Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
C. R. Physique 4 (2003) 1–5
COMPTES RENDUS PHYSIQUE

Optical telecommunications/Les télécommunications optiques

# Foreword

## 1. Introduction: the history

Compared to so many fields in Applied Physics and Technology Engineering which are over one or two centuries old, *optical telecommunications* is still in a relative infancy. Indeed, the field was born from the invention of semiconductor lasers in the mid 1960s, and that of low-loss glass fibers in 1970, which represent the two parent technologies. With the current level of achievement in optical communication systems, it is difficult to imagine what the challenges were in these early times. Indeed, the very first *semiconductor diodes*, realized in GaAs, had to be operated at liquid-nitrogen temperatures, and under pulsed excitation. It took to develop more complex hetero-junctions and sophisticated current-confined structures in GaAlAs to achieve, in 1970–71, *room-temperature* and *continuous-wave* operation [1]. The origin of *optical fibers* can be traced back to 1966–1971 proposals by researchers from the Standard Telecommunication Laboratories (UK), to convey optical telecommunications signals through fiber lightguides [2,3]. Consider that at the time, the fiber attenuation over a kilometer length was of the order of $10^{-100}$, or 1000 decibels/km! Painstaking efforts to improve glass purity and fiber design led Japanese laboratories then Corning (USA) to demonstrate fiber transmissions of $10^{-10}$ (100 dB/km) in 1969, and of $10^{-2}$ (20 dB/km) in 1970, respectively, [1]. This last number corresponds to 1% of transmitted light power after one kilometer distance, which opened the perspective of realistic *lightwave communications* (today, this parameter is close to 96% (0.2 dB/km), corresponding to 1% over 100 kilometers, representing average inter-city distances).

Following these heroic times, the new optical telecommunications field developed at a dramatic pace. The key achievements concerning the first 20 years-period (1970–1990) were the following:

– the transition from 0.8 µm wavelength operation to 1.3 µm (minimum fiber dispersion) then to 1.55 µm (minimum fiber attenuation), the latter being referred to as the *third transmission window*;
– the realization of *single-frequency laser diodes* (distributed feedback lasers) at 1.3–1.55 µm;
– the development of *dispersion-shifted fibers*, having both minimum dispersion and loss at 1.55 µm;
– the introduction of *digital electronics* at 155 Mbit/s, then 622 Mbit/s;
– the conception of sensitive, low-noise and high-frequency *photo-diodes* and *electronic receivers*.

By 1985–1988, the above progress was illustrated by the deployment of huge optical systems at continental and oceanic scales [4]. The *North-East Corridor system* linked Massachusetts and Virginia over a 1250 km route. The cable had 30 fiber pairs, representing no less than 80 000 km of total fiber length. The system operated at 90 Mbit/s and used opto-electronic 'repeaters' to regenerate the signals every 40 km. As second example is provided by the first *transatlantic/transpacific cables* using optical fibers instead of coaxial wires (TAT-8 and TPC-3). These two undersea cables, with respective lengths of 6700 km and 13 400 km, had two fiber pairs. The $2 \times 280$ Mbit/s optical signals were opto-electronically regenerated every 60 km. To provide an idea, this total capacity corresponded to about 9000 simultaneous telephone conversations. This performance is to compare with the first repeated transatlantic coaxial-cable system (TAT-1), installed in 1956 and which offered 72 telephone circuits.

A second phase of optical telecommunications history was to begin in the period 1985–1995, which could be called the 'golden age of optical amplifiers' [5]. The revolution introduced by optical amplifiers opened the perspective of today's Gbit/s (1000 Mbit/s) to Tbit/s (1000 Gbit/s) global telecommunication systems. The underlying concept was to remove opto-electronic repeaters from the light path, and achieve optical regeneration directly on the light signal, without previous electronic-bandwidth limitations. Amplifying light in the fiber can be done either by *stimulated Raman scattering* (a fiber nonlinearity) or by stimulated emission from *rare-earth* dopants included into the fiber core. The idea of doping fibers with rare-earths elements such as *neodymium* dates back from the mid 1960s, although there were no compact pump sources available and the dopant was excited by flashlamps [6,7]. It then resurfaced in the 1970s and 1980s through both crystalline- and glass-fiber devices. Raman fiber amplifiers were also investigated in the early 1980s. Yet the overall fiber–amplifier


doi:10.1016/S1631-0705(03)00009-4

approach momentarily fell into oblivion, because there was no real need for optical amplifiers/regenerators at the time. In 1985, the University of Southampton (UK) reactivated the field, doping fibers with the element *erbium*, which exhibits a laser transition at 1.55 μm. During the years 1987–1990, both Southampton and AT&T Bell Laboratories (USA) demonstrated and developed workable and optimized *erbium-doped fiber amplifiers* (EDFA), which could be efficiently pumped by semiconductor laser diodes [7,8]. The available EDFA bandwidth revealed to be huge: 30 000 GHz, to compare with 2–5 GHz of existing repeater technologies. Thus several signals at different wavelengths could be simultaneously amplified in the same EDFA device. The combination of *wavelength-division multiplexing* (WDM) and EDFA-based technologies explains the phenomenal developments which took place over the last decade [9,10]. Current terrestrial and submarine-cable systems, in use over and between continents, offer capacities between 100 Gbit/s and 1 Tbit/s per fiber, equivalent to 10–100 million compressed-voice telephone circuits [11].

The thirty-year history of optical telecommunications, crowned by the ‘recent’ EDFA/WDM revolution, made possible to develop broadband networks and services for voice and data, and overall, made possible the global, world-wide deployment of the *Internet* through what is called the *optical transport backbone*.

## 2. The physics behind history

Progress in optical telecommunications has resulted from a fruitful hybridation between a great diversity of engineering technologies, from semiconductor epitaxial growth to advanced fiber design and manufacturing, in addition to those of opto-electronic signal processing and microelectronics. All this glittering top-technology could make one forget that optics is first and foremost grounded in fundamental principles of physics. It is a well-known feature that the laser is a direct application of *quantum mechanics*. Indeed, a laser is a physical system where both atoms and fields are quantized, resulting into the coherent emission of *photons*. The world ‘photonics’ recalls such a high conceptual origin. But there is more. Basic optical amplifiers such as EDFAs exemplify Einstein’s theory of *spontaneous* and *stimulated emission*, Heisenberg’s *Uncertainty Principle* and the concept of *vacuum-noise fluctuations*. Without these three concepts, the noise limitations due to amplified spontaneous emission could not be explained. The effect of photon multiplication in such amplifiers thus brings us to the core of quantum uncertainty. The homogeneous gain-broadening properties of EDFAs are also explained by fundamental physics. Indeed, the broadening is due to a combination of the *Stark effect* on the orbital (LSJ) states (degeneracy lifting by the glass’s crystalline field) and *Boltzmann’s law* for the corresponding atomic populations (black-body thermalization). In the domain of semiconductors, the properties of *quantum wells* are explained by *exciton* resonances, a result of one-dimensional confinement of the electron’s wave-function in the multi-layer structure.

On the classical physics side, the excitation of propagation modes in fiber and integrated waveguides rests upon *Maxwell’s equations* for *electromagnetic waves*. No matter how complex the symmetry and structure of the waveguides, this unique set of equation generates all possible modal solutions with their dispersive properties. Recent ‘holey’ fiber structures have revealed new photonic-bandgap behavior with promising applications to either tight or loose single-mode confinement (nonlinear or linear fibers) and single-mode visible-light waveguiding. In the *nonlinear* and *dispersive* propagation regime of fibers, *solitons* have appeared as new forms of ‘*solitary*’ light pulses described by the so-called nonlinear *Schrödinger equation*, by analogy with a particule-like motion in potential wells [12]. Even more fundamental physics principles are approached in *quantum communications*, where light bits are transmitted photon by photon, enabling new types of secure cryptography. Finally, *Shannon’s information theory* brings in the concept of *information entropy*, by analogy with Boltzmann’s definition in statistical mechanics.

The ‘science’ of optical telecommunications, grounded into the above fundamentals, in fact represents the cross-fertilization of different applied-physics domains: semiconductor and materials physics, atomic and laser physics, nonlinear optics, opto-electronics, acousto-optics, fiber and integrated optics, high-speed electronics and digital signal processing. Each of these domains set physical limitations of their own, but their clever combination has seemingly made possible to always boost system performance limits. An illustrative example is provided by the implementation of *error-correction coding*. While in long-distance, high bit-rate systems the noise due to amplification and nonlinearity correspond to absolute physical limitations, error correction makes possible to restore signal quality to the required level, hence circumventing the physical barrier.

In the global communications field, optical telecommunications belong to the ‘physical layer’, which lies at the bottom of a seven-layer network model. With the accelerated development of broadband networks and the Internet, the focus has steered itself towards service performance and capital investment returns. Such an evolution has temporarily eclipsed the reality of the optical backbone layer, its highly elegant engineering, the result of 30 years of pioneering research and development. True enough, optical telecommunications have shifted from an *exploratory* age to an *exploitation* age. Moreover, its physics is well understood, and its performance level is well in excess of current needs. It is now a mature field which, for future growth, needs to take into account non-physical but essential considerations such as technology re-use, costs reduction, time to market, quality of service and added-value benefits. At the same time, innovation and technology breakthroughs require investigators to remain imaginative and creative, without being too much constrained nor held up by the above considerations. This represents an essential paradoxical situation for research in this field. At the same time, the growth of the Internet will require more innovation and new optical technologies in order to meet its irresistible capacity demand. This special issue on *Optical Telecommunications* provides the opportunity to present an inventory of the current optical technologies, from components to systems. It is also a privileged occasion to share with the physics and engineering communities as many expert views on what could be the next steps and challenges towards the development of future generations of systems.

## 3. Organization and contents of this volume

This volume is made from the contributions of 45 authors from both industry (Alcatel, Fujitsu) and Government/Academic institutions (Aston University, CNRS, Russian Academy of Sciences, University of Southampton). The conceptual order in which the 15 papers are presented is the following:

– limits of the optical communications channel;
– phoonic components, passive and active;
– multi-wavelength (WDM) transmission, terrestrial and submarine;
– WDM optical networks;
– forward-looking research: solitons, all-optical regeneration, holey fibers;
– quantum optical communications.

The ultimate transmission limits of the *optical communication channel* (article 1) are imposed by the accumulation of quantum noise, as generated by periodic optical amplification, and non-linearity noise, as caused by nonlinear interactions between – and within – WDM channels carriers. It is recalled that both noise types can be modeled by vacuum-noise couplings, or more simply, through Langevin-like quantum operators. Recent progress in the analysis made possible to revisit the famous *Shannon–Hartley* theorem, which links the channel capacity to the signal-to-noise ratio (SNR). The new formula takes into account both quantum and non-linearity noises, predicting maximum system capacities in bit/s per cycle of light oscillation. The concept of *information entropy* is also discussed, and an original analytical definition is obtained for binary-coded channels. It is shown that in-line optical regeneration corresponds to introducing *negative entropy* in the channel.

The following presentations (articles 2–5) cover issues in *passive optical components*. The first one concerns *designing fibers* for both WDM signal transmission and periodic dispersion compensation, and the key parameters involved. New perspectives for futuristic fiber designs are also described, such as *holey fibers* (see also article 14). The second concerns *fiber Bragg gratings*. From the possibility of 'writing' minute gratings in the core of fibers, a broad family of new optical components and functions was born. These concern optical filtering, gain equalization, optical add-and-drop multiplexing (OADM), dispersion compensation, and many other applications essential to WDM systems. The third concerns *planar lightwave circuits*. They also form a diversified family of passive photonic devices for WDM systems, in particular with large channel numbers and dense-multiplexing. Hybrid integration with *semiconductor optical amplifiers* (SOA) or micro-optoelectromechanical (MOEM) devices make possible dynamic loss compensation or variable attenuation, respectively. The last article of this group concerns *erbium-doped fiber amplifiers* (EDFA) and *Raman fiber amplifiers*. Although both devices must be pumped by semiconductor sources, they are passive to that extent that they only change the average signal power, without altering the signal's temporal shape. The parameters involved in the EDFA and Raman gain bandwidths, as well as the optimal choice of glass materials, are explained. For EDFAs, the presentation considers several component- and system-design issues, such as: gain saturation, power conversion efficiency, conventional and long-wavelength band operation, noise figure and SNR. Raman-based devices, which are used for *distributed amplification* over the transmission fiber, and as a complement of EDFA technology, are shown to cause significant SNR improvement.

The next set of presentations (articles 6–7) concerns *active optical components*. The first describes *photonic switches*, as based upon free-space and three-dimensional beam-steering technologies. Original design rules for switching scalability in WDM networks are provided. The second presentation focuses on *opto-electronic components*, which play a central role in telecommunication systems. This broad and interdisciplinary family includes laser-diode sources, modulators, WDM transmitters and receivers, in-line opto-electronic repeaters, all-optical regenerators and wavelength converters, to quote some of the main applications. The key integration technologies and their hybrid implementations are also described.

We consider next the domain of *signal transmission* (articles 7–9), as applied to both *terrestrial* (land-based) and *submarine* (undersea, transoceanic) WDM systems. While the two system types have lots of technologies in common, such as WDM sources, broadband optical amplifiers and high-speed receivers, they substantially differ in constraints such as transmission distance, amplifier spacing, and fiber type. According to these system constraints it is possible to select from a variety of sophisticated *signal modulation formats* and *error-correction coding algorithms*, which is described in the first presentation. The above signal-modulation and coding approaches have made possible to bring amplified terrestrial transmissions in the performance range of 6000 Gbit/s (6 Tbit/s) over 3000 km distances, as described in the second presentation. The progress in *long-haul WDM transmission*, as achieved from 1995 to date, is reviewed in detail. The different technologies involved in terrestrial systems, including 40 Gbit/s modulation formats, novel dispersion-managed transmission fibers and broadband Raman/EDFA amplifiers are also described. The domain of submarine communications is covered in the next presentation. Undersea systems have also greatly benefited from the aforementioned technology advances, bringing the performance to 400–3000 Gbit/s per fiber over transoceanic distances (10 500–6500 km). As in the previous case, the related system technologies are reviewed in detail. The niche domain of *unrepeatered* submarine links, which concern multi-Tbit/s transmission over 100–400 km spans without active line components, is also described.

After point-to-point WDM transmission technologies, the next layer of consideration is that of multi-*wavelength optical networks* (article 11). As mentioned in the previous subsection, optical transmission only represents the first (physical) layer of a multi-layer network concept. Higher-levels concern addressing, data encapsulation according to various protocols (SDH/SONET, Ethernet, ATM, TCP/IP, ...), switching, routing, all the way to the top session and application levels. Yet, as the presentation describes, the optical network layer represents a world in itself, because of the high complexity involved in managing multi-wavelength traffic, both in route allocation and node control. Issues such as network protection against link/terminal failures, their restoration, network services, design and planning from legacy, with emphasis on next-generation core and metropolitan networks, are also described.

The following three presentations (articles 12–14) concern what could be called *forward-looking technologies* in optical communication systems. The concept designates steadily-growing technologies which have not proven yet immediate potentials for disruptive innovation and implementation. This is partly because of the fact that older and classic technologies (as above described) have met most capacity needs so far. But innovative approaches will still be required in the next generation of systems, which illustrate the importance of long-term research. As mentioned in the introduction, optical fiber *solitons* represents a new form of pulse propagation in the nonlinear-dispersive regime. An important and recent discovery is that the soliton concept also applies to a wide range of pulsating regimes which can be controlled by appropriate line design and launching conditions, hence the name *dispersion-managed solitons*. Progress in this domain, as well as the tedious solving of the nonlinear Shrödinger equation are discussed in the first presentation. The domain of *all-optical signal regeneration*, described in the second presentation, represents the conceptual upgrade from passive in-line amplification. Indeed, the functions of pulse *re-shaping* and *re-timing* complete that of 're-powering' by amplification, hence the name '3R' signal processing. It is shown that all-optical 3R makes possible to asymptotically stabilize the SNR, corresponding to a regime of virtually 'infinite' transmission. Moreover, *simultaneous WDM regeneration* is possible, as was demonstrated by several experiments with rates up to 160 Gbit/s, which open new perspectives for low-noise, ultra-long distances and ultra-high bit-rates systems. The last presentation concerns the domain of *holey fibers*, also referred to as *photonic-bandgap* fibers. Their intriguing feature is that light is guided through *air*, more specifically through a micro-structured array of air holes clustered near the core center, resulting in an effective index profile. The different modeling approaches for such guiding structures are reviewed first. A description is made of *tigthly-confined* holey fibers (modal areas of the order of 1 $\mu m^2$), for applications to highly nonlinear devices, with a review of different glass materials. The presentation then considers *large-area* (of the order of 700 $\mu m^2$), and *rare-earth-doped* holey fibers. A wide range of telecom and other applications is then described, including femto-second and high-power tunable fiber lasers.

We finally conclude this review with a fundamental-physics flavor, considering the domain of *quantum optical communications* (article 15). The transmission of single photons (actually less than one photon per pulse in average) has important implications for secure *cryptography*. More precisely, the goal of the quantum-communications channel is to convey a one-time cryptographic key, with absolute confidence that no third party can intercept it, being provided by quantum laws. The presentation first describes the *quantum-uncertainty* aspects of laser sources, attenuators and amplifiers (see also article 1). Various techniques aiming to circumvent this quantum noise limitations are discussed. Then the state of the art in *quantum information, quantum-key distribution* and *quantum-entanglement*-based communications is reviewed.

## References

[1] S.E. Miller, A.G. Chynoweth (Eds.), Optical Fiber Telecommunications, Academic Press, New York, 1979.
[2] K.C. Kao, C.A. Hockham, Dielectric fibre surface waveguide for optical frequencies, Proc. IEE 113 (7) (1966) 1151.
[3] M. Chown, K.C. Kao, Wide-band fiber-waveguide communication systems for optical frequencies, Electr. Commun. 46 (2) (1971) 118.
[4] S.E. Miller, I.P. Kaminow (Eds.), Optical Fiber Telecommunications II, Academic Press, New York, 1988.
[5] E. Desurvire, The Golden age of optical fiber amplifiers, Phys. Today (1994) 20–27.

[6] C.J. Koester, E.A. Snitzer, Amplification in a fiber laser, Appl. Opt. 3 (10) (1964) 1182.
[7] J. Hecht, Optics and Photonics News, Optical Society of America, Washington, DC, 2002, pp. 36–39.
[8] A.M. Glass, Fiber optics, Phys. Today (1993) 34–38.
[9] E. Desurvire, D. Bayart, B. Desthieux, S. Bigo, Erbium-Doped Fiber Amplifiers, Device and System Developments, Wiley, New York, 2002.
[10] E. Desurvire, J. Chesnoy, Des milliers de conversations dans une fibre optique, La Recherche (1997) 64–71 (in French).
[11] J. Chesnoy (Ed.), Undersea Fiber Communications Systems, Academic Press, New York, 2002.
[12] A. Hasegawa, Optical solitons in fibers, in: Optics and Photonics News, Optical Society of America, 2002, pp. 34–37.

Emmanuel Desurvire
*Alcatel Submarine Networks*
*Centre de Villarceaux*
*91625 La Ville du Bois*
*France*
*E-mail address:* Emmanuel.Desurvire@alcatel.fr