i-ETC: ISEL Academic Journal of Electronics,
Telecommunications and Computers
CETC2016 Issue, Vol. 3, n. 1 (2017) ID-5

Optics in Data Processing and Data Transmission

João M. A. Frazão
Área Departamental de Engenharia Electrónica e Telecomunicações e de Computadores (ADEETC),
Instituto Superior de Engenharia de Lisboa (ISEL), Lisboa, Portugal

e-mail: jfrazao@deetc.isel.ipl.pt

***Abstract*- Today optical systems are more and more important in data communications (optical fibers) and are also becoming important in data processing (optical and quantum computing) allowing for a fully optical communication network where all signals will be processed and transmitted in the optical domain. This paper gives an overview of optical fiber communications and analyses some optical devices and applications such as optical computing, holographic memory and optical pattern recognition.**

Keywords: Optical Fibers, NLO, Soliton, Optical Computing.

1 INTRODUCTION

Optical technology is capable of providing the required capacity for the rapidly increasing demand in data transmission and processing.

Optics is of greatest importance in telecommunications due to the high bandwidth and lower attenuation obtained in optical fibers. In addition it begins to be implemented in real information processing as pattern recognition using optical computing.

In future is desirable that all processes involved in data networks, such as amplification, multiplexing, de-multiplexing, switching and signal processing take place in the optical domain which can be more efficient than electrical signal processing and avoid bottlenecks of electrical to optical and optical to electrical conversions [1-5].

2 OPTICAL FIBER COMMUNICATIONS

In figure 1 is shown a state of the art wavelength division multiplexing (WDM) optical fiber system used for long-distance, high-bandwidth telecommunication. In the present work, the performance and limitations of the different elements that are part of this system are analysed.

2.1 Optical fiber characterisation and elements

In this optical WDM fiber system the emitter consists of *n* independent optical beams coming from *n* laser sources with proper λ_i wavelength individually modulated by *n* electrical signals. The external modulation employing electro-optic materials is much faster than direct modulation of laser output power. The different modulated λ_i laser beams are coupled (Mixer Coupler) in the same optical fiber. In long distance fibers the optical amplifier allows signals to be regenerated without the use of electro-optical converters. Erbium-doped fiber amplifiers (EDFA) pumped usually by diode lasers are used. In WDM or dense wavelength division multiplexing (DWDM) systems fiber Bragg gratings are used to separate closely spaced wavelengths (< 0.8 nm). The elementary fiber Bragg grating comprises a short section of single-mode optical fiber in which the core refractive index is modulated periodically. For optical detection the most commonly used devices are the PIN or avalanche photodiodes (APD).

2.2 Optical fiber limitations

The most important limitations in single mode fibers are the attenuation due to material absorption, linear dispersion due to the variation of linear refractive index n_l as a function of wavelength causing the pulses to broaden (limiting the overall bandwidth) and Rayleigh scattering (or elastic scattering) due to random fluctuations of the refractive index on a scale smaller than the optical wavelength.

All previous processes described are linear or intensity-independent, but in single mode fibers with high light intensity, due to the small cross section inside the fiber, another type of intensity-dependent processes occur. These nonlinear effects are described by nonlinear optics (NLO). In optical fibers the NLO effects can be divided in nonlinear refractive processes and inelastic scattering phenomena.

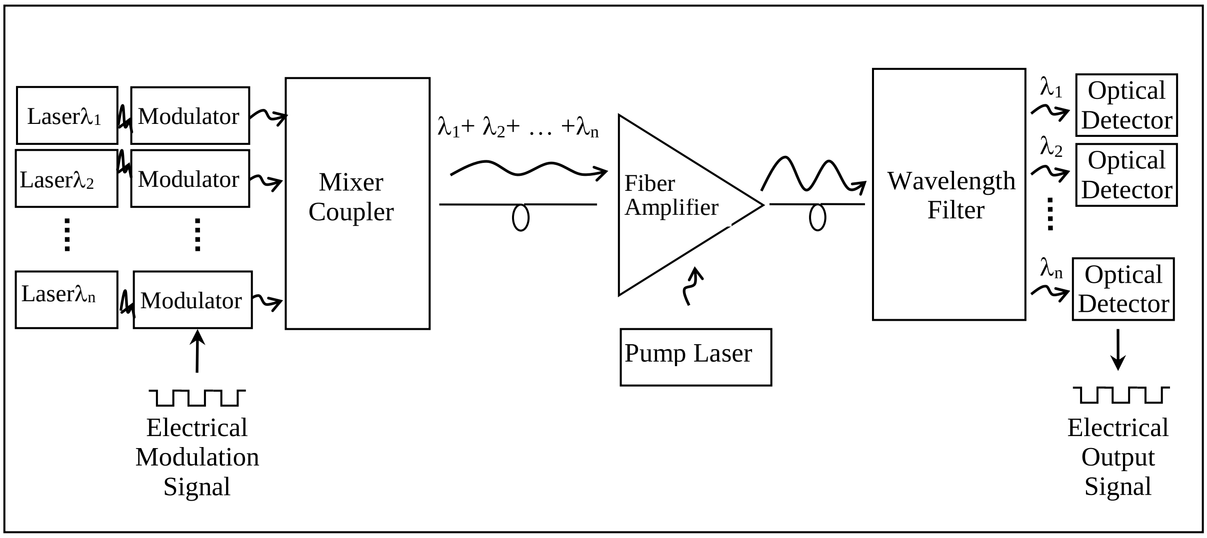

Fig 1. *Typical wavelength-division multiplexing-fiber optic communication system.*

Nonlinear refractive index change includes: Self-phase modulation (SPM) related to changes of refractive index caused by variation in signal intensity and resulting in a temporarily varying phase change that leads to additional dispersion; Cross-phase modulation (CPM) related to change of refractive index of an optical beam produced by the intensity of that beam and the intensity of other beams co-propagating in the same optical fiber; Four-wave mixing (FWM) process originated from 3rd order susceptibility ($\chi^{(3)}$) resulting in a fourth frequency ω_4 related to ω_1, ω_2 and ω_3 frequencies which co-propagate simultaneously inside a fiber by $\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$.

If the light intensity in the optical fiber exceeds a certain threshold value the inelastic scattering light grows exponentially. Contrary to elastic scattering, the frequency of scattered light is red-shifted during inelastic scattering and can induce stimulated effects such as stimulated Brillouin-scattering (SBS) and stimulated Raman-scattering (SRS).

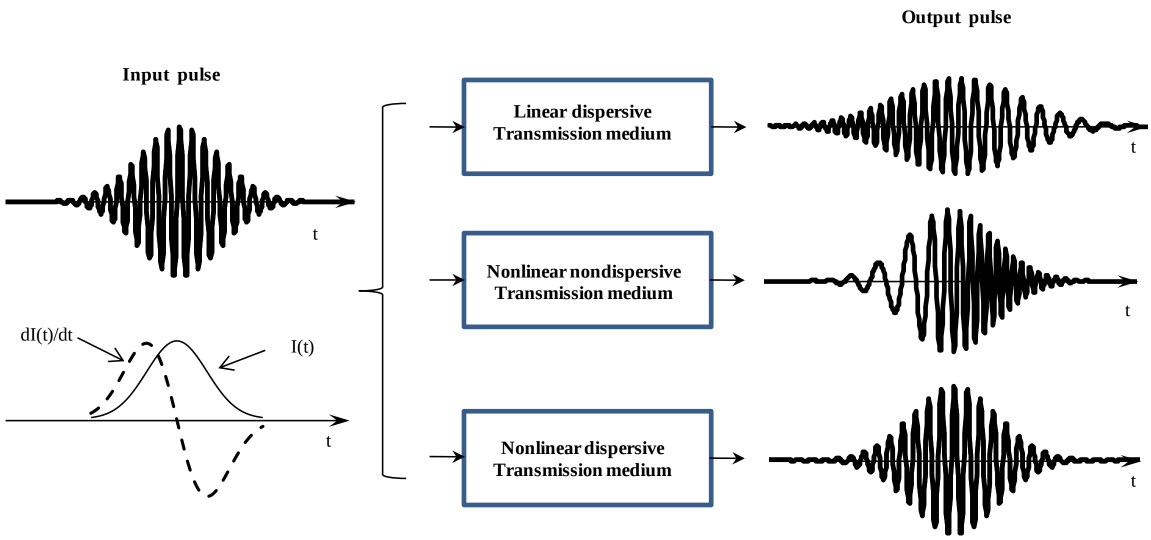

Fig 2. *An input pulse of intensity I(z=0,t) and central angular frequency ω_0 travelling in the z direction in a linear anomalous dispersive, nonlinear (with n_{nl} > 0) nondispersive and nonlinear dispersive medium, respectively. When the input pulse travels a distance z in the three different transmission mediums the output pulse exhibits different shapes. At the top output pulse spreading can be observed with higher frequencies travelling faster than lower frequencies. In the middle the output pulse is chirped with the same shape and with a negative frequency shift in the leading half of the pulse, and a positive frequency shifted in the trailing half. At the bottom, the output pulse is identical to the input pulse (optical solitons), depending on the amplitude and sign of the linear dispersion and nonlinear effects.*

All these linear and nonlinear processes in general result in degrading the overall performance of an optical fiber telecommunication system but in certain situations can interact positively. An example is the effects of linear and SPM dispersions that can be compensated mutually by proper choice of light pulse shape and amplitude as illustrated in figure 2.

For a linear dispersion medium a chirp pulse with initial value C (see Appendix A12) at a distance z the chirp changes to:

$$C(z) = C + (1 + C^2)\beta_2 z / T_0^2 \quad (1)$$

The chirp value and sign depends of C and β_2 values, but even for initial unchirped pulse (C=0) the pulse will be chirped as a function of z. For a linear anomalous dispersion medium (which usually occurs in fiber optics for wavelengths in vacuum $\lambda_0 > 1{,}312$ μm) the dispersion coefficient D is positive and β_2 is negative the instantaneous frequency decreases linearly as function of z (Appendix A13). Even for an unchirped pulse (C=0) broadening is observed. Thus in a pulse the higher frequencies travel faster than the lower frequencies (see top output pulse in figure 2).

During propagation the pulse width T_1 is a function of z given by [3]:

$$\frac{T_1}{T_0} = \left[\left(1 + \frac{c\beta_2 z}{T_0^2}\right)^2 + \left(\frac{\beta_2 z}{T_0^2}\right)^2\right]^{1/2} \quad (2)$$

The chirped pulse may broaden or compress depending on the sign of the product β_2C. For $\beta_2 C > 0$ the chirped Gaussian pulse broadens monotonically. For $\beta_2 C < 0$, the pulse width initially decreases and becomes minimum at a distance z_{min} after which it increases monotonically. In figure 2 consider the top output pulse as $\beta_2 C > 0$.

For a nonlinear medium the dispersion related to SPM may be understood by examining a pulse of intensity I(z,t) of carrier angular frequency ω_0 traveling a distance z in a nonlinear medium with refractive index $n_{eff} = n_l + n_{nl} I$ (see Appendix equation A9). For such pulse the argument of the electric field or instantaneous phase (see Appendix equation A2) is

$$\varphi(t) = \omega_0 t - Kz = \omega_0 t - n_{eff} K_0 z = \omega_0 t - \frac{2\pi}{\lambda_0}[n_l + n_{nl} I(z,t)]z \quad (3)$$

so that the instantaneous angular frequency is

$$\omega = \frac{d\varphi}{dt} = \omega_0 - \frac{2\pi}{\lambda_0} n_{nl} \frac{\partial I(z,t)}{\partial t} z \quad (4)$$

If n_{nl} is positive, the frequency of the trailing half of the pulse (the right half) is increased since $\frac{\partial I(z,t)}{\partial t} < 0$, whereas the frequency of the leading half (the left half) is reduced since $\frac{\partial I(z,t)}{\partial t} > 0$ as illustrated in middle output pulse of figure 2.

At a certain level of intensity and for certain pulse profiles, the effects of self-phase modulation and group-velocity dispersion are balanced so that a stable pulse travels without spread, as illustrated in bottom output pulse of figure 2. In such situation the pulse would propagate undistorted and is called optical soliton, with applications in high bandwidth optical communication systems [6].

3 OPTICAL DATA PROCESSING

We can divide optical computing in digital and analogue processes. Digital optical computing employs optical gates and switches. The main technical difficulty remains in the creation of large high-density arrays of fast optical gates.

The principle of analogue optical computing [7-10] is based in the property of the lens which perform in their back focal plane the Fourier transform of a 2D image located in their front focal plane as illustrated in figure 3.

An object consisting of a fine wire mesh is illuminated by a parallel coherent light beam. In the back focal plane of the imaging lens appears the Fourier spectrum of the periodic mesh. By placing a narrow horizontal slit in the focal plane to pass only a single row of spectral components (horizontal pass filter) vertical frequencies are blocked and horizontal frequencies are transmitted. The corresponding image, (seen in image plane of figure 3), contains only the vertical structure of the mesh. The suppression of the horizontal structures is quite complete.

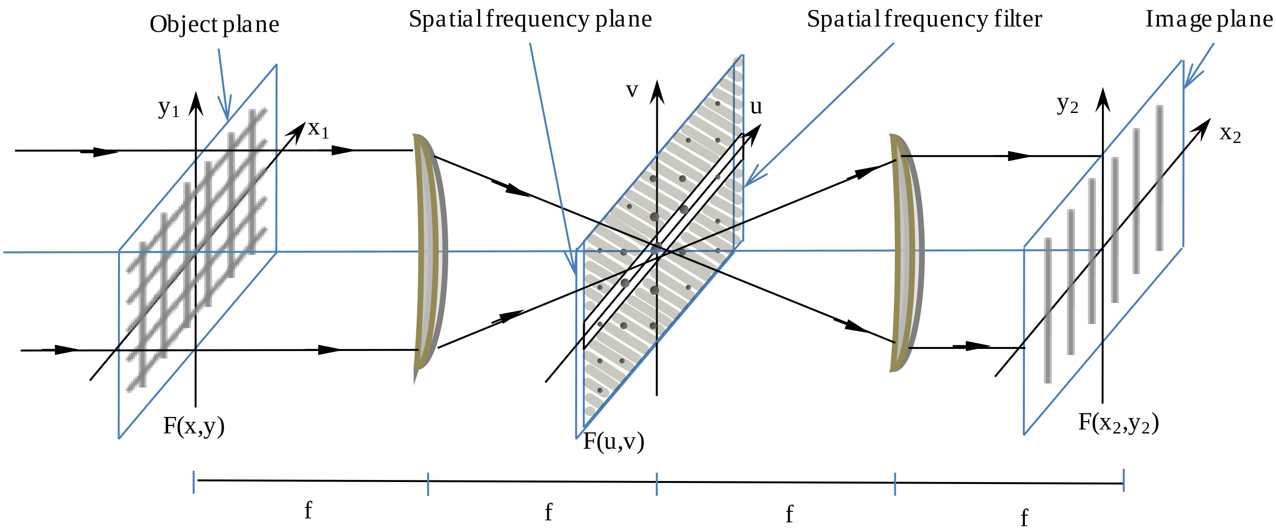

Fig 3. *Two dimensional optical frequency processor*

The inherent parallel processing is one of the key advantages of optical processing compared to electronic processing that is mostly serial. Optical analogue processing is useful when the information is optical and no electronics to optical transducers are needed.

In a parallel optical computer, a parallel access optical memory is required as for example 3D optical holographic memories using different materials such as photorefractive crystals.

To date the optical computers were not able to compete with the electronic computers essentially due to the lack of appropriate optical components, but in the future the employment of nanotechnologies can change this situation [11-14].

REFERENCES

[1] F. Idachaba, D. U. Ike, and O. Hope, Proceedings of the World Congress on Engineering, Vol I (2014).
[2] S. P. Singh and N. Singh, Progress In Electromagnetics Research, PIER, 249-275 (2007).
[3] G. P. Agrawal, "Fiber-Optic Communication Systems" 4th Edition, Willey & Sons (2010).
[4] B. E. A. Saleh and M. C. Teich, "Fundamentals of Photonics" 2nd Edition, Wiley & Sons (2007).
[5] G. D. Baldwin, "An Introduction to NONLINEAR OPTICS" Plenum Publishing Corporation (1974).
[6] S. Oda and A. Murata, Optics Express, Vol. 14, 7895-7902 (2006).
[7] J. W. Goodman, "Introduction to Fourier Optics" 3rdEdition, Roberts § Company (2005).
[8] K. Preston, "*Coherent Optical Computers"* McGraw-Hill (1972).
[9] E. N. Leith, *IEEE Journal on Selected Topics in Quantum Electronics*, vol. 6, no.6, 1297–1304 (2000).
[10] S. H. Lee, "*Optical Information Processing Fundamentals"* Springer (1981).
[11] D. R. Smith, J. B. Pendry and M. C. K. Wiltshire, Science, 305, 788-792 (2004).
[12] C. M. Soukoulis and M. Wegener, *Nature Photonics* **5**, 523-530 (2011).
[13] J. K. Gansel, *et al. Science* 325, 1513-1515 (2009).
[14] T. Utikal, M. I. Stockman, A. P. Heberle, M. Lippitz and H. Giessen, Phys Rev Lett, 104, 113903 (2010).

APPENDIX

For a nonlinear nondispersive dielectric medium the vector polarization ***P*** induced by electric dipoles satisfies the general nonlinear relation:

$$\boldsymbol{P} = \varepsilon_0\chi^{(1)}\boldsymbol{E} + \varepsilon_0\chi^{(2)}\boldsymbol{E}^2 + \varepsilon_0\chi^{(3)}\boldsymbol{E}^3 + \cdots \quad \text{(A1)}$$

where ε_0 is the permittivity of vacuum and $\chi^{(i)}$ (i = 1, 2, ...) is i^{th} order tensor susceptibility.

For isotropic medium, as in optical fibers, we can use scalar notation instead of vector notations because the polarization vector ***P*** has the same direction of the electrical field ***E***. For an electrical field associated to a plane wave propagated in z direction

$$E = E_0\cos(\beta z - \omega t), \quad \text{(A2)}$$

where β is the phase constant, the polarization *P* becomes

$$\begin{aligned} P =& \frac{1}{2}\varepsilon_0\chi^{(2)}E_0^2 \\ &+ \varepsilon_0 E_0\left[\chi^{(1)} + \frac{3}{4}\chi^{(3)}E_0^2\right]\cos(\beta z - \omega t) \\ &+ \frac{1}{2}\varepsilon_0\chi^{(2)}E_0^2\cos[2(\beta z - \omega t)] \\ &+ \frac{1}{4}\varepsilon_0\chi^{(3)}E_0^3\cos[3(\beta z - \omega t)] \\ &+ \cdots \end{aligned} \quad \text{(A3)}$$

In the above equation the first term is constant and gives a constant field in the medium. The second third and fourth terms correspond to oscillating frequencies ω, 2ω and 3ω respectively known as fundamental, second, third harmonics of polarization. As silica used in optical fibers consists of symmetric molecules, $\chi^{(2)}$ vanishes, and neglecting 3ω term due to variation in refractive index of the fiber inducing a phase mismatch between frequencies ω and 3ω equation (A3) becomes

$$P = \varepsilon_o \chi^{(1)} E_0 \cos(\beta z - \omega t) + \frac{3}{4} \varepsilon_o \chi^{(3)} E_0^3 \cos(\beta z - \omega t) \quad \text{(A4)}$$

where $\chi^{(i)}$ terms are neglected for $i > 3$. For a plane wave propagating in a dielectric linear isotropic and homogeneous the intensity (I) is

$$I = \frac{1}{2} c \epsilon_0 n_l E_0^2 \quad \text{(A5)}$$

where c is velocity of light in vacuum and n_l is the linear refractive index of the medium. Therefore,

$$P = \varepsilon_0 \left[\chi^{(1)} + \frac{3}{2} \frac{\chi^{(3)}}{c \varepsilon_0 n_l} I \right] E_0 \cos(\beta z - \omega t) \quad \text{(A6)}$$

Defining the effective susceptibility (χ_{eff}) of the medium as

$$\chi_{eff} = \frac{P}{\varepsilon_0 E} = \chi^{(1)} + \frac{3}{2} \frac{\chi^{(3)}}{c \varepsilon_0 n_l} I \,. \quad \text{(A7)}$$

Hence, effective refractive index (n_{eff}) can be written as

$$n_{eff} = (1 + \chi_{eff})^{1/2} = \left[1 + \chi^{(1)} + \frac{3}{2} \frac{\chi^{(3)}}{c \varepsilon_0 n_l} I \right]^{1/2} = n_l \left[1 + \frac{3}{2} \frac{\chi^{(3)}}{c \varepsilon_0 n_l^3} I \right]^{1/2}, \quad \text{(A8)}$$

where $n_l = \left(1 + \chi^{(1)}\right)^{1/2}$ is the linear refractive index.

In equation (A8) the last term in parenthesis is usually very small compared to unity, so n_{eff} can be approximated by the first term of the Taylor's series expansion as

$$n_{eff} = n_l + \frac{3}{4} \frac{\chi^{(3)}}{c \varepsilon_0 n_l^2} I = n_l + n_{nl} I, \quad \text{(A9)}$$

where $n_{nl} = \frac{3}{4} \frac{\chi^{(3)}}{c \varepsilon_0 n_l^2}$ is the nonlinear refractive index.

For a linear dispersive medium n_l (for simplicity we replace n_l by n) is a function of angular frequency ω. For pulses with spectral width Δω much smaller than the carrier frequency ω_0 ($\Delta\omega << \omega_0$) the propagation constant $\beta(\omega) = n(\omega)\omega/c$ can be expanded in a Taylor series around the carrier frequency:

$$\beta(\omega) \cong \beta_0 + \beta_1(\Delta\omega) + \frac{\beta_2}{2} (\Delta\omega)^2 \quad \text{(A10)}$$

In the above equation

$$\Delta\omega = \omega - \omega_0 \;, \quad \beta_1 = \left(\frac{d\beta}{d\omega} \right)_{\omega = \omega_0} = \frac{1}{v_g} \;, \quad \beta_2 = \left(\frac{d^2\beta}{d\omega^2} \right)_{\omega = \omega_0} = -\frac{D \lambda_0^2}{2\pi c} \quad \text{(A11)}$$

where v_g is the group velocity and D is the dispersion parameter.

Let us consider the propagation in z direction in a linear dispersive medium of a frequency modulated Gaussian pulse (chirped pulse) with an initial electric field (at z = 0)

$$E(0,t) = E_0 exp\left[-\frac{1}{2} \left(\frac{t}{T_0} \right)^2 \right] \times exp\left[-i \frac{C}{2} \left(\frac{t}{T_0} \right)^2 \right] exp[-i\omega_0 t] \quad \text{(A12)}$$

where E_0 is the amplitude, T_0 the half width at 1/e intensity point, C parameter that control the frequency chirp and ω_0 the carrier frequency. The instantaneous frequency is the derivative of the phase,

$$\omega = \frac{d}{dt} \left(\omega_o t + \frac{C}{2T_0^2} t^2 \right) = \omega_0 + \frac{C}{T_0^2} t \quad \text{(A13)}$$

and is a linear function of time.

The electric field at z position E(z,t) is from [3]

$$E(z,t) = \frac{E_0}{\sqrt{Q(z)}} exp\left[-\frac{(1 + iC) \left(t - \frac{z}{v_g} \right)^2}{2 T_0^2 Q(z)} \right] \times exp[i(\beta_0 z - \omega_0 t)] \quad \text{(A14)}$$

where $Q(z) = 1 + (C - i)\beta_2 z / T_0^2$. This equation shows that a Gaussian pulse remains Gaussian on propagation but its width, chirp, and amplitude changes continuously.