# Troubleshooting fiber Bragg grating fabrication with modeling

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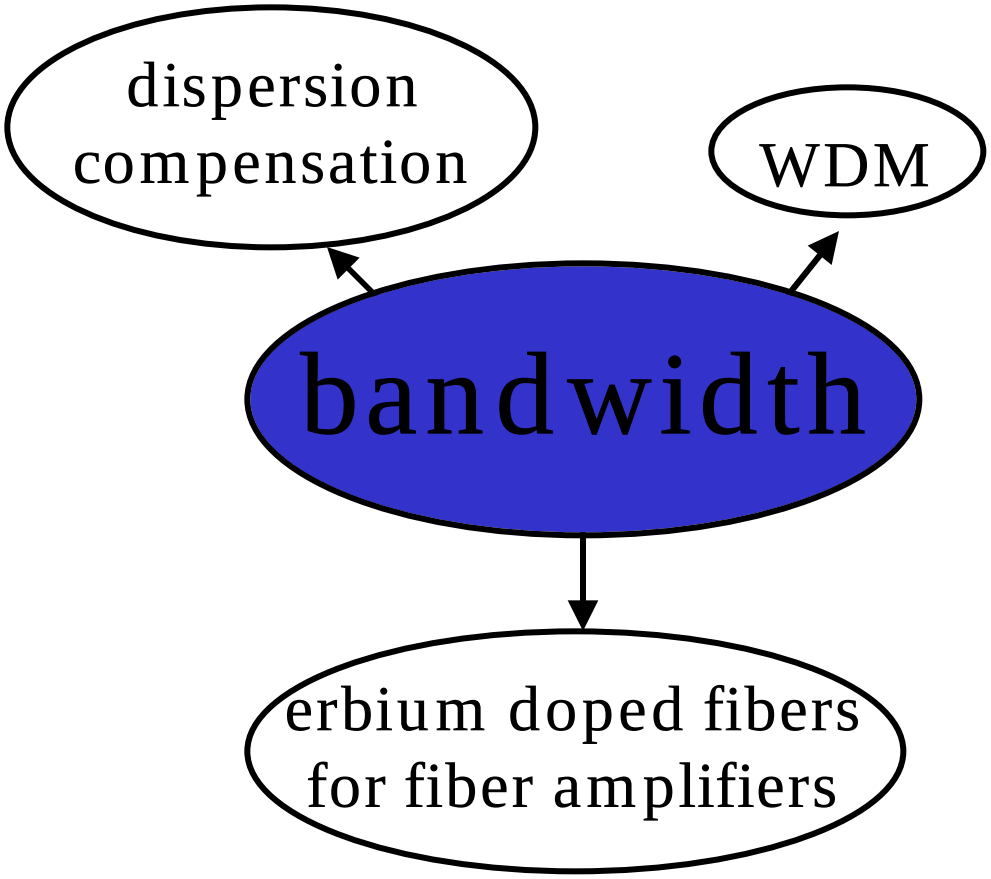
# Abstract

Several approaches are available for modeling fiber Bragg gratings, each having their own strengths and weaknesses. In this talk, we will discuss how different techniques for solving coupled mode theory equations can provide complementary information that is not easily attainable by using one technique alone. This work is particularly applicable to very long length fiber Bragg gratings.

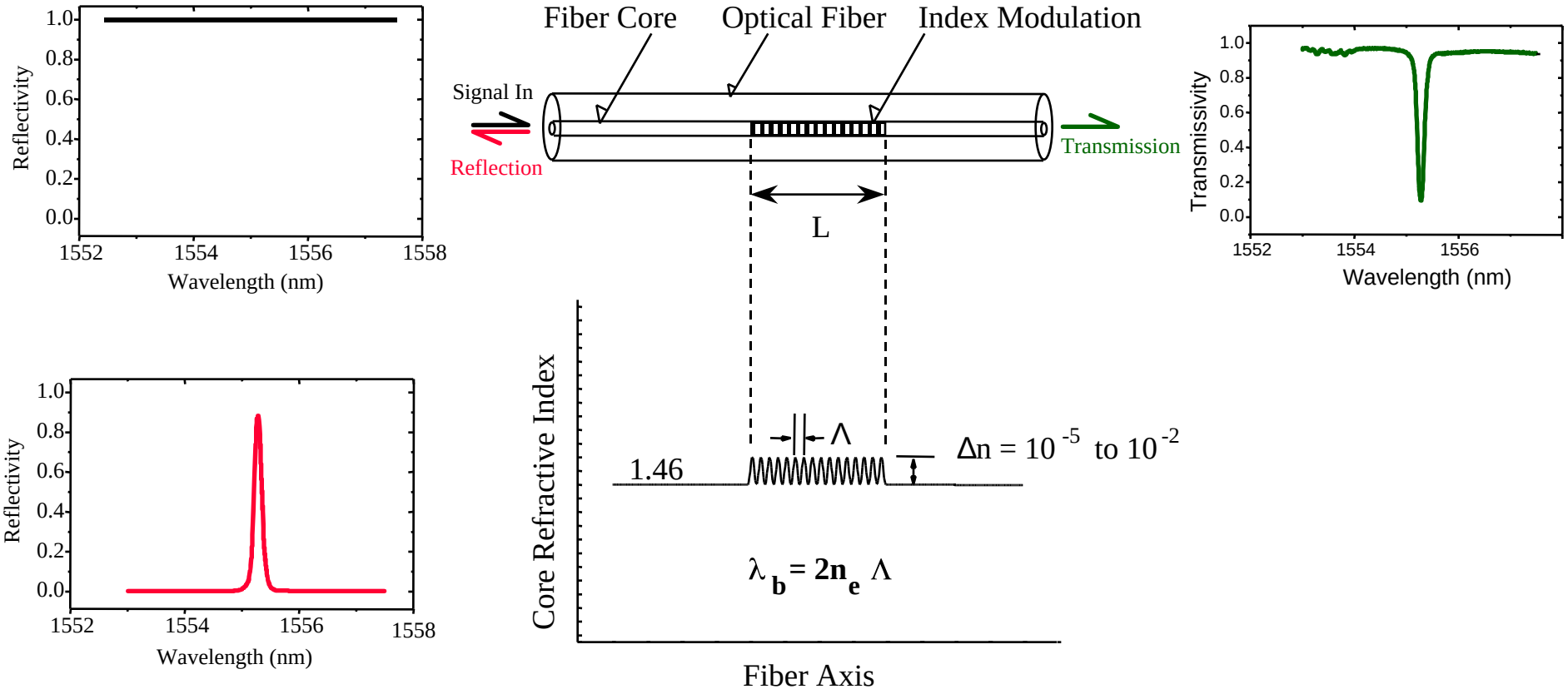
# Outline

- Motivation
- What is a fiber Bragg grating
- Reviewing chromatic dispersion
- FGB as dispersion compensator
- We made one and it does not look good
- Using modeling to understand why and to set fabrication tolerances
- Conclusion

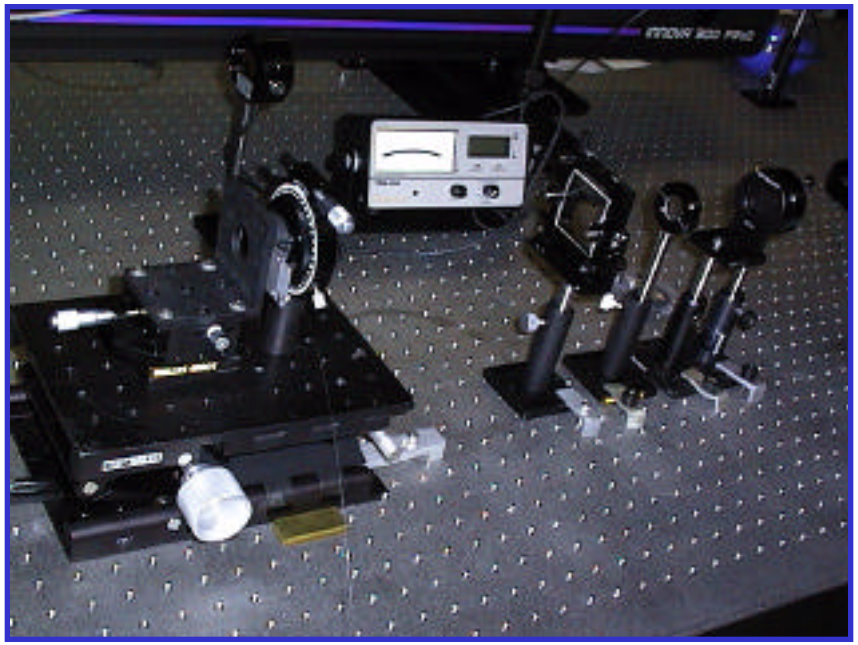
# Telecommunications has a bandwidth problem

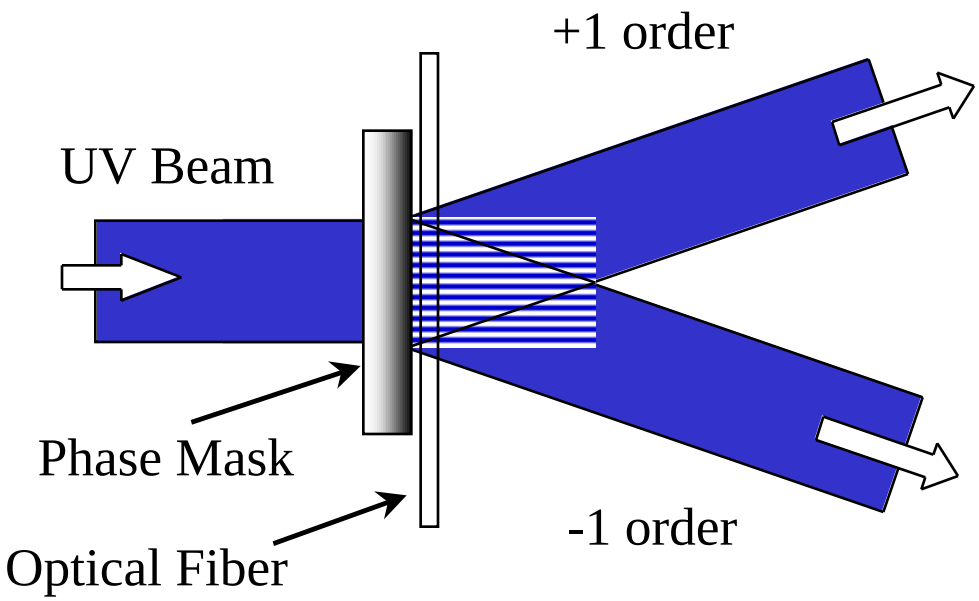


# Introduction



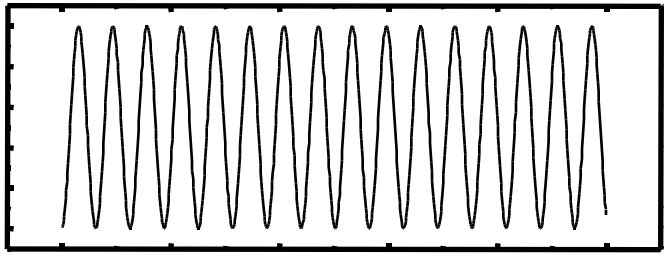
# Phase Mask: Direct Imprinting





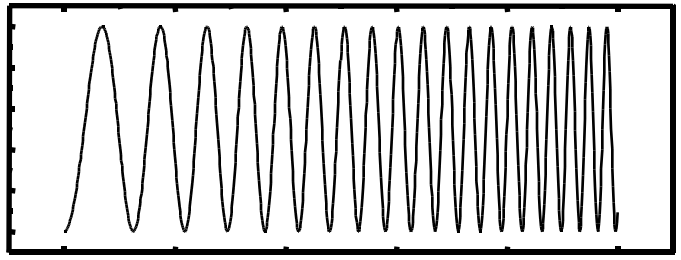
# Bragg Gratings:Basic Definitions

Δn



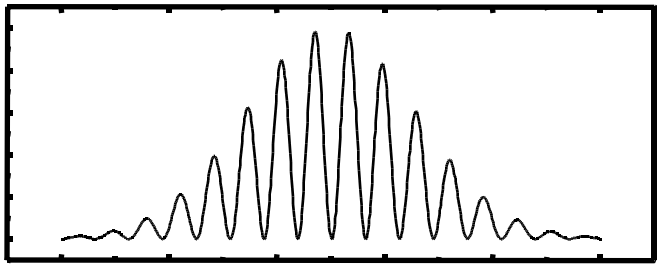
**Uniform Profile** : Uniform Bragg Grating Period (typical).

Δn



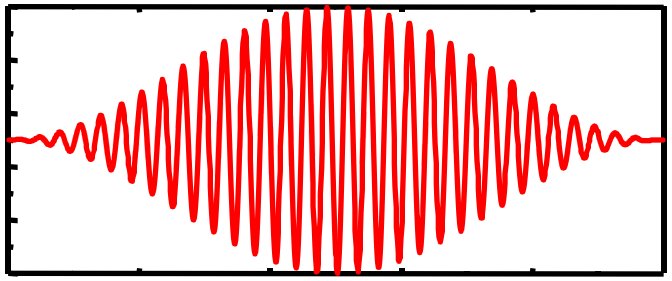
**Chirp** : Non-Uniform Bragg Grating Period.

Δn



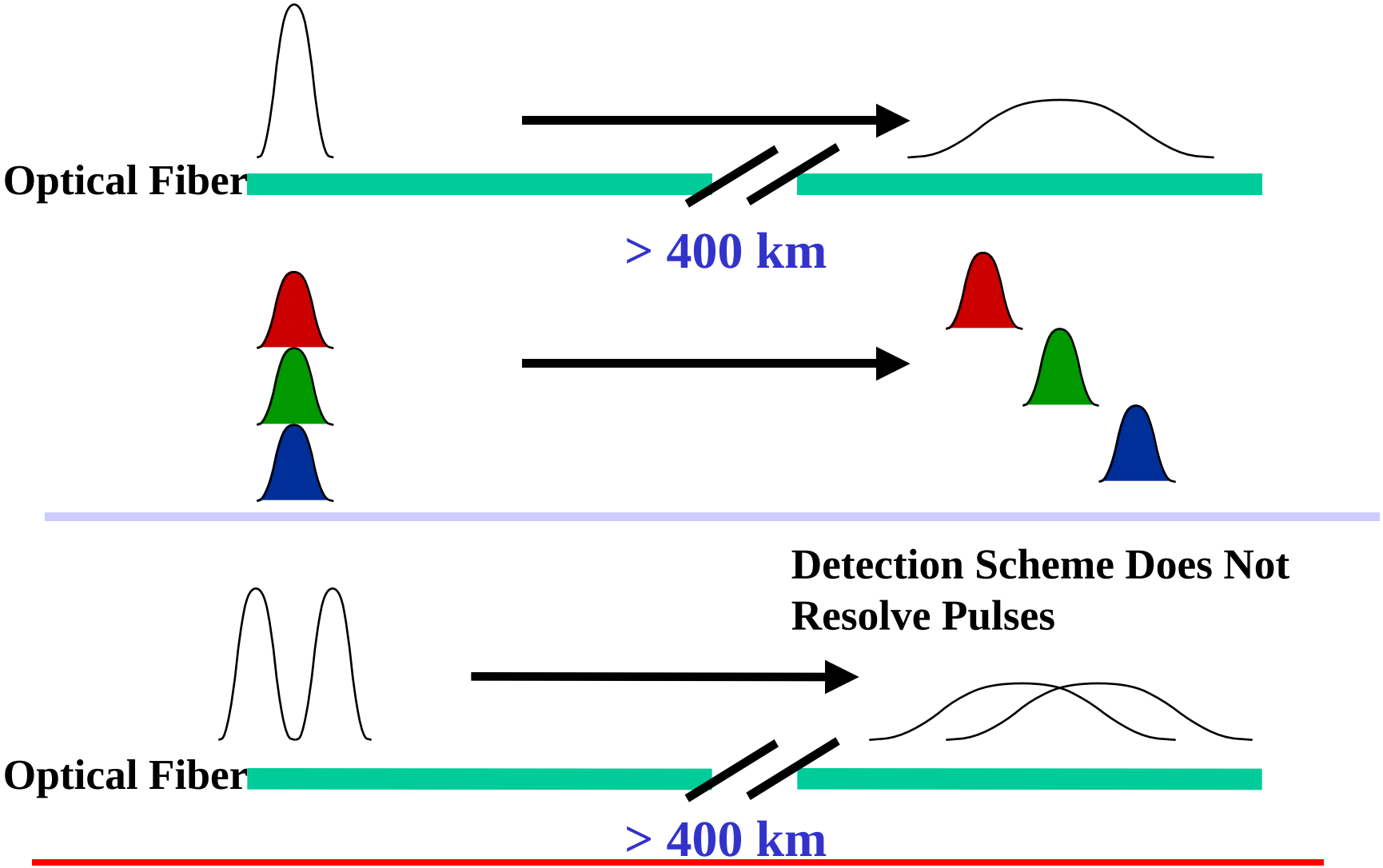
**Apodization** : Tailored Spatial Exposure.

Δn



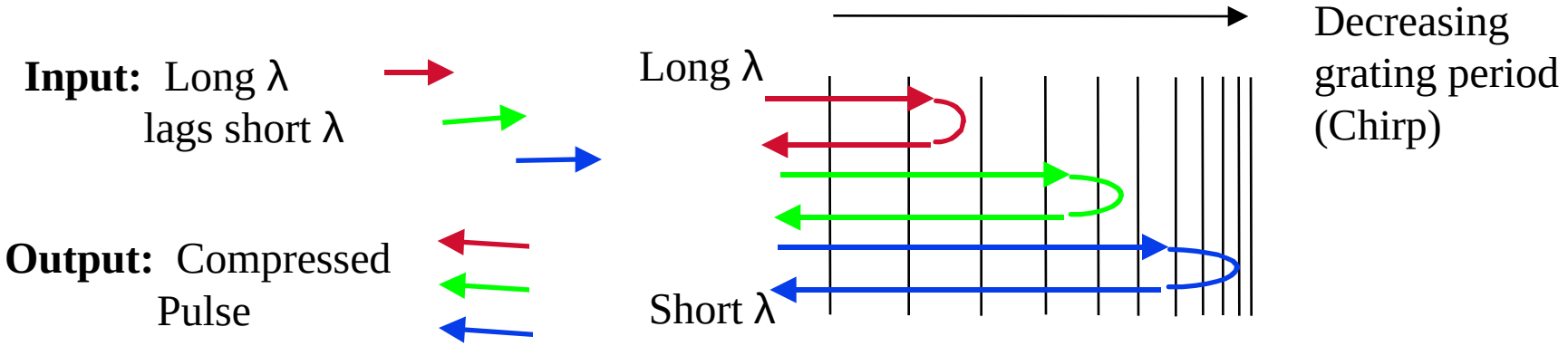
**Apodization** : Tailored Spatial Exposure.

# Chromatic Dispersion Problem

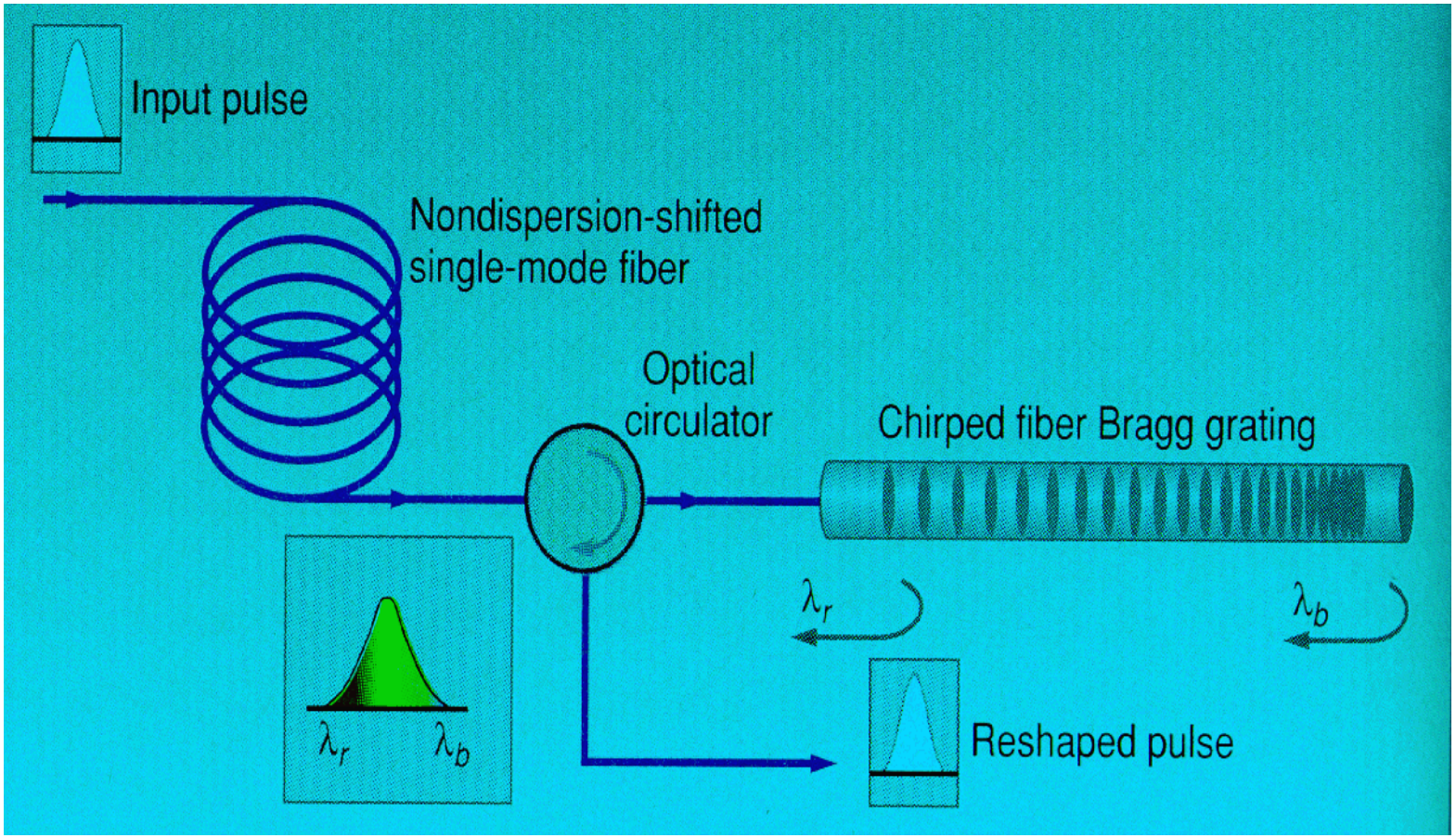


# Dispersion Compensation

- **The Problem**
  - Standard single-mode fiber has zero dispersion at the 1310nm transmission band. It is not corrected at the 1550nm band. Dispersion broadens optical pulses as they travel in single-mode fiber, limiting the ultimate data rate supported by fiber.
- **A Solution**
  - Recompress the optical pulses using chirped gratings.



# Fiber Bragg Grating Dispersion Compensator



# Dispersion Compensator Goal

- to compensate the large bandwidth $\Delta\lambda$ of erbium fiber amplifiers for long distances of fiber links $L_f$ with dispersion D (D=17ps/nm/km @ 1550 nm)

$$DL_f = \frac{2L_g n_{eff}}{c\Delta\lambda}$$

D - dispersion per unit length
$L_f$ - fiber link length
$L_g$ - grating length
$n_{eff}$ - effective index
c - speed of light
$\Delta\lambda$ - grating bandwidth

- For a 80 km link, need to compensate 1360 ps/nm
- For a bandwidth of 7 nm, need about 1 m granting

# Approach to FBG Spectrum Simulation: coupled-mode theory

•Good quantitative predictor of diffraction efficiency and spectral dependence of fiber gratings

Couple Mode amplitude equations

Where R and S are the forward and backward propagating modes, respectively, and σ and κ are coupling coefficients

# Some Solution Approaches

- **Direct numerical integration of coupled mode eqs.**
  - **advantage - can resolve effect of small scale fabrication errors**
  - **disadvantage - not fast**
- **Transfer matrix (piecewise-uniform approach)**
  - **advantage - reasonable simulation times for long gratings**
  - **disadvantage - smallest section must be about 50 periods in length**

# Main Modeling Parameters

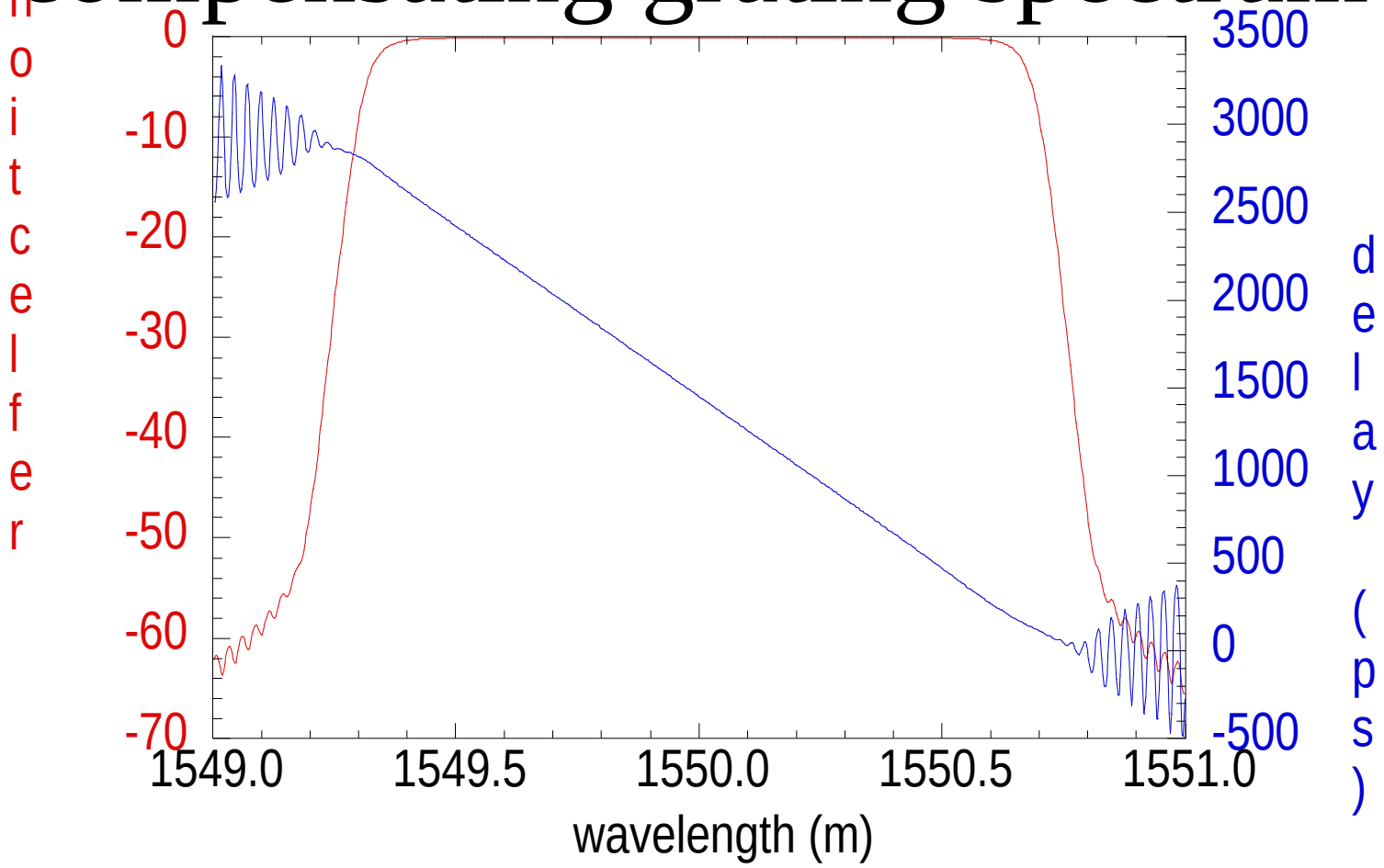
**Input**

- **fiber geometry (dimension, refractive indices,photosentivity)**
- **grating length**
- **central period**
- **chirp/bandwidth**
- **grating strength**
- **apodization**
- **phase shifts**

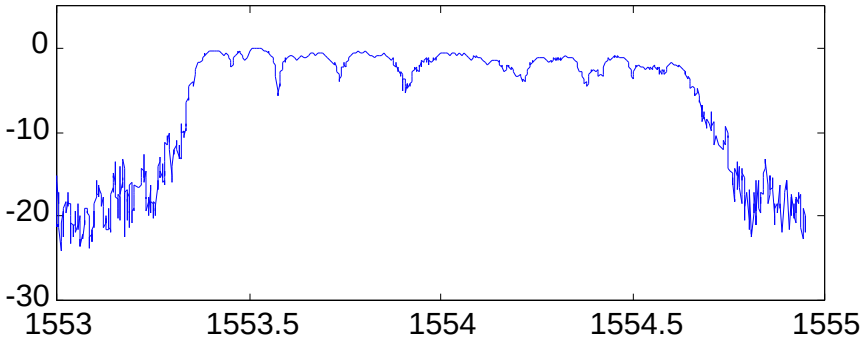
**Output**

- **reflection**
- **transmission**
- **delay (ripple factor)**
- **dispersion**

# What is an ideal dispersion compensating grating spectrum?

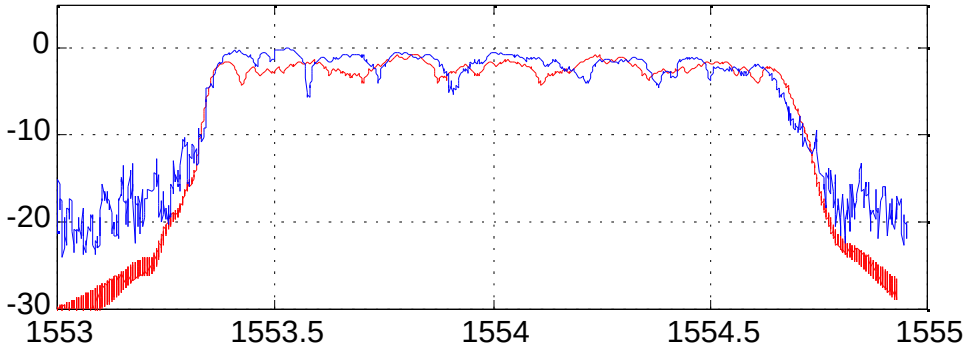


# Grating showing instability in fabrication process



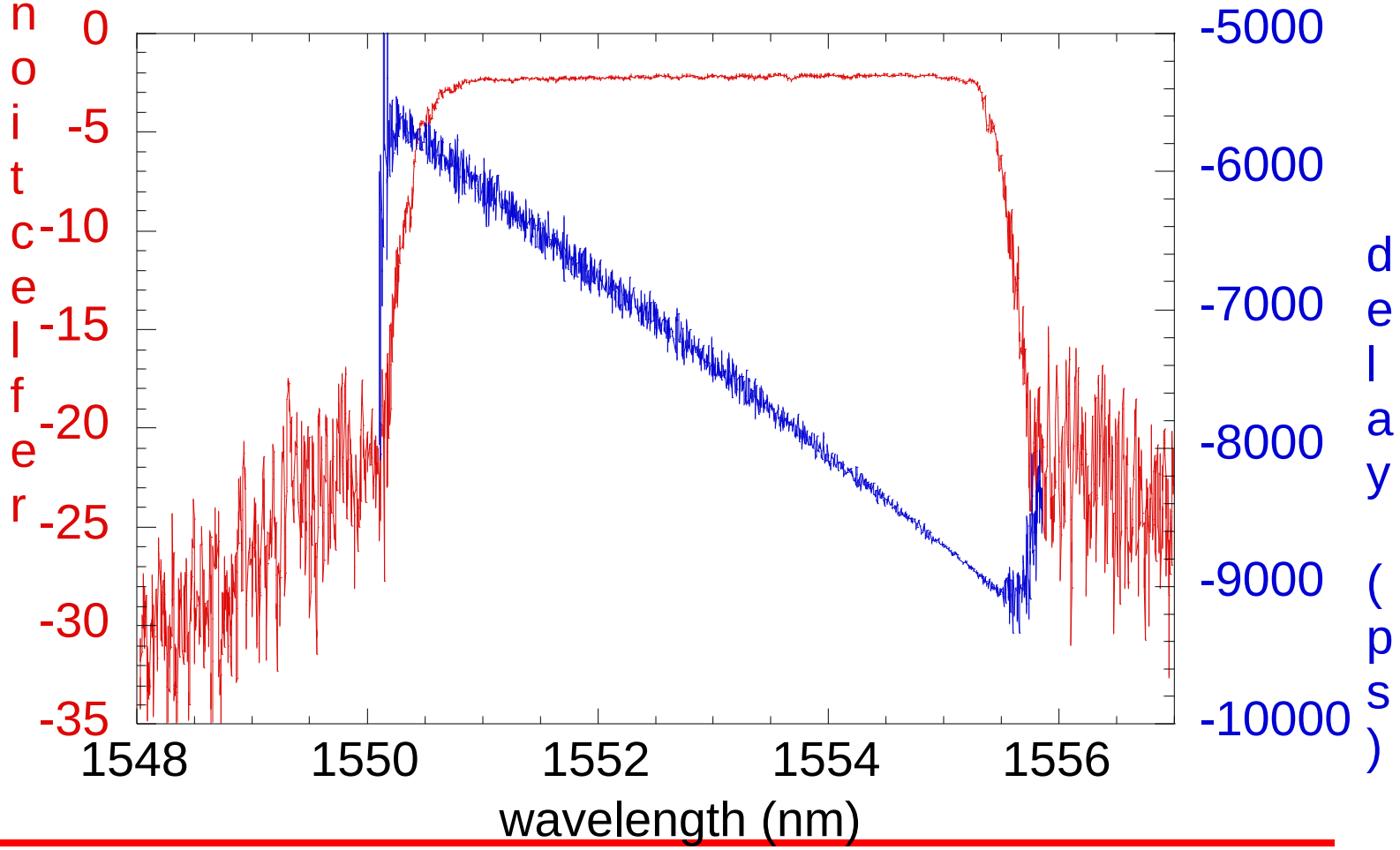
# Analysis Result
# direct numerical integration

Measurement in blue & Simulation in Red

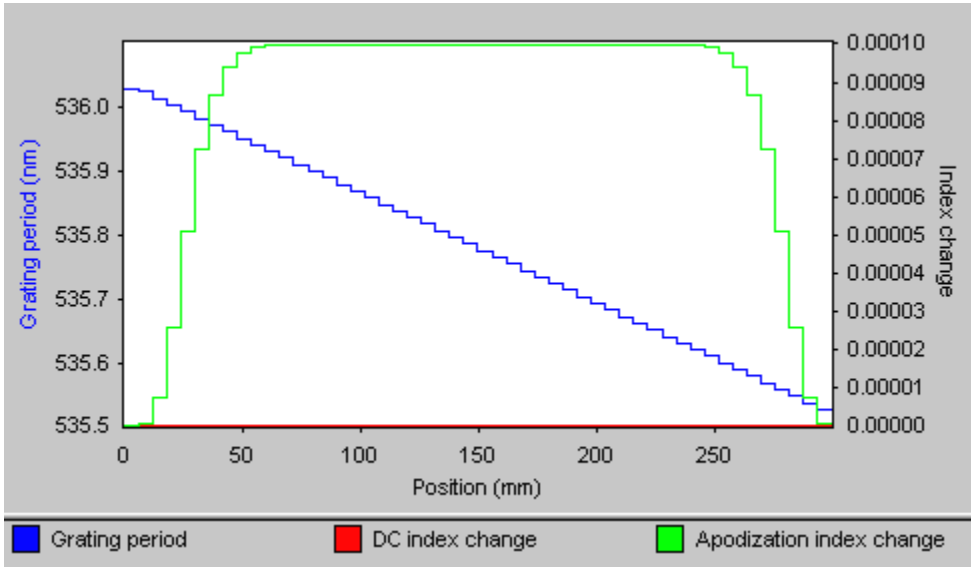


# Another fabricated DCG: why the fuzz?

deviation from linear delay is called delay ripple

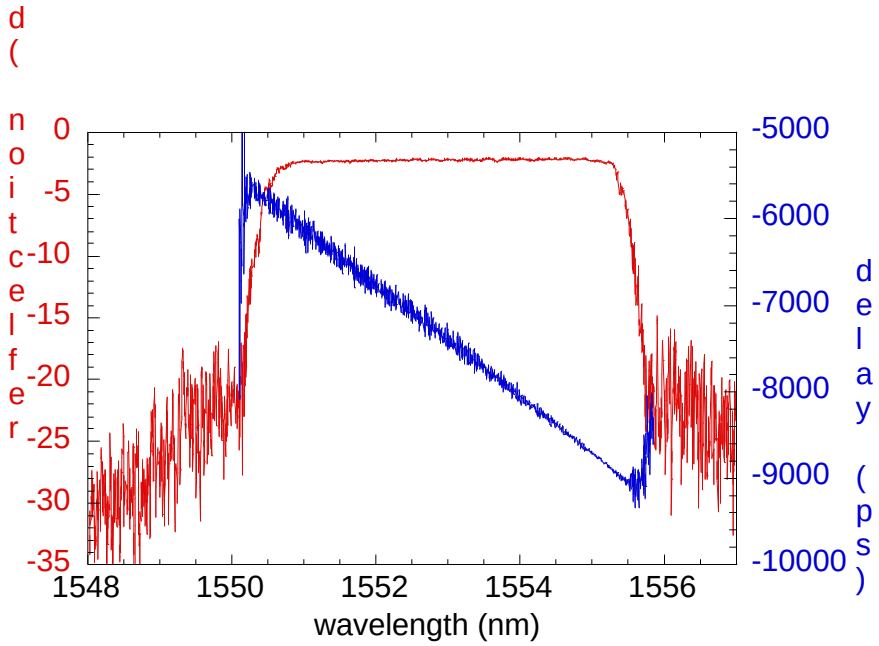


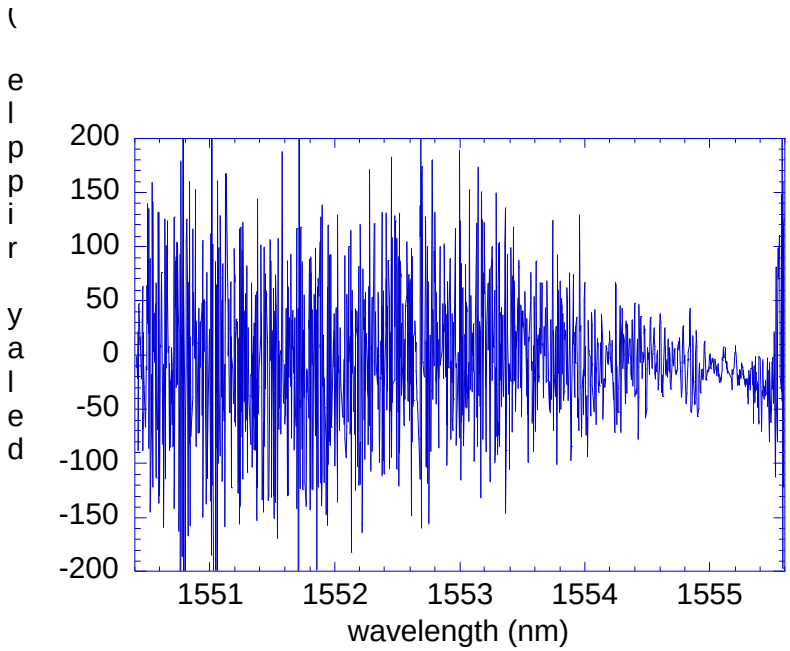
# Transfer Matrix piecewise-uniform approach




We imposed stochastic phase shifts and studied their effect on grating spectra as we varied their max. amplitude and their frequency along the grating.

# Figure of merit



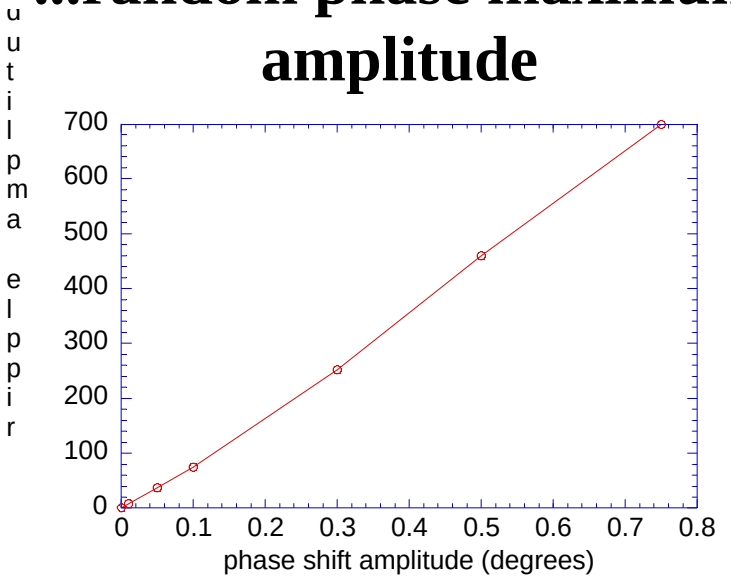




# Ripple standard deviation

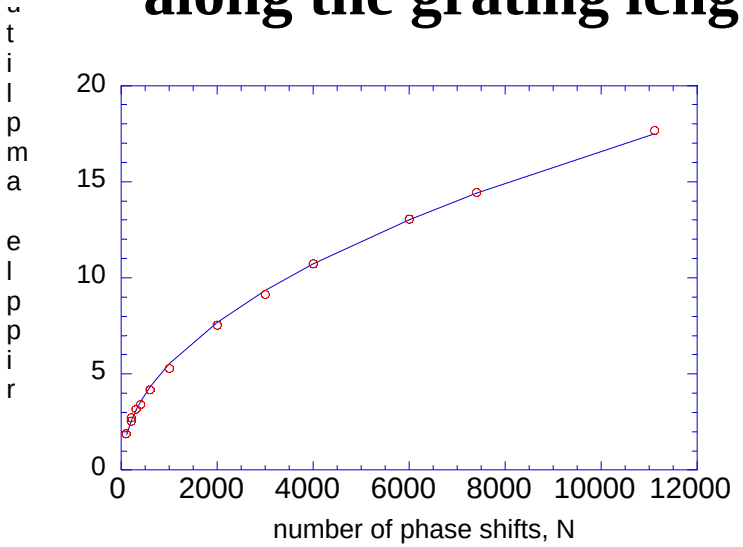
# Analysis Result
# transfer matrix approach

## Delay ripple amplitude as a function of...

**...random phase maximum amplitude**



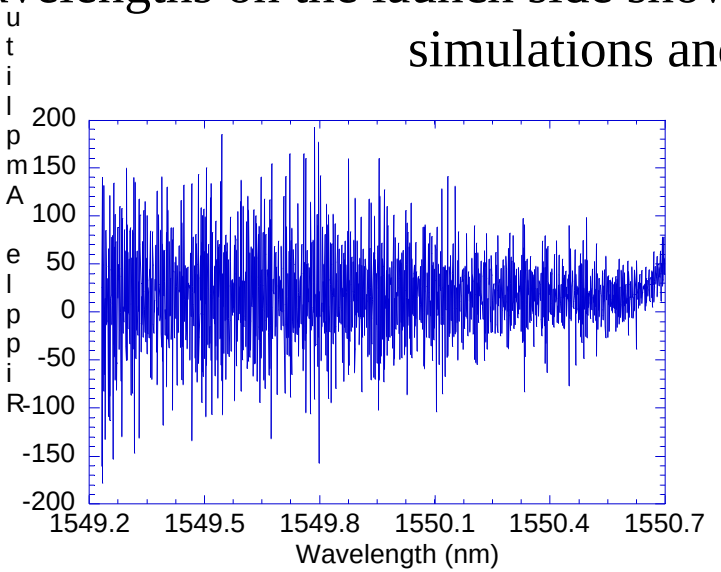

**... number of random phase shifts along the grating length**

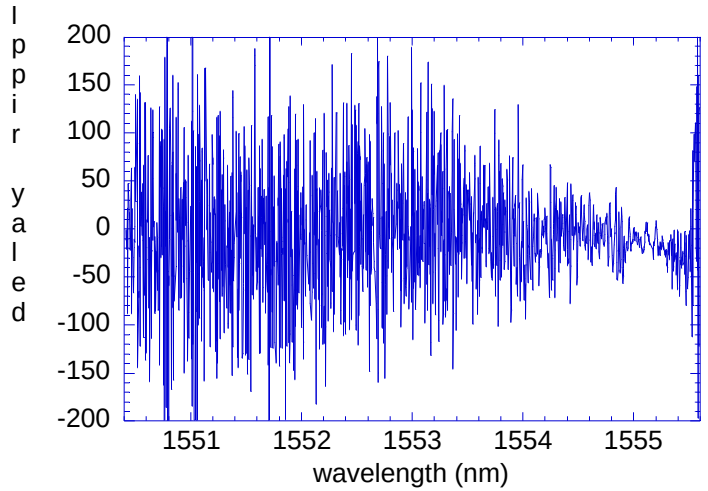



**The simulation results (circles) follow a power law relationship (line).**

# Delay ripple

Delay ripple for chirped FBG with periodic phase shifts across its length is shown below. The ripple increases with the optical path length through the grating. The wavelengths on the launch side show the least amount of ripple both in the simulations and measurements.




simulation: delay ripple across chirped FBG with light launched into long wavelength side

measurement: delay ripple across chirped FBG with light launched into long wavelength side.

# Conclusion

A variety of modeling & computational tools is needed to get the work done.