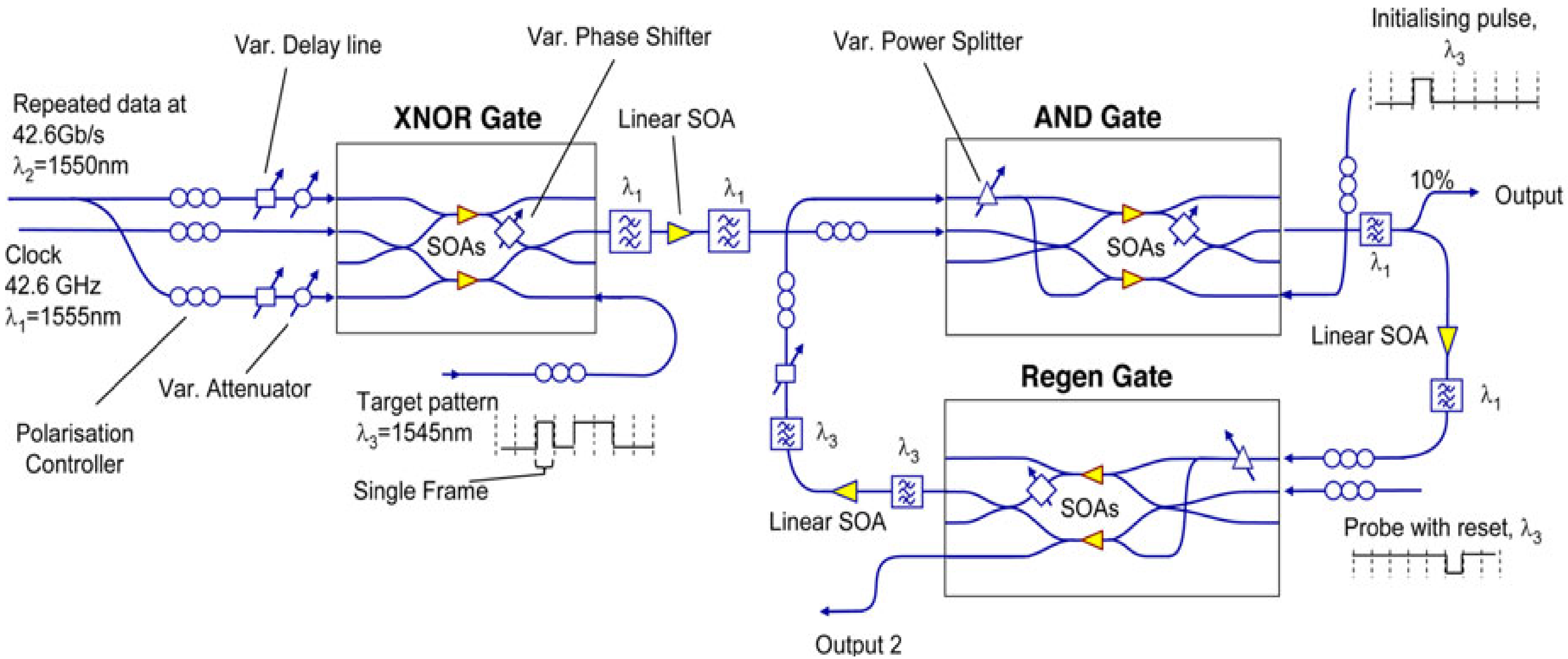
All-Optical Wavelength Conversion Using Four Wave Mixing

Speaker: Ying Tang

1/17/2020

Background

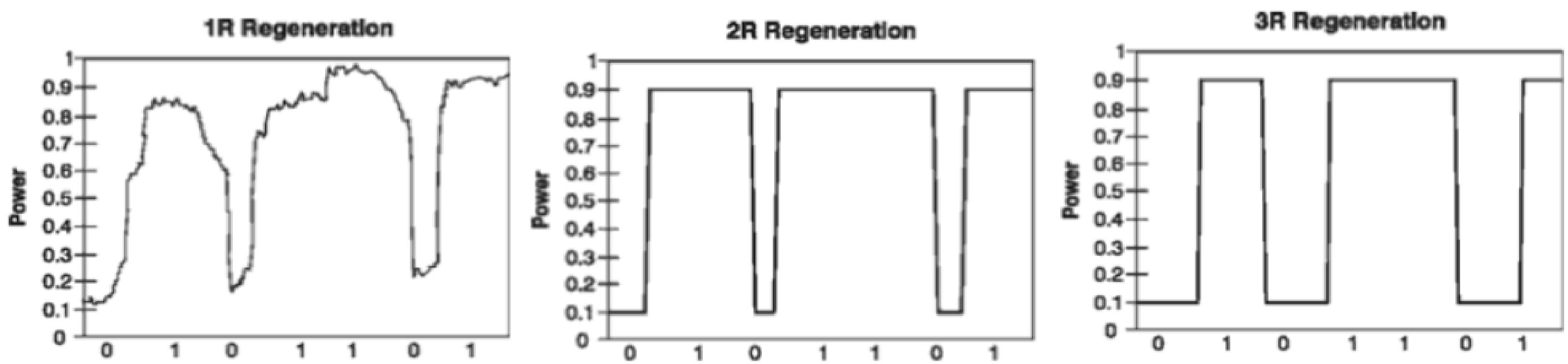


Experimental implementation of the optical pattern recognition system.

The feedback loop includes a regenerator to reverse the wavelength conversion necessarily caused by the type of AND gate used in the experimental demonstration.

Background

- There are three different levels of regeneration:
  - 1R regeneration: re-amplification.
  - 2R regeneration: re-amplification and re-shaping.
  - 3R regeneration: re-amplification re-shaping and re-timing.
- All-optical 2R regenerator can be achieved by:
  - Self-phase modulation (SPM)
  - Cross-phase modulation (XPM)
  - **Four Wave Mixing (FWM)**



1R/2R/3R regeneration.

Theory of FWM

The origin of FWM lies in the nonlinear response of bound electrons of a material to an electromagnetic field.

$$P_{NL} = \varepsilon_0 \chi^{(3)} \vdots EEE$$

where E is the electric field and P_{NL} is the induced nonlinear polarization.

Consider four CW waves oscillating at frequencies ω_1, ω_2, ω_3, and ω_4 and linearly polarized along the same axis x. The total electric field can be written as

$$E = \sum_{j=1}^{4} E^{(\omega_j)} \frac{1}{2} \hat{x} \sum_{j=1}^{4} E_j \exp\left[i\left(\beta_j z - \omega_j t \right) \right] + c.c.$$

where the propagation constant $\beta_j = \tilde{n}_j \omega_j / c$, $\tilde{n}_j$ being the mode index.

Theory of FWM

If we express P_{NL} in the same form as E using

$$P_{NL} = \frac{1}{2}\hat{x}\sum_{j=1}^{4} P_j \exp\left[i\left(\beta_j z - \omega_j t\right)\right] + c.c.$$

P_j (j = 1-4) consists of a large number of terms involving the products of three electric fields. For example, P_4 can be expressed as

$$P_4 = \frac{3\varepsilon_0}{4}\chi^{(3)}\begin{bmatrix} \left|E_4\right|^2 E_4 + 2\left(\left|E_1\right|^2 + \left|E_2\right|^2 + \left|E_3\right|^2\right)E_4 \\ +2E_1E_2E_3\exp\left(i\theta_+\right) + 2E_1E_2E_3^*\exp\left(i\theta_-\right) + \ldots \end{bmatrix}$$

where θ_+ and θ_- are defined as

$$\theta_+ = \left(\beta_1 + \beta_2 + \beta_3 - \beta_4\right)z - \left(\omega_1 + \omega_2 + \omega_3 - \omega_4\right)t$$

$$\theta_- = \left(\beta_1 + \beta_2 - \beta_3 - \beta_4\right)z - \left(\omega_1 + \omega_2 - \omega_3 - \omega_4\right)t$$

Theory of FWM

FWM occurs when photons from one or more waves are annihilated and new photons are created at different frequencies such that the net energy and momentum are conserved during the parametric interaction.

- θ_+: $\omega_4 = \omega_1 + \omega_2 + \omega_3$, which is responsible for the phenomena such as third-harmonic generation ($\omega 1 = \omega 2 = \omega 3$).
- θ_-: $\omega_3 + \omega_4 = \omega_1 + \omega_2$, in which phase-matching $\Delta k = \beta_3 + \beta_4 - \beta_1 - \beta_2 = 0$ is required.

There are two cases in FWM:

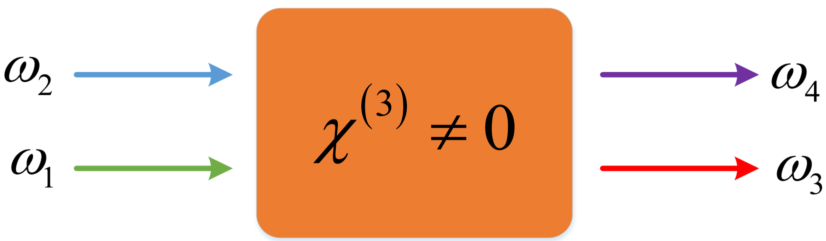
Case 1: non-degenerate four-wave mixing where four frequency components are different.

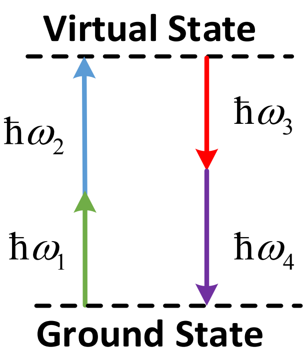
Case 2: degenerate four-wave mixing where two of the four frequencies coincide.

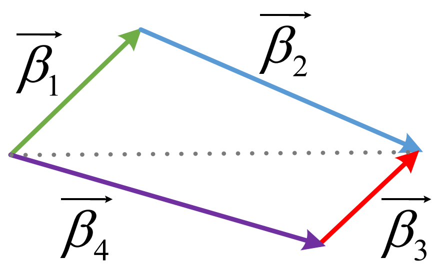
Theory of FWM

Degenerate FWM

$$\omega_1 + \omega_2 = \omega_3 + \omega_4$$





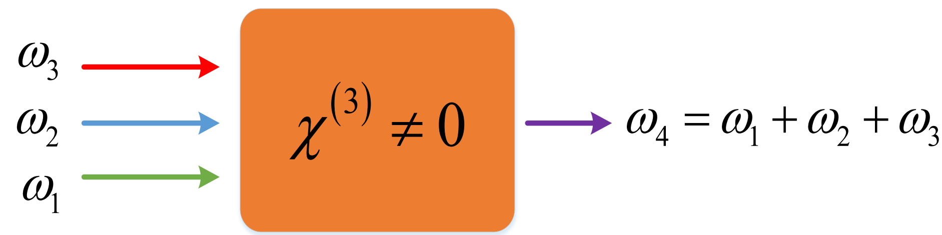


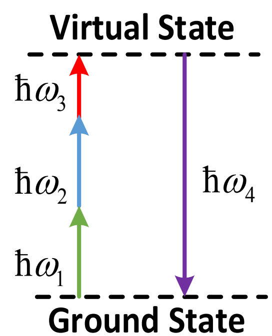
Momentum conservation

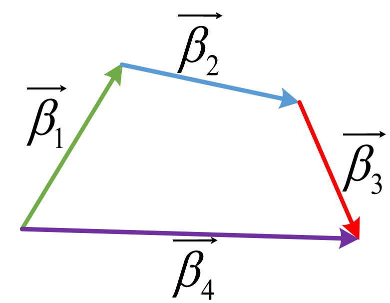
$$P_{NL} = \varepsilon_0 \chi^{(3)} \left(E^{(\omega_1)} + E^{(\omega_2)} \right)^3$$

Non-degenerate FWM

$$\omega_4 = \pm\omega_1 \pm \omega_2 \pm \omega_3 \ \left(\omega_1 \neq \omega_2 \neq \omega_3 \right)$$







Momentum conservation

$$P_{NL} = \varepsilon_0 \chi^{(3)} \left(E^{(\omega_1)} + E^{(\omega_2)} + E^{(\omega_3)} \right)^3$$

Theory of FWM

The evolution of the amplitude $A_j(z)$ inside an optical fiber is governed by the following set of four coupled equations:

$$\frac{dA_1}{dz} = i\gamma\left[\left(\left|A_1\right|^2 + 2\sum_{k\neq 1}\left|A_k\right|^2\right)A_1 + 2A_2^* A_3 A_4 e^{i\Delta kz}\right]$$

$$\frac{dA_2}{dz} = i\gamma\left[\left(\left|A_2\right|^2 + 2\sum_{k\neq 2}\left|A_k\right|^2\right)A_2 + 2A_1^* A_3 A_4 e^{i\Delta kz}\right]$$

$$\frac{dA_3}{dz} = i\gamma\left[\left(\left|A_3\right|^2 + 2\sum_{k\neq 3}\left|A_k\right|^2\right)A_3 + 2A_1 A_2 A_4^* e^{-i\Delta kz}\right]$$

$$\frac{dA_4}{dz} = i\gamma\left[\left(\left|A_4\right|^2 + 2\sum_{k\neq 4}\left|A_k\right|^2\right)A_4 + 2A_1 A_2 A_3^* e^{-i\Delta kz}\right]$$

where $\Delta k = \beta_3 + \beta_4 - \beta_1 - \beta_2$, and γ is the nonlinear coefficient.

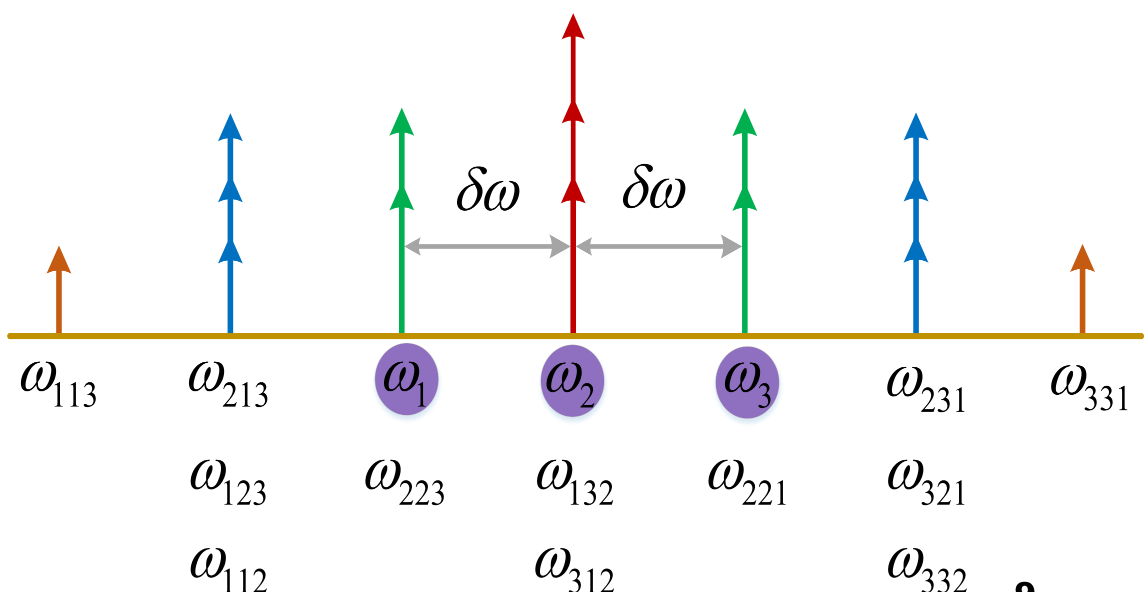
Cross talk frequency

Depending on the individual frequencies, this beat signal may lie very close to the individual input frequencies, resulting in significant cross talk to that channel.

$$\omega_{ijk} = \omega_i + \omega_j - \omega_k \quad (i \neq k, j \neq k)$$

$$\left.\begin{matrix} \omega_{112} & \omega_{221} & \omega_{331} \\ \omega_{113} & \omega_{223} & \omega_{332} \end{matrix}\right| (i \neq k, j \neq k)$$

$$\left.\begin{matrix} \omega_{123} & \omega_{231} & \omega_{312} \\ \omega_{132} & \omega_{213} & \omega_{321} \end{matrix}\right| (i \neq j \neq k)$$

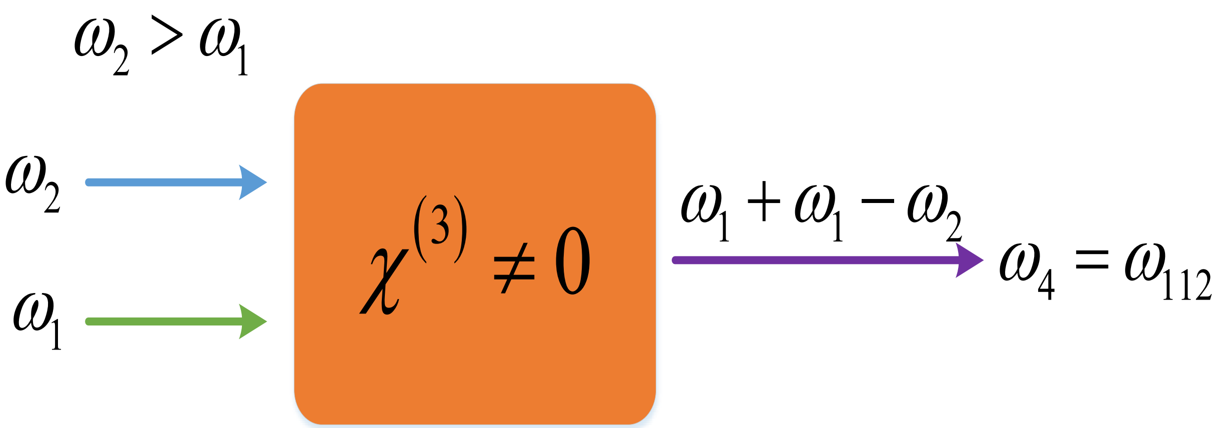


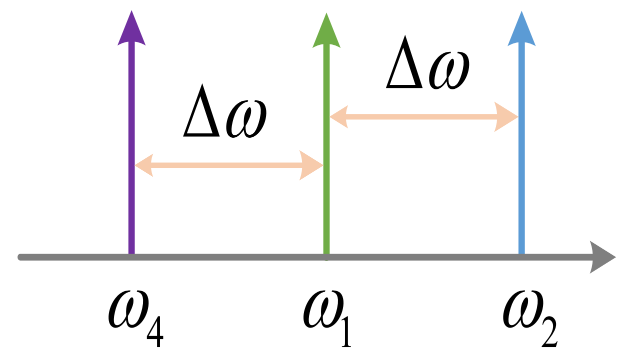
$$\omega_{132} = \omega_1 + \omega_3 - \omega_2 = \omega_1 + \delta\omega = \omega_2$$

$$\omega_{223} = \omega_2 + \omega_2 - \omega_3 = \omega_2 - \delta\omega = \omega_1$$

$$\omega_{221} = \omega_2 + \omega_2 - \omega_1 = \omega_2 + \delta\omega = \omega_3$$

Excitation of cross-talk frequency





Phase matching condition:

$$\omega_4 = \omega_1 + \omega_1 - \omega_2$$

$$\omega_4 - \omega_1 = \omega_1 - \omega_2 = \Delta\omega$$

$$\Delta k = \beta_4 - \left(2\beta_1 - \beta_2\right) = 0$$

$$\Delta k = \beta\left(\omega_4\right) - 2\beta\left(\omega_1\right) + \beta_2\left(\omega_2\right)$$

$$\Delta k = \beta\left(\omega_1 - \Delta\omega\right) - 2\beta\left(\omega_1\right) + \beta_2\left(\omega_1 + \Delta\omega\right)$$

Excitation of cross-talk frequency

Phase matching condition:

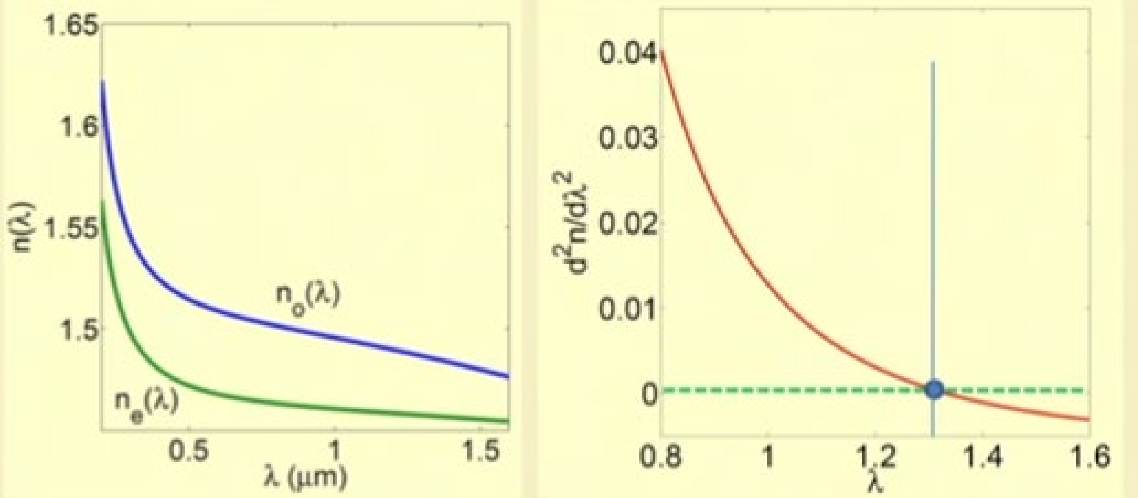
$$\Delta k = \beta(\omega_1 - \Delta\omega) - 2\beta(\omega_1) + \beta_2(\omega_1 + \Delta\omega)$$

$$\approx \beta(\omega_1) + \Delta\omega \frac{d\beta}{d\omega}\bigg|_{\omega_1} + \frac{\Delta\omega^2}{2}\frac{d^2\beta}{d\omega^2}\bigg|_{\omega_1} - 2\beta(\omega_1) + \beta(\omega_1) - \Delta\omega\frac{d\beta}{d\omega}\bigg|_{\omega_1} + \frac{\Delta\omega^2}{2}\frac{d^2\beta}{d\omega^2}\bigg|_{\omega_1}$$

$$\approx \Delta\omega^2 \frac{d^2\beta}{d\omega^2}\bigg|_{\omega_1}$$

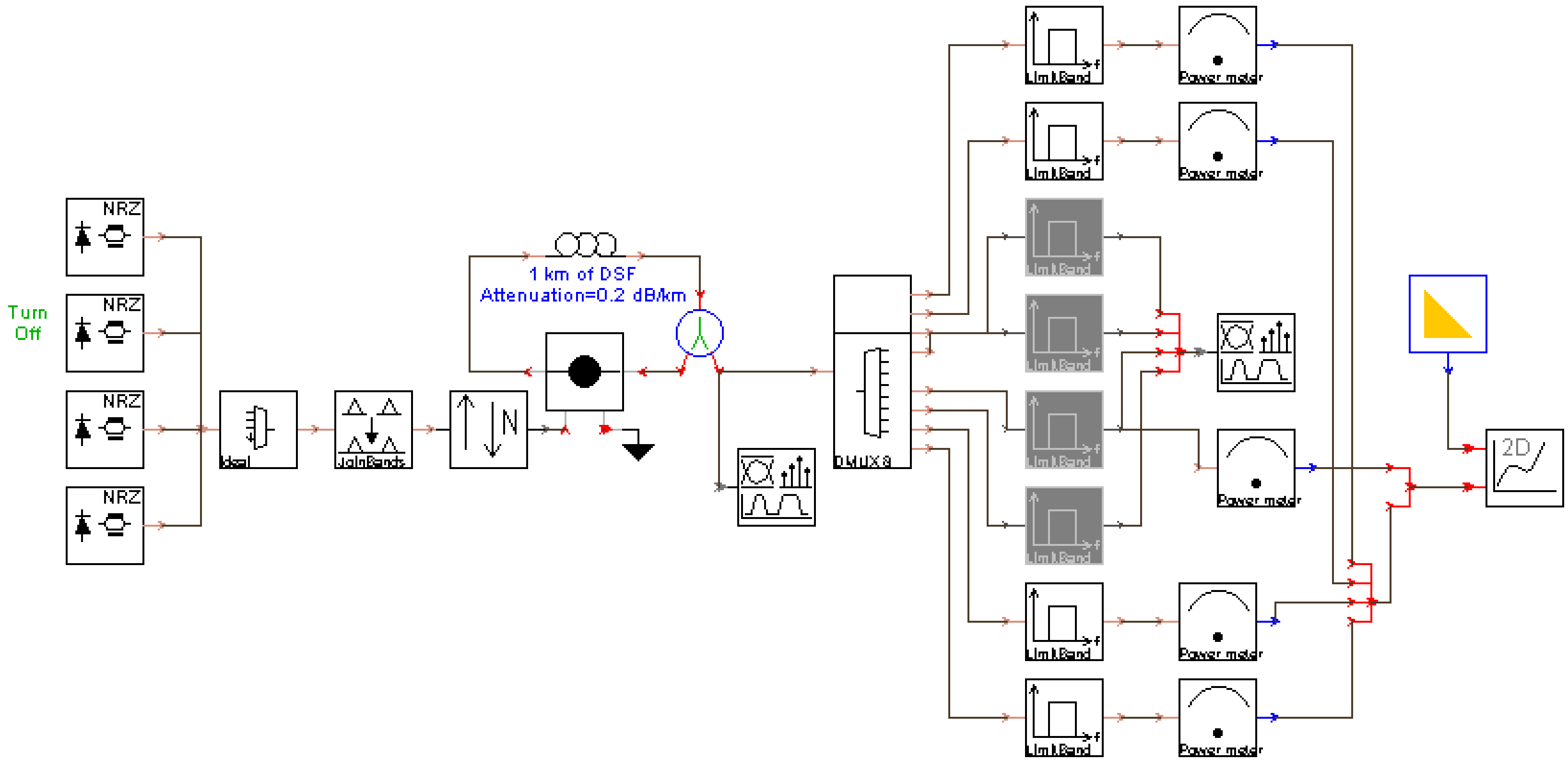
$$\frac{d^2\beta}{d\omega^2} = \frac{\lambda^3}{2\pi c^2}\frac{d^2 n(\lambda)}{d\lambda^2}$$

$$\Delta k = 0 \rightarrow \frac{d^2\beta}{d\omega^2} = 0 \rightarrow \frac{d^2 n(\lambda)}{d\lambda^2} = 0$$



Zero dispersion wavelength

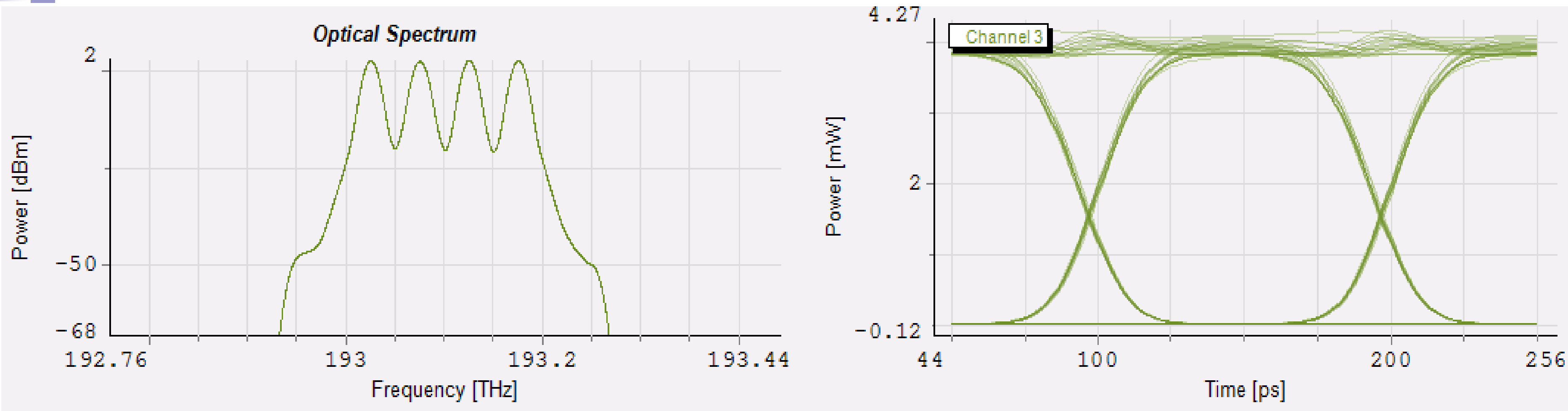
Simulation setup



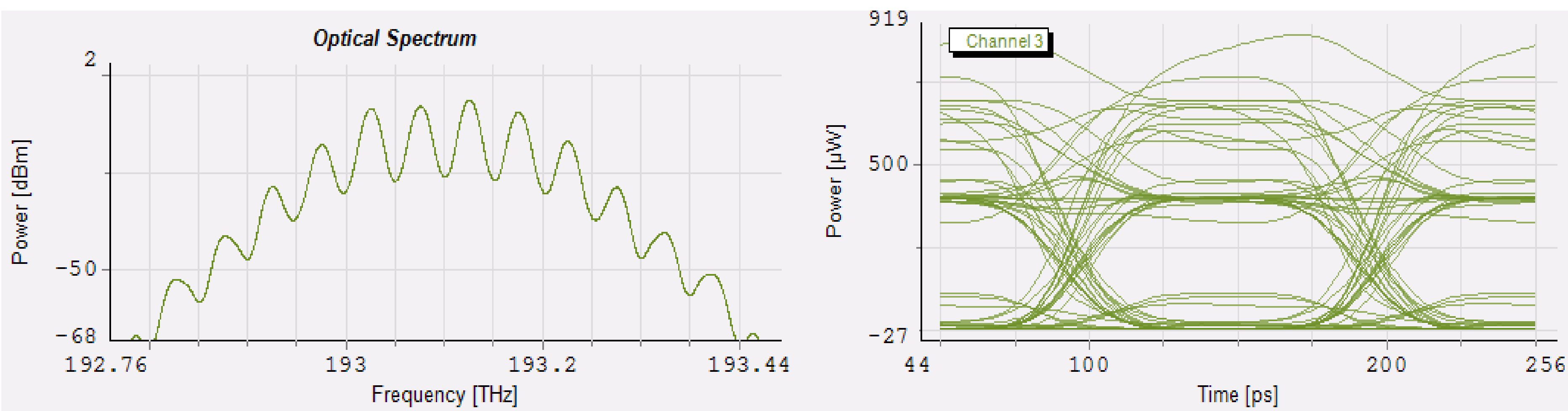
Growth of Four-Wave Mixing along a fiber

4 x 10 Gbit/s WDM transmission system over Dispersion Shifted Fiber (DSF), demonstrating the power levels of FWM products along the fiber.

Result 1



Signals before the fiber



Signals after the fiber

Result 2

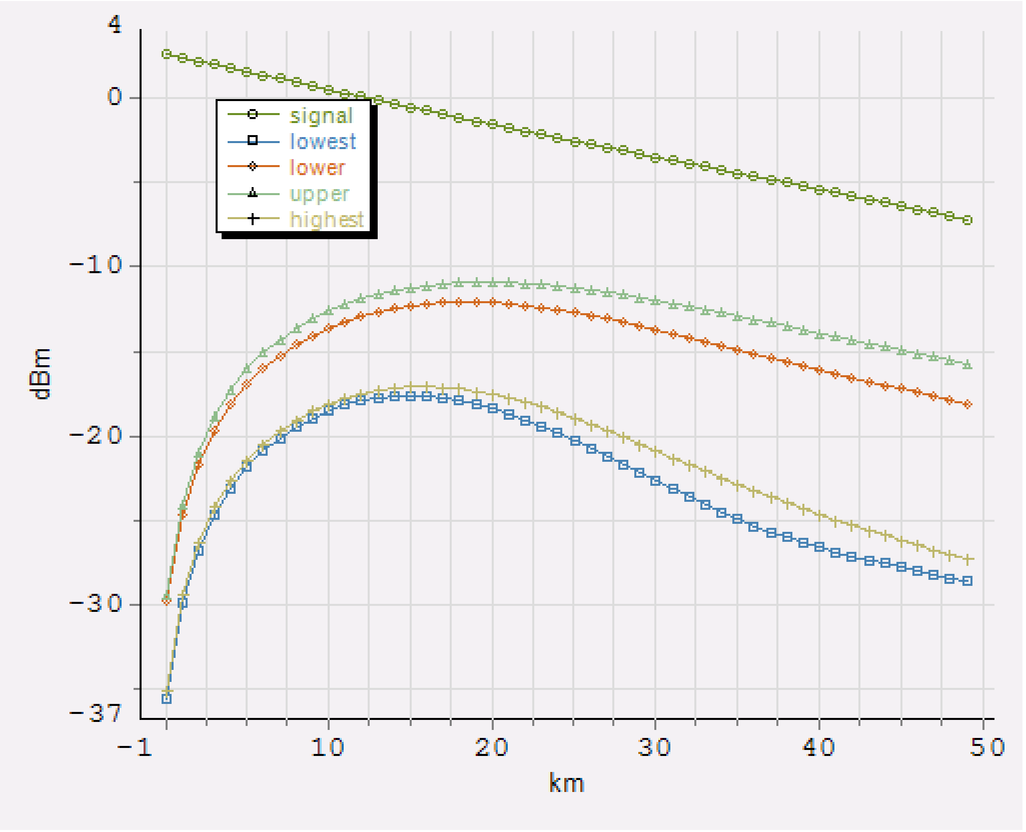
$$P_{idler}(z) = P_{signal}(0)\left(1+\kappa^2/4g^2\right)\sinh^2(gz)$$

$$\kappa = \Delta k + 2\gamma P_{signal}$$

$$g = \sqrt{\left(\gamma P_{signal}\right)^2 - (\kappa/2)^2}$$

$$\sinh(x) = \frac{e^x - e^{-x}}{2} = -i\sin(ix)$$

The power of idler increases as z^2 initially, but grow exponentially after a distance such that $gz > 1$. Then, it decreases due to attenuation.

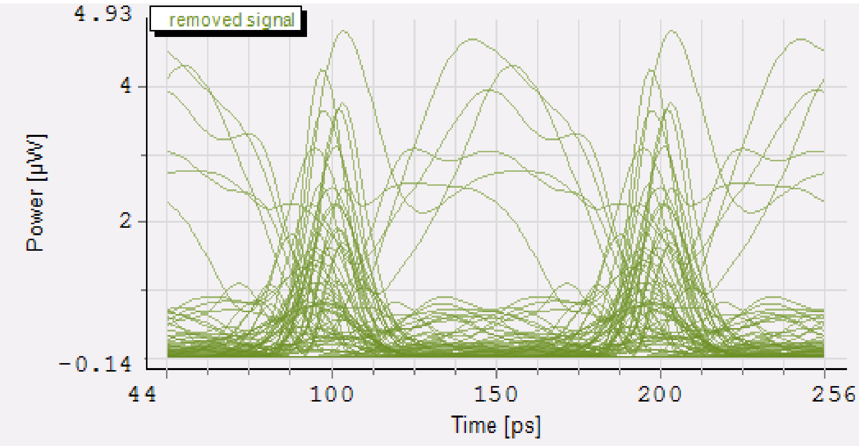


FWM products with desired signal

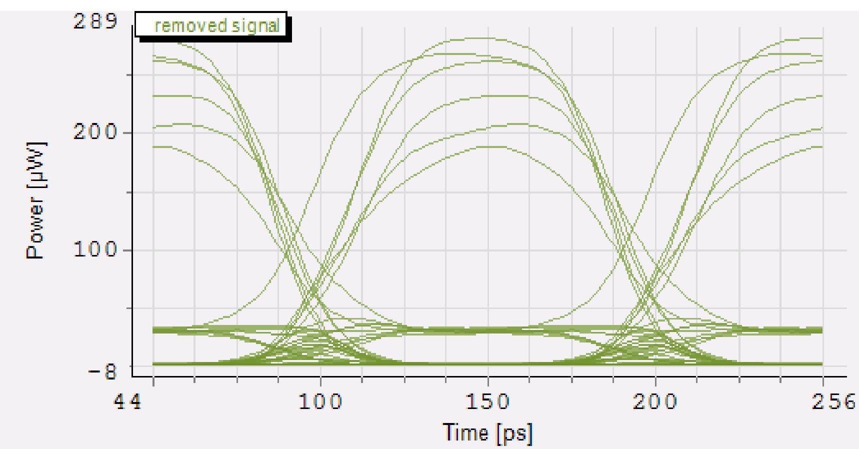
Beijing University of Posts and Telecommunications

UC Davis Computer Science

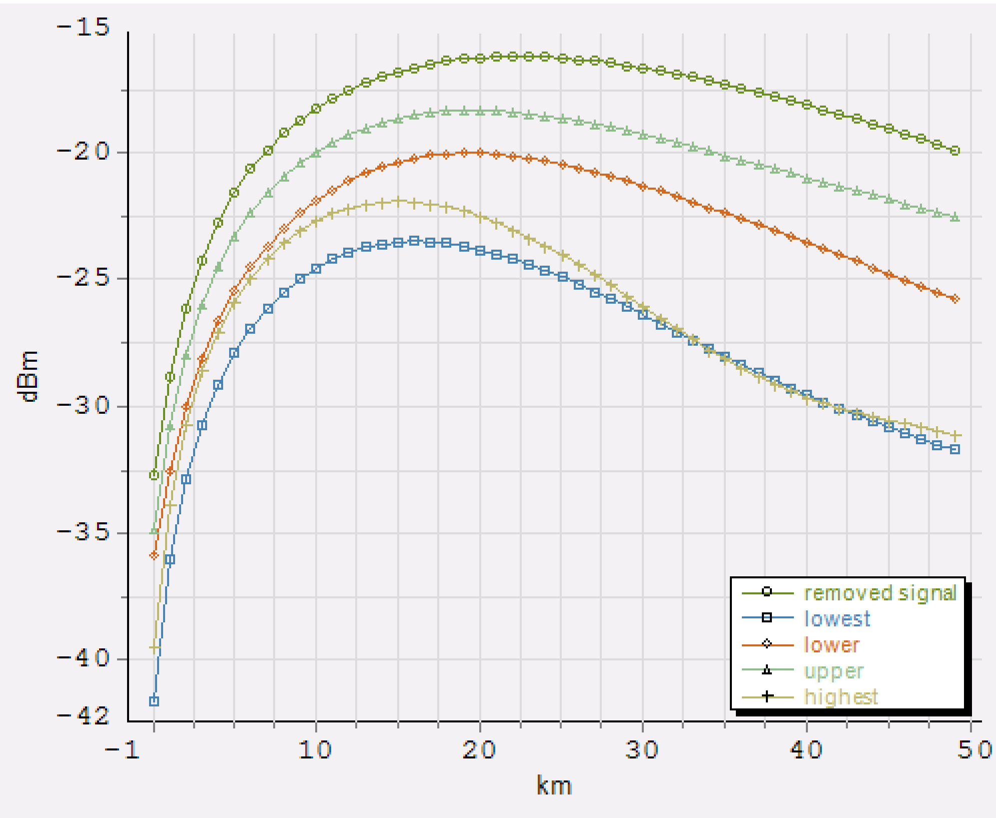
Result 3



Signals before the fiber



Signals after the fiber



FWM products with removed signal

北京邮電大學 BEIJING UNIVERSITY OF POSTS AND TELECOMMUNICATIONS

UCDAVIS COMPUTER SCIENCE

Conclusions & future works

Conclusions:

- The concept of FWM. It is an intermodulation phenomenon between two or three wavelengths produce new wavelengths.
- The problem caused by cross-talk frequency in WDM system
- In order generate the cross-talk frequency efficiently, phase matching condition must be satisfied.

Future works:

- Complete the re-shaping function of regenerator with improved OSNR.
- Apply all completed components to the architecture of WISDOM.

Thanks!

Speaker: Ying Tang

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