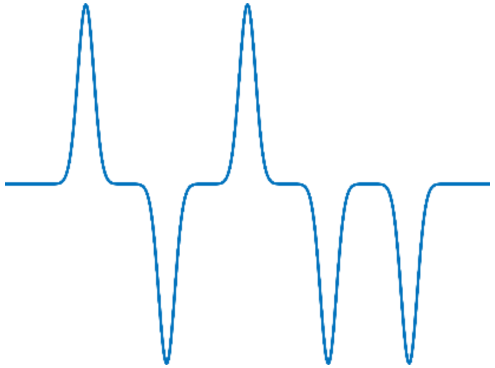
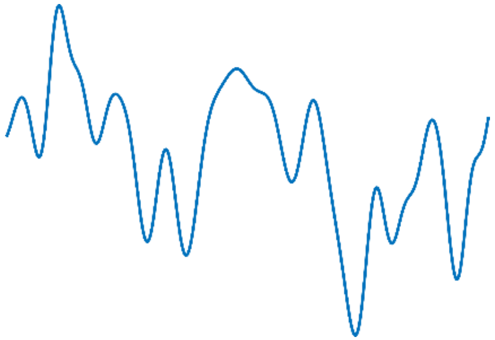
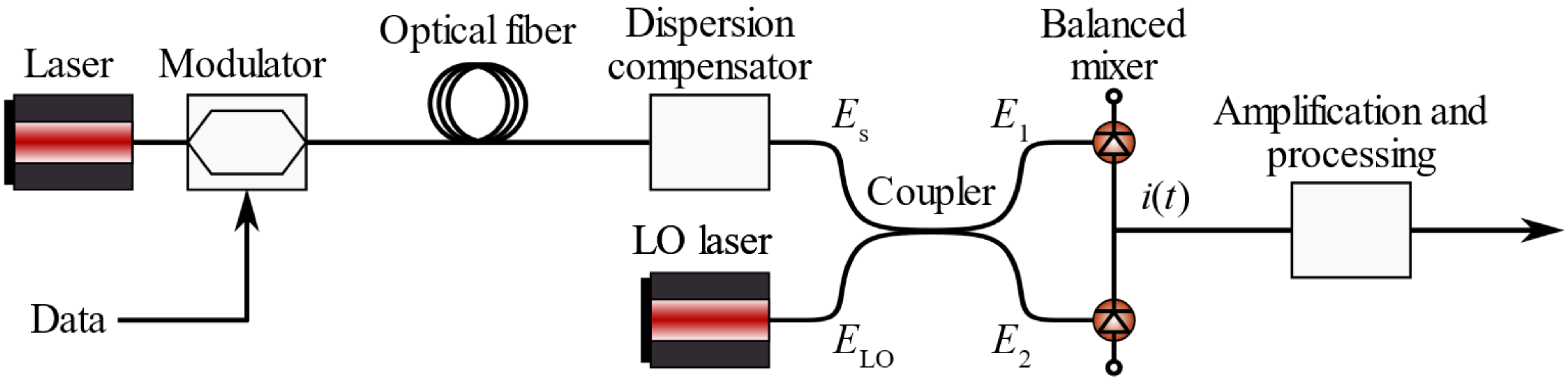
Recovery of signal distorted by nonlinearity in optical communications using deep learning





DL PROJECT 2021

Coherent communications



Fiber chromatic dispersion → pulse broadening

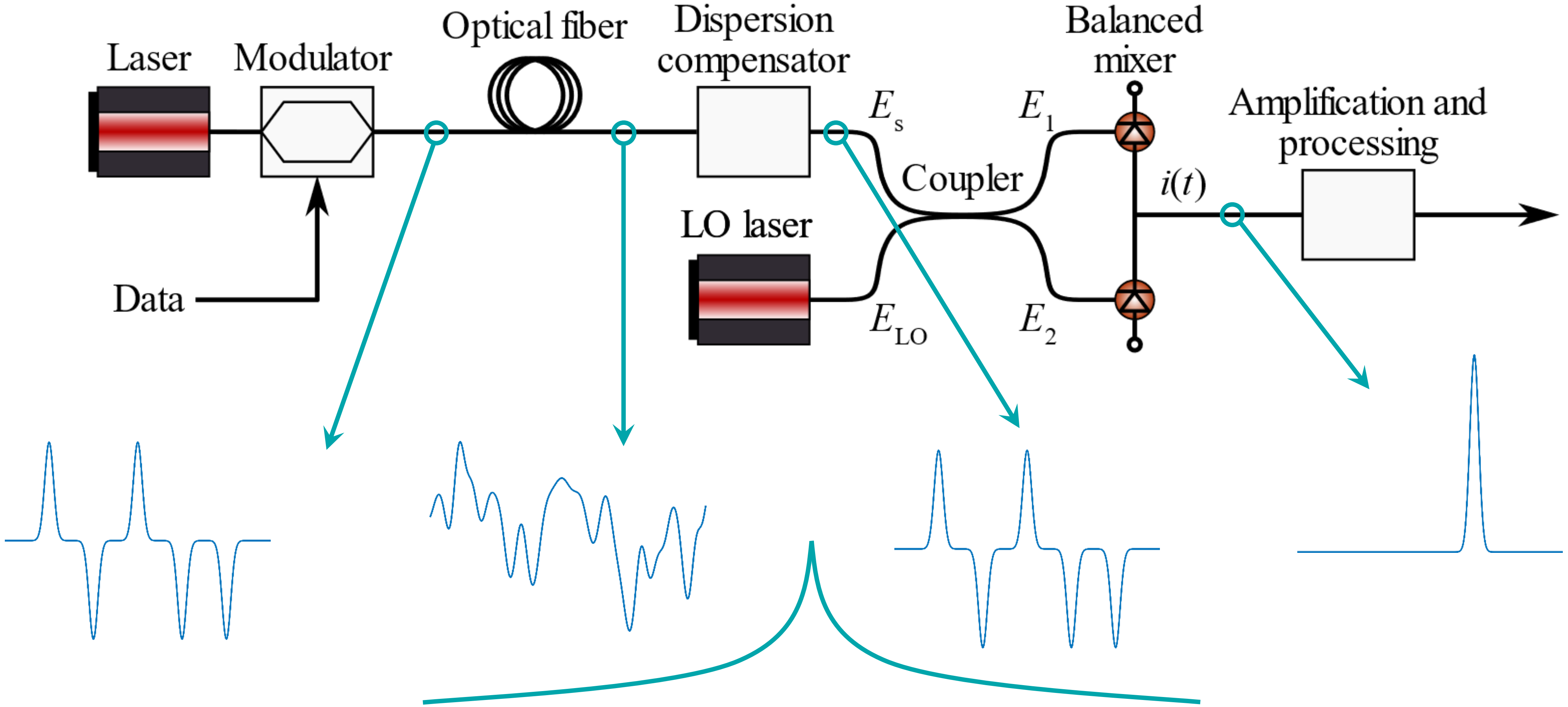
Kerr nonlinearity ($n = n_0 + \alpha|E|^2$) → phase distortion ⇒ errors after decoding.

Nonlinearity is limiting system performance:

higher bit-rate or longer transmission distance

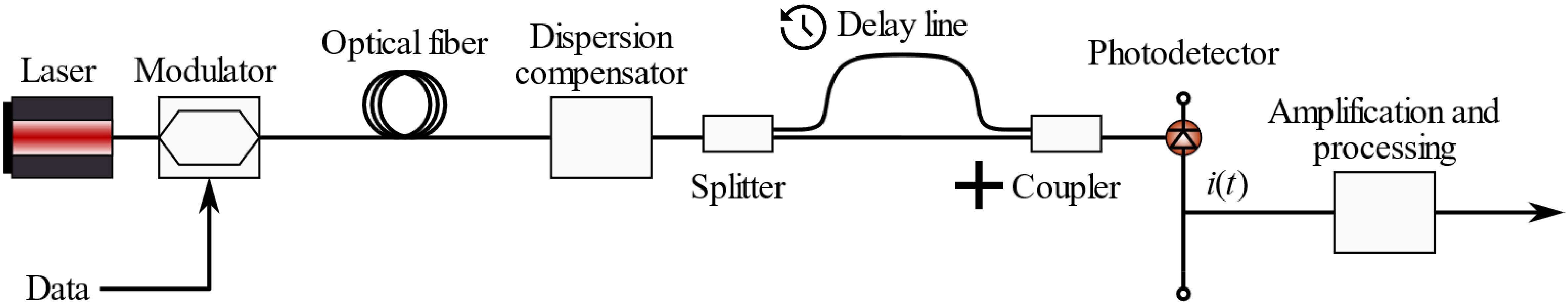
1. **higher bit-rate**: $\mathcal{E} \approx |E|^2\tau_0 \approx |E|^2/BR \geq \mathcal{E}_{cr} \Longrightarrow |E|^2 \geq \mathcal{E}_{cr}BR$
2. **Length of nonlinearity**: $z_{nl} \approx (\alpha|E|^2)^{-1}$.
   Nonlinearity becoming noticeable when $L \sim z_{nl}$

Waveform change during propagation

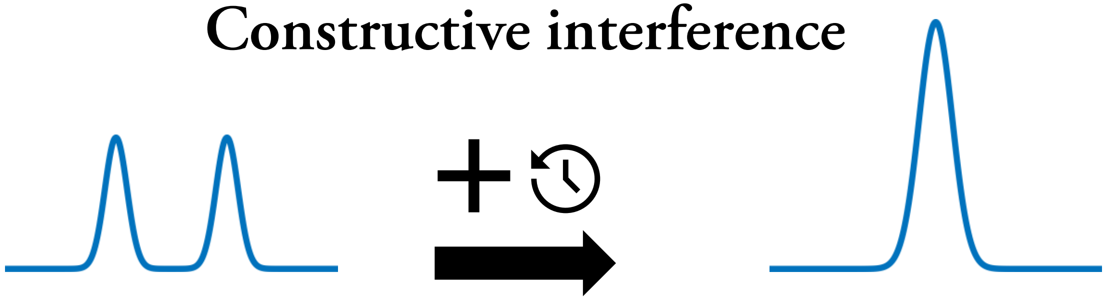


Digital back propagation

Direct decoding. Ideal case

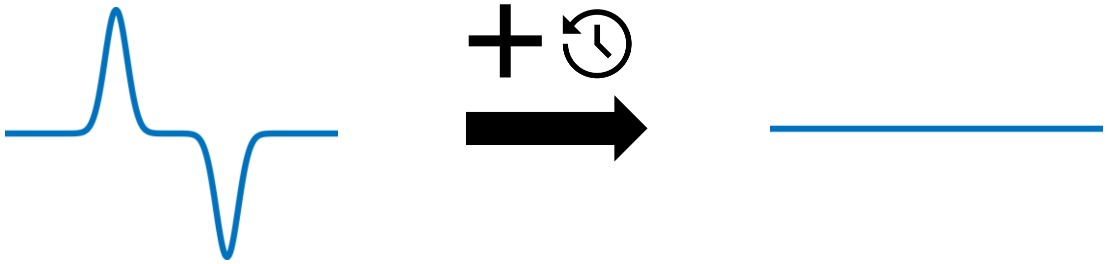


Constructive interference



The sum of pulses with the same phase, generates a doubled amplitude pulse (logical “1”)

Destructive interference

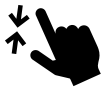


The sum of pulses with the opposite phase results in zero (logical “0”)

Renormalization of NLS

Nonlinear Schrödinger equation:

$$iE_z + dE_{tt} + \alpha |E|^2 E = 0 \qquad (1)$$



Rescaling:

$$E = E_0 U; \quad \tau = \frac{t}{\tau_0}; \quad y = \frac{z}{z_0}; \qquad (2)$$

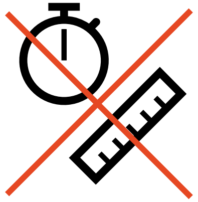
$$iU_y + d\frac{z_0}{\tau_0^2} U_{\tau\tau} + \alpha E_0^2 |U|^2 U = 0 \qquad (3)$$

Dispersion and nonlinearity length:

$$z_d = \frac{\tau_0^2}{d}; \quad z_{nl} = \frac{1}{\alpha E_0^2} \qquad (4)$$

Let it be:

$$\frac{z_0}{z_d} = \frac{1}{2}; \quad \varepsilon = \frac{z_d}{2z_{nl}} \qquad (5)$$



Finally, **dimensionless** NLS:

$$iU_y + \frac{1}{2} U_{\tau\tau} + \varepsilon |U|^2 U = 0 \qquad (6)$$

Modeling equation

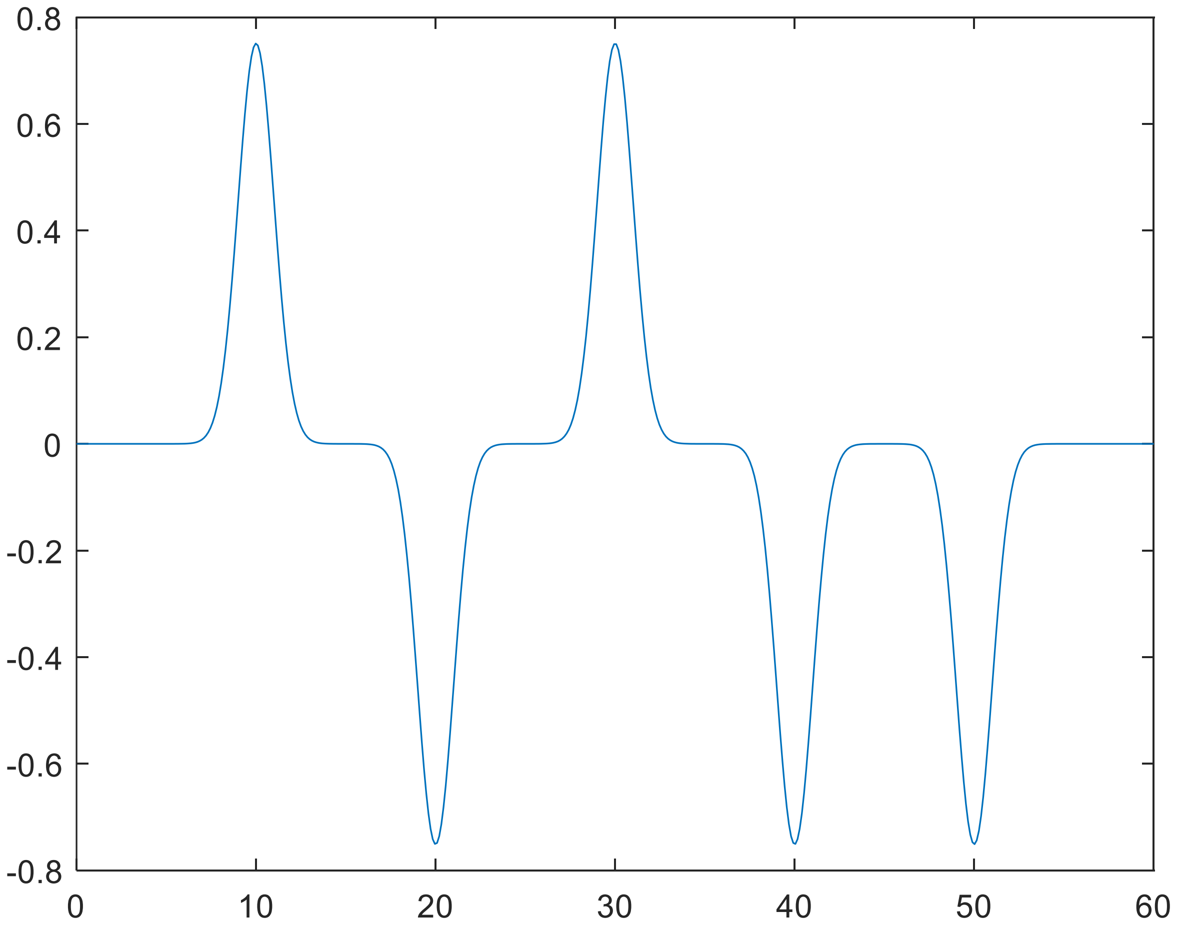
Dimensionless NLS:

$$iE_z + \frac{1}{2}E_{tt} + \varepsilon |E|^2 E = 0 \qquad (7)$$

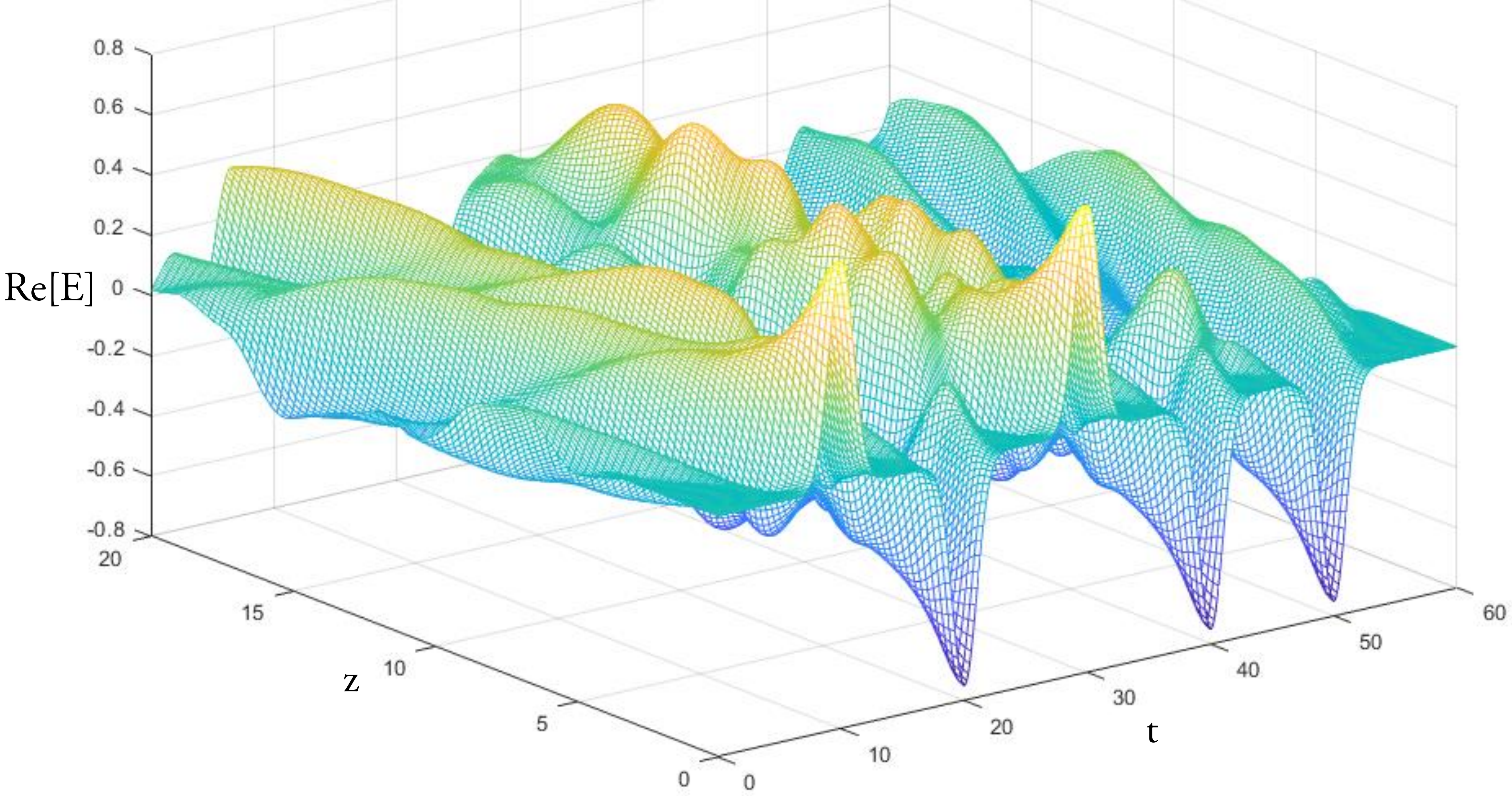
Bit-sequence launched at the front end of the system is represented by periodic train of **gaussian pulses** with Differential Phase Shift Keying (DPSK)

$$E(t,0) = \sum_{k=1}^{N} a_k \pi^{-1/4} \exp\left[-\frac{1}{2}\left(t - kT^2\right)\right] \qquad (8)$$

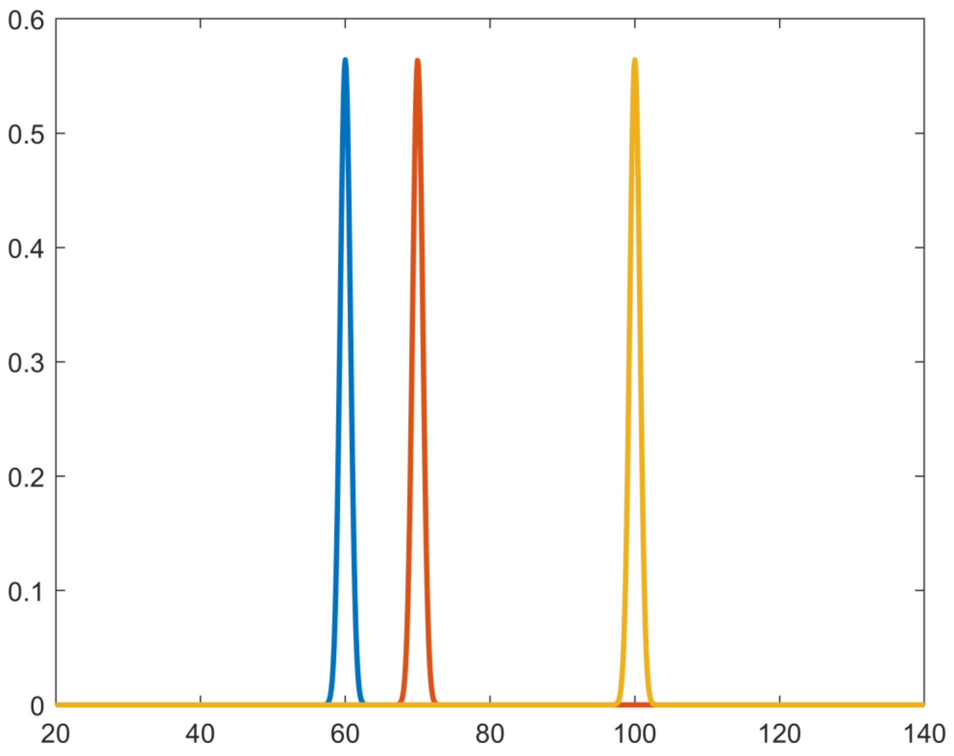
$$\begin{aligned} a_k &= 1 \quad \text{with probability} \quad p_1 = 1/2 \\ a_k &= -1 \quad \text{with probability} \quad p_2 = 1/2 \end{aligned} \qquad (9)$$

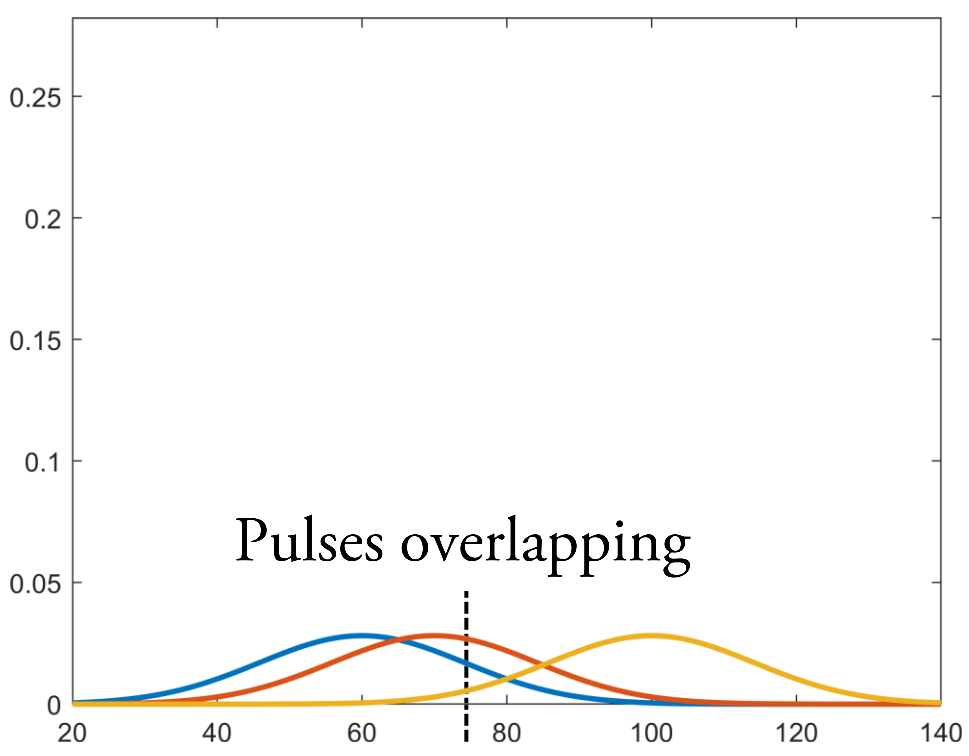


Linear evolution



Mamyshev effect



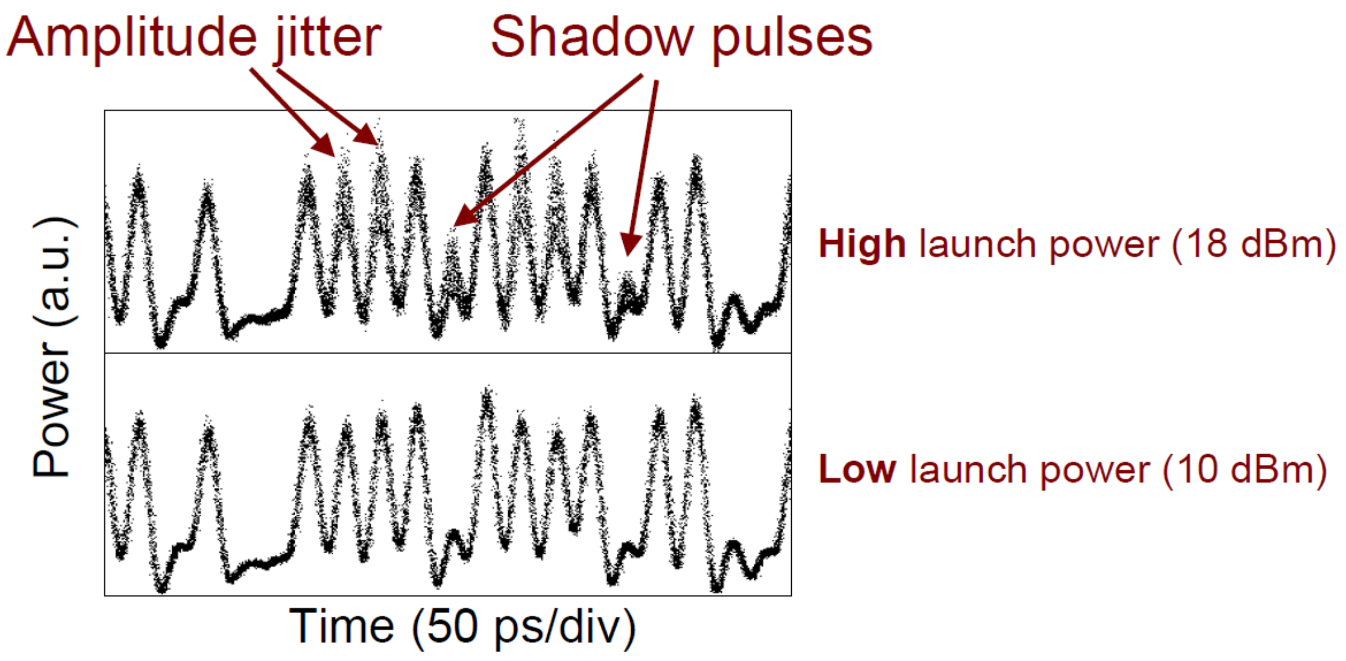


For wave interaction is a mechanism that create **energy redistribution** along bit pattern which lead to **amplitude jitter** of the output signal – Mamyshev effect

- Has the Gaussian shape
- Collects energy from the triplet surrounding pulses

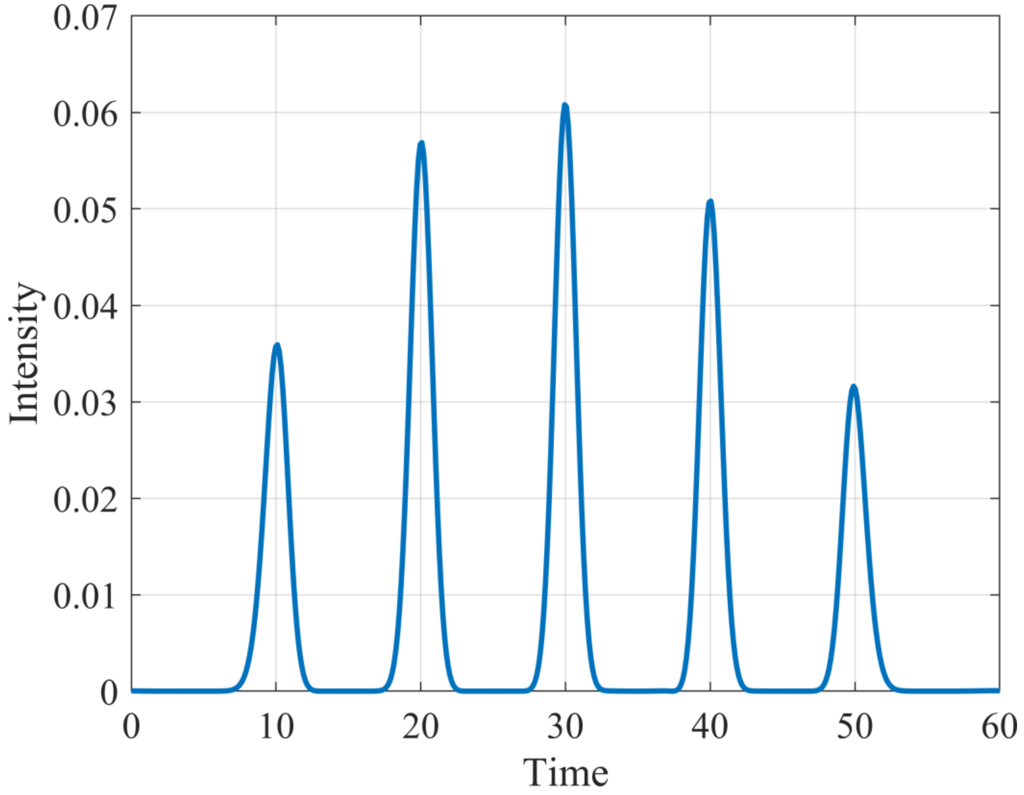
Mamyshev effect: experiment

Rene Essiambre, Lucent: 40Gbit/s, 80km, and 100% dispersion compensation



Mamyshev effect: modeling

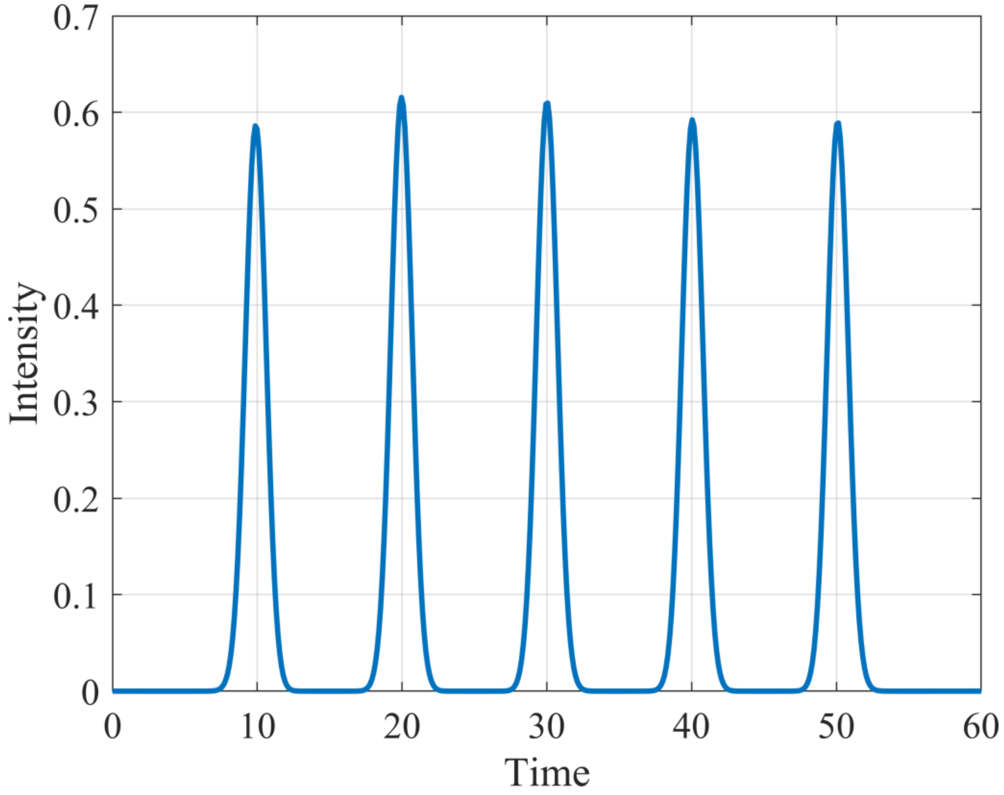
Perturbations



$\varepsilon = 0.1$

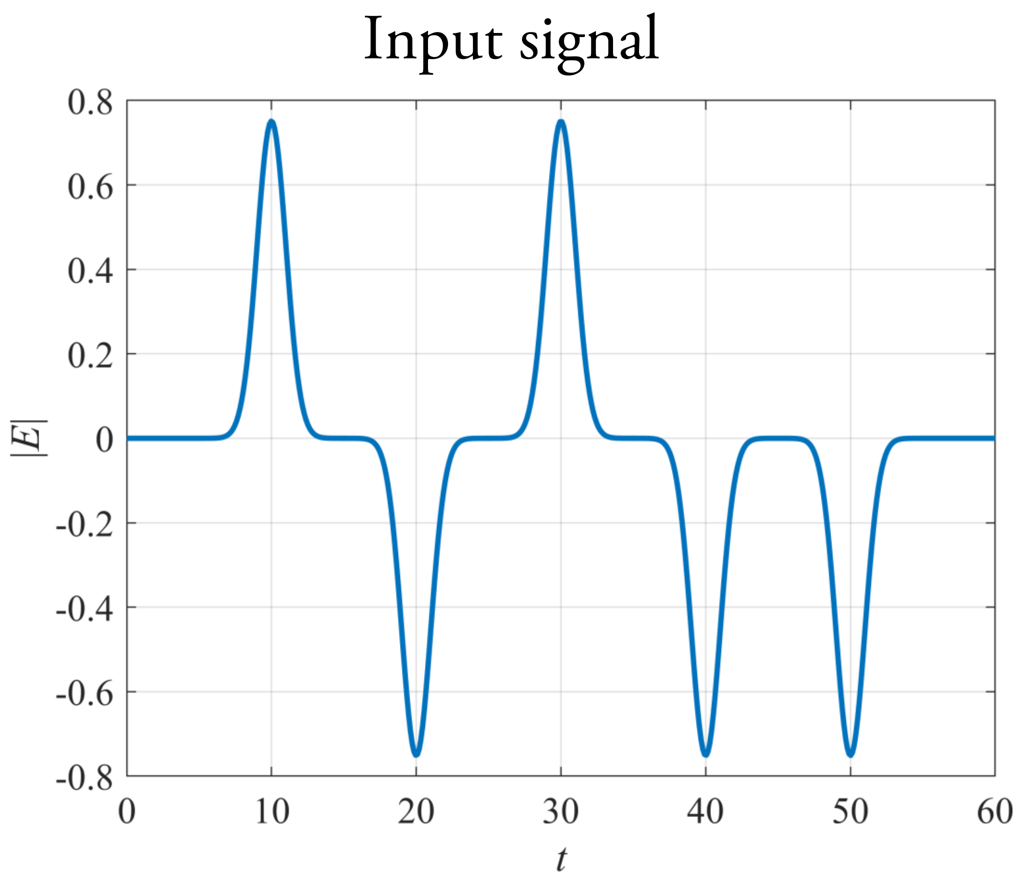
$L = 20$

Output intensity (before decoding)

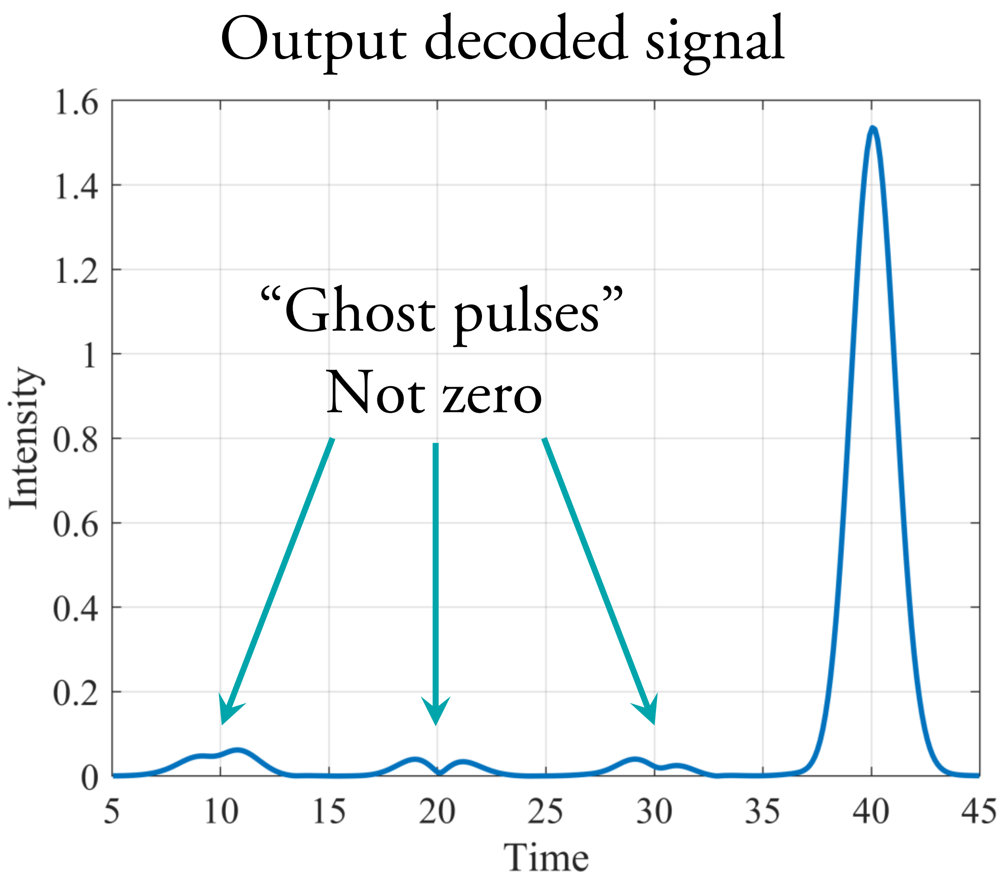


Here we can see amplitude jitter – the result of Mamyshev effect

Direct decoding. Modeling case



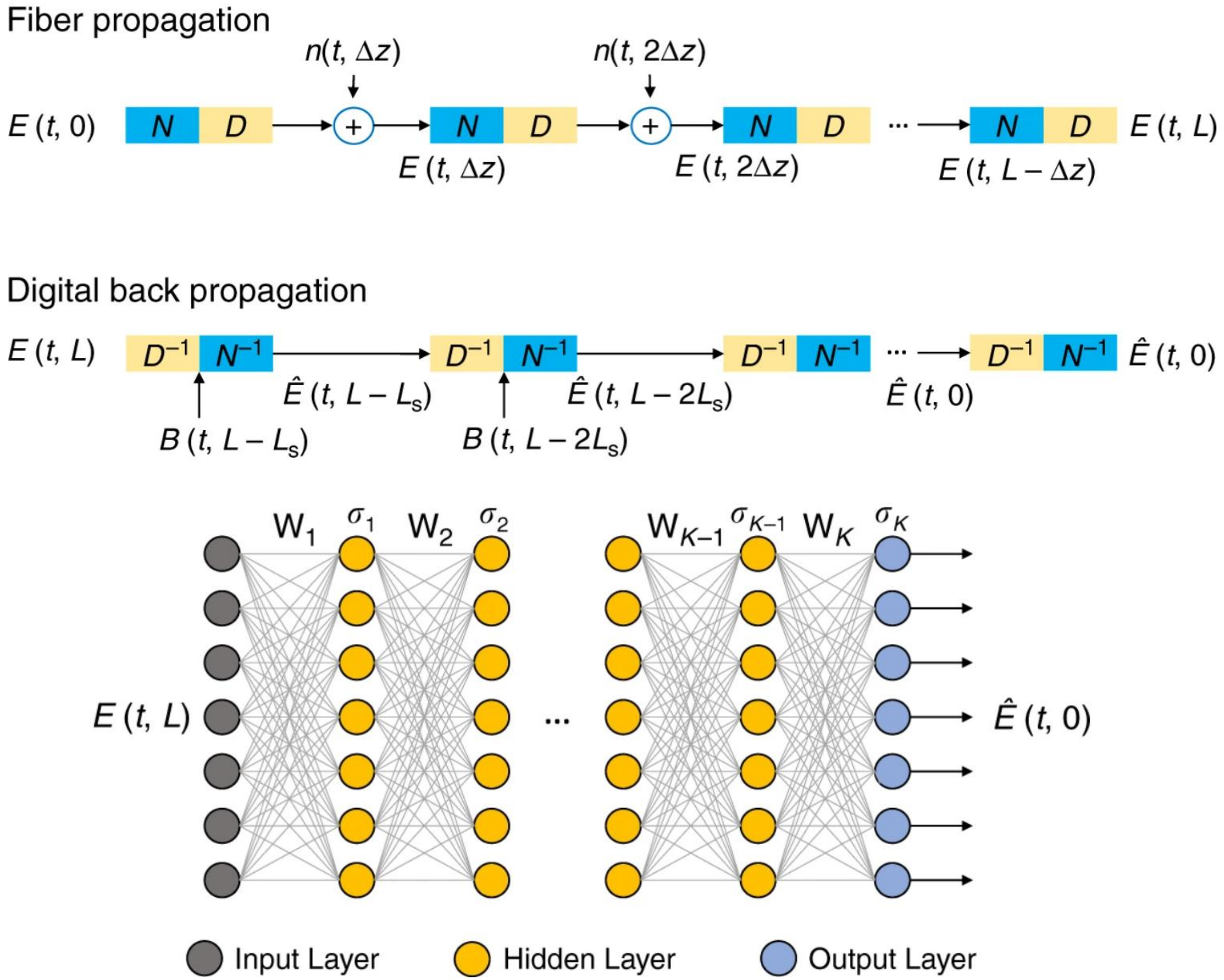
Encoded sequence: 0 0 0 1



$\varepsilon = 0.1$

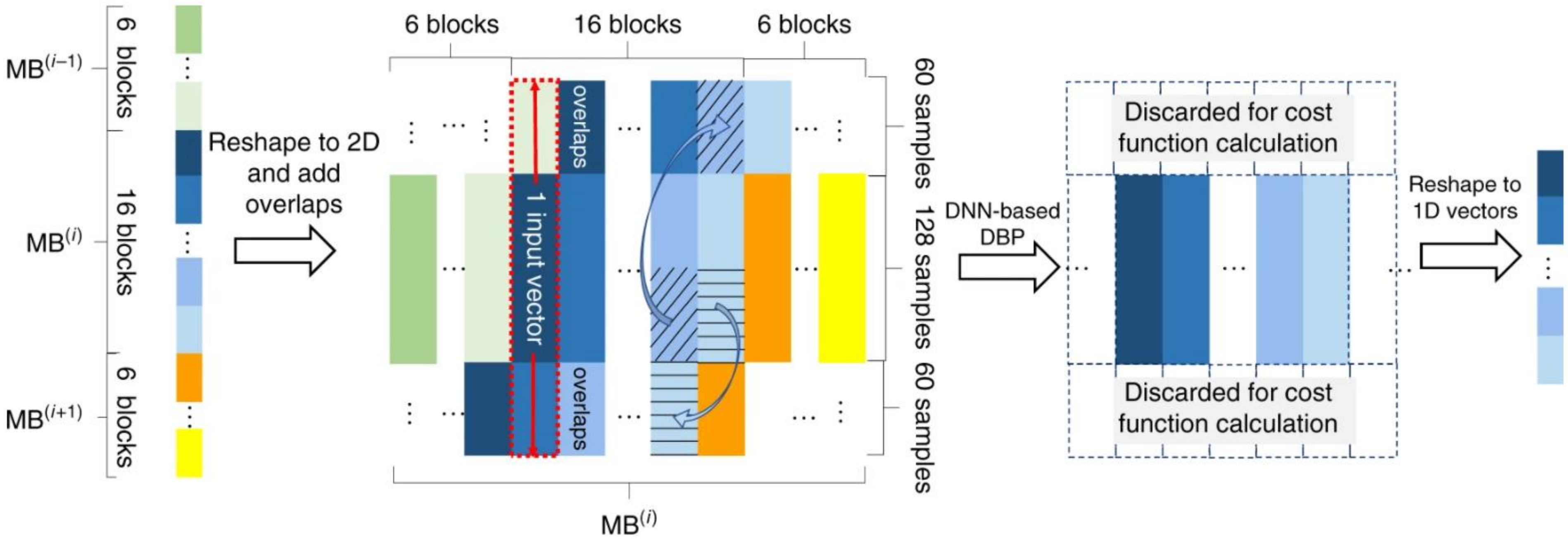
$L = 20$

DNN based DBP



Source: https://www.nature.com/articles/s41467-020-17516-7

Data preparation



Source: https://www.nature.com/articles/s41467-020-17516-7

Literature

- **Nonlinear optics:** Agrawal, G. P. (2000). Nonlinear fiber optics.
- **Coherent communications:** https://www.osapublishing.org/jlt/abstract.cfm?URI=jlt-34-1-157
- **DNN based DBP:** https://www.nature.com/articles/s41467-020-17516-7

Another Textbooks for Additional Reading:

- B E A Saleh, M C Teich, "Fundamentals of Photonics", ISBN 978 0 471 35832 9 2007
- G P Agrawal, "Fiber optic communication systems", ISBN 0 471 21571 6 John Wiley Sons Inc New York, 2002
- Ivan P Kaminow Tingye Li, Alan E Willner "Optical Fiber Telecommunications Systems and Networks", SIXTH EDITION, ISBN 978 0 12 396960 6