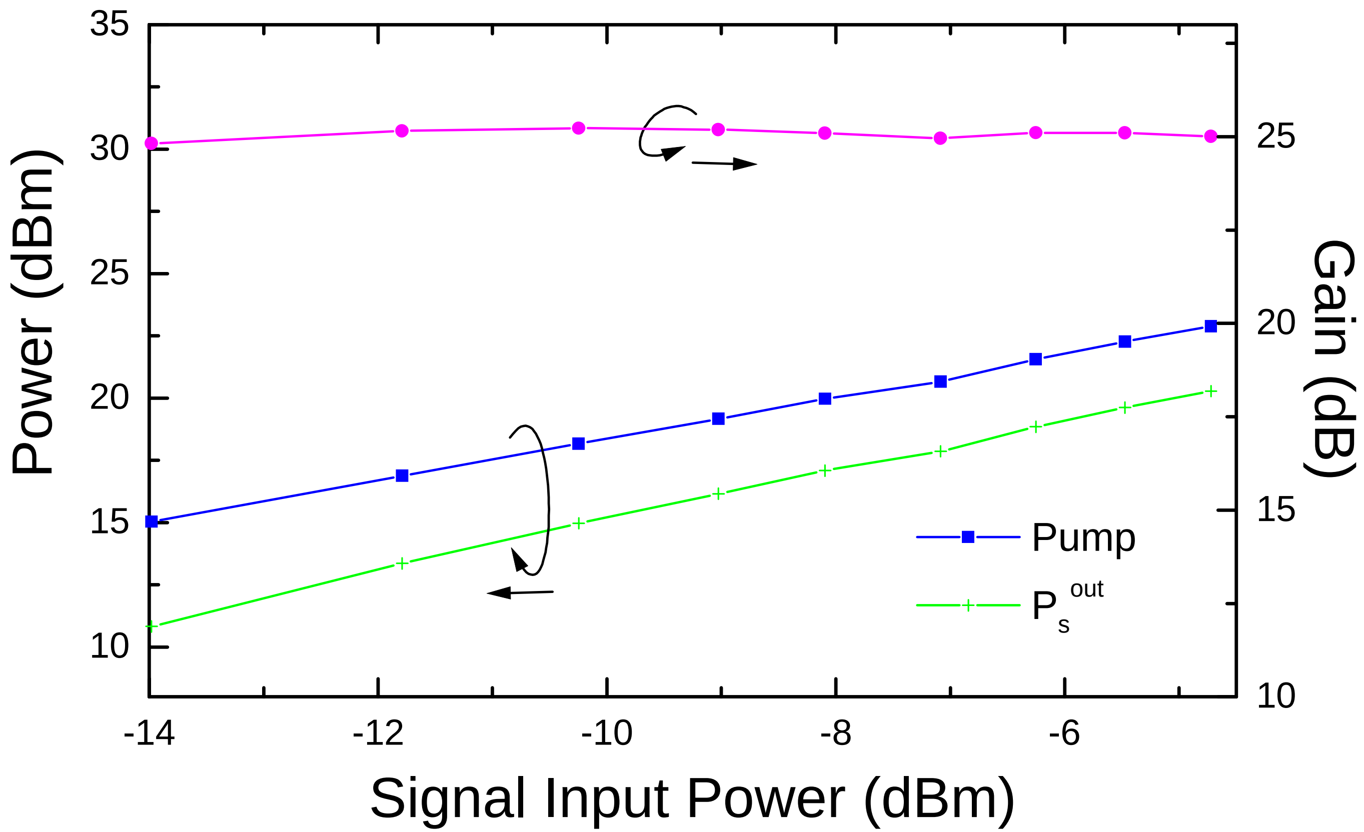


Analysis

	Input Power (dBm)	Reflected Input (dBm)	Output Power (dBm)	Reflected Output (dBm)	Gain (dB)
1530.0 nm	-20	- INF	3.28675	-35.0278	23.2874
1540.0 nm	-20	- INF	3.01788	-43.6271	23.018
1550.0 nm	-20	- INF	6.1488	-37.5499	26.149
1560.0 nm	-20	- INF	5.84214	-39.7482	25.8423
Min	**-20**	**N/A**	**3.01788**	**-43.6271**	**23.018**
Max	**-20**	**N/A**	**6.1488**	**-35.0278**	**26.149**
Delta	**0**	**N/A**	**3.13093**	**8.59931**	**3.13102**
Total	**-13.9794**	**N/A**	**10.8256**	**-31.9426**	**24.8136**

Optimized pump power

Checking Results



Automatic Power Control (APC)

Function: Maintains the EDFA output power at a fixed level during signal perturbation

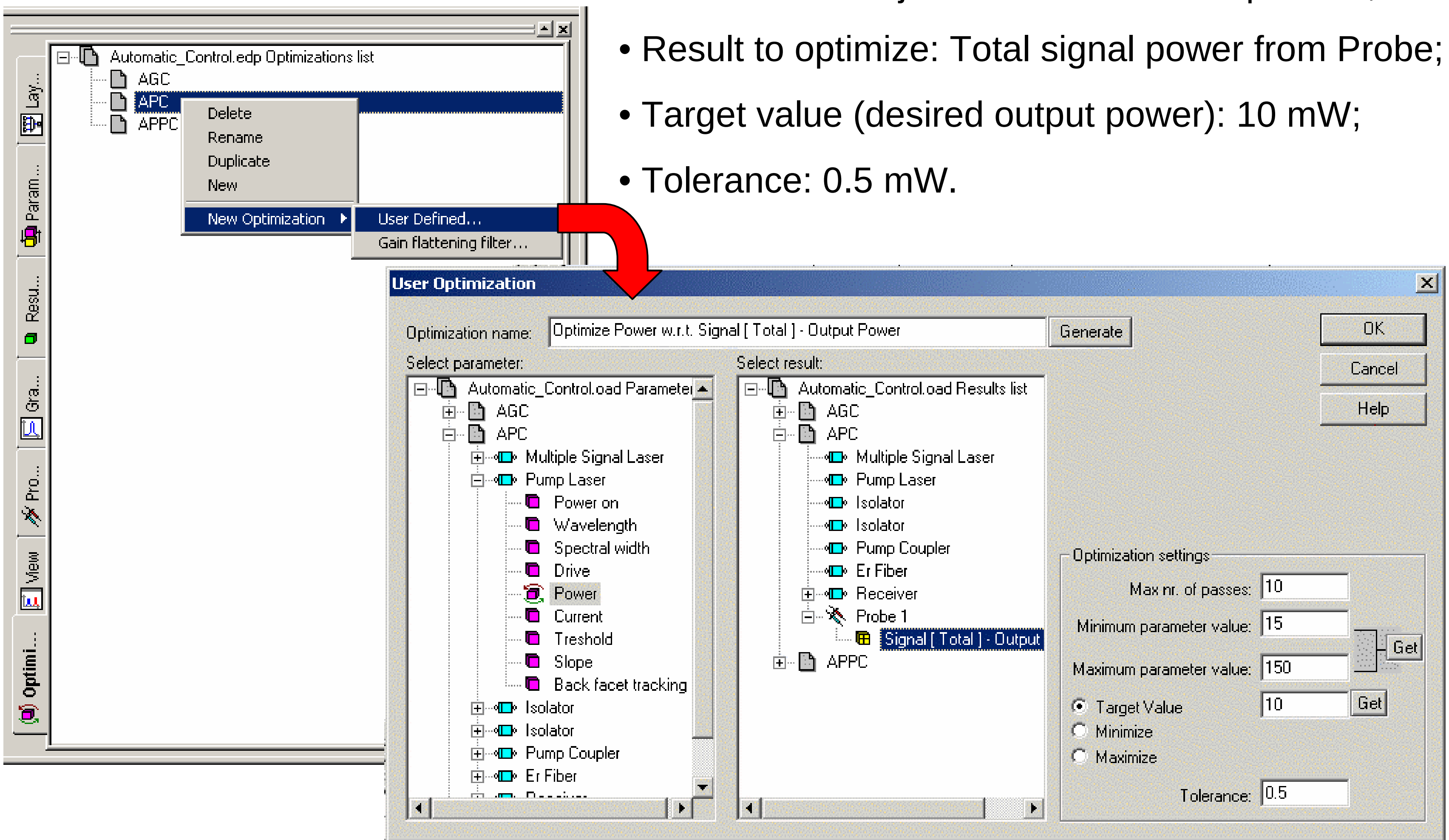
How to accomplish: Pump power varies to maintain “approximately” constant output power

How to simulate APC with steady-state solution:

Insert a probe in the layout which calculates the signal output power, and set an optimization to calculate the pump power to achieve the target signal output power

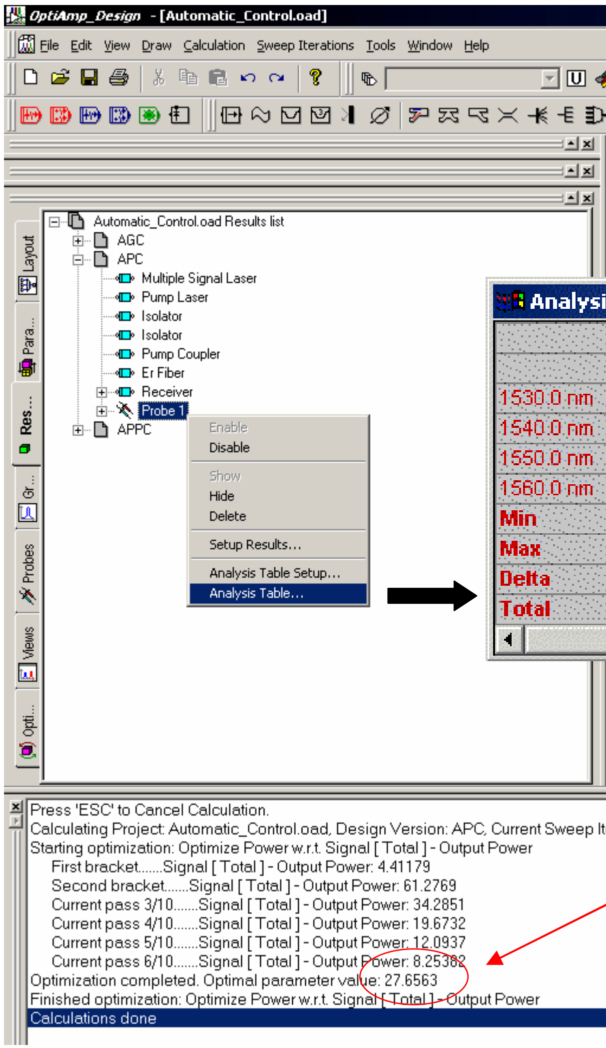
Specifying APC Simulation

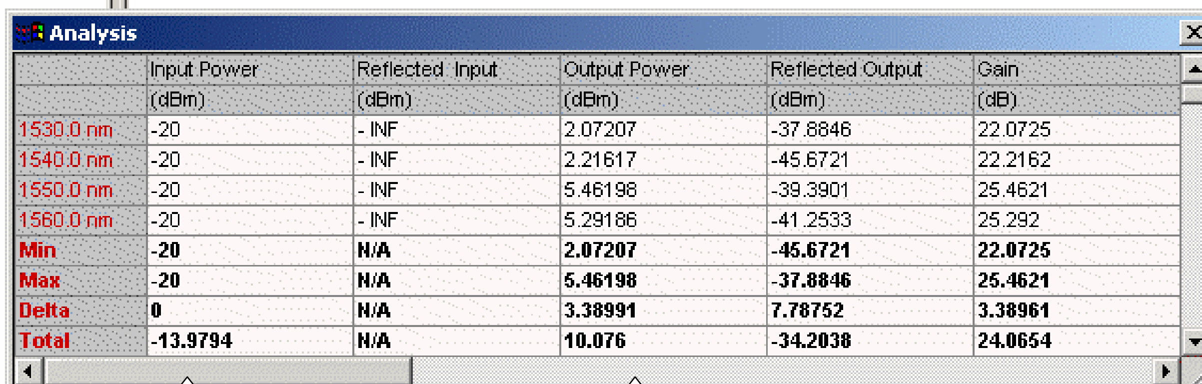
- Parameter to adjust: Power from Pump Laser;
- Result to optimize: Total signal power from Probe;
- Target value (desired output power): 10 mW;
- Tolerance: 0.5 mW.



Running Simulations

Total Input Power: –13.98 dBm
Total Output Power: 10.08 dBm

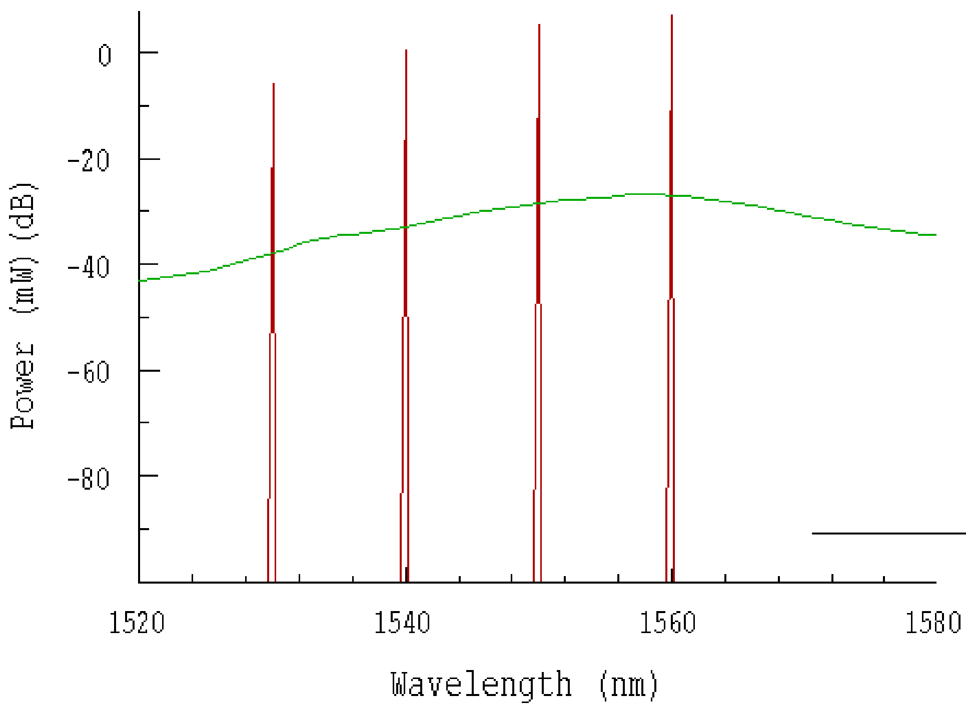



Analysis

	Input Power (dBm)	Reflected Input (dBm)	Output Power (dBm)	Reflected Output (dBm)	Gain (dB)
1530.0 nm	-20	- INF	2.07207	-37.8846	22.0725
1540.0 nm	-20	- INF	2.21617	-45.6721	22.2162
1550.0 nm	-20	- INF	5.46198	-39.3901	25.4621
1560.0 nm	-20	- INF	5.29186	-41.2533	25.292
Min	**-20**	**N/A**	**2.07207**	**-45.6721**	**22.0725**
Max	**-20**	**N/A**	**5.46198**	**-37.8846**	**25.4621**
Delta	**0**	**N/A**	**3.38991**	**7.78752**	**3.38961**
Total	**-13.9794**	**N/A**	**10.076**	**-34.2038**	**24.0654**

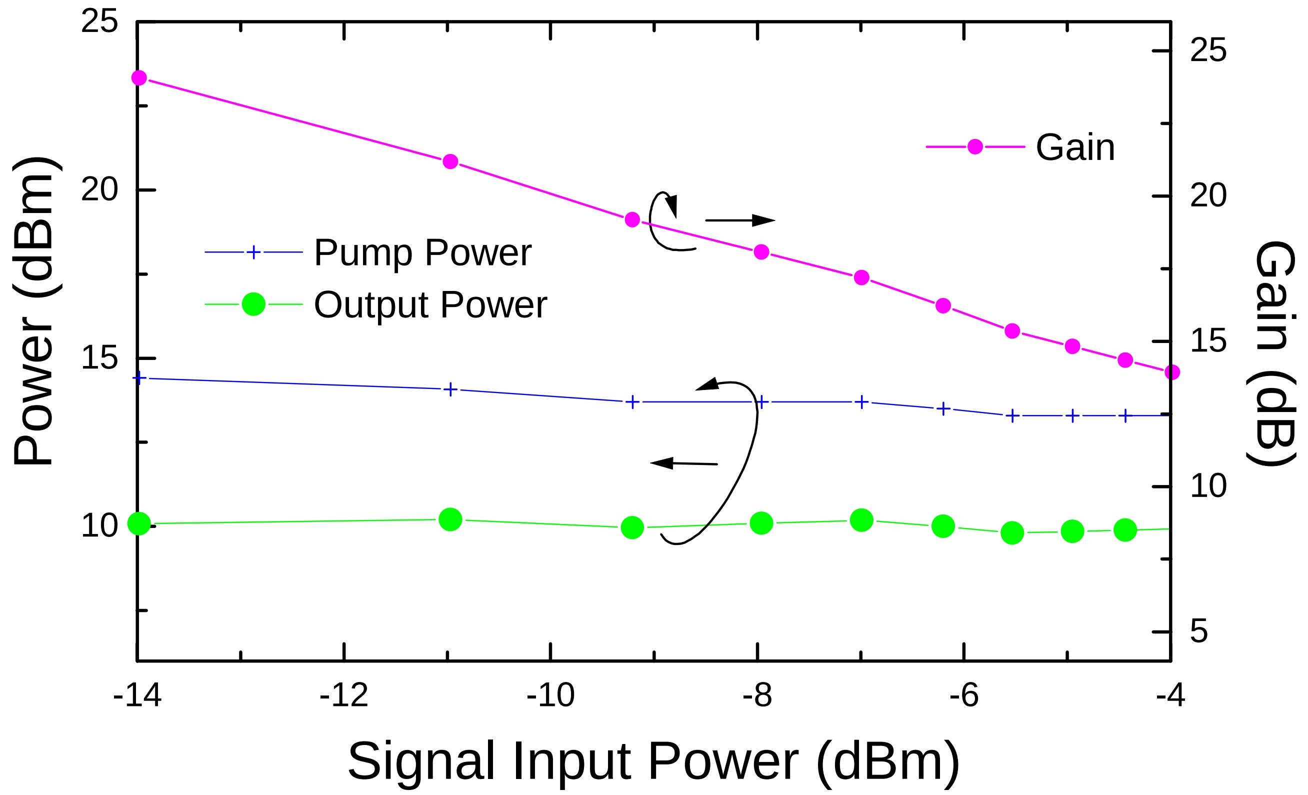
Optimized pump power

Calculated Total Output Power



	Signal [Total] - Output Power
1	10.17649386155
2	10.47569064244
3	9.906634185003
4	10.21254189818
5	10.4272013802
6	10.00523224594
7	9.545618238076
8	9.654137845988
9	9.749942038673
10	9.836441617298

Calculated Total Power



Automatic Peak Power Control

How to simulate APPC:

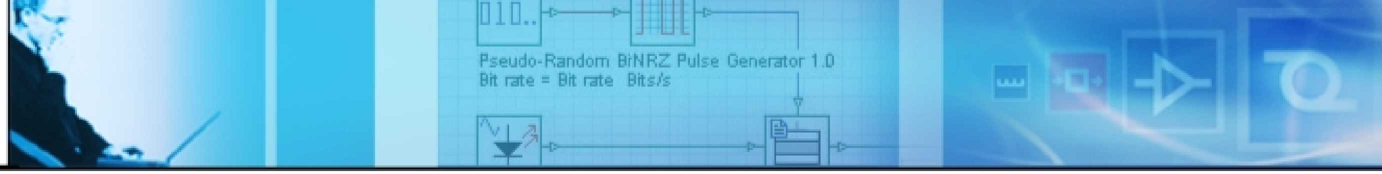
Monitor the output power of one signal at a particular wavelength.

Adjustable Parameter:

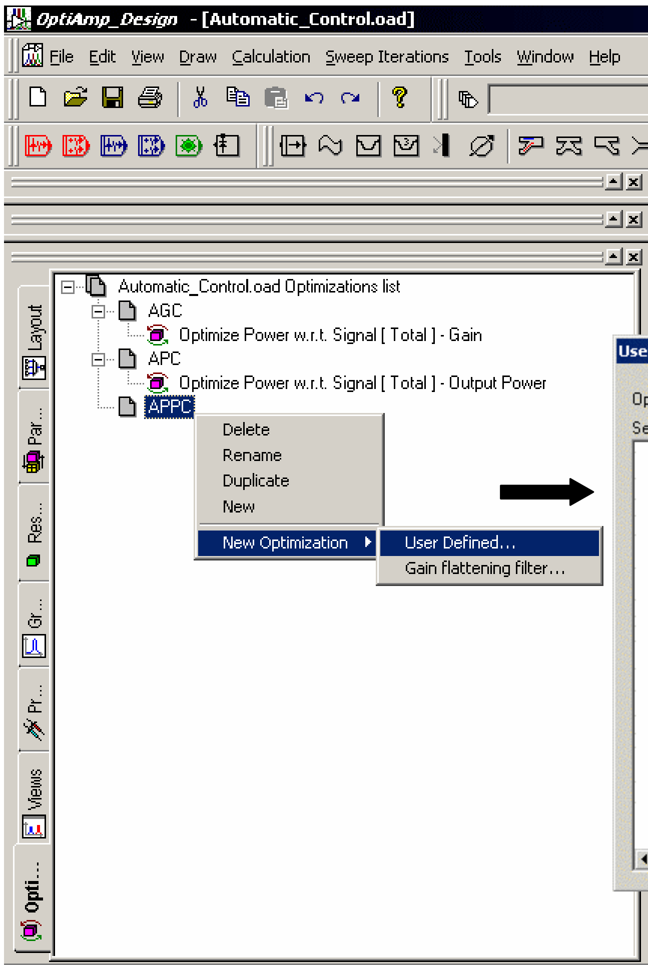
The output power will be maintained constant thereby controlling the pump power.

Focusing the Peak Power:

The probe tool must export the results to be used by the optimization. In this case we are interested in one signal power.



Setting the Optimization



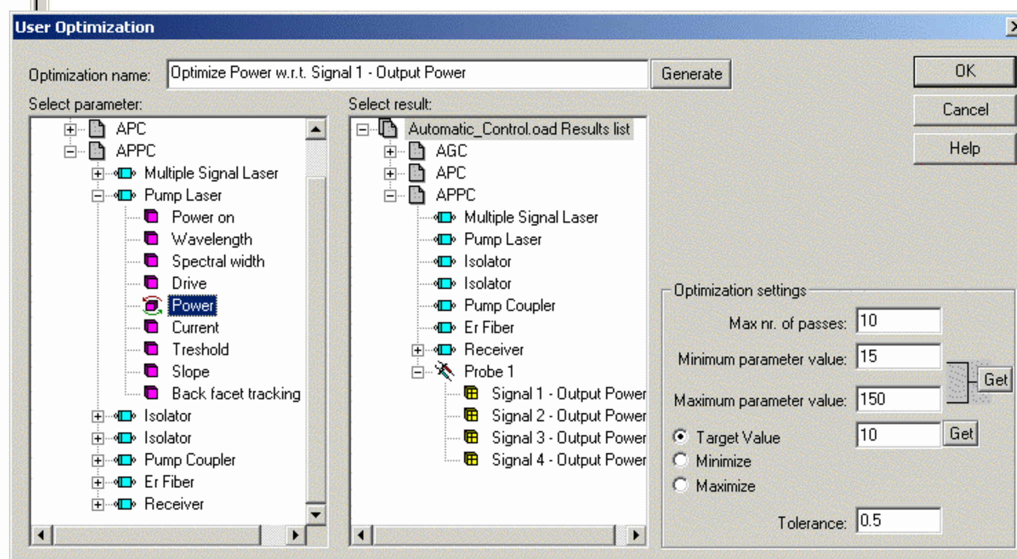
Adjusting: Power from Pump Laser

Selected Result to optimize:

First signal power from Probe

Target value: 10 mW

Tolerance: 0.5 mW

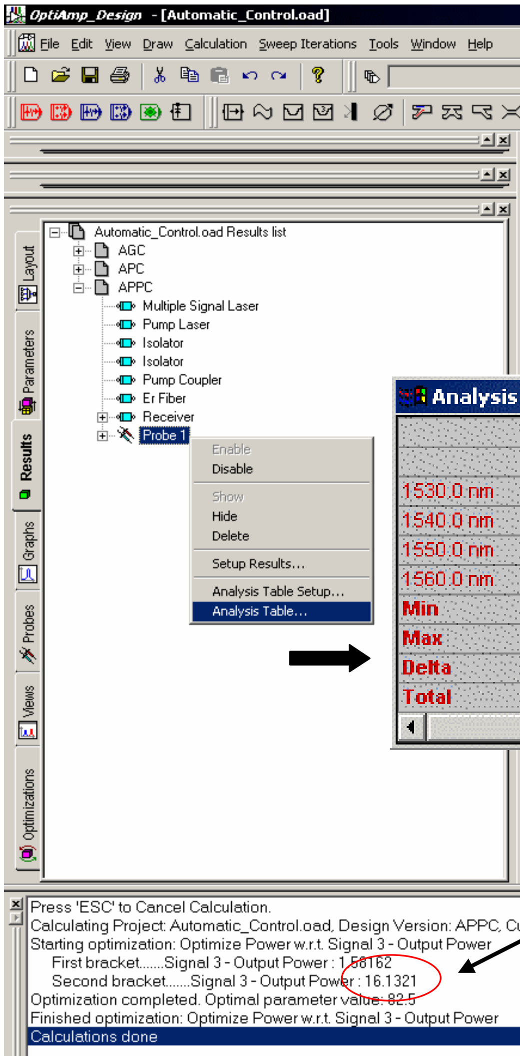


Checking Optimized Power

Signal Input Power: –20 dBm

Output Power: 10 dBm

Pump Power: 82.5 mW



Analysis

	Input Power (dBm)	Reflected Input (dBm)	Output Power (dBm)	Reflected Output (dBm)	Gain (dB)
1530.0 nm	-20	- INF	10.2101	-17.9965	30.2167
1540.0 nm	-20	- INF	7.5874	-31.5723	27.5879
1550.0 nm	-20	- INF	10.0635	-26.8032	30.0644
1560.0 nm	-20	- INF	8.97863	-30.995	28.9791
Min	**-20**	**N/A**	**7.5874**	**-31.5723**	**27.5879**
Max	**-20**	**N/A**	**10.2101**	**-17.9965**	**30.2167**
Delta	**0**	**N/A**	**2.62272**	**13.5758**	**2.62876**
Total	**-13.9794**	**N/A**	**15.3511**	**-17.1128**	**29.3315**

Optimized pump power

Calculated Output Power

WDM List

Multiple Signal	1530	1
Multiple Signal	1540	2
Multiple Signal	1550	3
Multiple Signal	1560	4
Pump Laser	980	1

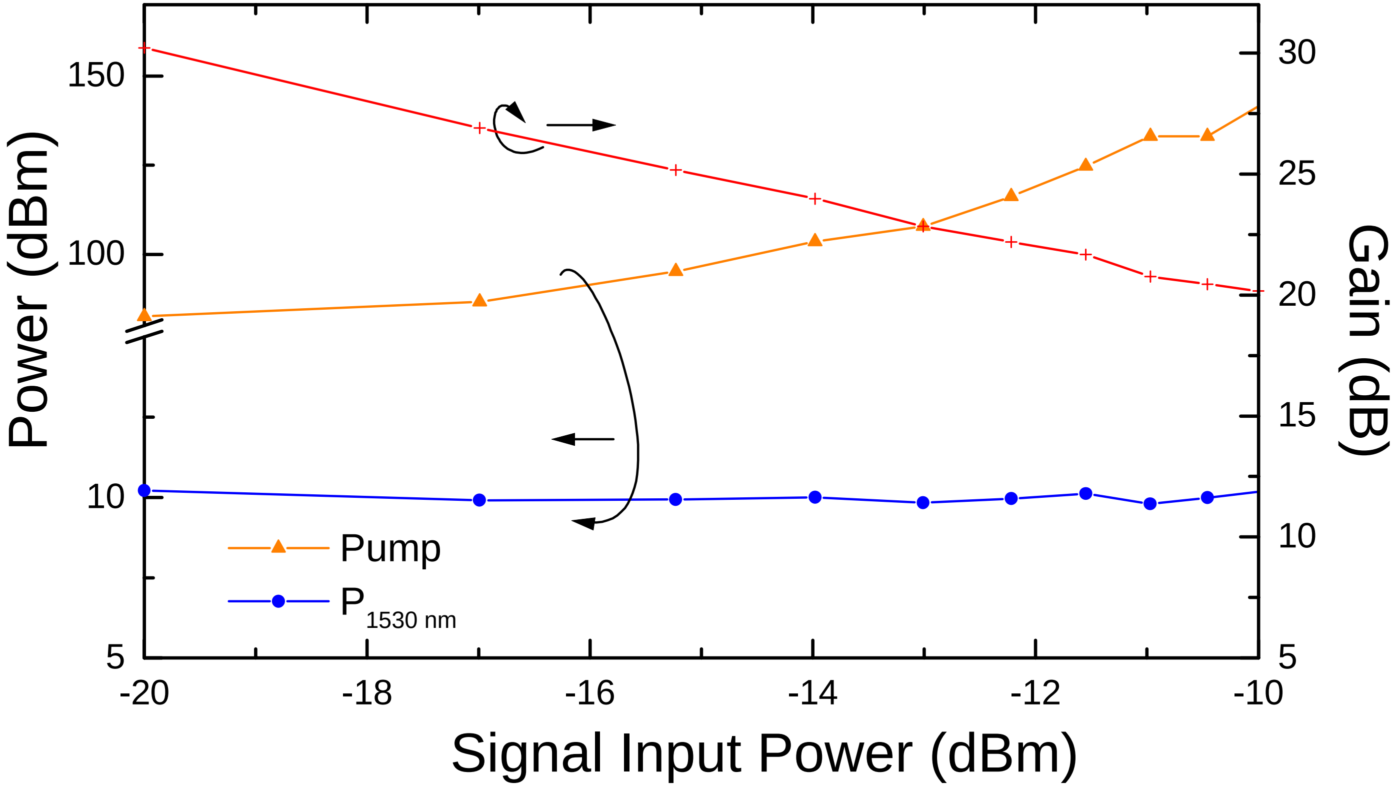
- Signal input power from –20 dBm to –10 dBm;

- Trying to maintain 10 dBm of signal output power;

- Output power to channels 1, 2, 3 and 4.

	Signal 4 - Output Power	Signal 3 - Output Power	Signal 2 - Output Power	Signal 1 - Output Power
1	7.904285643504	10.14738068842	5.737731779037	10.49572912496
2	11.19304698035	13.18966719571	6.939316793945	9.796163193554
3	14.00496079082	15.77702830362	7.992195339107	9.846864777534
4	16.50829060363	18.03706340323	8.904998169211	10.0023112756
5	18.31510025416	19.4276016021	9.355618705078	9.60863347797
6	20.53568142584	21.41922586703	10.16956466148	9.92580886947
7	22.69888776845	23.36039837901	10.96687735646	10.27889724293
8	23.60880499531	23.73534684781	10.92584671768	9.54128821814
9	25.67878402974	25.60120513471	11.70202630397	9.963610360651
10	27.73176847455	27.45351932181	12.474395438	10.39688713443

APPC Results



Conclusions

- Simulating EDFAs with optical automatic control;
- User-defined optimizations allow you to select a parameter and a result;
- Vary the pump power to maintain the gain or output power at “approximately” constant values;
- Different parameter selection is possible.

Part IV -
Gain-Clamped EDFAs Simulations

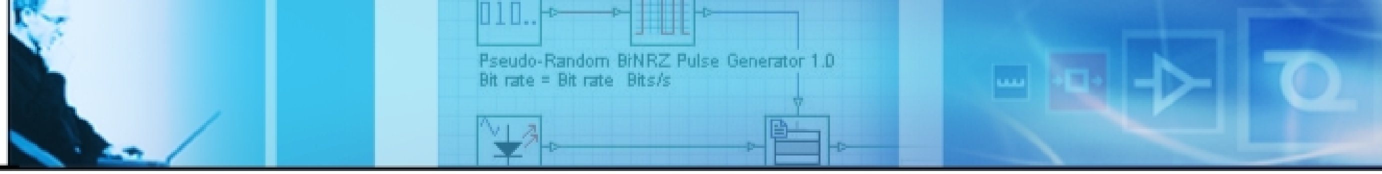
Outline

- Introduction
- Gain Clamped Function
- How to Simulate a Gain-Clamped Function
- Simulating a Gain-Clamped L-Band Amplifier
- Conclusions

Introduction

- The gain spectrum of optical amplifiers depends on the input power.
- In WDM networks, the gain of the EDFA must be the same at any input power over a desired range.
- The EDFA gain-clamped function can be carried out using optical or electrical control.
- Example: A simple all-optical gain control system in which reflective filters are placed at both ends of the doped fiber.

Optiwave



Gain-Clamped Function

Objective: Make the gain less dependent on the input signal power

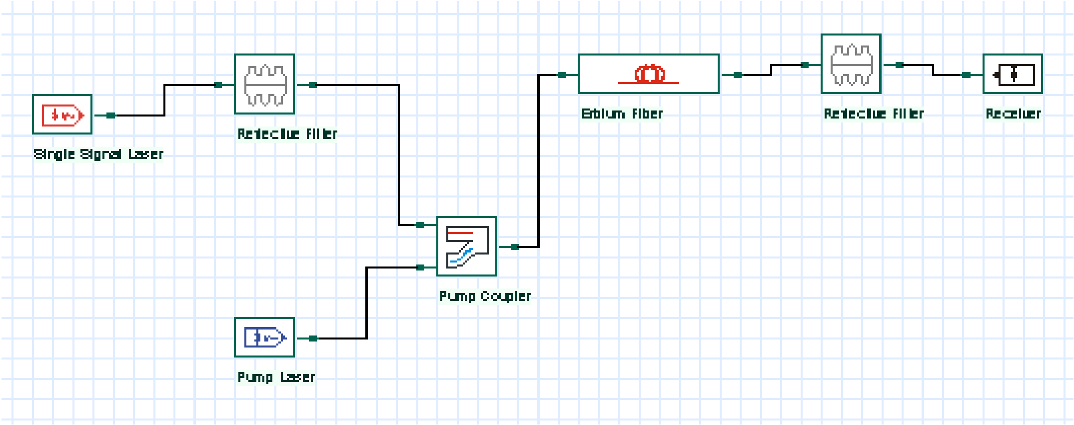
Application:

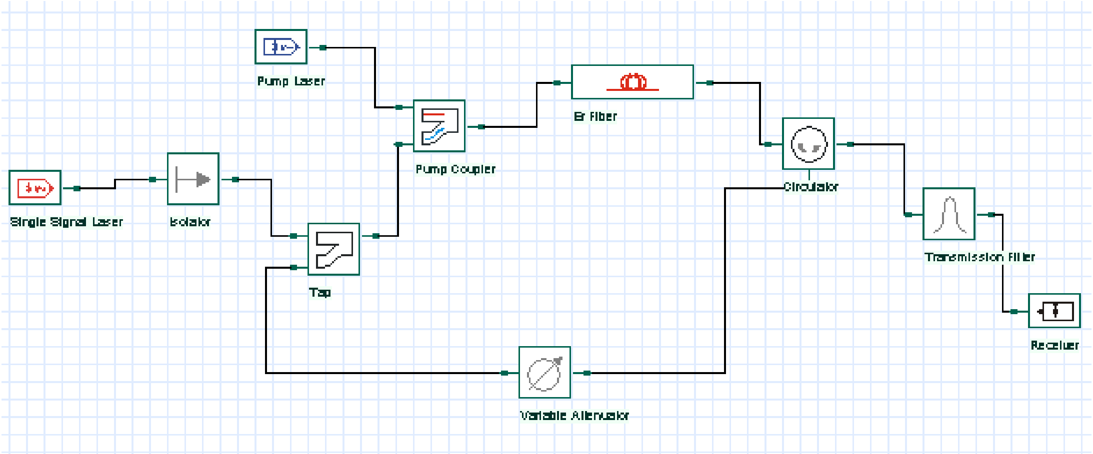
Useful in WDM networks, where the gain of EDFA must be the same at any input power, over a desired range

How it works:

- Reflective filters are placed at both ends of the doped fiber
- The created cavity generates a laser oscillation at the reflection wavelength of the filters
- The stimulated emission clamps the average population inversion of Er atoms
- The saturation fixed by the lasing effect clamps the gain at any other wavelength

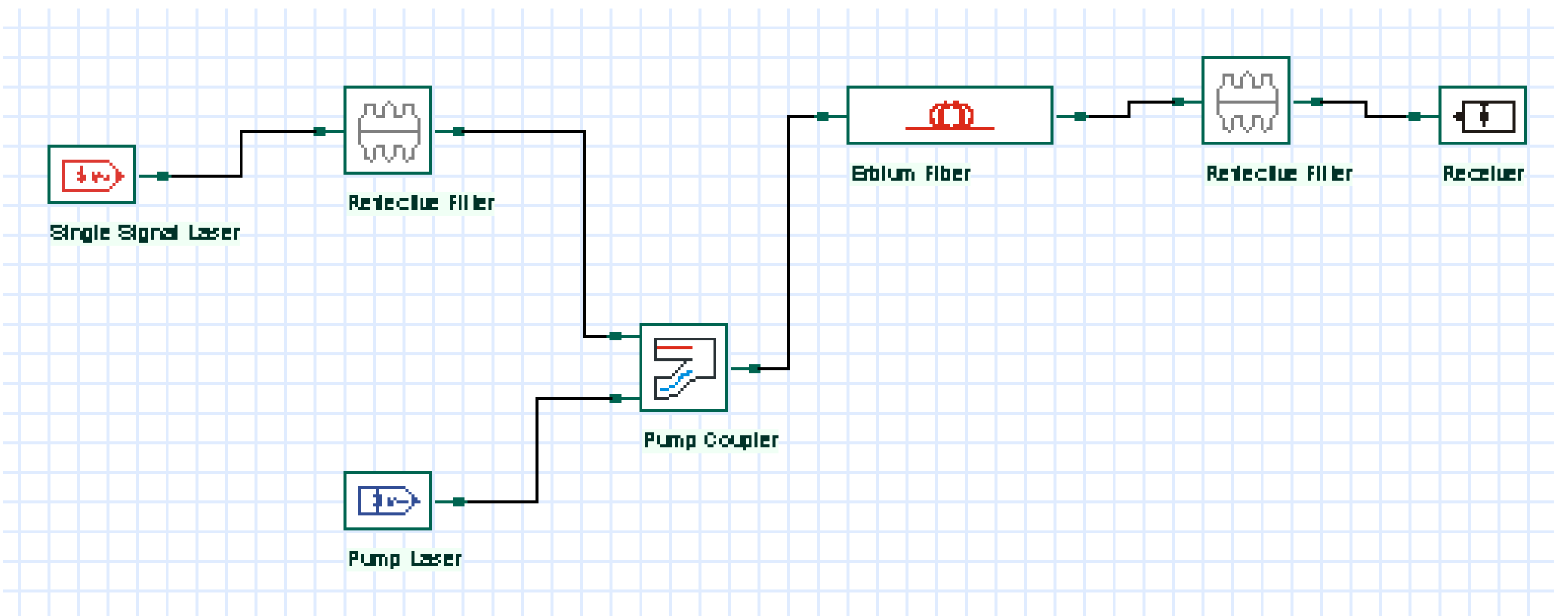
How to Simulate a Gain-Clamped Function





Subramaniam et al. IEEE Photon. Techn. Lett. Vol.13, No. 8, 785, 2001

Gain-Clamped Including Two Reflective Filters



Components Settings

Signal Input

In most studies of C-band GC-EDFA based on single-channel operation [*Kobayashi, Electron. Lett. 27, p.486, 1999; Inoue, IEEE Photon. Techn. Lett. 11, p.1108, 1999*].

Or saturation operation [*Takushima et al. IEEE Photon. Techn. Lett. 9, p. 271, 1999; Luo et al. IEEE Photon. Techn. Lett. 9, p.1346, 1997*].

L-band GC-EDFA single and multiple channel operation [*Hsu et al. Opt. Commun., Jul 2001*].

Components Settings

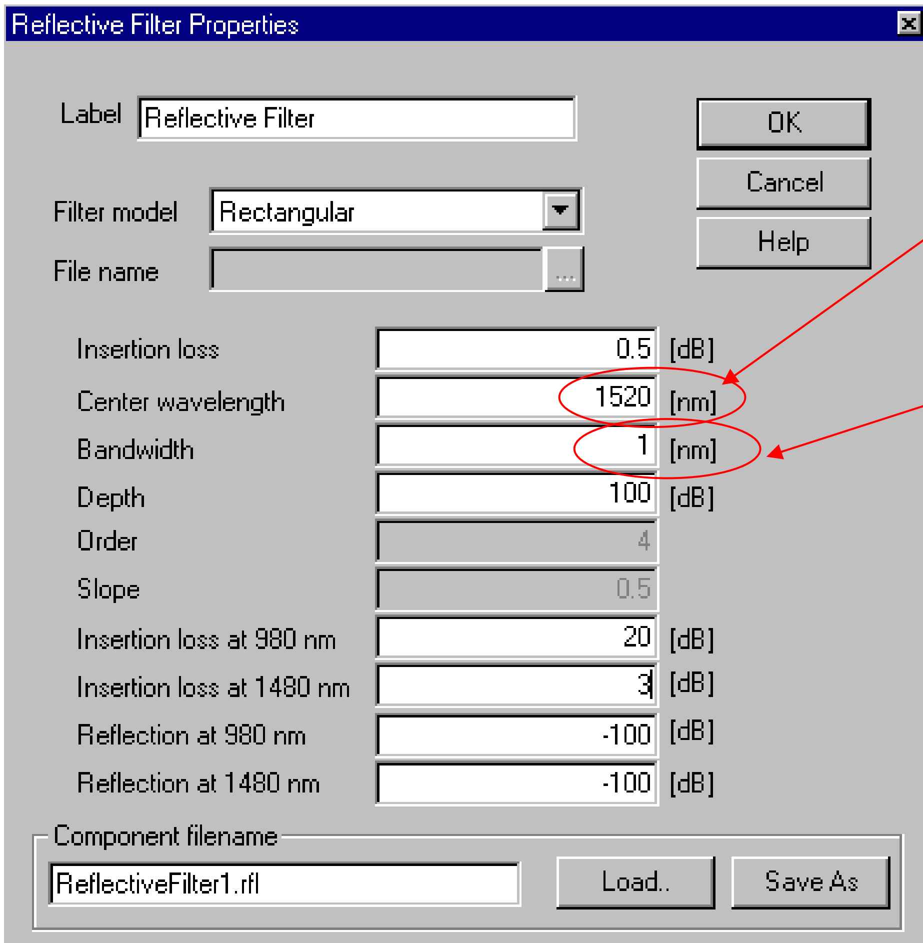
Erbium Doped Fiber

Silica erbium doped fiber

Typical fiber length ~ meters in multiples of ten

Single and Multiple fiber stage

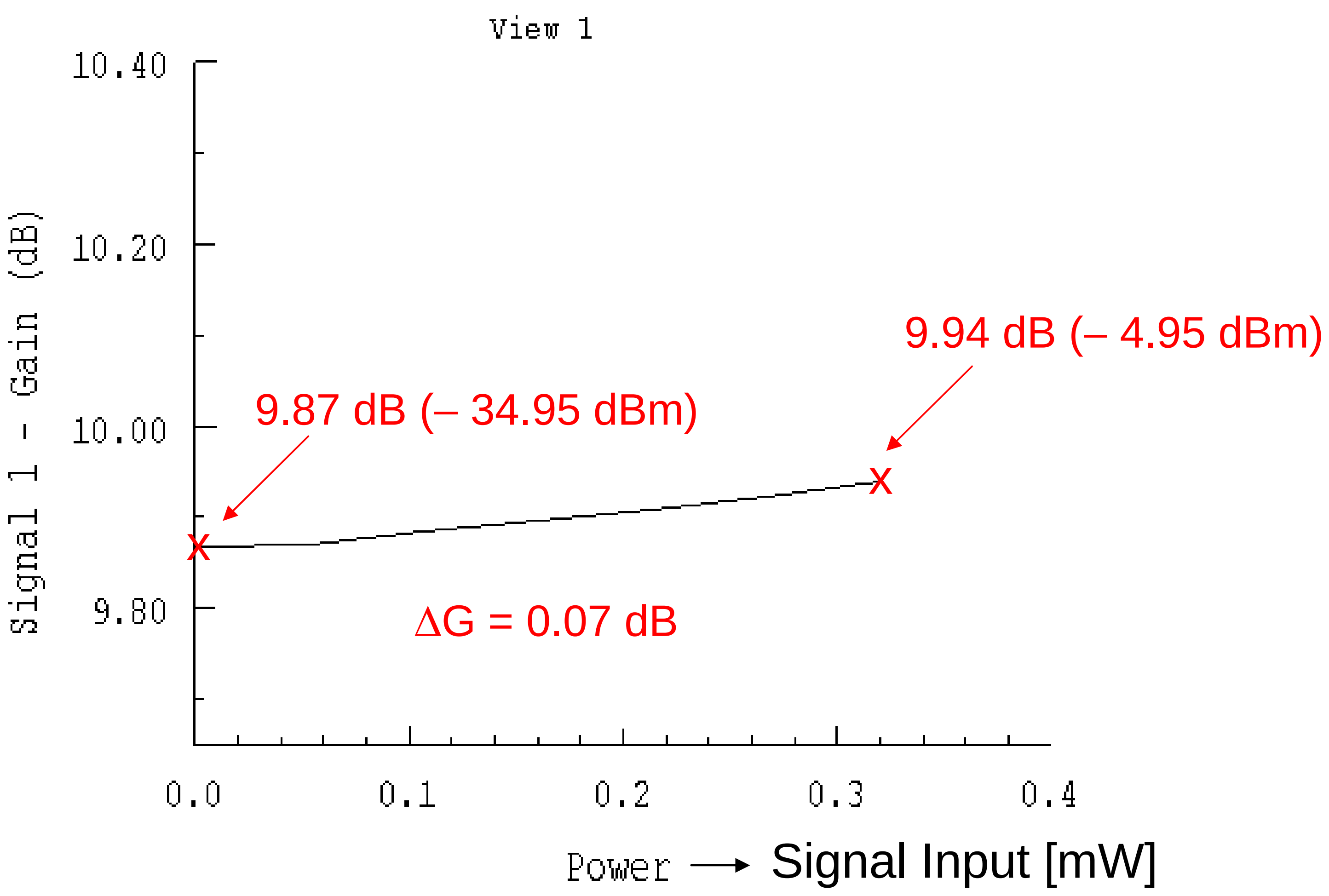
Reflective Filter Settings



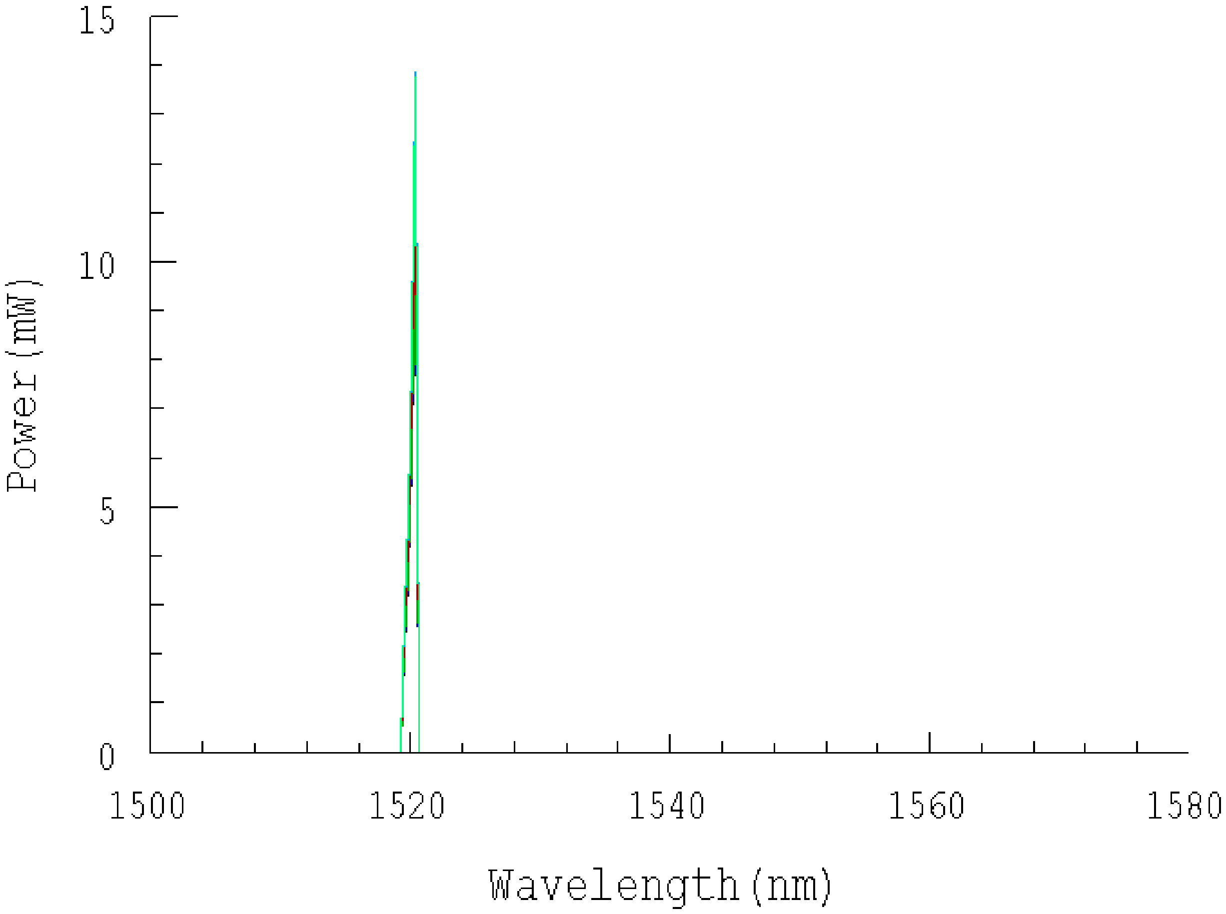
Center Wavelength defines lasing frequency of the cavity

Bandwidth defines linewidth

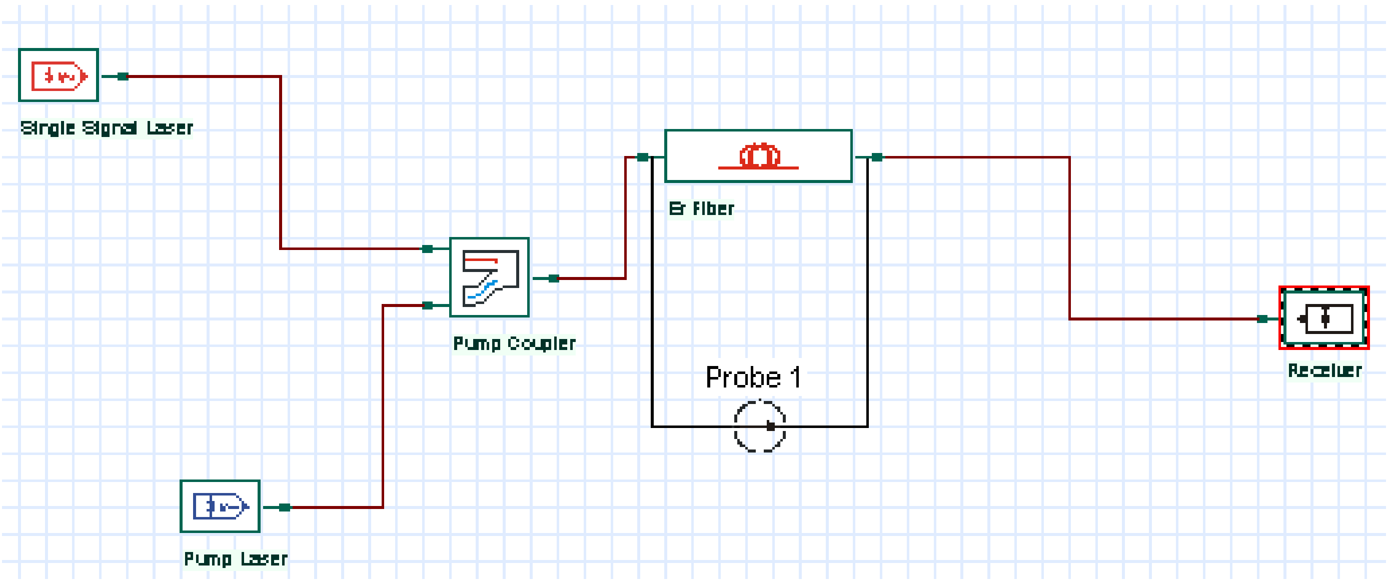
Gain Results



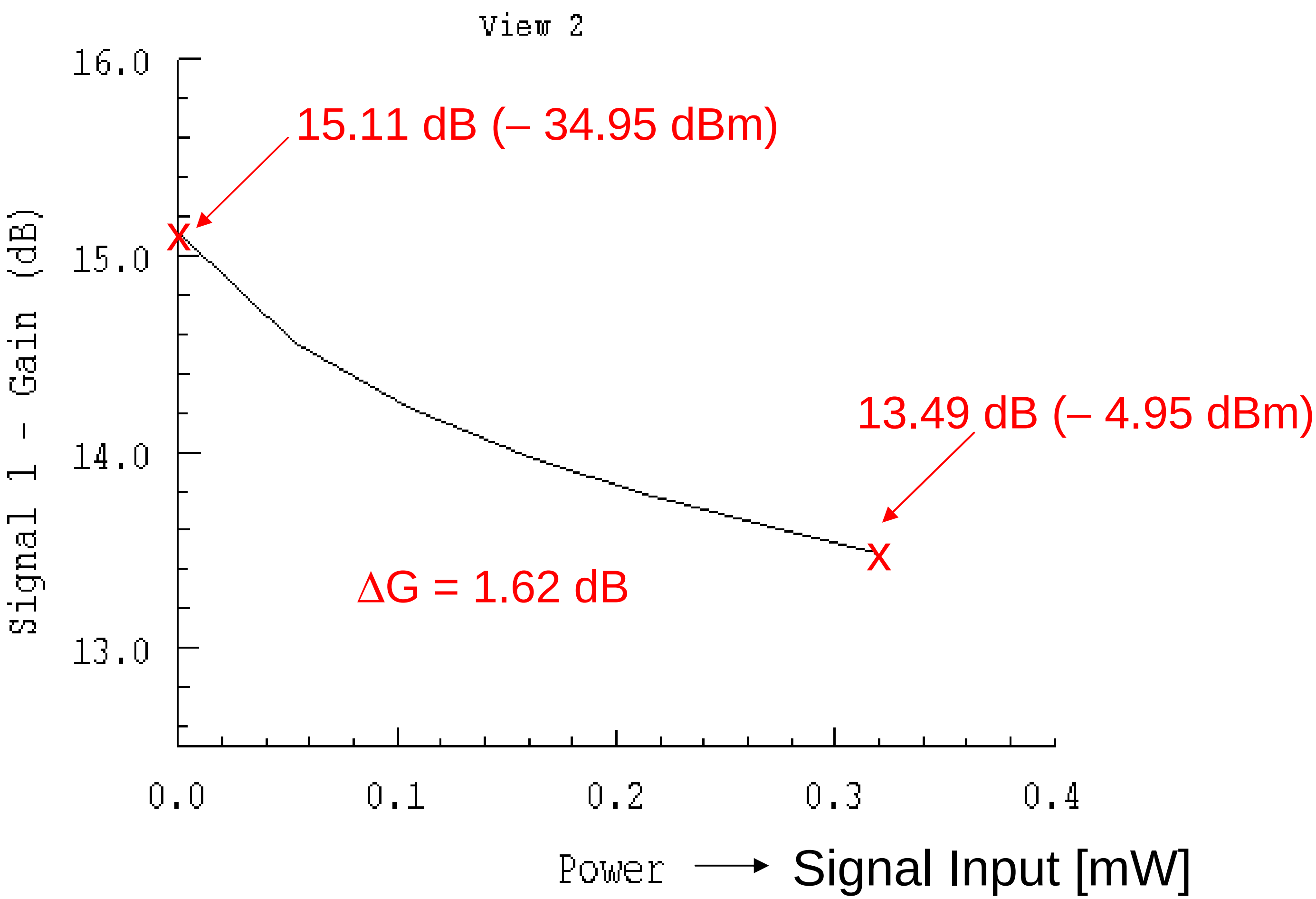
Laser Oscillation Generated at 1520 nm



Repeating Simulations without Reflective Filters/Clamping



Gain Results with No Clamping



Simulating a Gain-Clamped L-Band Amplifier

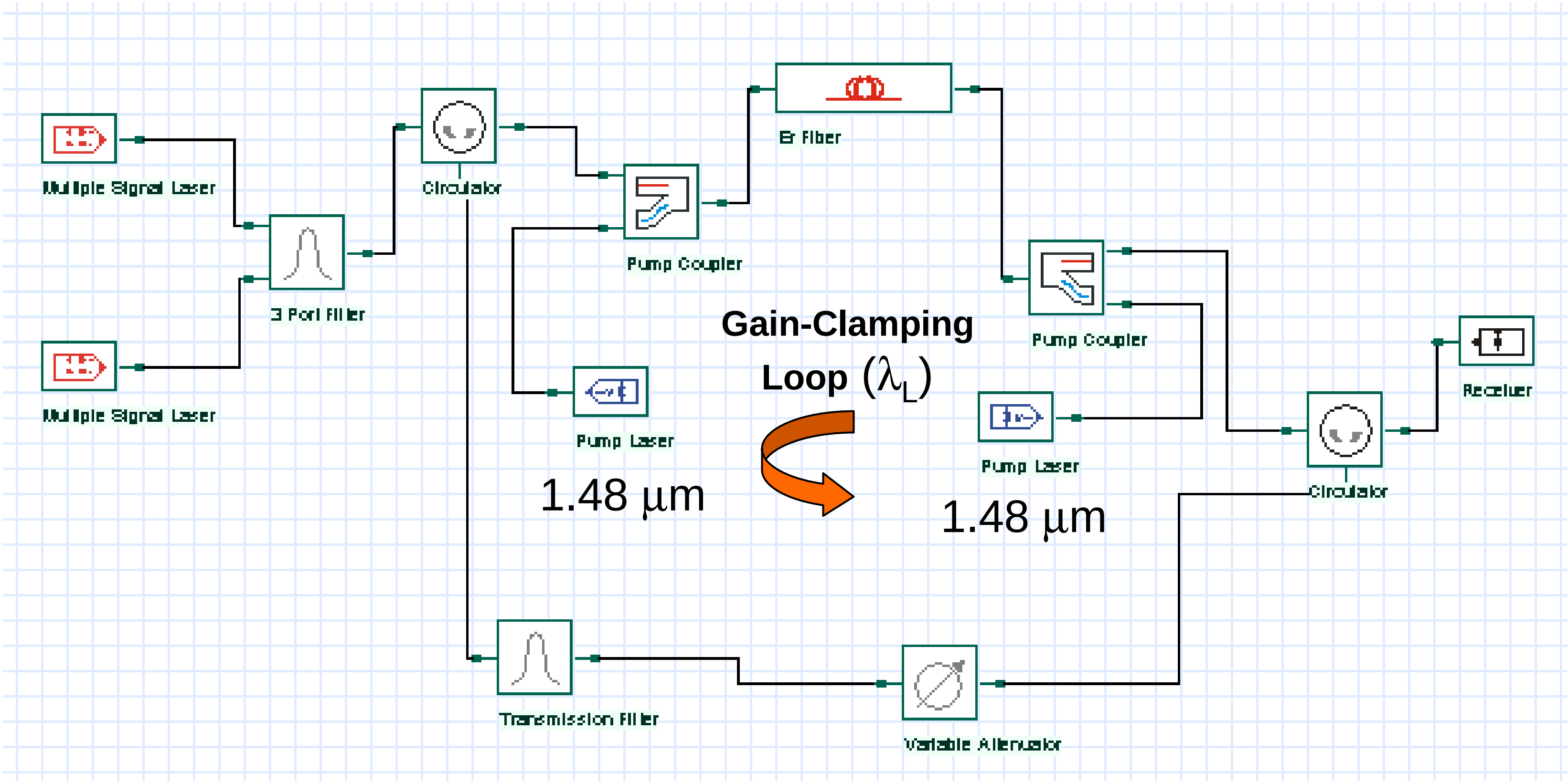
- *Basic principles*:

  - Develop optimum design of GC L-Band EDFA to achieve constant gain variation under input power variation

  - Use Single and Multiple-channel schemes

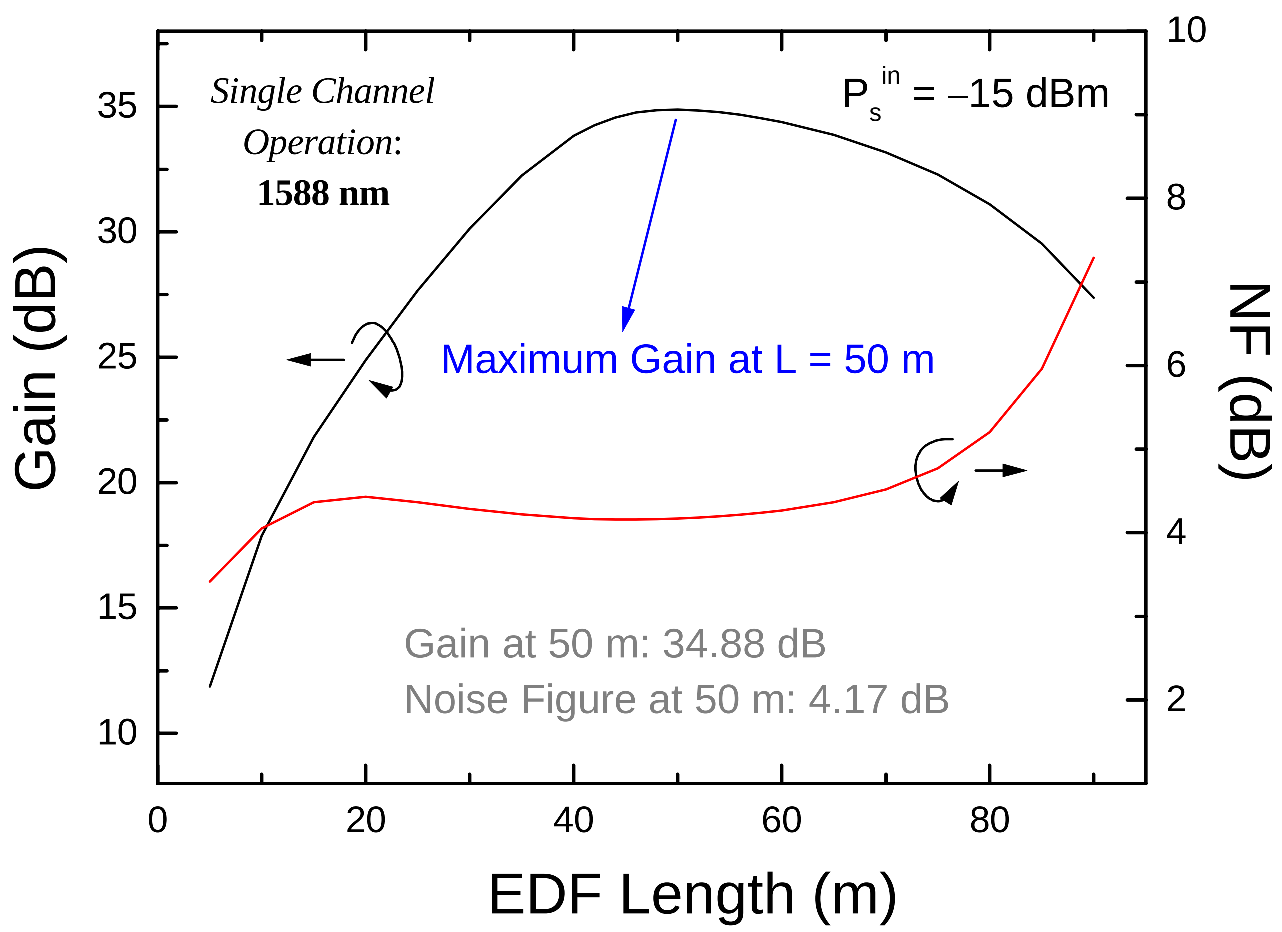
  - Determine best selection of wavelength lasing which offers large gain-clamping dynamic ranges and low NF characteristics

Configuration of Optically GC L-Band EDFA*



*S. Hsu et al., *Opt. Commun.* Issue 5-6, Vol. 19S, Sept. 2001

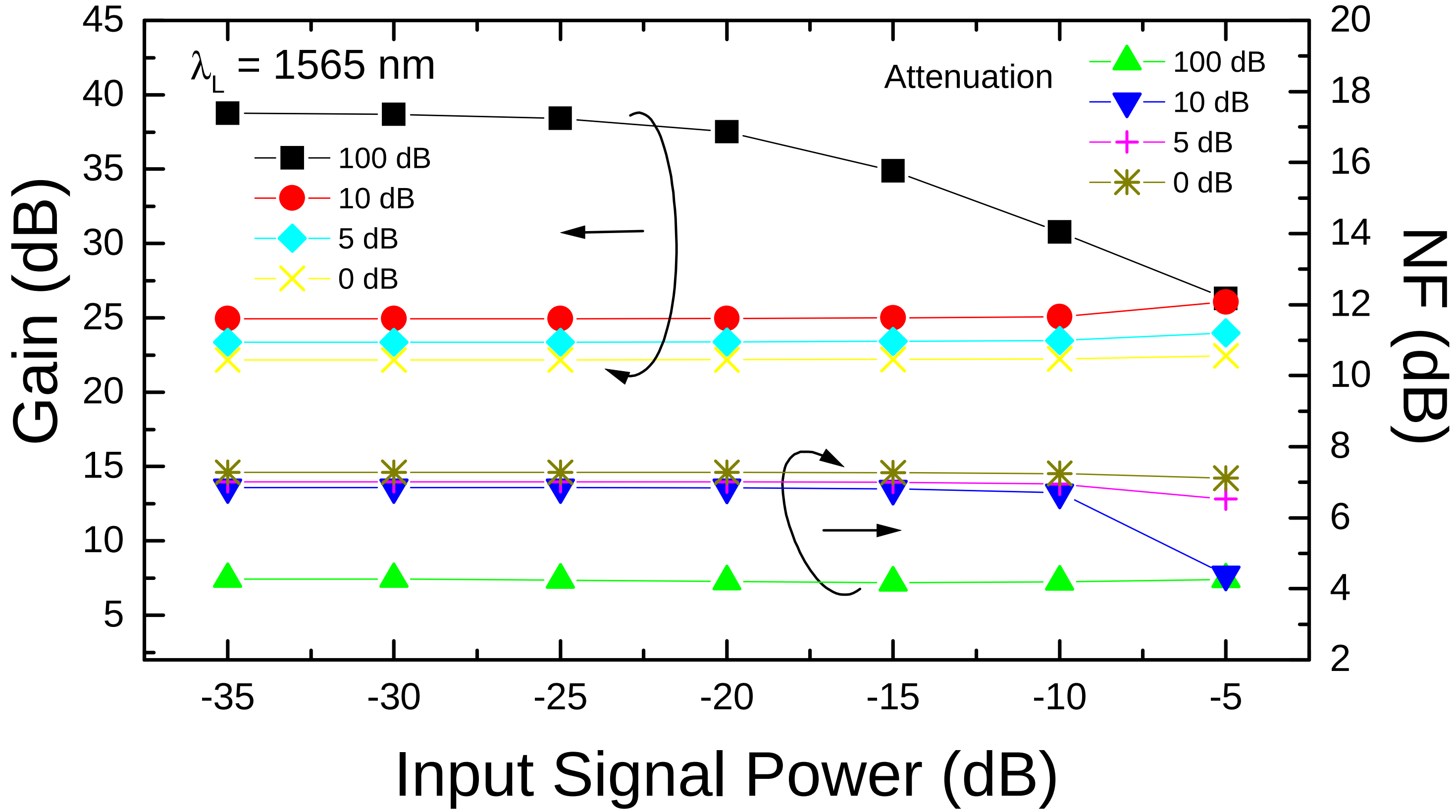
Non-Clamped Optical Gain and NF



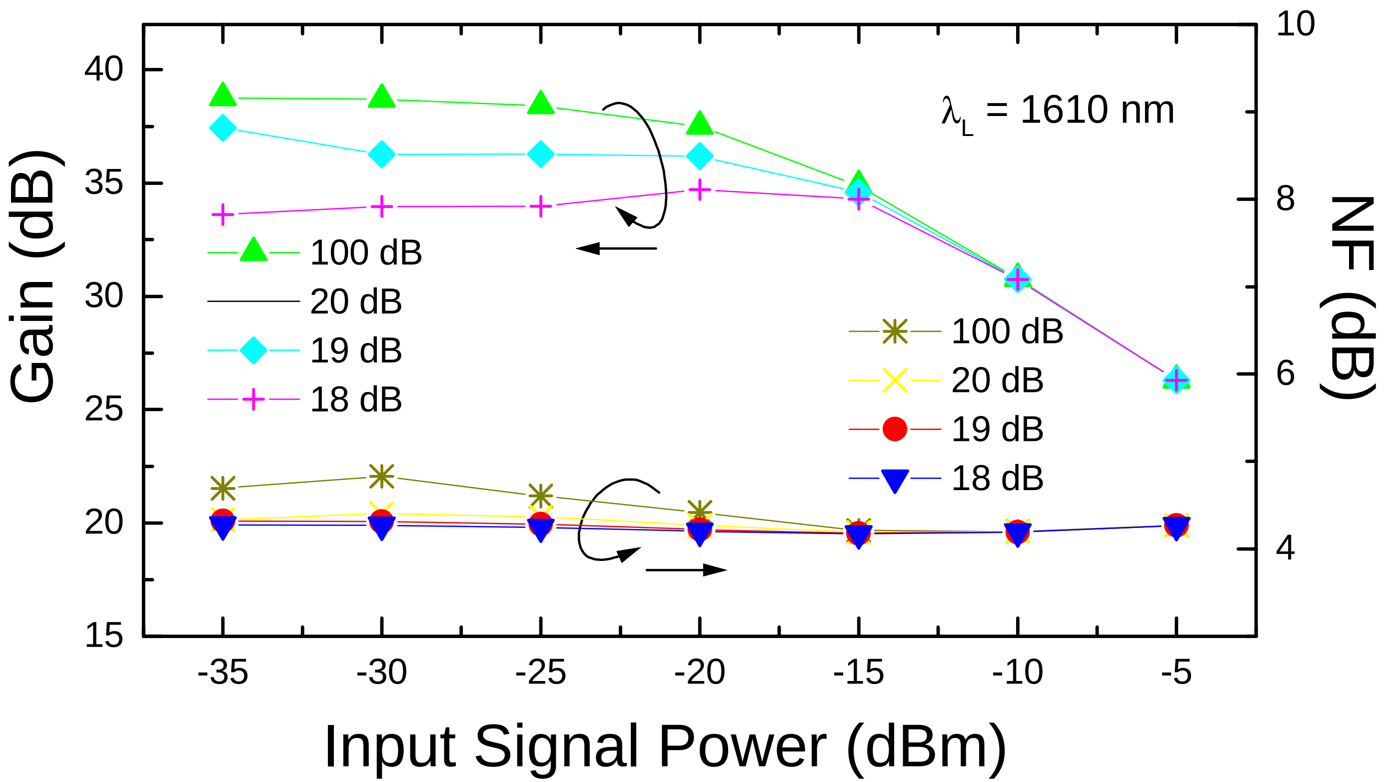
Best Selection of Loop Attenuation

λ_L=1565 nm

Single Channel Operation

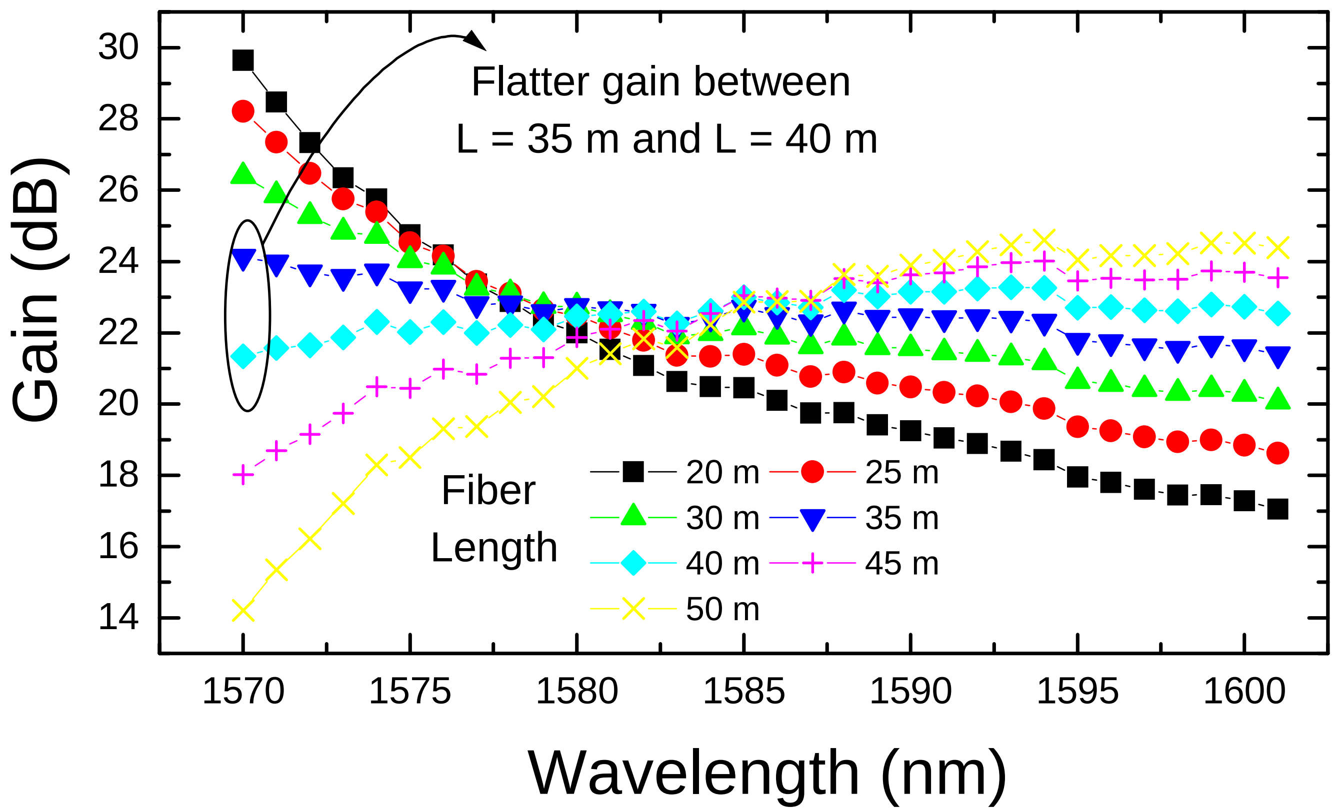


Best Selection of Loop Attenuation
$\lambda_L = 1610$ nm

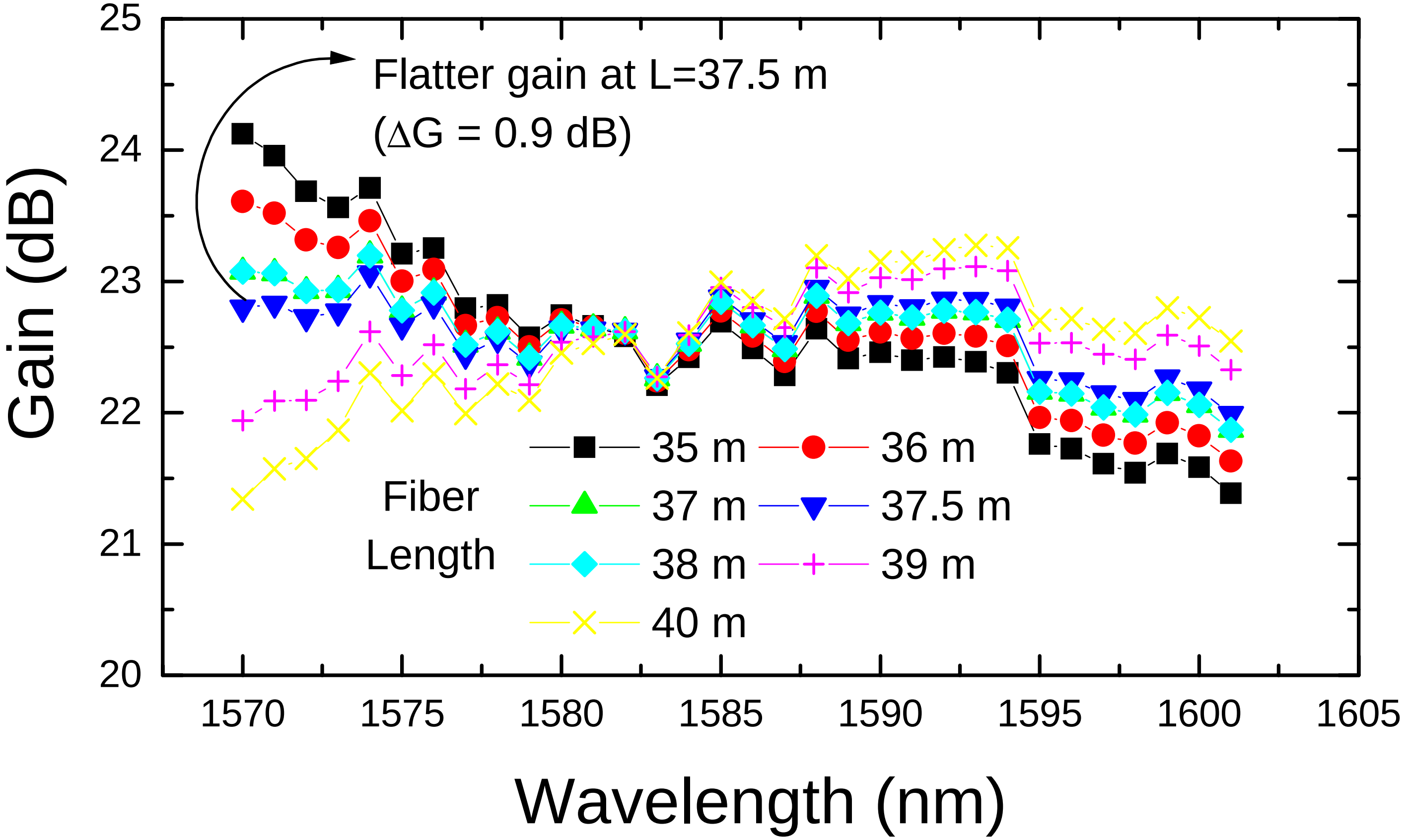


Multiple Channel Based Design

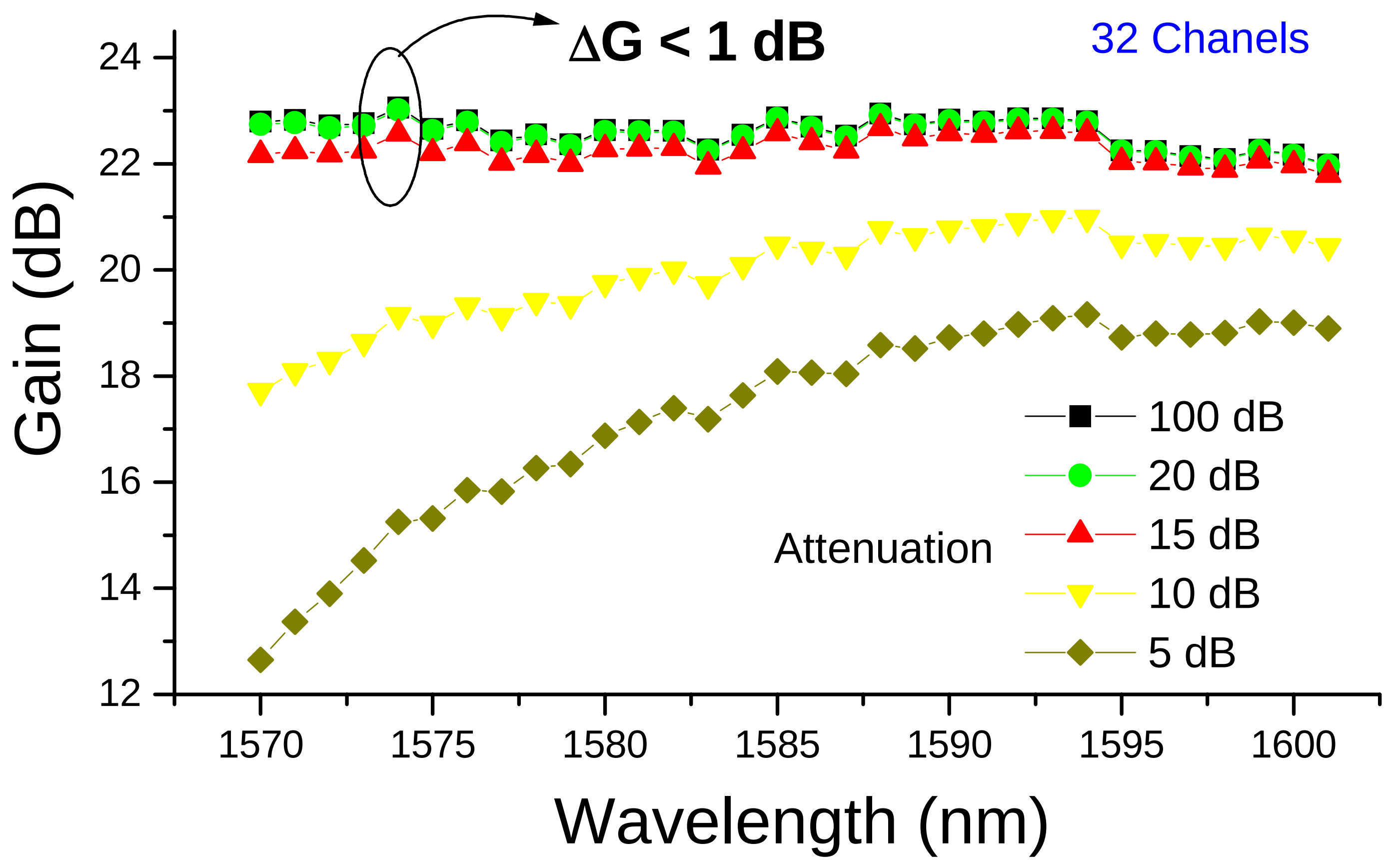
The Characteristics of Spectral Gain in the L-Band EDFA



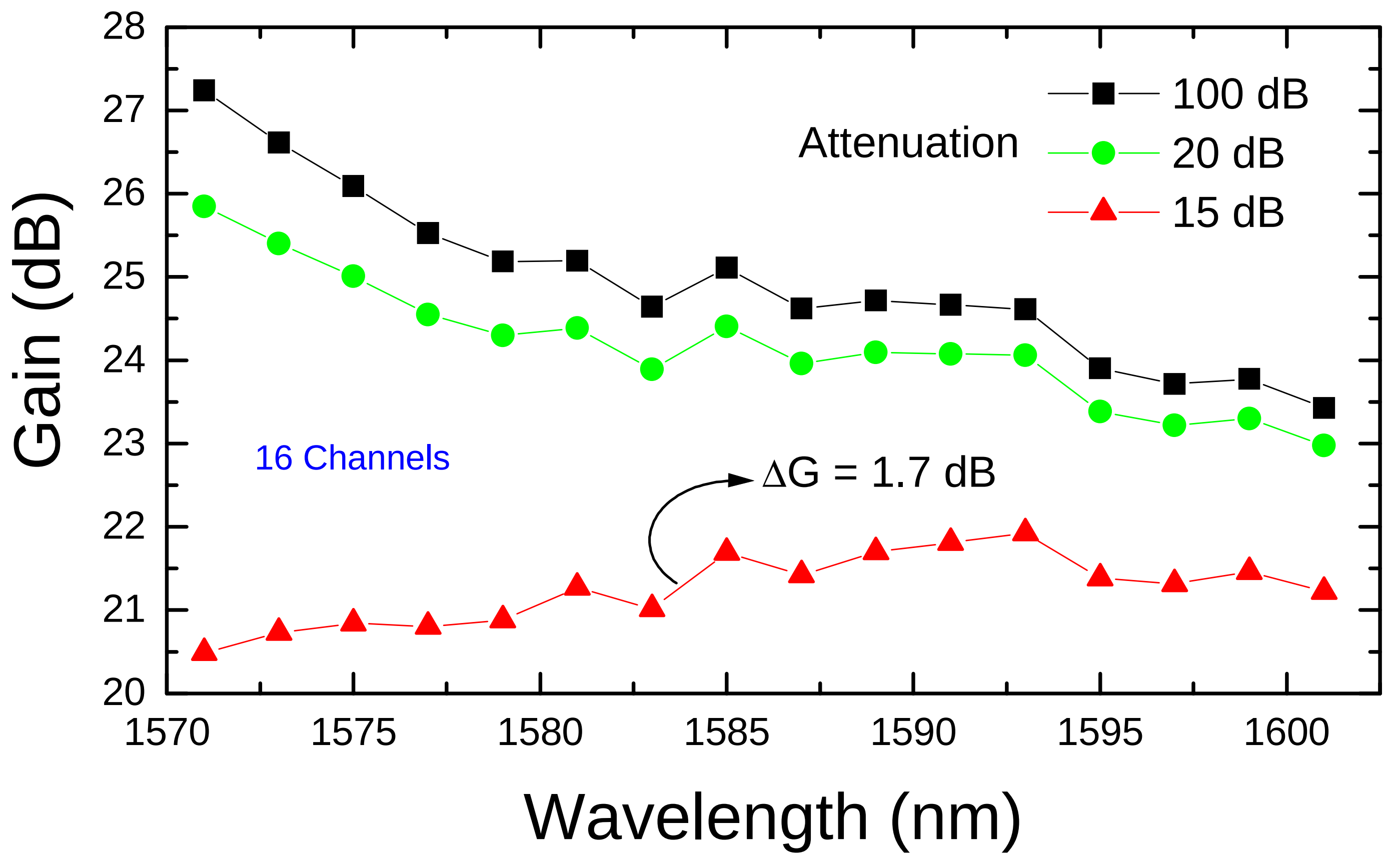
Selecting the Flatter Gain Between L = 35 m and L = 40 m



Spectral Gain Observed Considering Different Attenuations



Considering 16 Channels



Conclusions

- Gain-clamped amplifiers simulations considering different configurations;
- Multiple signal analysis;
- Important applications in DWDM broadband systems.