Paper

The present and future of nonlinear optics applications in photonic telecommunication networks

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Abstract — A state-of-the art of photonic telecommunication technology is reviewed and possible directions of future developments are outlined. In particular, the impact of nonlinear optical phenomena inherent to silica glass on the transmission performance of wavelength-division multiplexed optical signal through fibres is discussed. Also potential applications of nonlinear photonic devices for the purposes of optical signal processing that is foreseen in future all-optical networks are pointed out.

Keywords — optical fibre communications, photonic networks, wavelength-division multiplexing, nonlinear optical phenomena.

Optical technology and infrastructure

Recent years have shown a rapid growth of demand for capacity of telecommunication networks. It has inspired many laboratories to explore new techniques of more efficient utilisation of the huge bandwidth offered by optical fibre links. One of the most promising and cost effective ways to increase optical link throughput is a technique known as Wavelength Division Multiplexing (WDM).

Optical transparent transmission offers almost infinite optical bandwidth. This is especially attractive in view of future information society needs for exchange of enormous information streams, resulting from a general use of multimedia and hypermedia services.

Transparent optical networks that are actually being introduced on the basis of existing silica cable infrastructure offer almost infinite transmission bandwidth [1]. This is of crucial importance in view of future information society needs for exchange of enormous information streams, resulting from a general use of multimedia and hypermedia services.

The transparent network technology is actually in a mature state: a number of elements are already commercially available. Those are: tunable laser diodes and laser arrays as WDM sources based on a ITU 100 GHz optical frequency grid, Arrayed-Waveguide Gratings (AWG) as multiplexers and demultiplexers including optical add-drop (de)multiplexers, fibre Bragg gratings as filters, etc.

Optically transparent technology is actually advancing very fast. Although almost unlimited capacity is available, the future technology has to meet new demands especially in the field of optical signal digital processing, including full 3R (Reamplification, Reshaping, Retiming) regeneration. Moreover, a new concept of 4R regeneration [2] has recently appeared that reclaims also a proper regeneration of the optical spectrum of the aggregate signal in introduced recently commercial transmission systems exploiting WDM technology.

In a WDM system many information channels are transmitted through one fibre using different optical wavelengths modulated by independent data streams. This method is analogous to Frequency Division Multiplexing (FDM) which is widely exploited in other communication systems, especially in radio broadcasting. Using WDM we can easily increase the capacity of already existing fibre links that is particularly significant in the areas where placing new cables is impossible or too expensive. One can also envision the application of WDM in broadcast networks and/or in subscriber loop [3].

The introduction of Erbium-Doped Fibre Amplifiers (EDFA) which have replaced electronic regenerators in fibre based transmission links in early 90 s resulted in optical transparency of the links. This was in contrary with electronic regenerator based links. In those a combination of electronic logic circuit along with electro-optical and opto-electrical conversions of the digital signal transmitted has been used in order to cope with signal distortion. In optical links the distortion results from physical limitations of the transmission of light signals through fibres, namely from fibre attenuation, dispersion, and nonlinear distortion.

An enhancement of optical link exploitation enabled by the EDFAs and WDM technologies have resulted in a dramatic decrease of cost of transmission bandwidth. Moreover, WDM offers an orthogonality between wavelength and time, so they can be processed independently and simultaneously. However, significant research challenges still remain to realize the huge potential offered by optical networking.

WDM transmission is actually being introduced in commercial fibre telecommunication systems. Transmitting several wavelengths (16, 32, 64 or more) and amplifying the aggregate signal in optical amplifiers results in an increase of the total optical power, what causes nonlinear interactions very effective. The transmission performance of the system can be then seriously degenerated, mainly via nonlinear signal distortion and nonlinear crosstalk (power transfer between different wavelength channels). Thus, there exists a great need to minimize the nonlinear distortion and to optimize the transmission parameters. On the other hand there is an urgent necessity to establish new international standards for WDM nonlinear systems.

Nonlinear limitations

Analogous features of a silica fibre: attenuation, dispersion, and nonlinear distortion result in distortion, crosstalk and noise of the transmitted optical signal. Therefore, a digital signal can be transmitted successfully only at certain distance of the fibre link, this distance is called transparent length.

Silica glass exhibits only small value of nonlinear coefficient. However, due to small spot-size of modal beams in the core of the fibre and high power at the output of optical sources and amplifiers, going up to 100 mW, and also extremely long distances of propagation which is of the order of hundreds or thousands of kilometres, nonlinear effects are accumulated along fibre link and can cause a significant change of the optical signal in positive or negative way. Moreover, the fibre nonlinearity is believed to decrease signal distortion caused by Polarisation Mode Dispersion, which is fibre intrinsic defect that is due to lack of ideal symmetry of practical fibres.

At present state of technology nonlinear effects affect the transmission system performance in great scale. This is due to combining high level of optical power at the output of modern lasers and amplifiers with extremely small cross-section of guiding core of the fibres.

In spite of its merits the WDM technique is not free from limitations. The most characteristic and essential problem for multichannel optical systems, beside attenuation and dispersion, is interchannel crosstalk [4]. One can distinguish crosstalk caused by nonlinear interactions between the light in different channels or between the light and the fibre material. In spite of the intrinsically small values of the nonlinearity coefficients in fused silica, the nonlinear effects in optical fibres can be observed at low power levels. This is possible because of important characteristics of single-mode fibres, a very small optical beam spot-size, and extremely low attenuation.

In WDM systems a nonlinear interplay between many different spectral components of the aggregate signal causes interchannel crosstalk. The nonlinear phenomena involved are Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), Four-Wave Mixing (FWM), Stimulated Raman Scattering (SRS), and Stimulated Brillouin Scattering (SBS).

System requirements

A number of functions in the optical domain can be realized only via nonlinear effects. This is an inherent feature of optics in contrary to electronics: two electrons interact strongly via electrostatic and magnetic forces even in the vacuum, while two photons do not at all. Actually this was the reason successful application of photonic transmission in fibre links. Unfortunately, this is also the reason why it is so difficult to realise processing of light by light. This can be done only via nonlinear interaction between light and matter or between the beams themselves.

Core networks

Core networks represent the backbone of the information superhighway. Optical cable infrastructure is well developed in many countries and no substantial investment is needed to upgrade the transmission capacity. The most promising one is WDM technology, which does not need to install faster electronics.

Broadband access networks

The expected introduction of optical transparency to subscriber loop will allow taking advantage also from WDM technology. A combination of various signals (i.e. analogue or digital television, interactive broadband services) could be transmitted simultaneously. New ways of providing access are emerging based upon the need for interactive broadband services. This means a need for a mass deployment of fibre in access.

ATM networks

Multimedia service networks based on fibre core networks and ATM technology can provide the broadband communications platform needed by business and residential users for integrated services with of voice, data and visual information transmission. This should provide high-quality performance and economic advantages of ATM networks.

The future transparent photonic network

It is generally believed that opticalisation which is a term standing for keeping the signal in optical domain thus avoiding its conversion to electronic domain in the whole transparent network should result in a much more complete exploitation of the combined huge low-loss fibre window and optical amplifier bandwidth, which is actually estimated to be equal to ten terahertz.

All optical networks offer new possibilities for high bandwidth applications. New techniques will be demonstrated for optical switching and network management for complex optical networks. WDM systems allow upgrading of the backbone optical network. This theme explores the current state of research and future developments of optical network technology and applications. End-to-end broadband transparent transmission is an essential condition to provide reliable broadband services. The demand for Internet is a driving force leading rapidly towards WDM. However, WDM is an analogue technology that suffers from analogue distortions of the signal. On the other hand, special kind of optical pulses exploring silica glass nonlinearity called solitons have a digital nature (they exist or do not). Solitons are then more compatible with digital transmission. A combination of both technologies appears as a very promising one. Solitons are better for synchronous (SDH) digital systems, while a passive WDM network is better suited for ATM.

WDM is a technique compatible with the idea of all-optical networks, where one can create transparent optical paths connecting successive network nodes by switching optical channels organized at the different light wavelengths. Wavelength converters (λC) are developed in order to profit from another degree of freedom of transparent network, which is the signal wavelength. This allows a realisation of wavelength routing functions.

Transparency is very attractive also from user point of view: he/she sends his/her own data streams and the transparent network transmits them regardless of their format, bitrate etc. A functional model of a transparent passive network consists of an optical telecommunication cloud through which clients send and receive their messages of various kinds.

Reduced cost of bandwidth enabled by the optical amplifier and WDM technologies have resulted in a dramatic reduction of cost of transmission bandwidth. Moreover, WDM offers an orthogonality between wavelength and time, so they can be processed independently and simultaneously [5]. However, significant research challenges still remain to realize the huge potential offered by optical networking.

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