北京郵電大學
BEIJING UNIVERSITY OF POSTS AND TELECOMMUNICATIONS

UC DAVIS COMPUTER SCIENCE

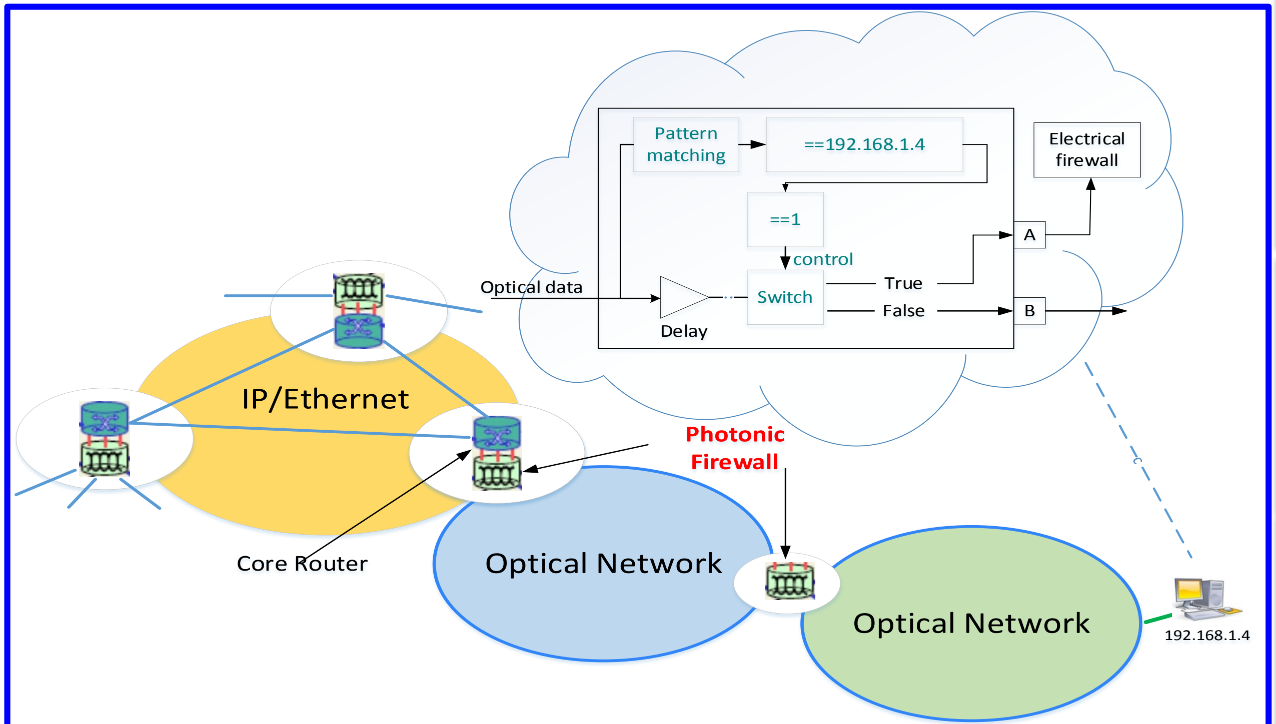
Spectral Broadening induced by XPM in HNLF

Speaker: Ying Tang

11/22/2019

Photonic Firewall

Photonic firewall: It leverages the all-optical pattern matching to directly identify the signals in the optical domain. It can distinguish hidden network intrusions and attacks, and finally selects corresponding defense means according to the set security policy.



Basic principle of photonic firewall

Main application:
1. Gateway node
2. Core node
3. Access node

Basic process:
1. Splitting
2. Pattern matching
3. Safe handling

Types of target:
1. IP address
2. Port number
3. Specific sequence
4. …

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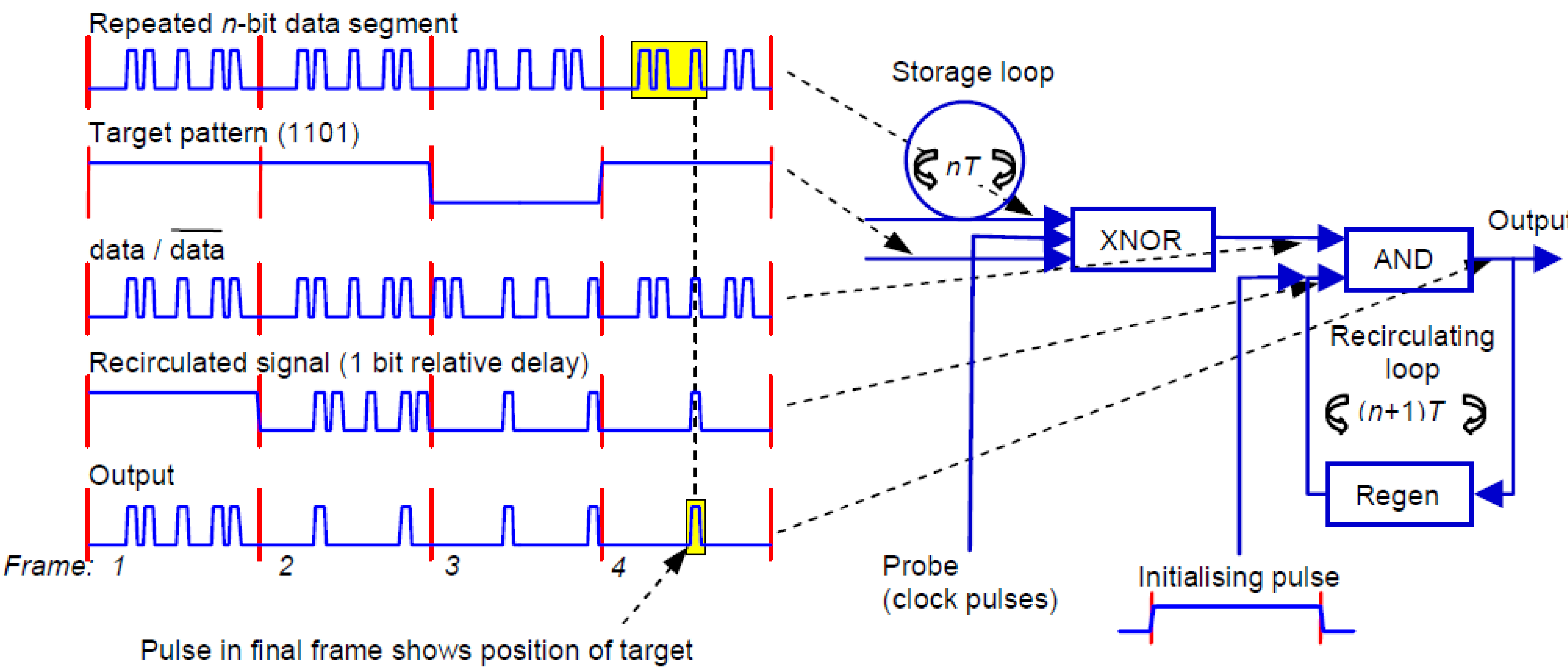
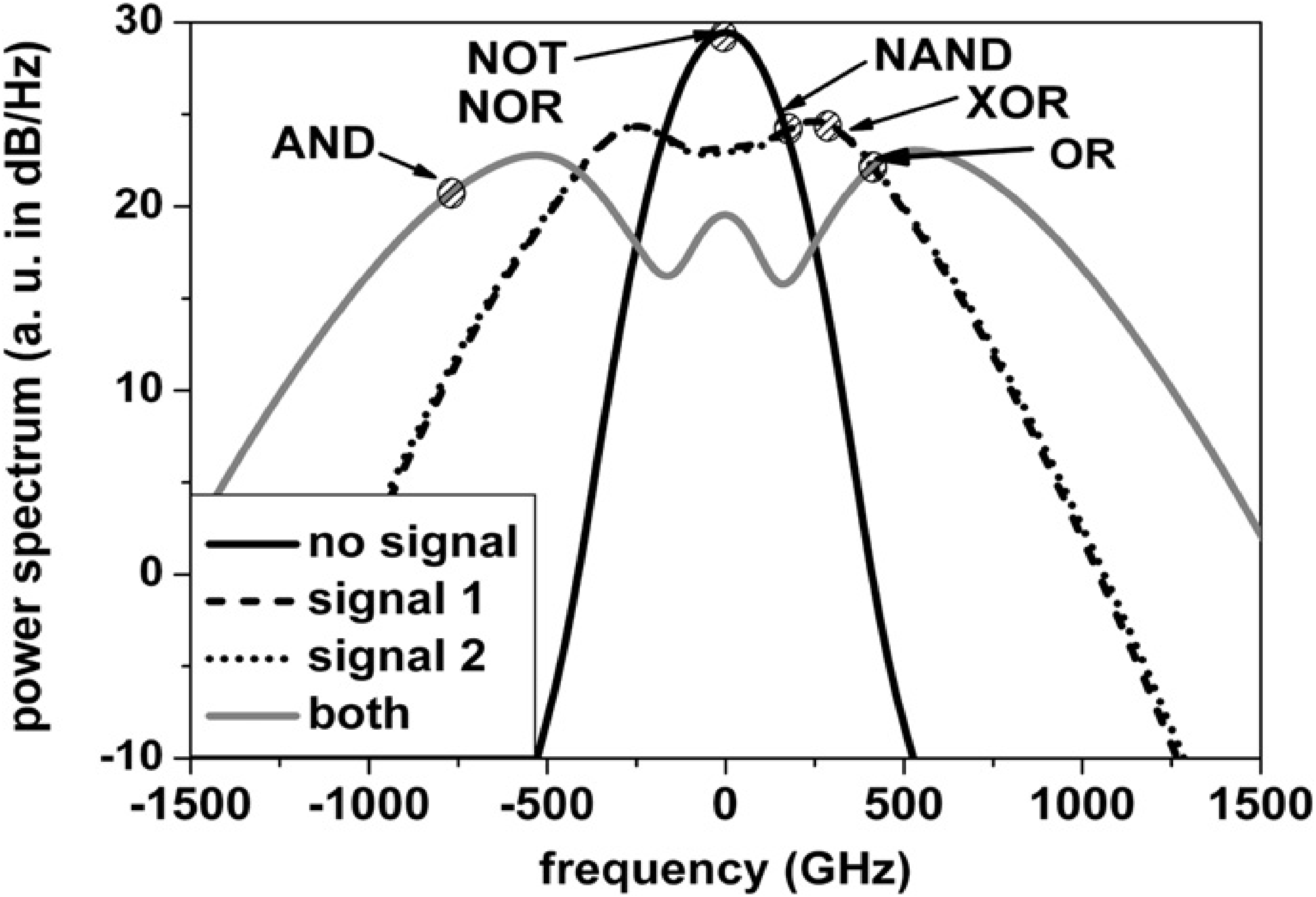
Compositions of Photonic Firewall



The key optical parts of the system are an XNOR gate and a recirculating AND gate loop. In project WISDOM, both are separately demonstrated at 42.6 Gbps using hybrid-integrated SOA-MZIs.

Logic Gates achieved with HNLF



Pantelis Velanas, Adonis Bogris, Dimitris Syvridis, "Operation properties of a reconfigurable photonic logic gate based on cross phase modulation in highly nonlinear fibers," *Opt. Fiber Technol.*, vol. 15, no. 1, pp. 65–73, Jan. 2009.

Fiber Nonlinearities

The response of any dielectric to light becomes nonlinear for intense electromagnetic fields, and optical fibers are no exception. As a result, the total polarization ***P*** induced by electric dipoles is not linear in the electric field ***E***, but satisfies the more general relation

$$P = \varepsilon_0\left(\chi^{(1)} \cdot E + \chi^{(2)}: EE + \chi^{(3)} \vdots EE + \cdots\right)$$

Where ε_0 is the vacuum permittivity and $\chi^{(j)}$ is *j*th order susceptibility. In general, $\chi^{(j)}$ is a tensor of rank *j* + 1.

Cross-phase modulation (XPM): It refers to the nonlinear phase shift of an optical field induced by another field having a different wavelength, direction, or state of polarization.

$$\phi_{NL} = n_2 k_0 L(\underbrace{|E_1|^2}_{\text{SPM}} + \underbrace{2|E_2|^2}_{\text{XPM}})$$

Spectral Effects

Considering the spectral change occurring as a result of XPM interaction between two co-propagating pulses with non-overlapping spectra.

$$\frac{\partial A_1}{\partial z} + \frac{i\beta_{21}}{2}\frac{\partial^2 A_1}{\partial T^2} = i\gamma_1(|A_1|^2 + 2|A_2|^2)A_1$$

$$\frac{\partial A_2}{\partial z} + d\frac{\partial A_2}{\partial T} + \frac{i\beta_{22}}{2}\frac{\partial^2 A_2}{\partial T^2} = i\gamma_2(|A_2|^2 + 2|A_1|^2)A_2$$

where

$$T = t - \frac{z}{v_{g1}}, \qquad d = \frac{v_{g1} - v_{g2}}{v_{g1}v_{g2}}$$

A_j is the slowly varying amplitude. Time T is measured in a reference frame moving with the pulse traveling at speed v_{g1}. The parameter *d* is a measure of group-velocity mismatch between the two pulses.

Spectral Effects

Using the width T_0 of the first pulse at the wavelength λ_1 as a reference, the walk-off length L_W and the dispersion length L_D are induced as

$$L_W = T_0/|d|, \qquad L_D = {T_0}^2/|\beta_{21}|$$

Case 1: Fiber length $L \ll L_D$ and $L \ll L_W$, the dispersive effects can be neglected.

Case 2: Fiber length $L \ll L_D$ and $L > L_W$, even though pulse shape does not change, the spectrum is affected drastically.

Case 3: Fiber length $L > L_D$ and $L > L_W$, XPM can affect both the pulse shape and the spectrum.

Asymmetric Spectral Broadening

Consider the simple case $L \ll L_D$ and $L > L_W$, as the pulse shapes do not change in the absence of GVD, A_j can be solved analytically. The general solution at $z = L$ is given by

$$A_1(L,T) = A_1(0,T)e^{i\phi_1}, \quad A_2(L,T) = A_2(0,T-dL)e^{i\phi_2}$$

where the nonlinear phase shifts are time-dependent.

As an illustration, consider the case of two unchirped Gaussian pulses of the same width T_0 with the initial amplitudes

$$A_1(0,T) = \sqrt{P_1}\exp\left(-\frac{T^2}{2{T_0}^2}\right), \quad A_2(0,T) = \sqrt{P_2}\exp\left(-\frac{(T-T_d)^2}{2{T_0}^2}\right)$$

where P_1 and P_2 are the peak powers and T_d is the initial time delay between the two pulses.

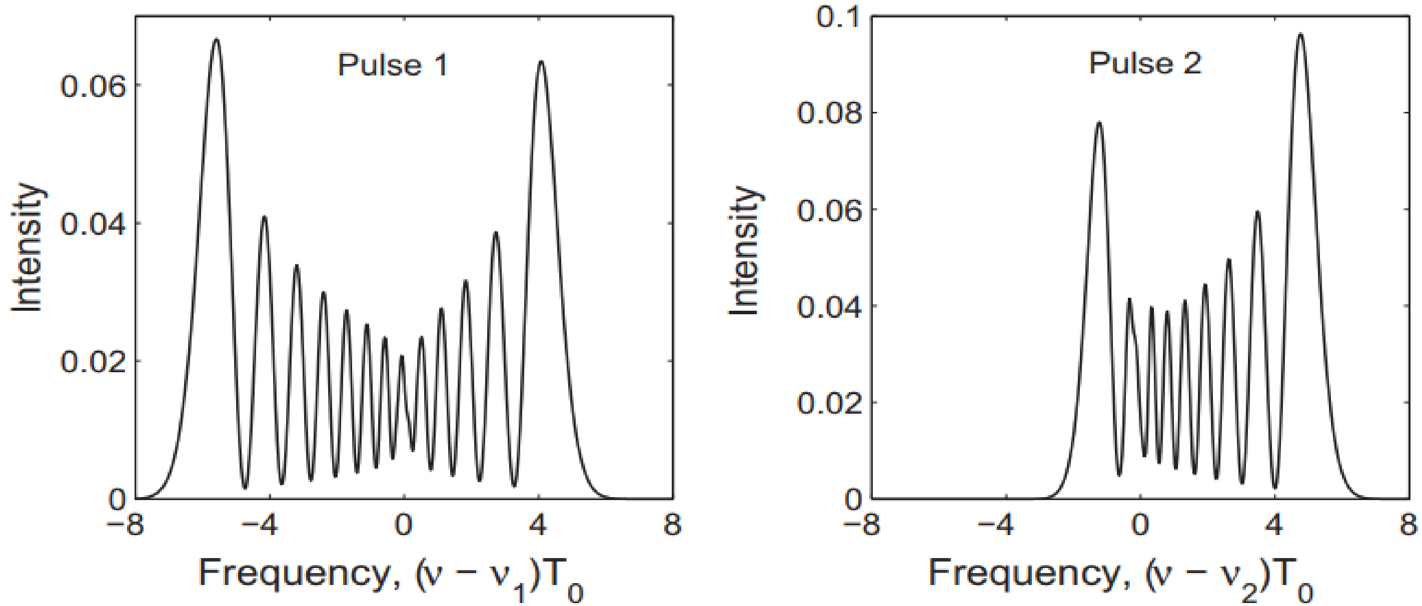
Asymmetric Spectral Broadening

Thus, the time-dependent nonlinear phase shifts are obtained from

$$\phi_j(\tau) = \gamma_j L\left(P_j e^{-\tau^2} + P_{3-j}\frac{\sqrt{\pi}}{\delta}\left|erf(\tau-\tau_d) - erf(\tau-\tau_d-\delta)\right|\right)$$

where *erf*(*x*) stands for the error function and

$$\tau = T/T_0, \qquad \tau_d = T_d/T_0, \qquad \delta = dL/T_0$$



Spectral of two pulses exhibiting XPM-induced asymmetric spectral broadening. The parameters are $\gamma_1 P_1 L$=40, P_2/P_1=0.5, $\gamma 2/\gamma 1$=1.2, τ_d=0, and L/L_W=5.

Asymmetric Spectral Broadening

A qualitative understanding of the spectral features can be developed from the XPM-induced frequency chirp using

$$\Delta v_j(\tau) = -\frac{1}{2\pi}\frac{\partial \phi_j}{\partial T} = \frac{\gamma_j L}{\pi T_0}\left[P_j \tau e^{-\tau^2} - \frac{P_{3-j}}{\delta}\left(e^{-(\tau-\tau_d)^2} - e^{-(\tau-\tau_d-\delta)^2}\right)\right]$$

We consider the pump–probe configuration assuming $P_1 \ll P_2$. The pump-induced chirp imposed on the probe pulse can be obtained by neglecting the SPM contribution and is of the form

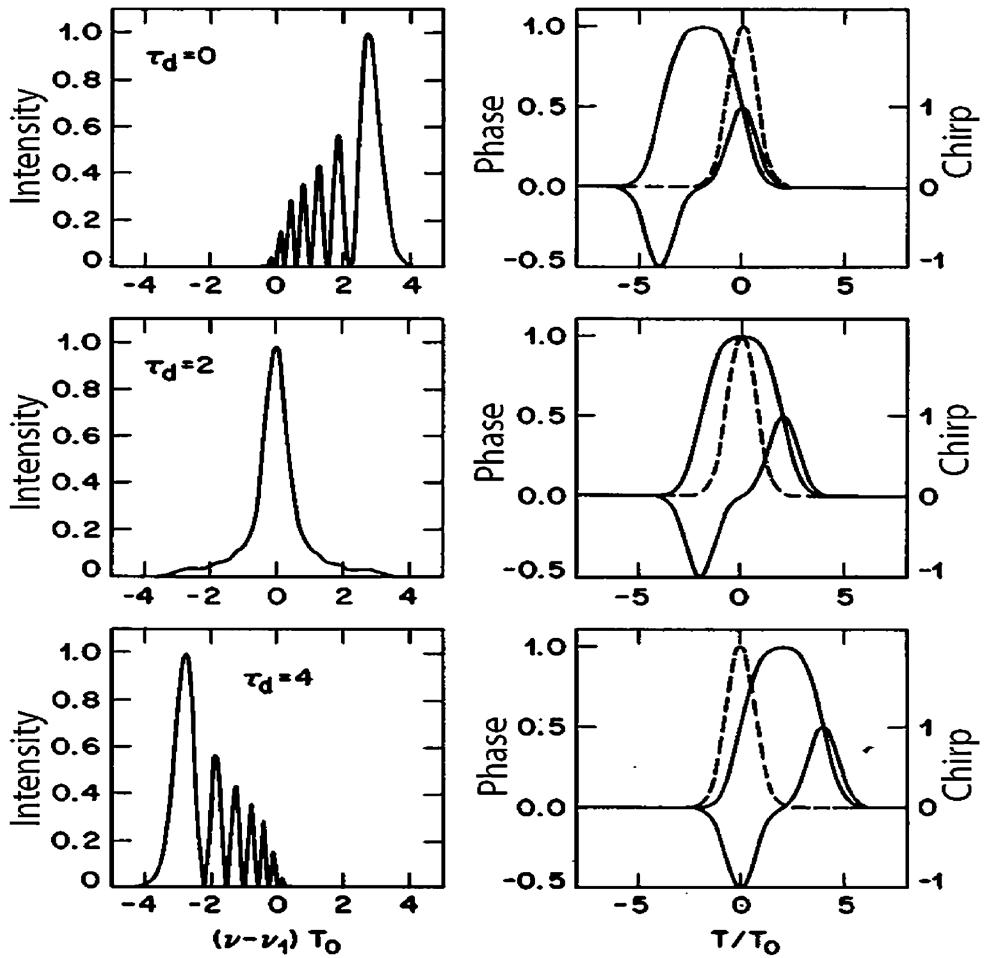
$$\Delta v_1(\tau) = -\mathrm{sgn}(\delta)\Delta v_{\max}\exp[-(\tau-\tau_d)^2] - \exp[-(\tau-\tau_d-\delta)^2]$$

Where $\Delta v_{\max}$ is the maximum XPM-induced chirp given by

$$\Delta v_{\max} = \frac{\gamma_1 P_2 L}{\pi T_0 |\delta|} = \frac{\gamma_1 P_2 L_W}{\pi T_0}$$

Asymmetric Spectral Broadening

$$\Delta v_1(\tau) = -\mathrm{sgn}(\delta)\Delta v_{\mathrm{max}}\exp[-(\tau-\tau_d)^2] - \exp[-(\tau-\tau_d-\delta)^2]$$



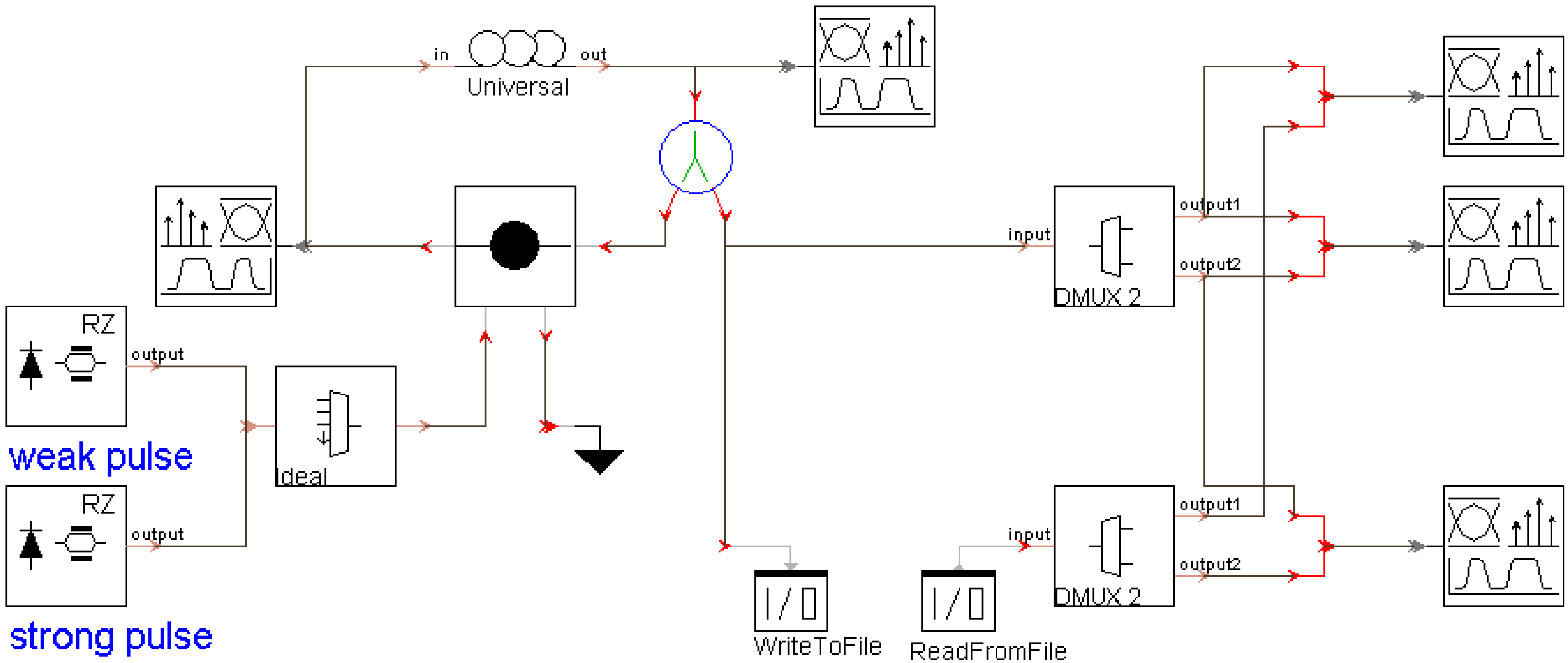
For $\tau_d = 0$, the probe spectrum is shifted toward blue with strong asymmetry.

For $\tau_d = 2$, the probe spectrum becomes symmetric.

For $\tau_d = 4$, the probe spectrum is again asymmetric with a shift toward red.

Probe spectrum together with phase and chirp for δ = -4 and τ_d = 0, 2, and 4.

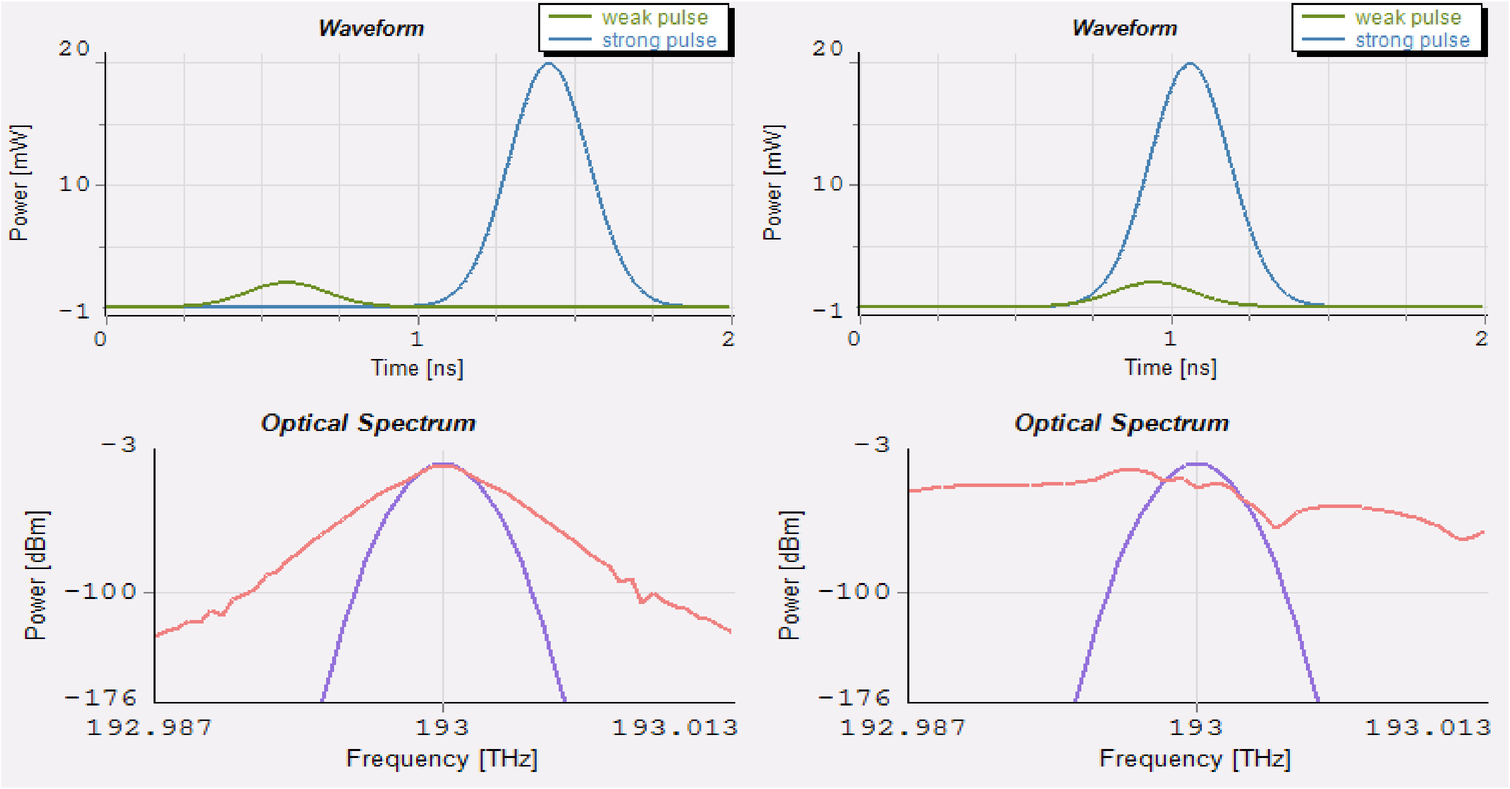
Simulations Setup



Design setup of spectral broadening induced by XPM

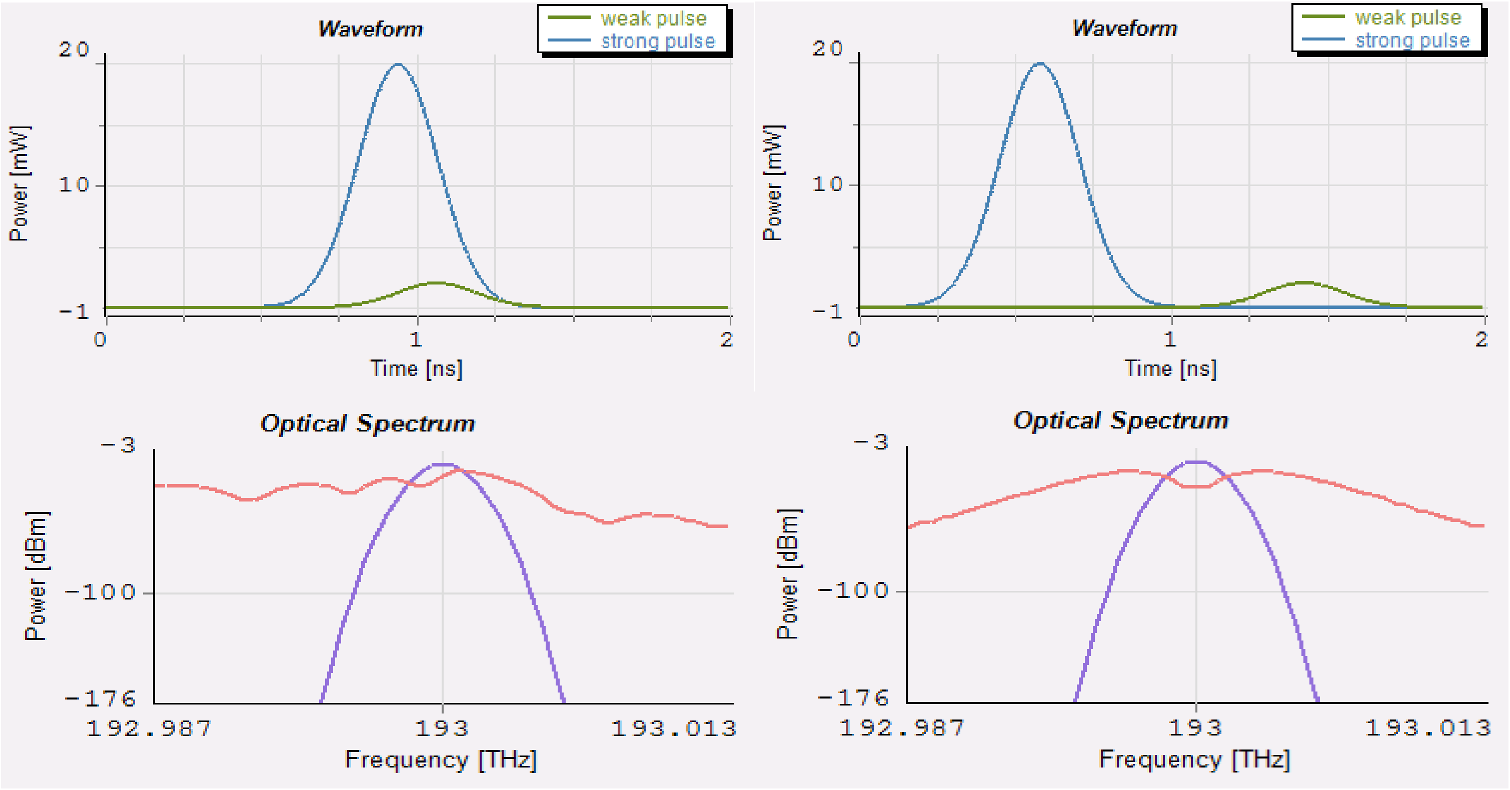
The fiber length L = 93.5 km, nonlinearity coefficient $\gamma = 34\ W^{-1}\cdot km^{-1}$, chromatic dispersion of 16 ps/nm·km at 193.1 THz, and dispersion slope of 0.08 $ps/nm^2\cdot km$.

Results



The leading edge of pump pulse interacts with the probe pulse, therefore the XPM-induced chirp is negative and the spectrum is shifted toward red.

Results



The probe pulse interacts with the trailing edge of the pump pulse. As a result, the XPM-induced chirp is positive and the probe spectrum starts to shift toward blue.

Conclusions & future works

Conclusions:

- Different from the case of pure SPM, the XPM-induced spectral broadening is usually asymmetric.
- The output spectrum of probe pulse depends on the chirp it experienced.

Future works:

- Realize a similar probe spectrum when the pulse width reduces, so that the logic gates with higher data rate can be achieved.
- Apply the constructed photonic logic gates to the architecture of WISDOM project.

Thank you for your attention!

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