Hybrid Amplifiers

Part I

Combining Raman Amplification with Amplification by EDFAs in Long Haul WDM Systems

Outline

1. Overview of Raman and EDFAs combined amplification
2. Hybrid amplifier issues
3. Comparison of different amplified system configurations
4. Gain balance between Raman and EDFAs

Overview of Raman and EDFAs Combined Amplification

Why use Hybrid Amplifiers

- Enlarges the transmission capacity of broadband systems
- "Upgrading" the existing systems built with EDFA amplifiers with broader/flatter bandwidth
- Ability to carry more wavelength-multiplexed optical channels at given spacing among the channels
- Raman amplification gives flexibility to the selected band amplification
- Less sensitive to nonlinear effects – systems' point-of-view

Basic Idea of Hybrid Amplifiers

Principle of working / Operating Mode

- Flatten EDFA gain by using Raman gain
- Improve gain performance at longer signal wavelengths

Typical Configurations

Raman Amplifiers setup in different configurations:

- discrete
- distributed
- backward-, forward- and bidirectional pumped
- numerous types of fibers (DSF, DCF to be used as SRS active media)

EDFAs setup considers:

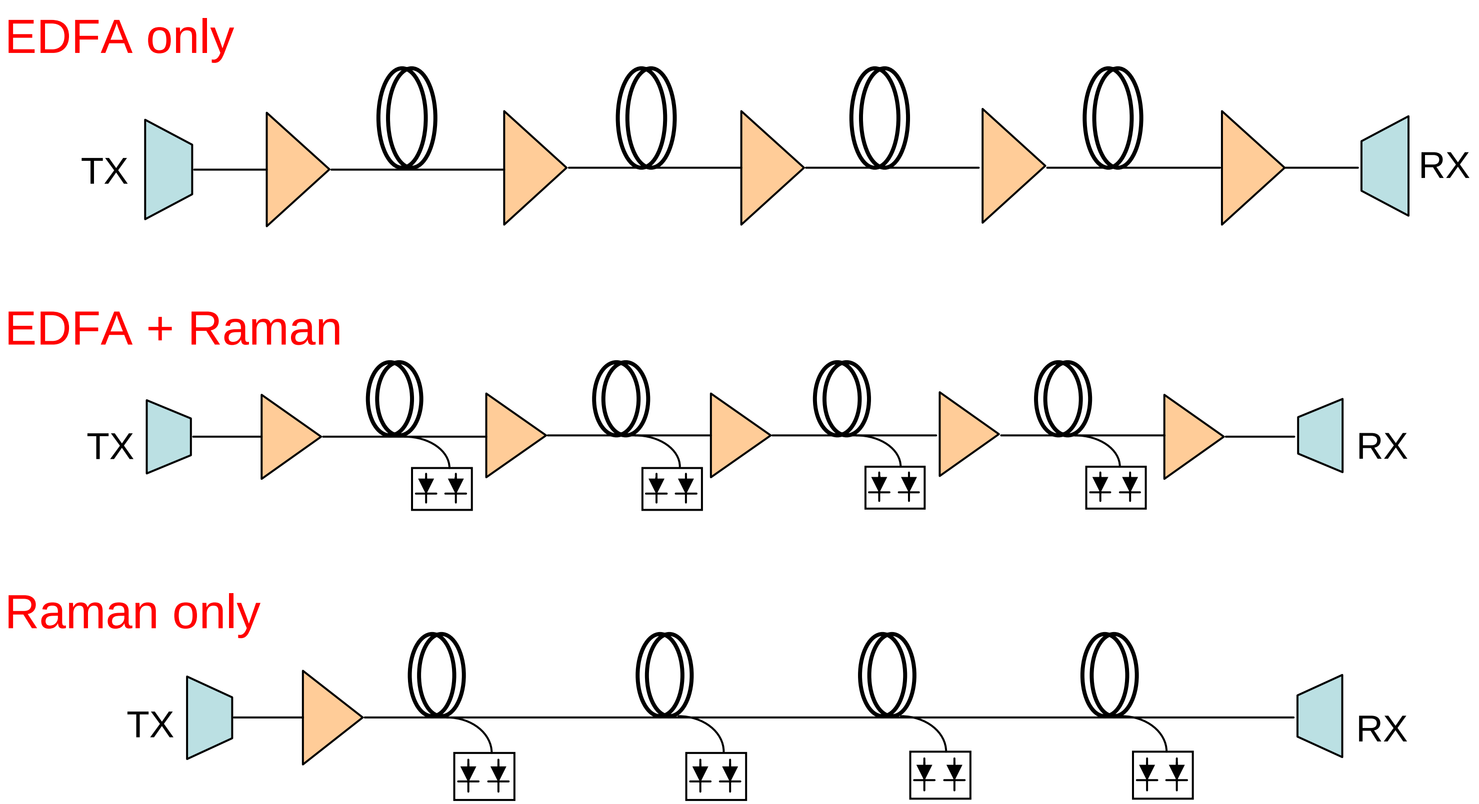
- single or multiple fiber stages
- series or parallel configuration
- C- and L-band regions

Hybrid Amplifiers Issues

The Hybrid Amplifiers studies are concerned with:

- maximizing the span length and/or minimizing the impairments of fiber nonlinearities
- enhancing the EDFAs' bandwidth
- designing "optimal" hybrid amplifiers in order to obtain flat and widest output gain performance

Comparing Different System Configurations

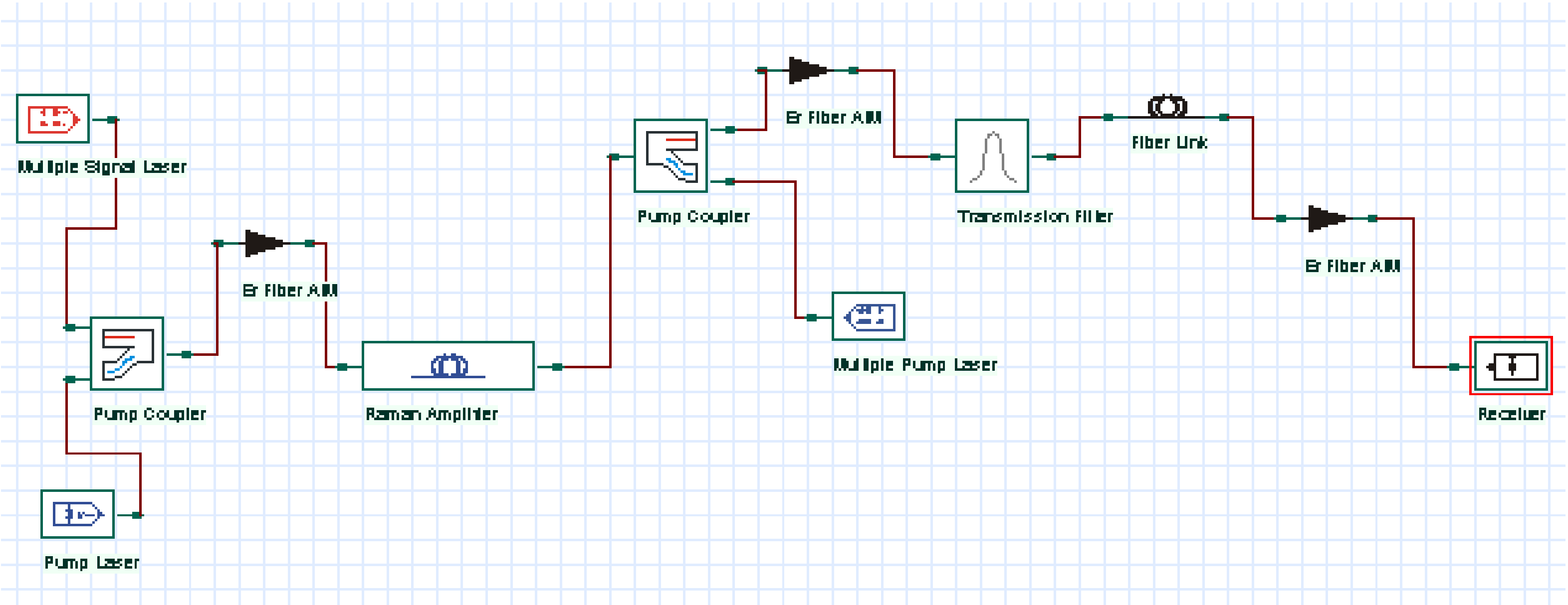


Results Obtained After Comparing the 3 Types of Systems

Considering in-line and pre-amplification functions:

- Long-haul EDFA-only systems are limited by OSNR and NL effects
- Raman-only systems tend to be limited by a reduction of SNR caused by double Rayleigh backscattering
- Combination of distributed Raman and EDFAs present better performance than conventional EDFA-only systems
- Raman complement EDFAs in terrestrial high capacity long haul applications

Optimizing HFA in a System



*Evaluate the optimum gain balance between the RAs and EDFAs that enables maximum transmission distance**

* *Carena et al., IEEE Photon. Techn. Lett. Vol. 13, No. 11, pp. 1170-1172, 2001.*

Gain Balance Between Raman and EDFAs

1. Complex problem with several degrees of freedom
   - optimization technique

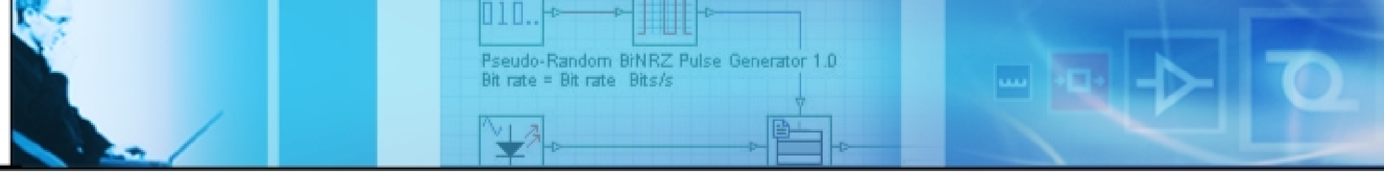
2. Main considerations to determine the optimum gain balance between Raman and EDFAs

3. Most important parameters
   - OSNR, gain-flatness, bandwidth
   - number of channels, number of spans, maximum transmission capacity

Focusing on Extending the Bandwidth

- Increase the number of transmitted channels
- Gain flatness
- Optimize the hybrid amplifier performance (gain, NF, OSNR)

Optiwave



Techniques that Enlarge Flattened Gain-Bandwidth of "Discrete" Fiber Amplifiers

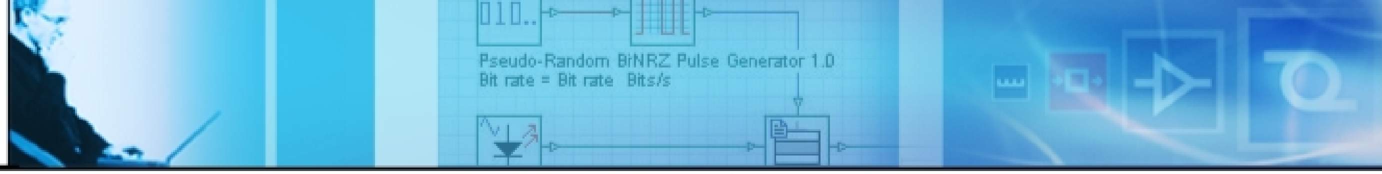
I. New host materials

- fluoride- and telluride-based EDFAs
- thulium-doped fiber amplifier

II. Using EDFAs with GEQ + discrete Raman amplifier

III. Different amplifier configurations

- two-gain band
- parallel/series configuration – multiple fiber stage
- gain-equalizing (GEQ) filters



Typical Values Observed in Hybrid Amplifiers

Bandwidth	> 40 nm
Gain	15 – 25 dB
Gain Ripple	< 11.3 %
Noise Figure	< 6 dB
OSNR	> 32 dB

Examples of Wide Flattened Bandwidth for Discrete Raman/Hybrid Fiber Amplifier

Bandwidth (nm)	***G Flatness (%)***	***Reference***
64	11.3	OAA 98, p. 103
76	4.7	OFC 98, paper PD7
75	3.7	Electron. Lett. 34, 897, 1998
40	3.2	IEEE PTL 9, 1343, 1997

Specifications

EDFA	*Discrete Raman*	*Nr. Pump*	*NF(dB)*
1 stage	2 stages	2	< 6
2 stage	1 stage	3	< 6

Part II

Designing Hybrid Amplifiers

Outline

1. Models required in the simulations
2. Hybrid amplifier designed to LAN
3. Gain and noise figure results
4. A hybrid amplifier setup in multiple fiber stages
5. Characterization and performance in a system

Models Required in the Simulations

EDFA Modeling:

Solve rate and propagating equations for pump, signal, and ASE, considering non-linear effects present in the fiber propagation.

Raman Amplifier Modeling:

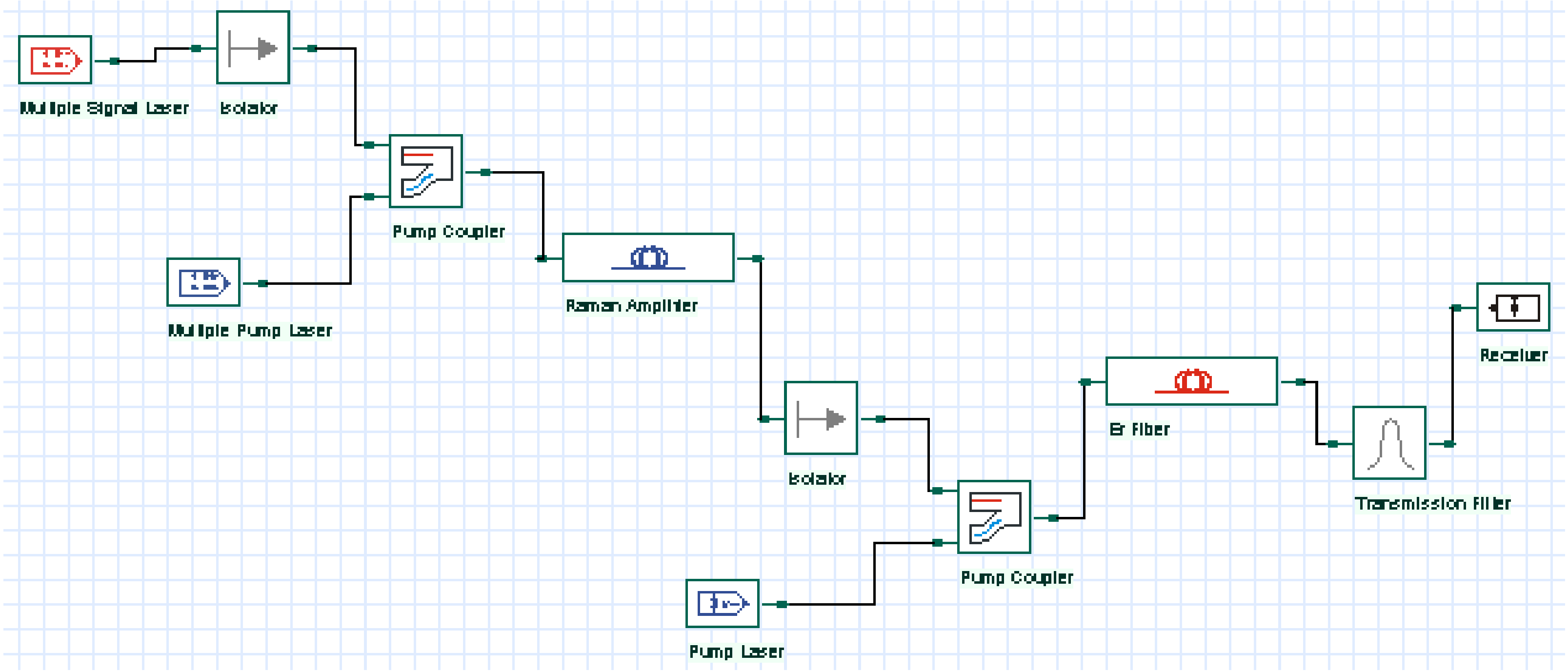
Solve the rate and propagation equations for pump, signal, and ASE in the Raman fiber amplifier.

*Hybrid Amplifiers Designed for Local Area Networks**

- LAN and MAN applications
  - G_{ave} ~ 20 dB
  - Net gain > 10 dB
- Distributed Raman fiber amplifier in series with a remotely pumped discrete EDFA
- C-band and L-Band
- WDM signal input
- Optimized design parameters

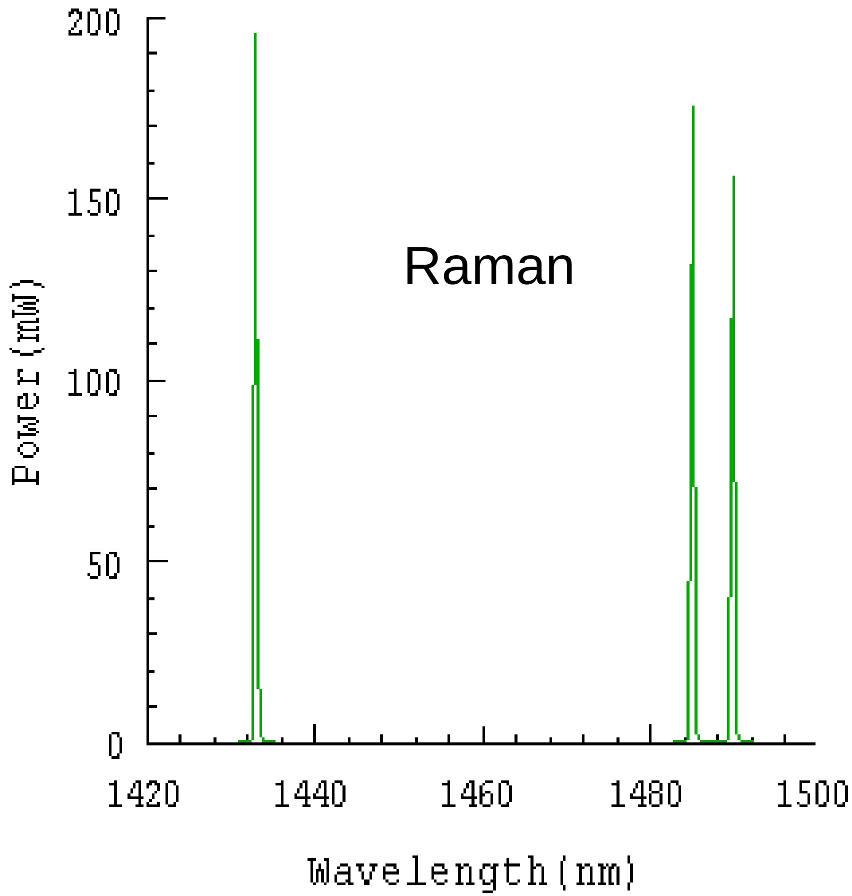
* *Karasek et al., IEE Proc.-Optoelectron. Vol. 148, No. 3, p. 150, 2001*

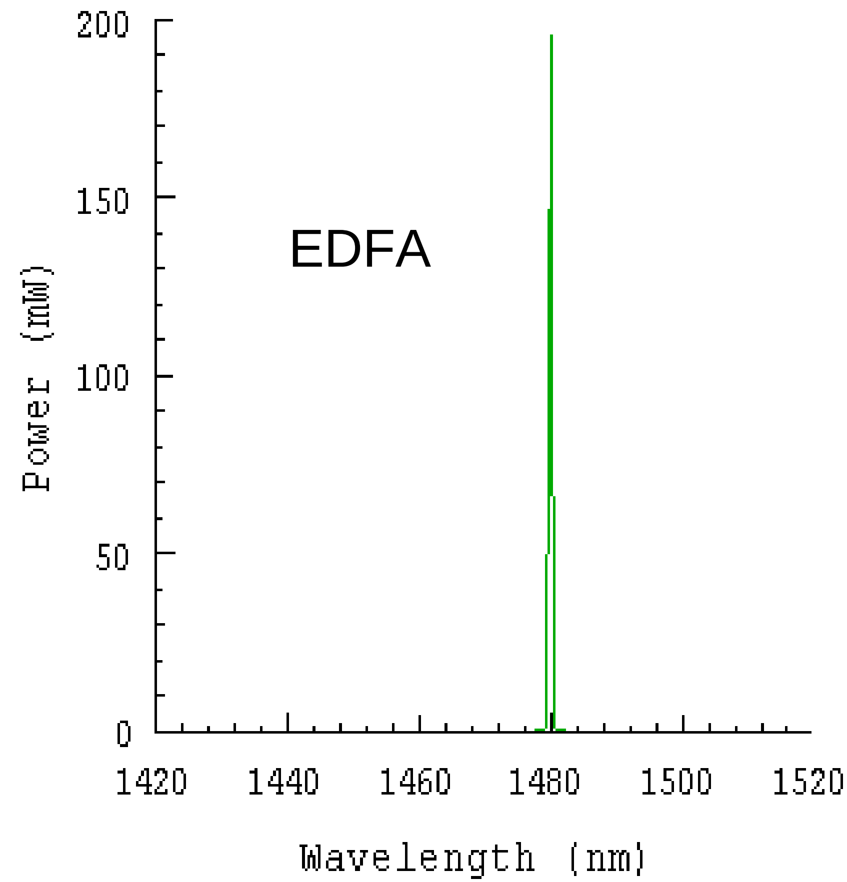
Hybrid Amplifier Layout



Pump Power Specification

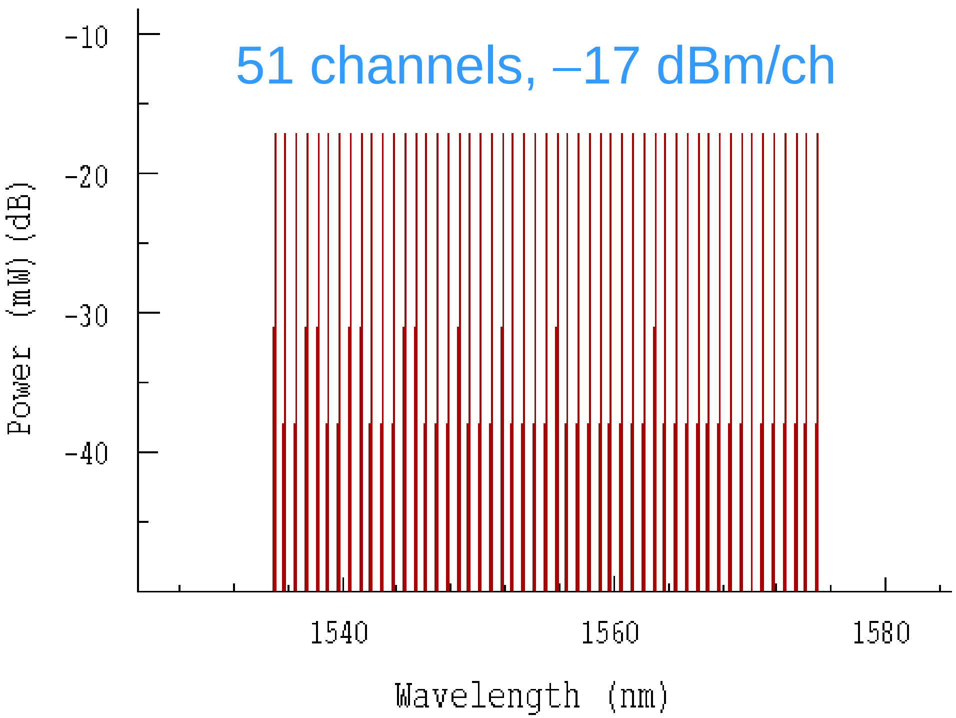
Co-propagating pump power



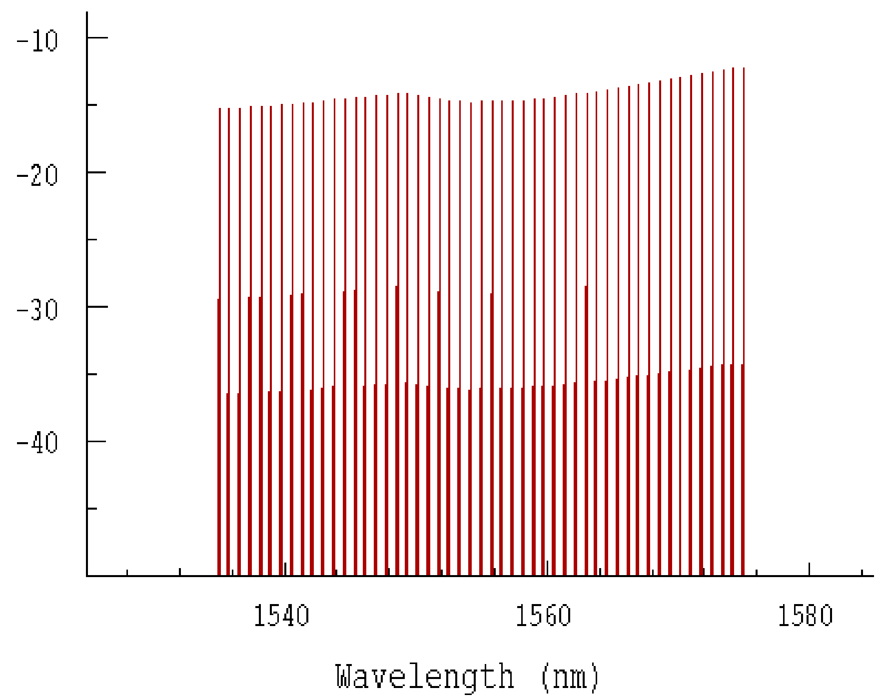


Signal Input Power

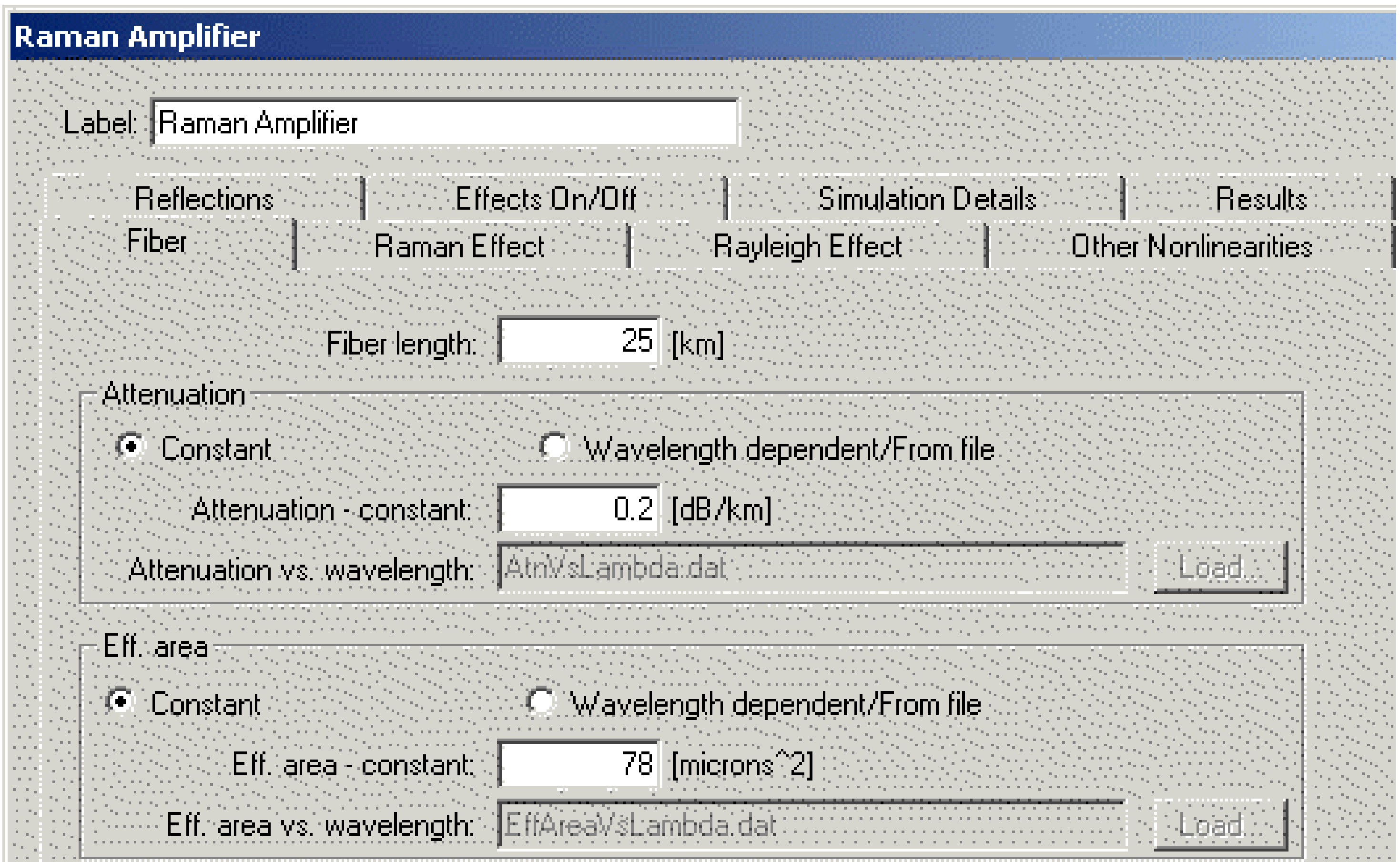
Raman



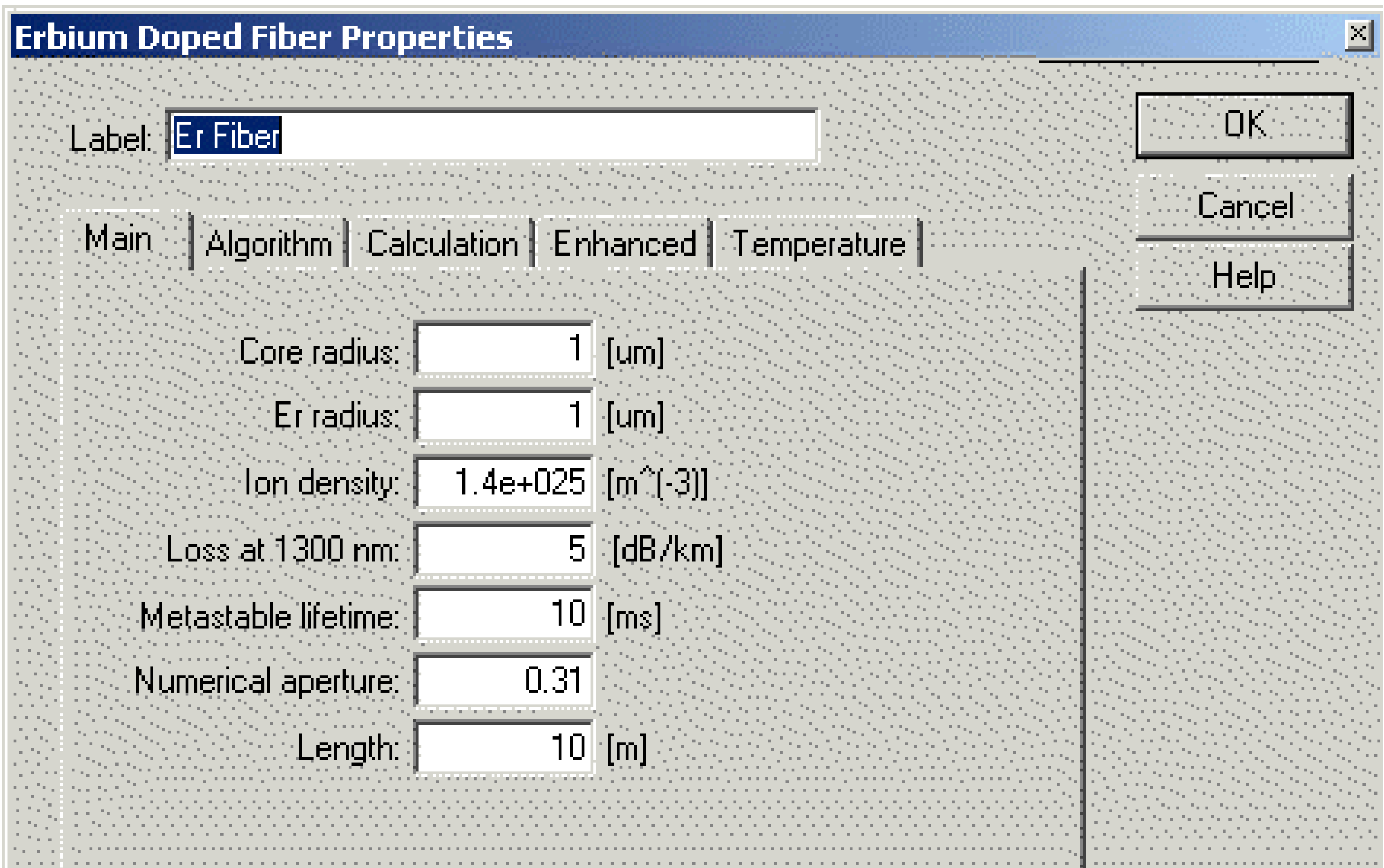
EDFA



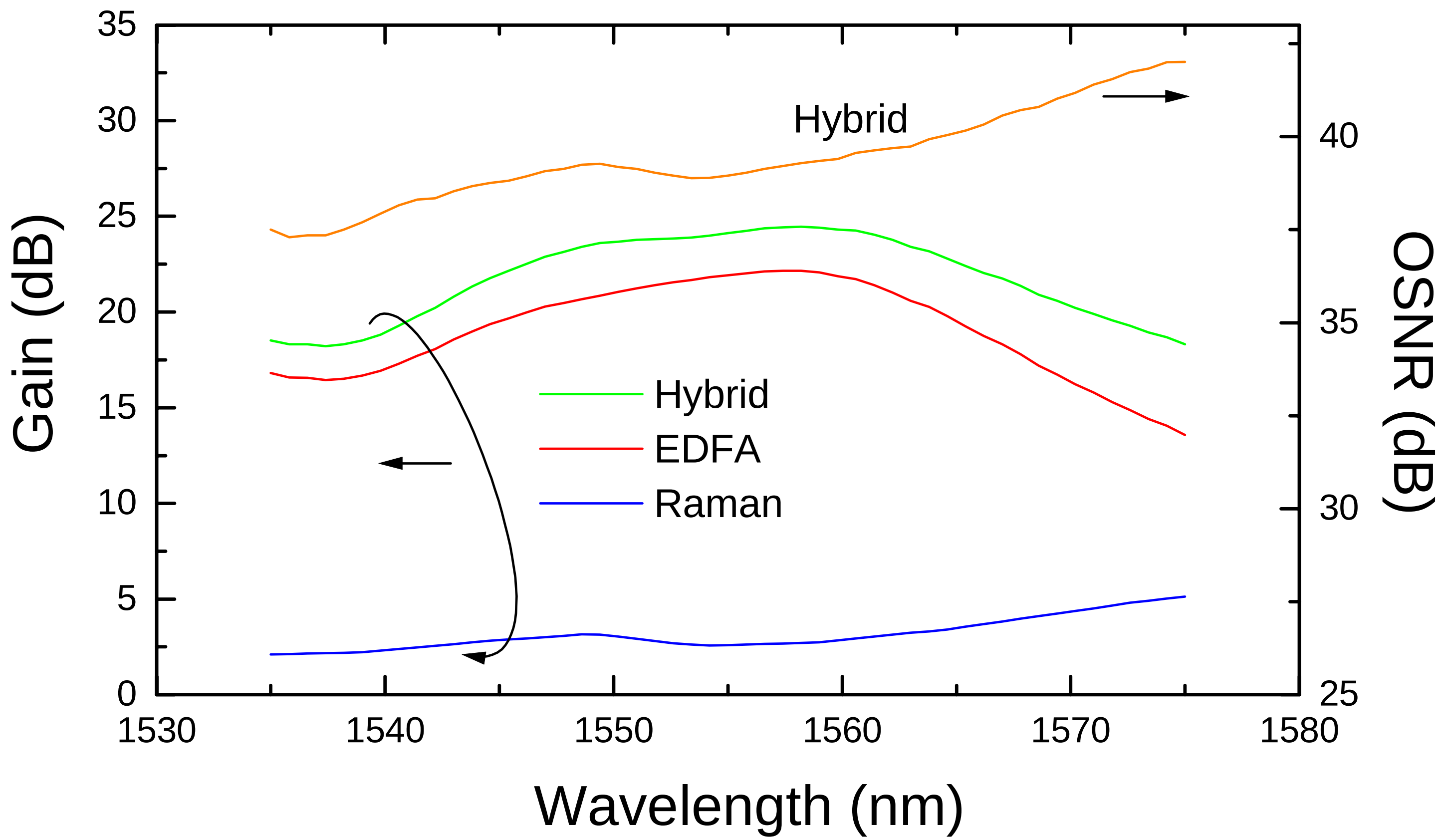
Raman Amplifier – Fiber Specifications



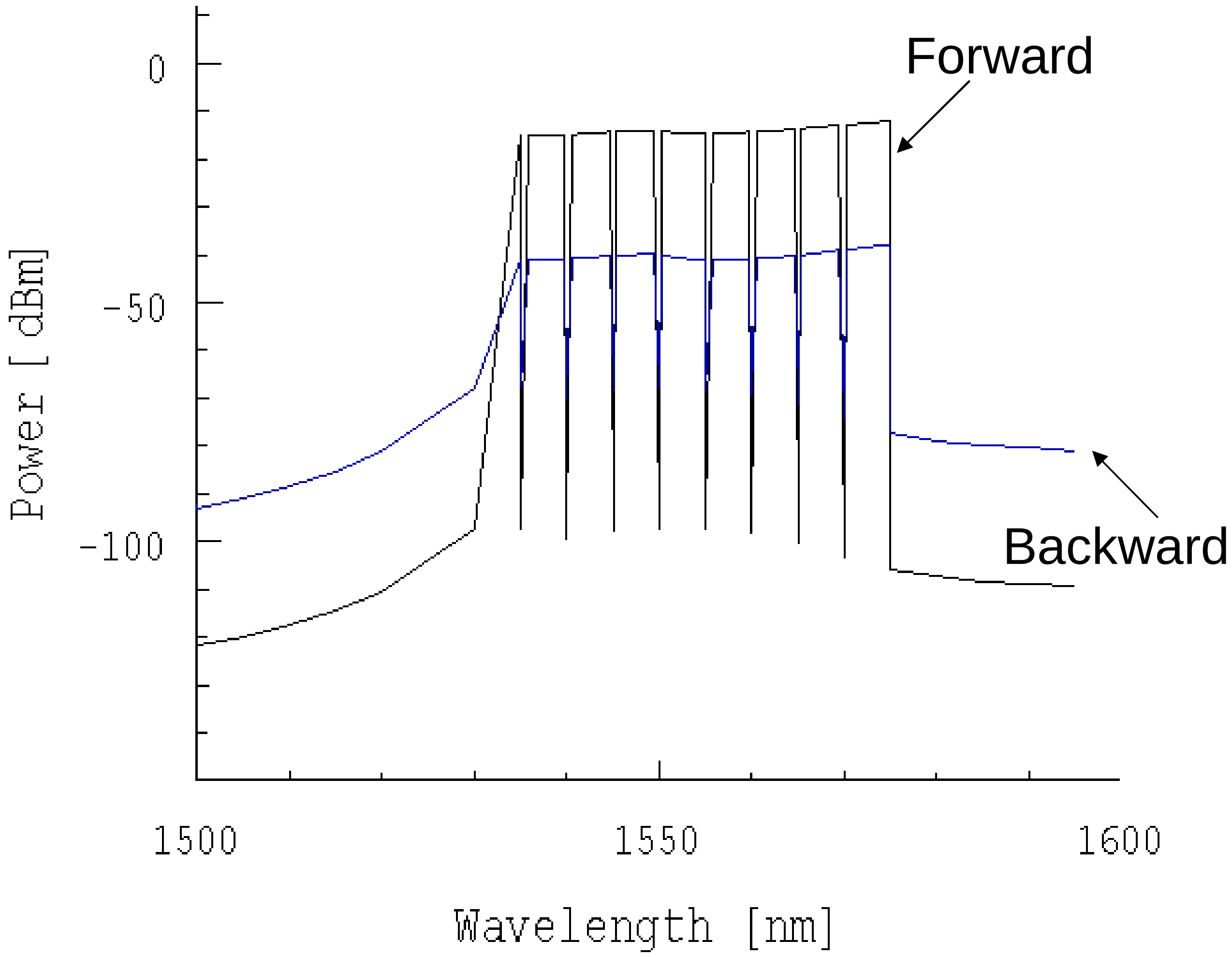
EDFA – Fiber Specifications



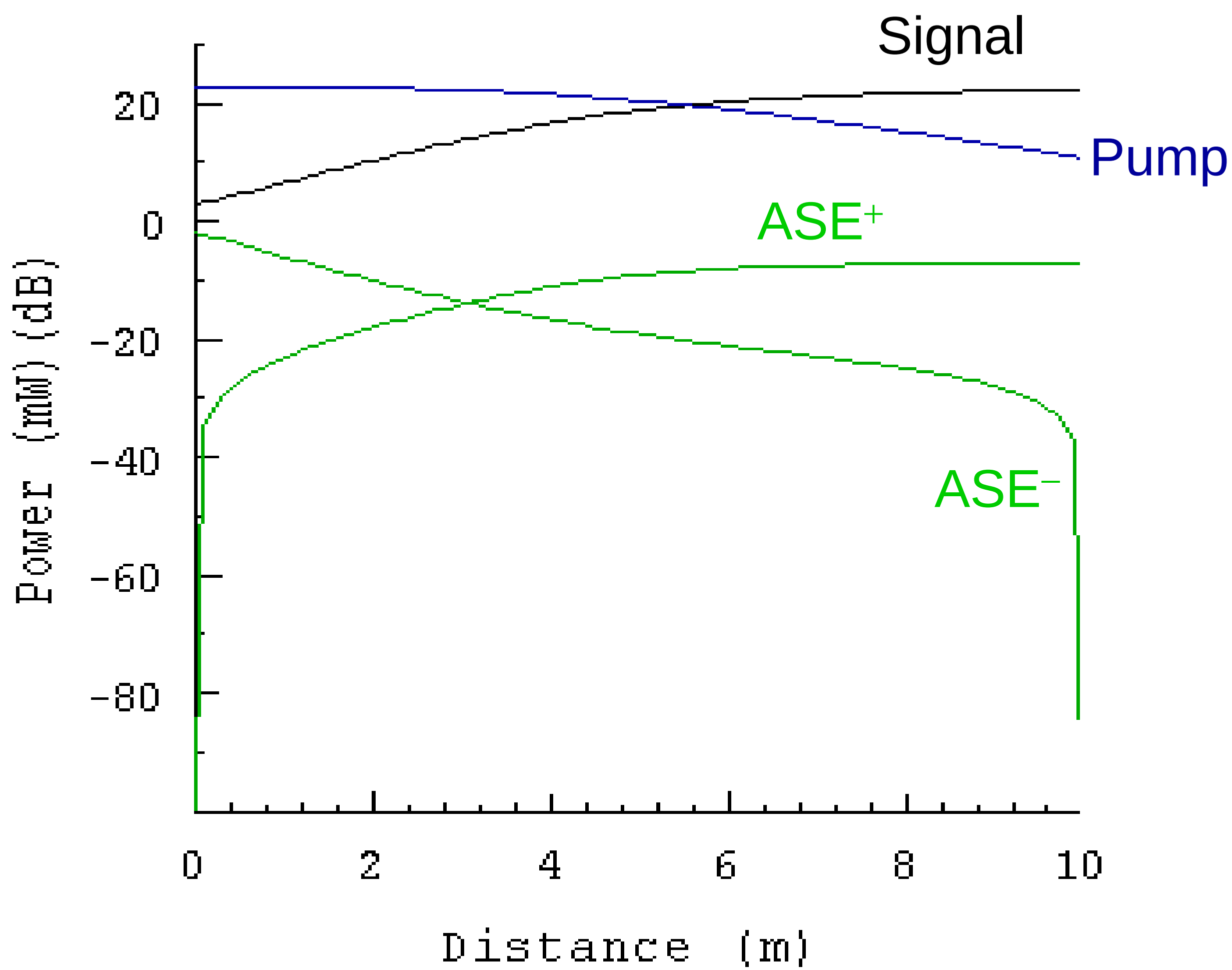
Evaluating Results in the C-Band Wavelength Range



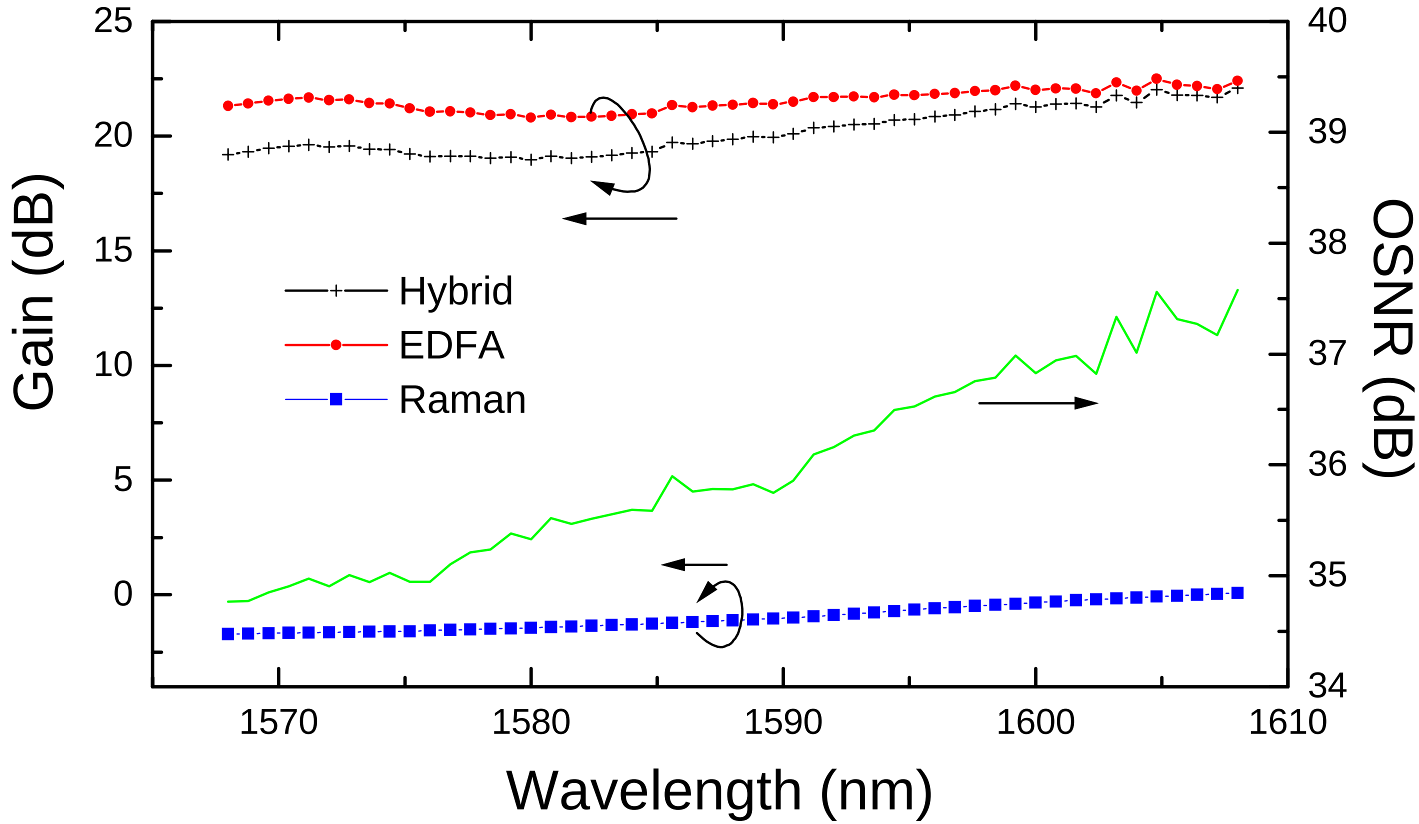
Raman Output Power Spectra



Total Powers Along the EDFA

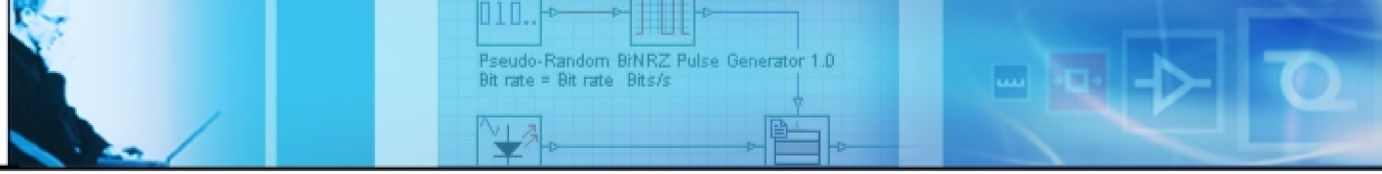


Results in the L-Band Wavelength Range



Additional Comments

- Hybrid fiber amplifier simulated for multi-wavelength operation in LANs
- Distributed RFA and remotely pumped EDFA
- Net gain 10 – 20 dB
- EDFA is excited by the pump power unabsorbed in the transmission fiber
- C-band and L-band results



Part III

Simulating Gain-Equalized Hybrid Raman-EDF Amplifiers

Outline

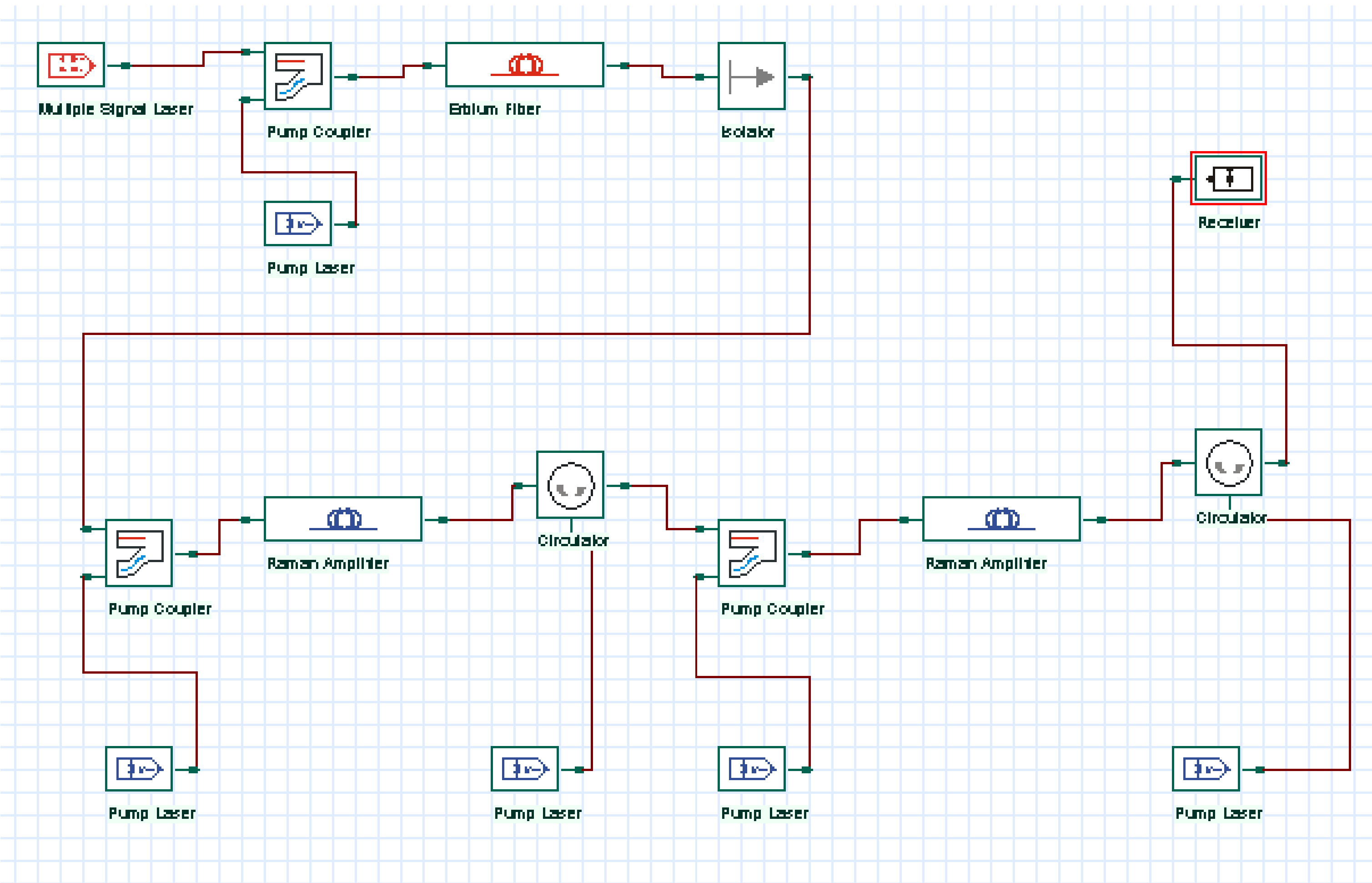
- Simulating hybrid amplifier with no filter
- Spectral gain results
- How to flatten the gain spectrum
- Conclusions

*Wide Band Gain-Flattening Hybrid Amplifier**

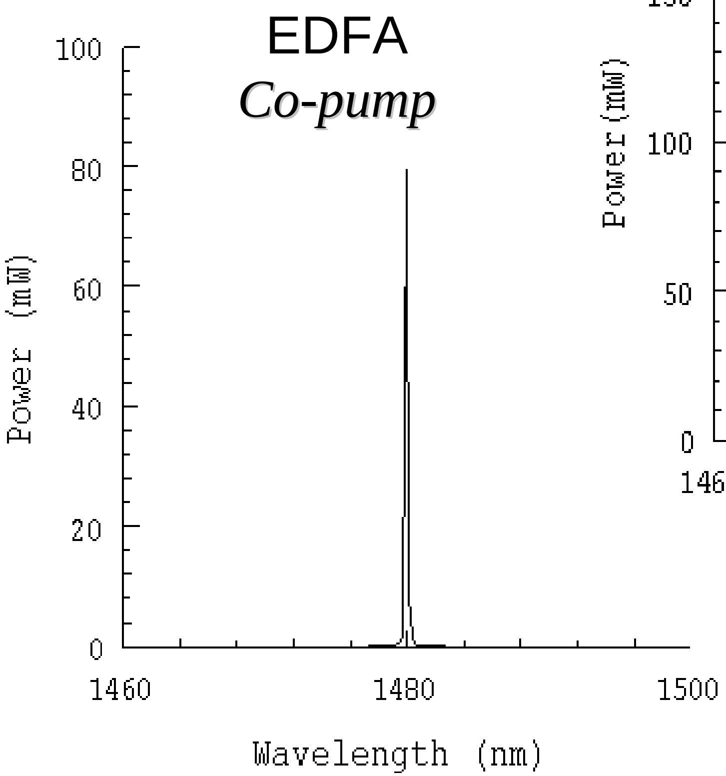
- Wide and flatness bandwidth
- Short EDF + discrete Raman amplifier
- Two-stage Raman amplifier
- Bidirectional pumped at 3 different λ_p
- C-Band and L-Band signal wavelength

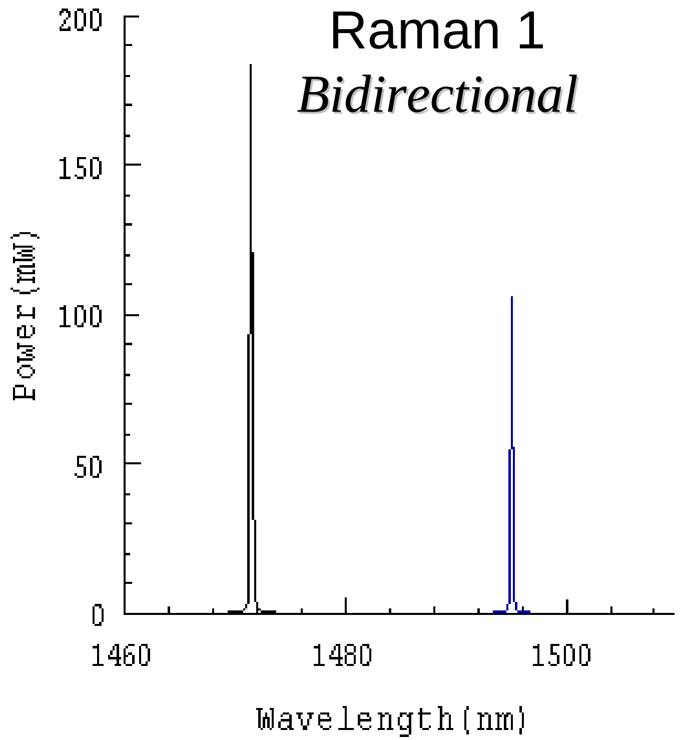
* *Masuda et al., IEEE Photon. Techn. Lett. Vol. 11, No.6, p. 647, 1999*

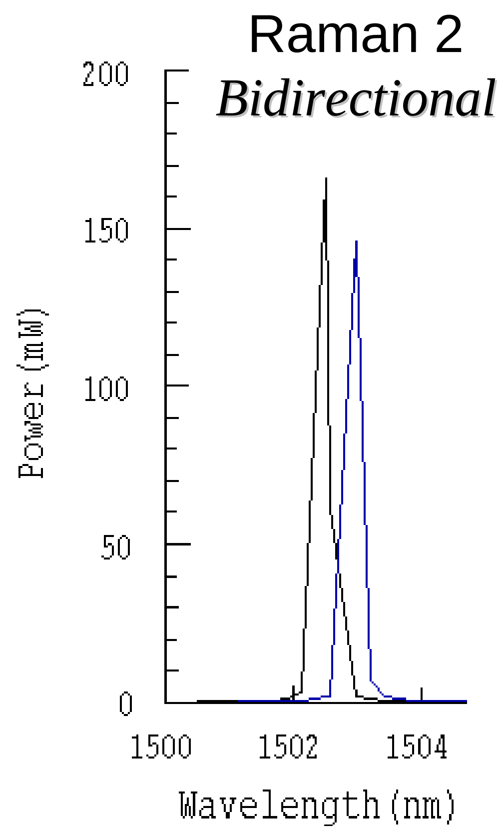
Hybrid Amplifier with no Filter



Pump Power Specifications



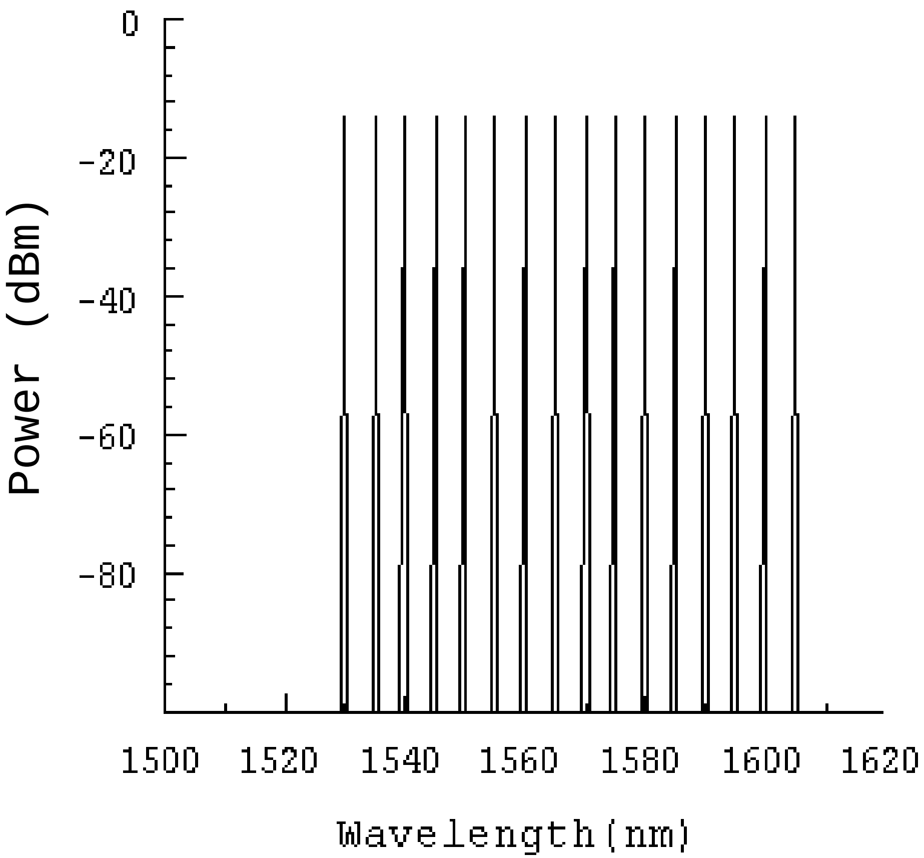




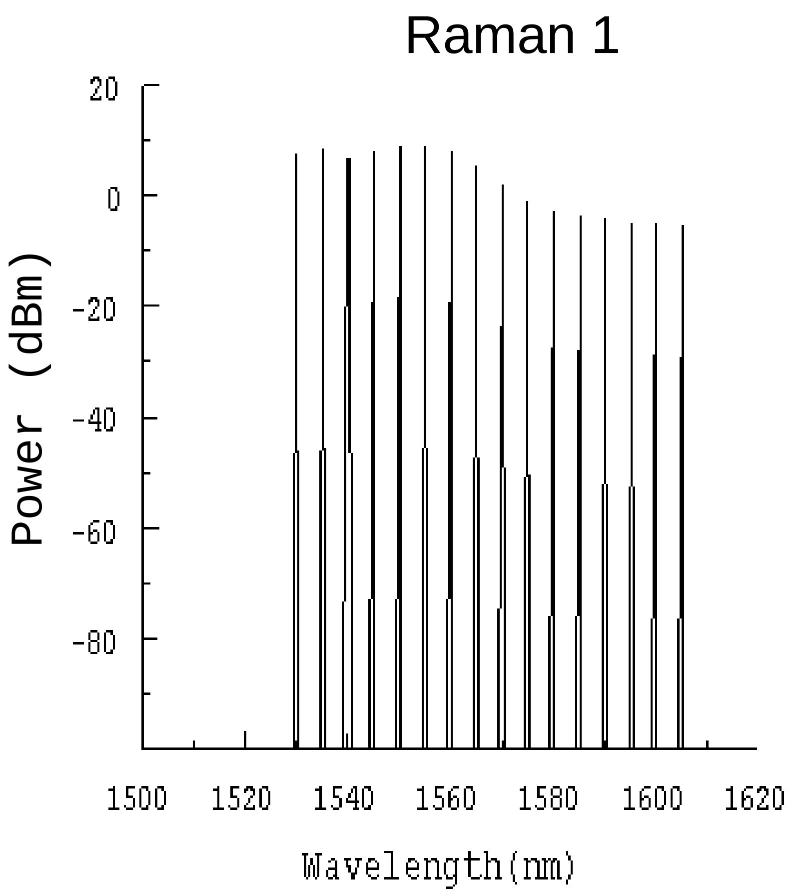
Signal Input Power Specifications

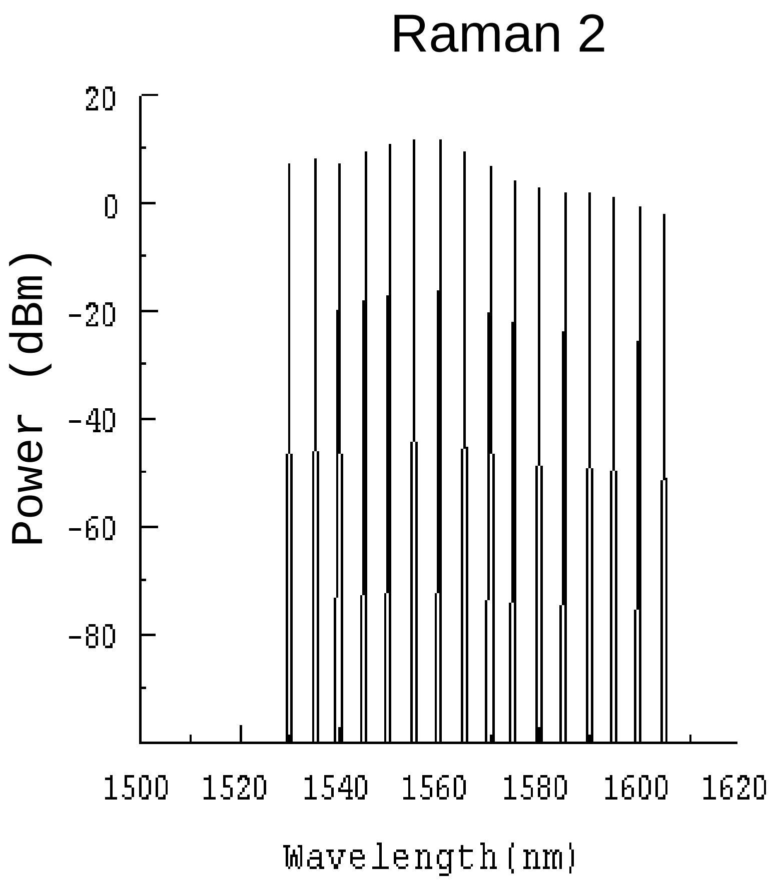
16 channels spaced by 5 nm

EDFA

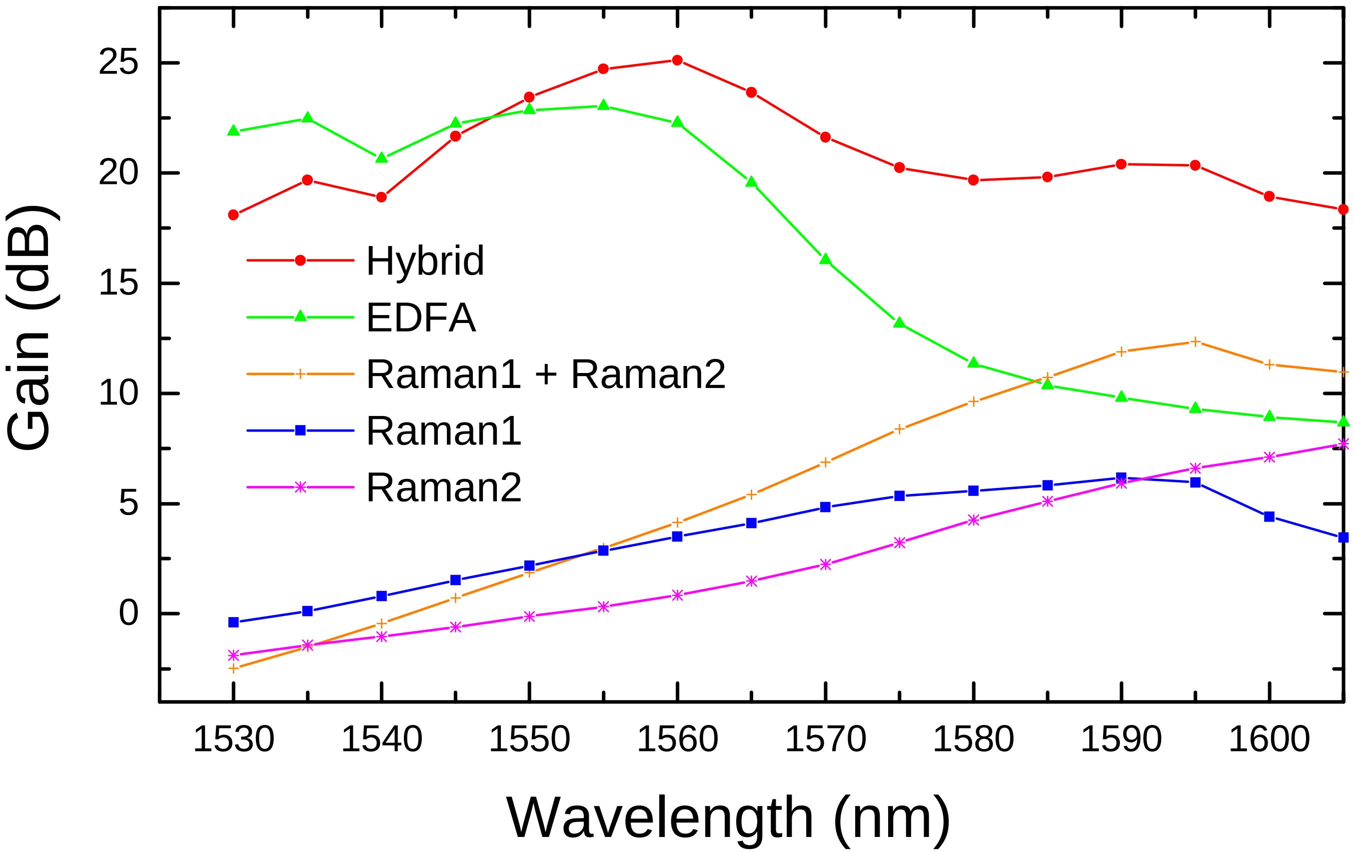


Signal Input Power Specifications

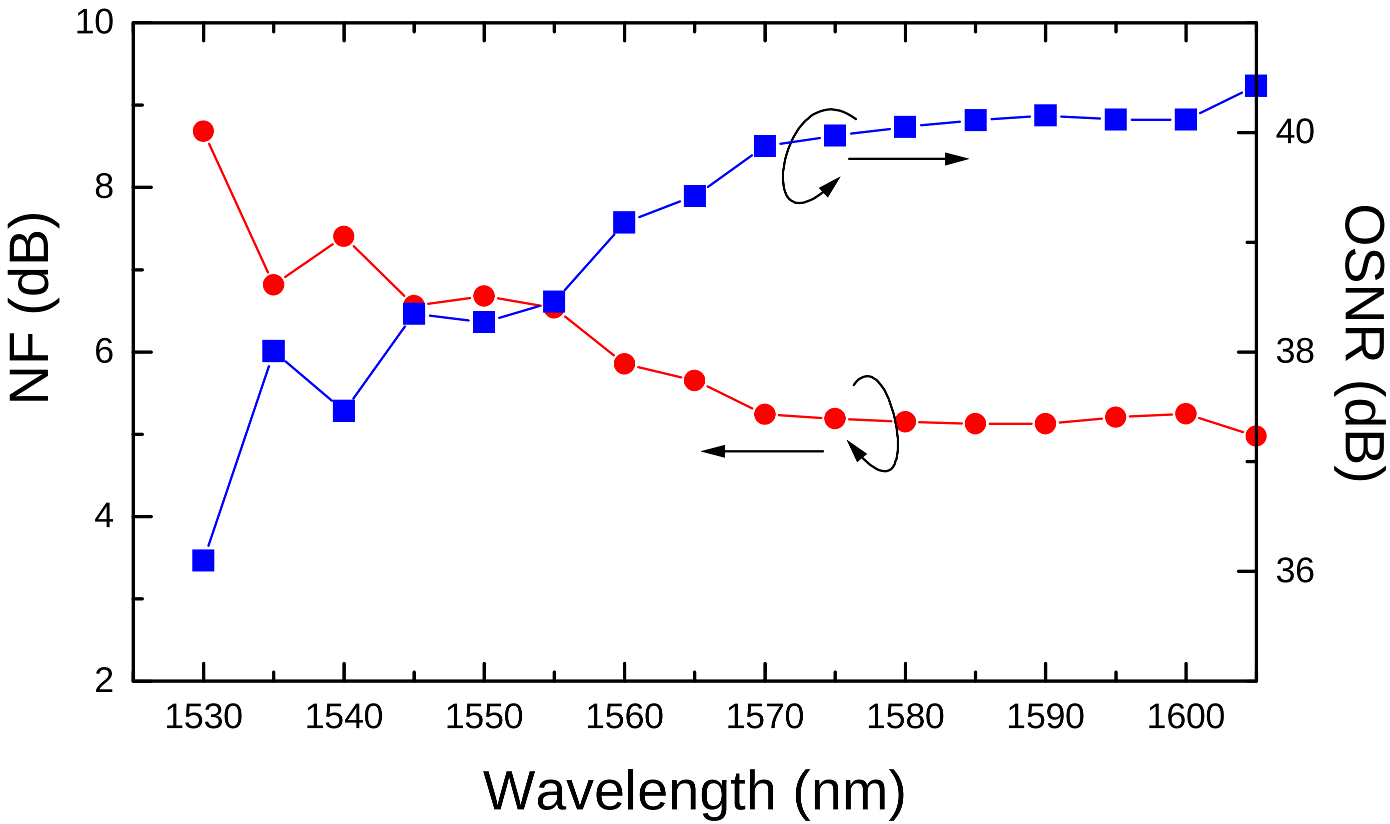




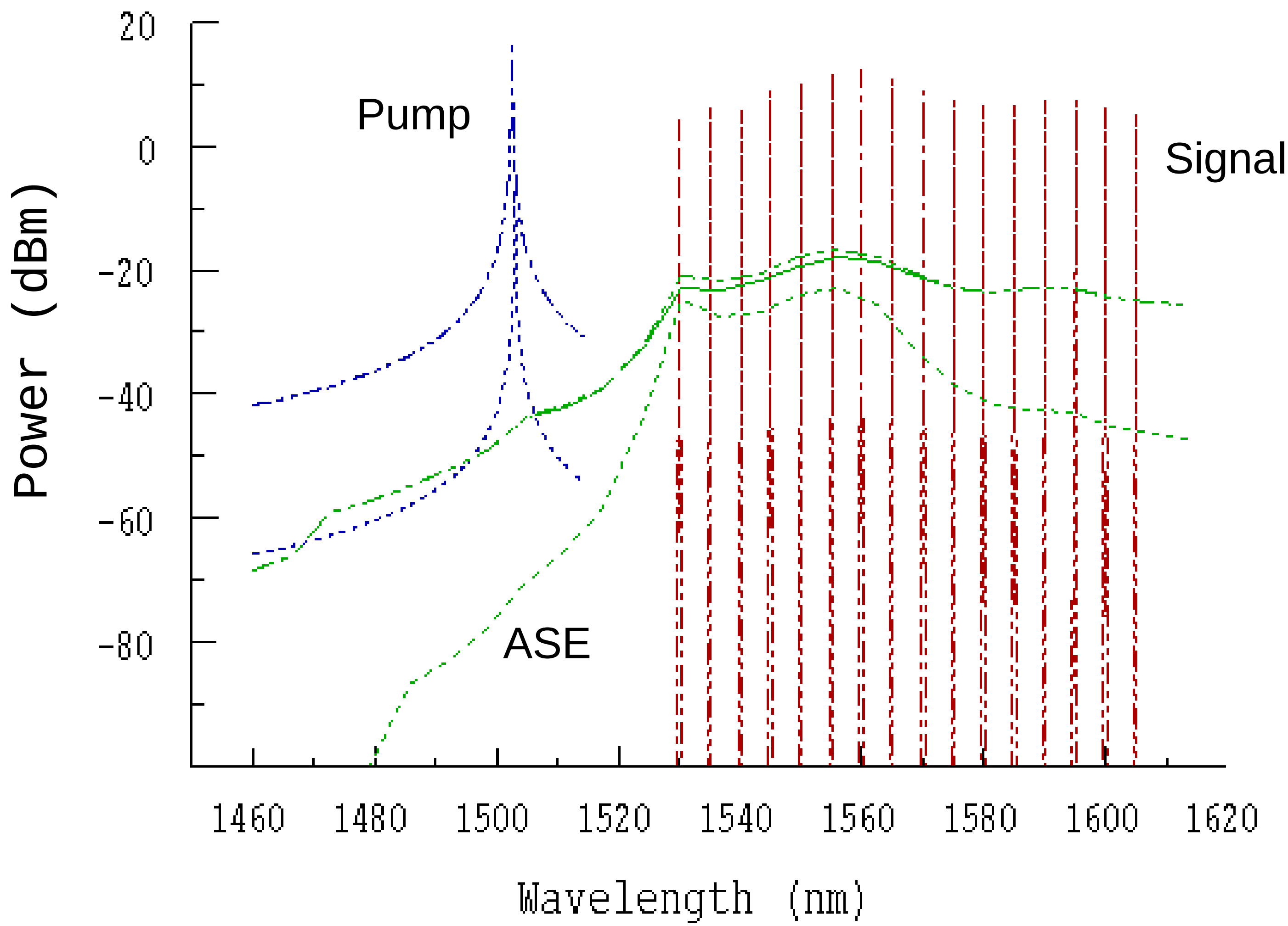
Spectral Gain Along the C-Band and L-Band Wavelength Range



Spectral NF and OSNR to C-Band and L-Band



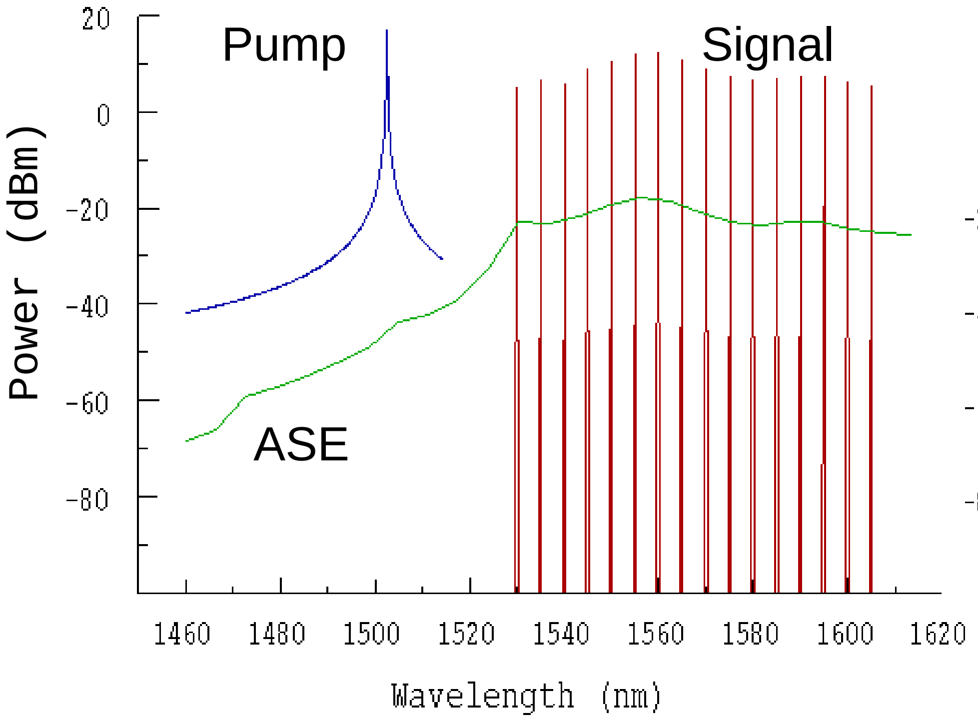
Hybrid Amplifier Output

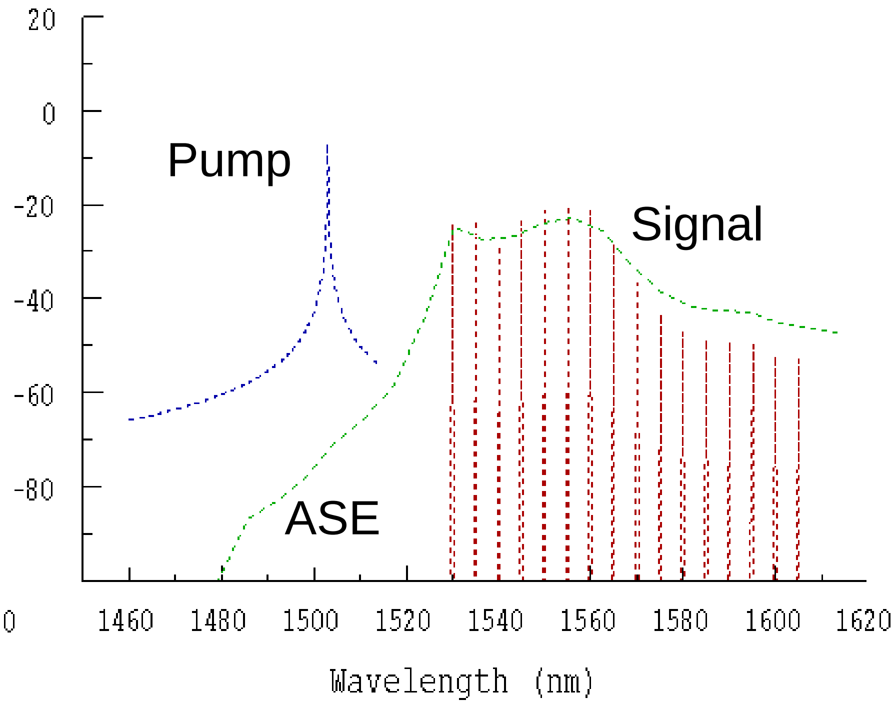


Hybrid Amplifier Output

Transmitted

Reflected



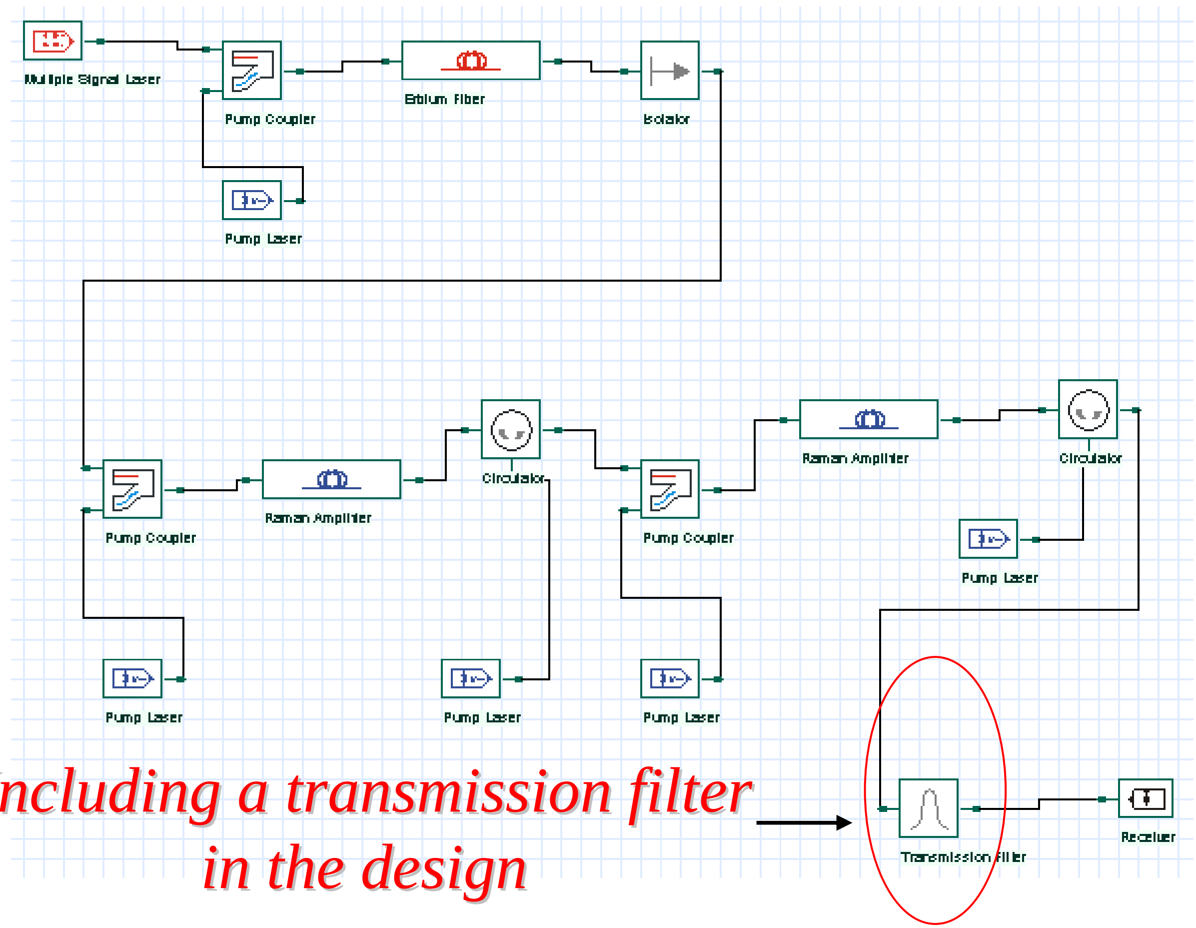


Comments

- Raman amplifier increases the gain at longer wavelength signal;
- Design can be optimized;
- Considerable gain ripple which limits usefulness for high capacity transport systems;
- Er doped fluoride fiber also presents the gain ripple observed for silica fiber.

How to Flatten the Gain Spectrum

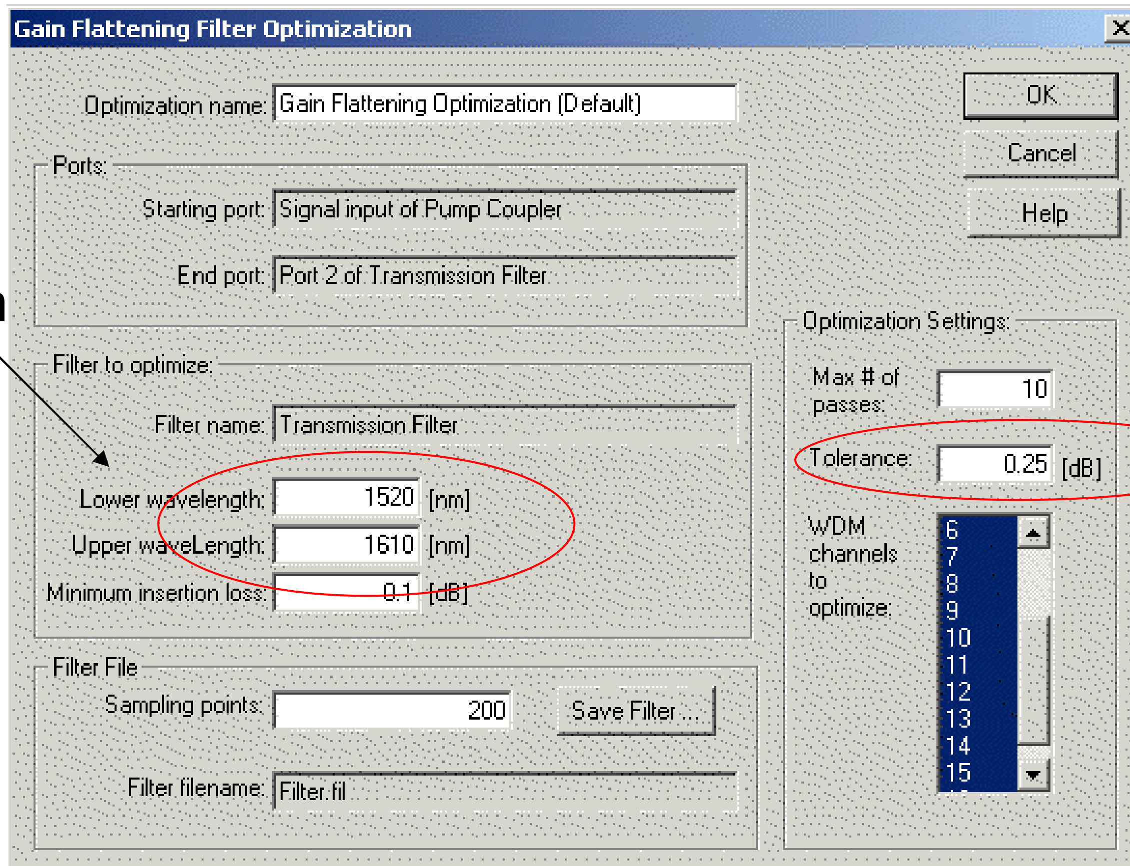
- Use a passive filter device such as thin film, fiber grating, etc.



Including a transmission filter in the design

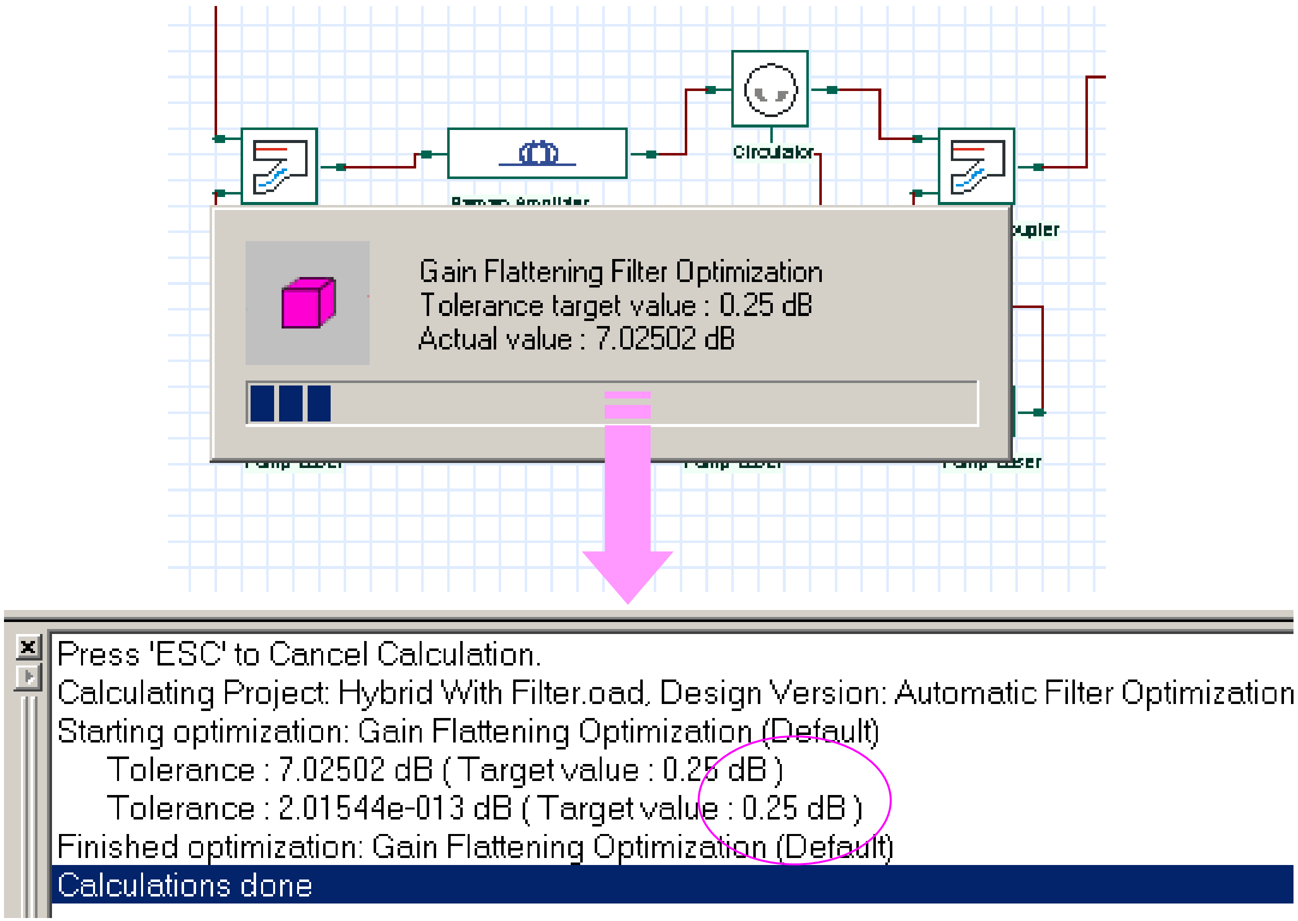
Gain Flattening Filter Specifications

Wavelength Range

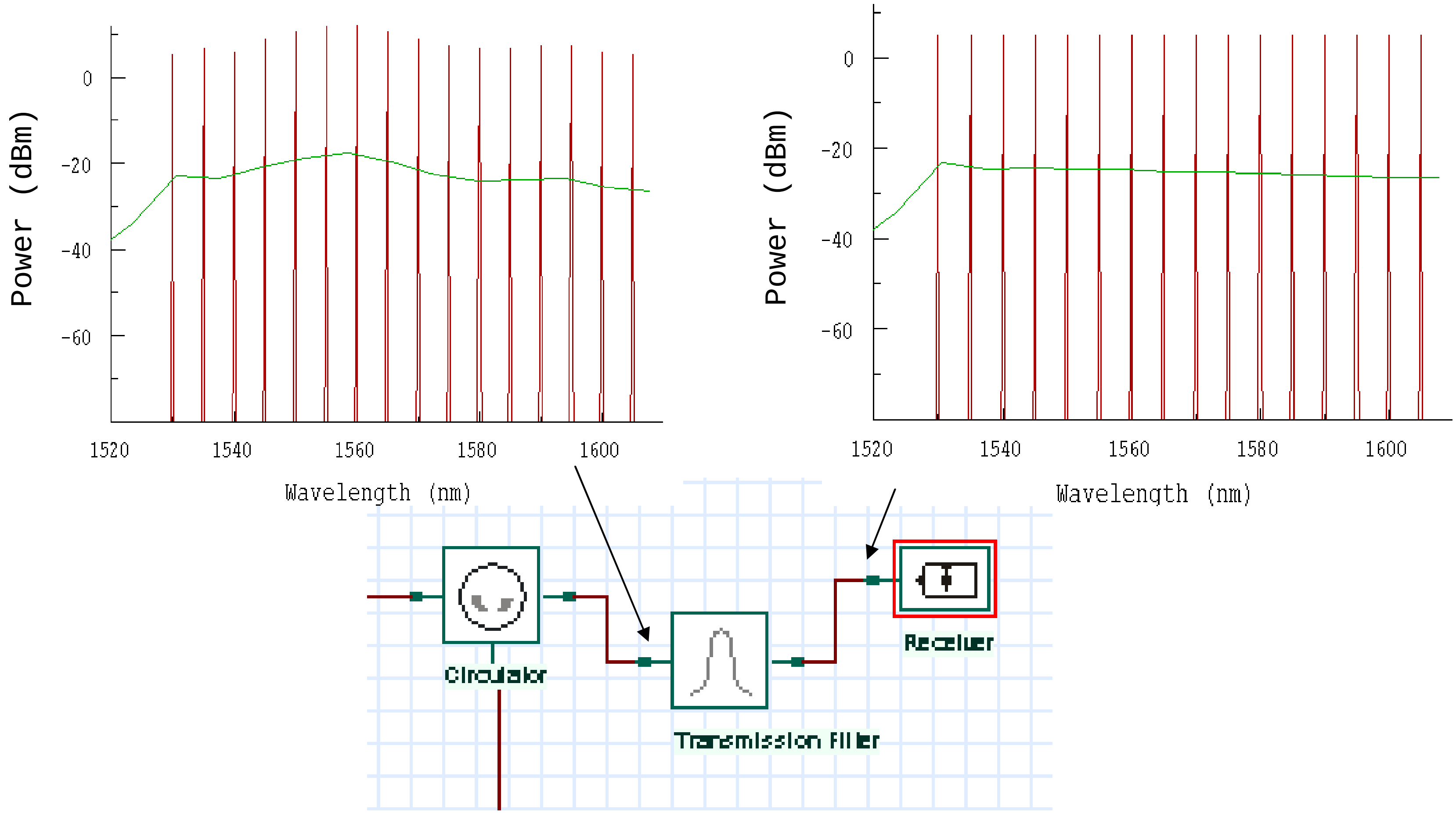


Specifies how flat the filter will be

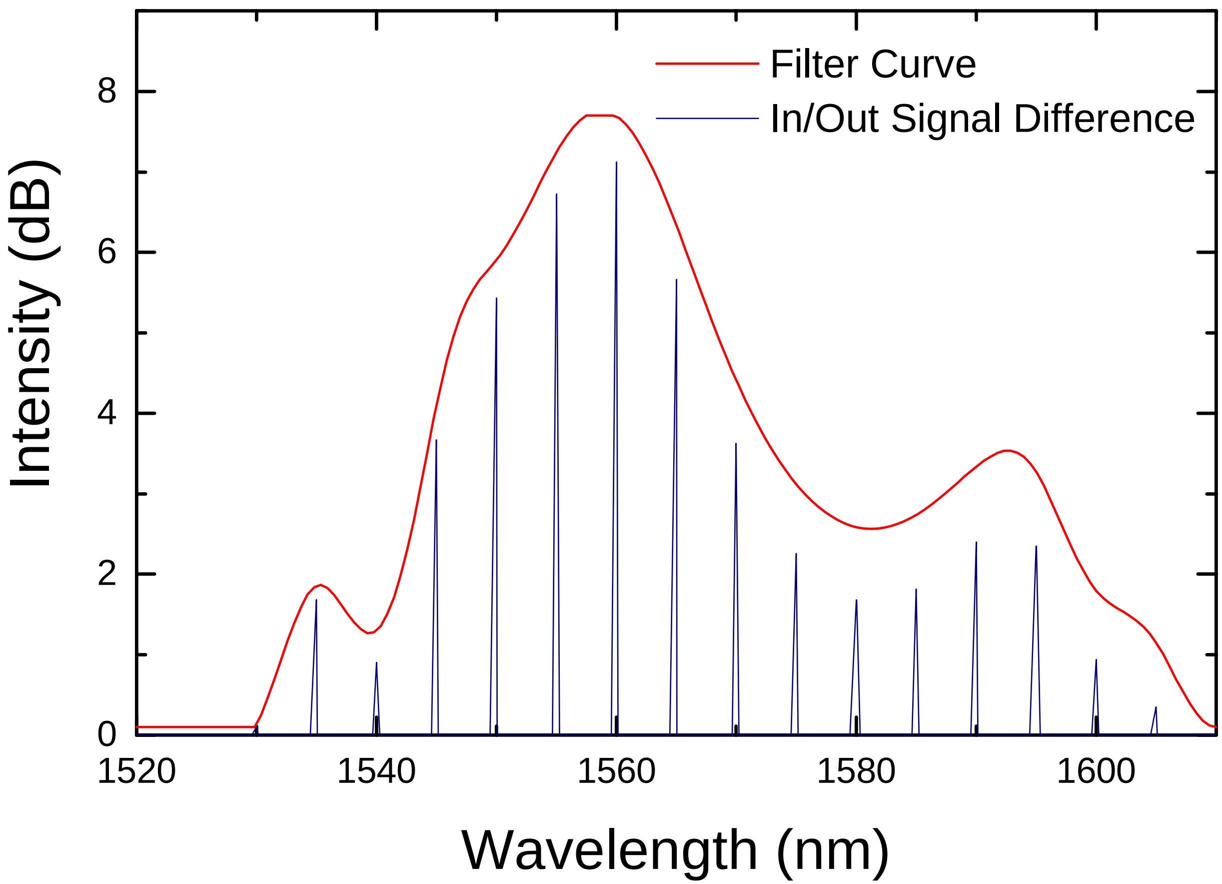
Gain Flattening Filter Optimization



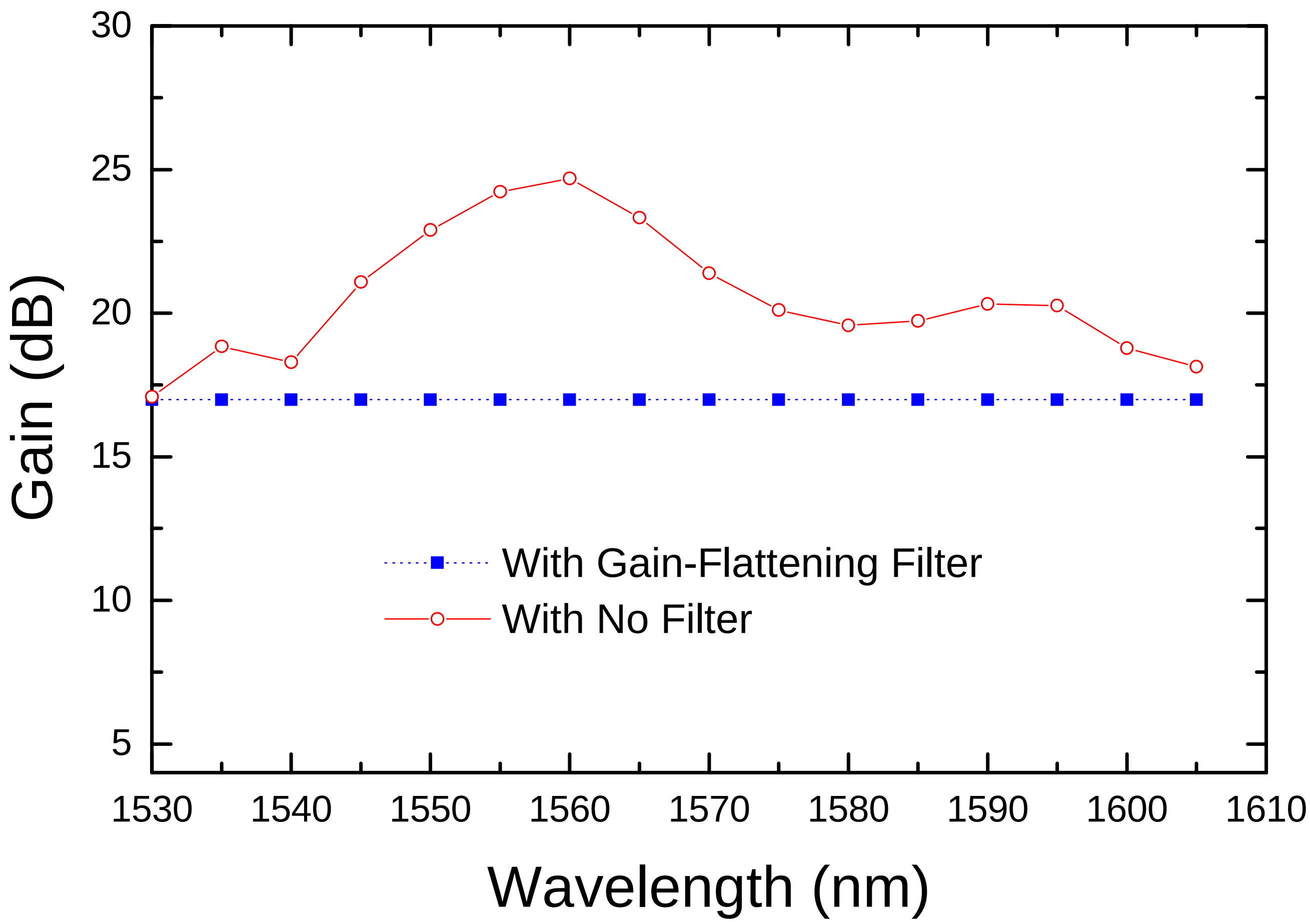
Spectra Observed Before and After the Filter



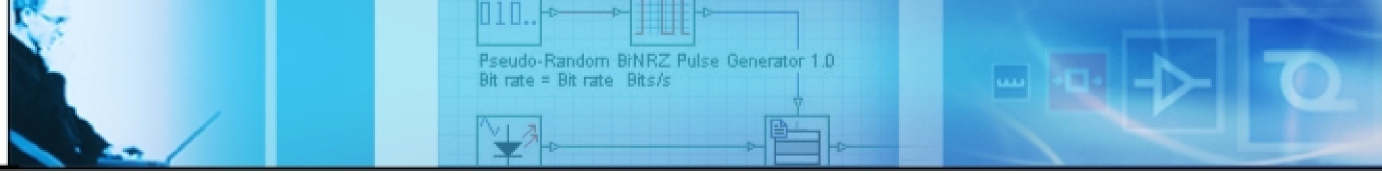
Filter Curve



Comparing Gain Results



Optiwave



Comments

- Hybrid amplifier was simulated using one EDF stage and two Raman amplifiers cascaded in series;
- C-Band and L-Band wavelength range;
- Qualitative results' analysis;
- Hybrid amplifier configuration was used as an in-line amplifier;
- Low gain variation (3.1 dB) was observed under strong input signal variation (– 30 dBm to –20 dBm);
- Gain bandwidth equal to 69 nm.

Conclusions

- Hybrid amplifiers simulations considered different amplifier configurations.
- Pump wavelength selection, EDFA and Raman specifications, and the configuration / combination of both amplifiers are critical in the design of hybrid amplifiers.
- Hybrid amplifiers compensate for the gain decay at longer signal wavelength.