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Optical telecommunications/Les télécommunications optiques

Active opto-electronic components

Composants actifs opto-électroniques

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Abstract

Opto-electronics has played a key role in long-distance cabled communications by offering high-performance, easy-to-use, compact devices at acceptable cost. Spreading throughout metropolitan networks and access networks and more generally facing the increasing demand for less expensive and wider bandwidth call for new functionalities and improved technologies. This evolution covers all fibre network components and their management: signal propagation and processing along fiber, opto-electronic interfaces, electronic processing, ... Issues, progress and perspectives of devices as enablers of capacity, flexibility and cost reduction are addressed. ***To cite this article: A. Carenco, A. Scavennec, C. R. Physique 4 (2003).***

Résumé

L'optoélectronique a joué un rôle majeur dans les liaisons câblées longue-distance en proposant à un prix raisonnable des composants de grande qualité, simples à mettre en œuvre et compacts. Pour aller plus loin dans les réseaux métropolitains ou dans les réseaux d'accès et plus globalement pour répondre à la demande croissante en bande passante à un coût réduit, il s'agit d'innover et d'améliorer les technologies. Cette évolution concerne tous les composants des réseaux à fibre, ainsi que leur gestion : gestion du canal de propagation dans la fibre, interfaces opto-électroniques, traitement électronique, ... Les difficultés, les avancées et les perspectives des dispositifs sont abordées ici sous l'angle de l'aide à la montée en débit, de la souplesse d'usage et de l'abaissement des coûts. ***Pour citer cet article : A. Carenco, A. Scavennec, C. R. Physique 4 (2003).***

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Mots-clés : Optique intégrée ; Opto-électronique ; Micro-électronique ; Télécommunications optiques

1. Introduction: optics everywhere?

Optics is playing a major role in telecommunications [1]. Wavelength-division multiplexing (WDM), enabled by the introduction of optical amplifiers (EDFA) [2], represents a simple solution for carrying on a single fibre very high rates of digital data multiplexed in the time domain. The mythic stream figure of 10 Tbit/s aggregating by 40 Gbit/s multi-wavelength tributaries has recently been achieved in point-to-point laboratory demonstration [3]. This expanding technology is both a

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driving force for optical components production and a source for innovation. It is also a powerful engine for the development of micro-electronics which has to provide the proper analog and digital interfaces with active optical components.

The past 25 years have clearly demonstrated the superiority of photons over electrons for long distance cabled communications: for core networks, the choice of the optical technology is well established, and current drivers for further developments are increase in bandwidth and implementation of switching and routing functions directly on the optical signal.

Optics keeps gaining parts in the telecommunication network market: from applications in long distance point to point links, optical technologies are now spreading throughout metropolitan and access networks. Within access networks, optical solutions are competing with several other broadband technologies. A major drawback of optical solutions is the cost of components. This will indeed require intensive developments on mass manufacturing and packaging.

The deeper diffusion of optical technologies into the network and the evolution towards a more transparent optical network infrastructure are largely correlated to the progress of opto-electronics. The following paragraphs will try to illustrate how opto-electronic technologies should enable us to meet the demands on capacity, flexibility and cost.

2. Status on opto-electronics for optical fiber transmission

Components and associated circuits have largely contributed to the development of optical transport networks. In the context of long haul and ultra long haul transmission, opto-electronics is playing a key role: firstly by offering devices or functionalities enabling simpler or higher performance architectures, secondly by establishing itself as a mature technology able to produce high-performance, easy-to-use, compact devices at acceptable cost.

It is worth noting the contribution of guided-wave optics approach to downscaling of opto-electronics, as well as the miniaturization of components which leads to increased performance, lower consumption, lower cost by batch processing.

'Off-the-shelf' transmitters, receivers, optical amplifiers, etc., are now available from a large number of suppliers.

2.1. Transmitters

See Fig. 1(a).

2.1.1. Fixed single-wavelength sources

Continuous-wave (cw) semiconductor lasers used in the 1.5 µm window have reached a high degree of maturity. Narrow linewidth devices with strained Multi-Quantum Well (MQW) structures based on InP/GaInAsP alloys are now produced by most manufacturers. Such lasers offer high performances, illustrated by DFB (Distributed FeedBack) lasers with up to 50 mW output power; with a Peltier cooler, their wavelength stability allows operation in conventional WDM systems with a 50–200 GHz wavelength spacing, without external stabilization. To allow a further reduction in wavelength spacing, a wavelength locker becomes mandatory, to be integrated in the module. Currently, many improvements are investigated aiming at reducing fiber coupling loss, extending wavelength coverage from 1500 nm up to 1610 nm and reducing cost, for instance by developing selection-free DFB structures with the proper spectral purity [4].

2.1.2. External modulators

Direct modulation of lasers can be used for bit rates of 2.5 or 10 Gbit/s. However, external modulation is required to reduce wavelength 'chirping' as needed in present $N \times 10$ Gbit/s transmission. A cw DFB laser and $LiNbO_3$ Mach–Zehnder modulator

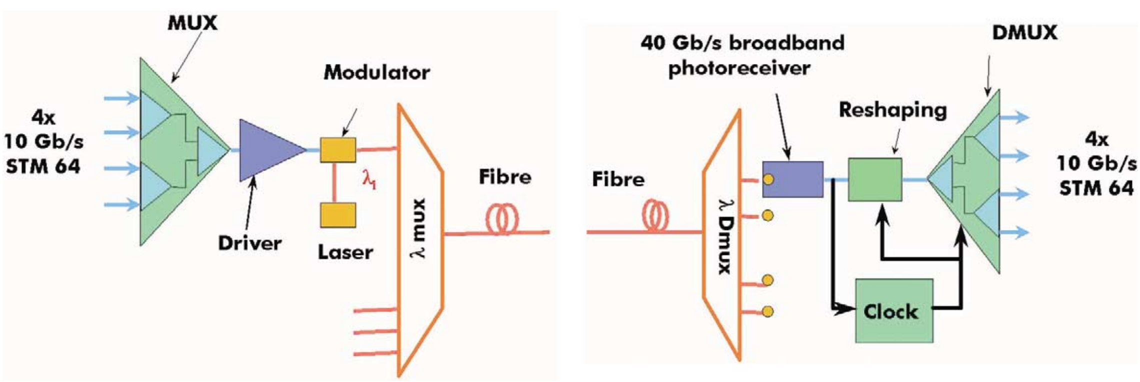


Fig. 1. Opto-electronics circuits layout: (a) transmitter; (b) receiver.

combination delivers a signal with low chirp, and is actually the reference for long distance transmission. The monolithically Integrated Laser Modulator (ILM) combination, in which an Electro-Absorption Modulator (EAM) is integrated with a DFB on the same InP substrate, has made much progress and presently appears as a choice solution for metropolitan networks. At 40 Gbit/s per channel, Mach–Zehnder (whether $LiNbO_3$ or GaAs) as well as EAMs are presently investigated, for RZ and NRZ transmission schemes, in order to assess their suitability to the different transmission applications. For future very high bit rates such as 80 Gbit/s or higher, EAMs offer a large potential for optical pulse generation and polarization-independent gating function, which are particularly important for time-division multiplexing (TDM) in the optical domain (OTDM) applications. Traveling-wave structures have also been demonstrated, well suited to extended bandwidth applications.

2.2. Receivers

See Fig. 1(b).

Front or back-side illuminated photodiodes designed for bit rates up to 10 Gbit/s provide easy fiber coupling, negligible dark current and high responsivity. High sensitivity photoreceivers are available, such as trans-impedance PIN-FETs (field-effect transistors) or receivers incorporating avalanche photodiodes. At 40 Gbit/s per channel, the responsivity of conventional InGaAs/InP surface illuminated photodiodes tends to decrease, and edge illuminated structures are developed to overcome this limitation, with direct or evanescent coupling. Such structures are characterized by a larger responsivity $\times$ bandwidth figure of merit (>40 A/W·GHz), and are suitable to a further increase in bit rate [5]. As electronic amplifiers with a flat gain over a large bandwidth are difficult to produce, optical preamplification is presently a preferred solution, providing enough signal to drive the receiver decision circuit. PIN photodiodes able to withstand a high optical power are being developed for such a scheme. This obviously leave little room for avalanche photodetectors (APD) which are difficult to design for high bit rate applications, due to their limited gain $\times$ bandwidth product.

2.3. In-line components

Optical amplifiers providing signal regeneration require increasing power from pump lasers. This increase in power results from the increasing count of channels in WDM systems: as the power per channel at the amplifier output is kept constant (1 mW or more), while the number of channels is getting close to 100, high pump powers (a few 100 mW) are now required. Pumps are presently developed, either using GaAs-based materials (980 nm pump) or InP-based materials (pump at 1480 nm for conventional amplifiers and at slightly lower wavelength for Raman amplifiers). Improved stripe design, low series resistance and good thermal dissipation are key criteria towards high coupled power.

2.4. Microelectronics

Presently, systems in operation are working at bit rate up to 10 Gbit/s per channel. 40 Gbit/s systems should be deployed in a few years from now. Different integrated-circuit (IC) technologies are used in transmitters and receivers. In recent years, much progress has been accomplished with SiGe bipolar and Si CMOS (complementary metal-oxyde semiconductor) technologies, tending to displace prevailing GaAs MESFET (metal-semiconductor FET) and HEMT (high electron-mobility transistor) technologies. Price and performance, including power consumption, are key drivers for these electronic parts. Obviously with the simultaneous requirements of high voltage (whether for driving Mach–Zehnder or EAM) and very high speed (Fig. 2), Si/SiGe technology is not meant to cover all needs. GaAs and InP microelectronics are expected to continue to play a key role at the higher bit rates, probably through a multi-chip approach combining Si and III–V technologies [6,7].

3. Technical barriers

Optics is a pervasive technology in the telecom network. To ensure provision of enough bandwidth in the core network and to allow further spreading of optical technologies in metropolitan-area networks (MAN) and local-area networks (LAN), several extra features are recommended by network engineers regarding opto-electronics. Research will have to overcome a number of technical barriers to make opto-electronics an attractive cost-effective solution. Some key areas for developments of new components and technologies are given hereafter.

3.1. Higher capacity

An increased number of wavelengths per fiber, which calls for extended wavelength bands, combined with higher bit rates per channel (e.g., 40 Gbit/s), which require opto-electronic components (modulators, detectors) and associated electronics

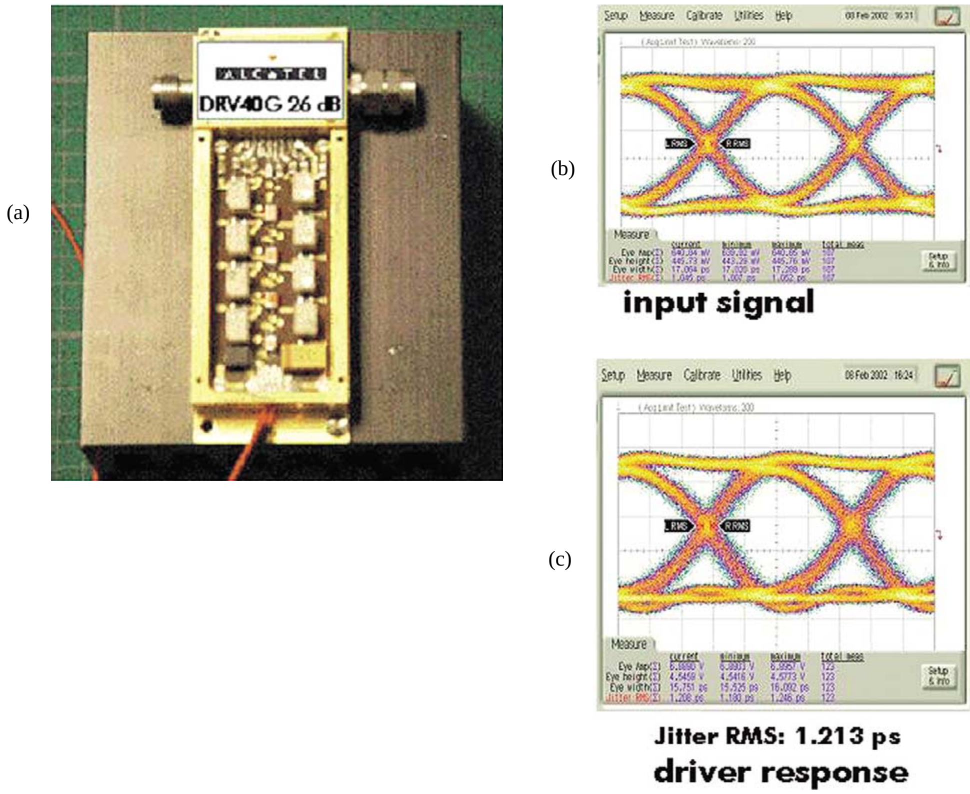


Fig. 2. Optical modulator driver based on p-HEMT GaAs technology: (a) 26 dB packaged module with a cold start circuit; (b) input 40 Gbit/s signal; (c) amplifier output.

(III–V, SiGe) with improved characteristics (reduced power consumption and footprint) will provide a reduced bit transmission cost.

Even if 10 Gbit/s-based transport will be exploited in the coming years, 40 Gbit/s-based technology will be a viable successor when various technical and business issues are solved. Advanced electronics functions beyond multiplexers, demultiplexers, and decision gates, will include high-bandwidth adaptive electrical equalizer filters, with the associated monitoring device.

3.2. In-line processing

Beyond improved optical amplifiers (and associated pumps), dispersion compensators are needed as well as opto-electronic and optical components for 2R and 3R regeneration (the three Rs standing for Re-amplification, Reshaping and Retiming), with WDM and dense-WDM (DWDM) compatibilities. The WDM technique is providing more and more channels per fiber, which means a corresponding increase of regenerative circuits number (one per wavelength). At the same time the bit rate per wavelength is evolving at a very fast speed in trunk lines, so that it could soon get beyond what electronics is able to process.

3.3. Optical interconnection

An increasing amount of data must be processed in the nodes of the network and it is clear that electronic signal processing will become a bottleneck very soon, in terms of power consumption, footprint and finally cost in regeneration. Room is left for optics to bring solutions for processing signals collectively or by wavelength sets.

Following Moore's law for electronics, and similar progress in other technologies such as optics, new generation switch/routers and cross-connects will pursue their roadmap towards higher capacity and smaller footprint. In order to reduce the number of costly opto-electronic conversions, optical routing and switching have to be considered. In particular slow (and large) switching matrices for routing applications, as well as fast switches (for packet switching for instance). A new hybrid generation, called 'electronic/photonic crossconnects' sounds attractive. The key underlying technologies are highly-integrated, 40 Gbit/s-granularity short-reach optical interconnects.

Tunable lasers and filters with a high wavelength stability would also provide useful solutions for future reconfigurable optical networks. Fast tuning could pave the way to optical packet management.

4. Challenging technologies: towards cost-driven, integrated, flexible optics

The opto-electronic components industry, which is quite recent, has to face the present key market drivers: cost and integration. Whether new *disruptive technologies* can be expected is also a point worth considering.

Recently a lot of effort has been devoted to optical technologies providing *wavelength agility*, such as tunable lasers and filters, wavelength converters and optical switches. Most tunable laser solutions on the market are not compatible with metro applications as they do not incorporate the multi-Gbit/s modulation capability that would make them attractive as far as cost is concerned. Small *optical switches* are now available, although cost is often felt to be too high. *Reconfigurable optical add-drop devices and filters* are more likely to be rapidly integrated in systems and networks.

A few examples where research is presently active and could bring new openings for enlarging the panel of available optical solutions are given below.

4.1. Low-cost techniques

Future networks will have a strong need for photonic systems with a variety of advanced functionalities including passive optical functions, non-linear optical functions, active opto-electronic functions and electronic functions.

The *challenge* is to fabricate low-cost package-able components from a wide range of material systems and to develop manufacturing platforms; to integrate multiple functions on a single photonic chip; to assess manufacturing and fabrication compatibility of functional blocks implemented in different material systems.

Monolithic integration on InP is already developed at the photonic integrated circuit level, with multi-section lasers, laser-modulators or transmit-receive devices. Opto-electronic integrated circuits have also been demonstrated, for example PIN-FET monolithic receivers with functional characteristics equivalent to their hybrid counterparts. However, integration is not meant to happen for optical devices the same way it did in microelectronics, since most often devices made in different technologies are to be integrated.

In a different approach (Fig. 3), *hybrid integration* and pig-tailing of active and passive devices onto SiO_2/Si mother boards bring what appears as the proper solution to the functional and technological variety of devices based on different material systems (GaAs, InP, $LiNbO_3$, glass, polymers, etc.) to be integrated [8].

With a substantial reduction in size and in alignment constraints both on fibers and on active components, hybrid integration is meant to bring major changes to the opto-electronic components industry.

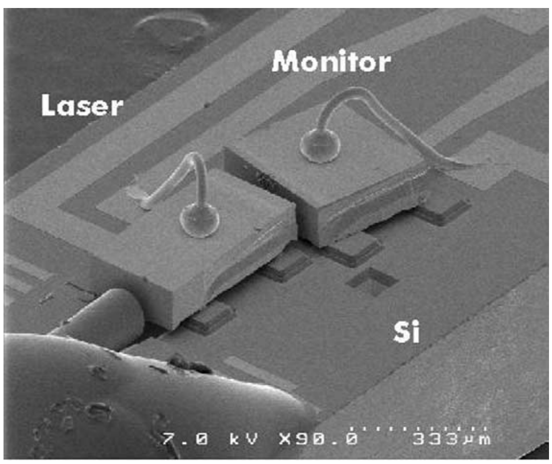
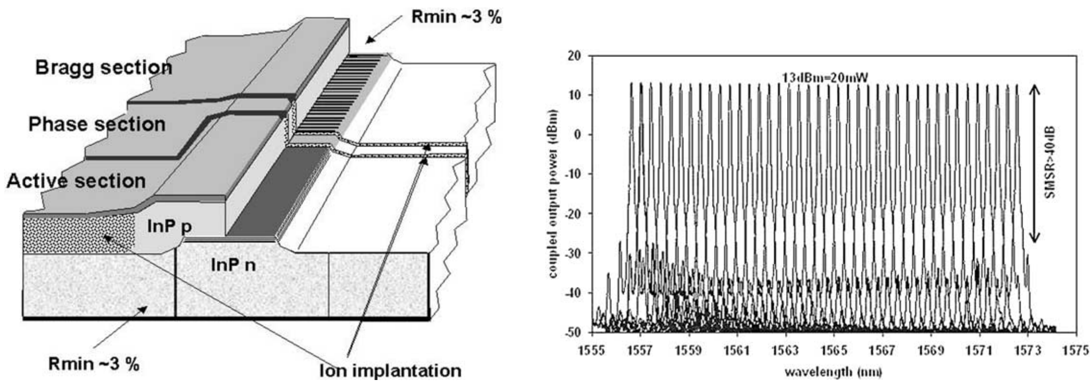


Fig. 3. Hybrid opto-electronics circuit: flip–chip InP laser with monitoring edge detector and fiber pigtail on a Si submount.



(a) (b)

Fig. 4. Three-electrode DBR laser: (a) cross section; (b) spectral tunability (47 channels – 18.8 nm at 20 mW).

4.2. New functionalities

4.2.1. Tunable WDM sources and filters

Tunable lasers address applications such as sparing and dynamical wavelength translation. A specific class of lasers includes tunable lasers: among them, Distributed Bragg Reflector lasers (DBR) are reaching commercial maturity [9]; DBRs (Fig. 4) can provide an output power of 20 mW and are able to cover a wavelength range of about 15 nm with a 50 GHz step on the standard ITU grid. DBRs are expected to find applications not only as spares for WDM transmitters, but possibly in network architectures based on wavelength routing. Of course, wavelength tuning requires some specific control electronics. More sophisticated structures, including vertical cavity devices with moving mirrors, such as the micro-opto-electro-mechanical (MOEM), are also investigated to provide continuous tuning or wider wavelength range.

Wavelength-selectable lasers are also of interest for future networks. Cooler-less Fabry–Perot lasers, with attached a-thermal in-fiber Bragg gratings (IFBG) have been shown to operate with a stable wavelength set by the IFBG.

4.2.2. Optical signal processing

For processing and switching, which are mainly addressed at present by the microelectronic technology, a growing importance of optical processing, in particular as the bit rate increases, can be envisioned.

For the next generations of nodes, it is therefore necessary to investigate the potential of ultra fast optical signal processing technologies. Ultimately, the increasing speeds needed for optical signal processing will require the use of femtosecond technology. This research area needs breakthroughs in material engineering and photonic integration technologies. Recent progress in semiconductor nano-technology and materials could fuel the required breakthroughs.

The evolution towards ultra high capacity optical packet switched networks requires the development of novel all-optical signal processing functionalities to generate, regenerate, route, switch, wavelength convert and detect optical data packets at ultra-high speed. In order to have those functionalities implemented, a number of issues will have to be solved, for instance, synchronization and clock extraction for different modulation formats.

4.2.2.1. Switching SOA gate arrays. Optical space switches of various kinds are developed for applications in optical network, intended to perform operations such as protection or routing. In both cases the required reconfiguration time is slow, of the order of 1 ms, and is best obtained from micro-optics solutions, including MOEMS matrices.

In future photonic networks, or when switching is envisioned at the packet level, much faster devices are required, calling for electro-optic or low voltage semiconductor technologies. Fast optical switches, with nanosecond response time, are required to turn such concepts into actual functions. The Semiconductor Optical Amplifier (SOA), used as an optical gate can bring the right solution. For the fabrication of switching matrices with sufficient capacity, SOA arrays are needed, integrated on a SiO_2/Si mother-board for instance [8].

Actually the SOA appears as a generic opto-electronic device, like a laser or a photodiode, allowing the design of many functions of interest: fast switching, wavelength conversion or selection, optical regeneration, not to mention its basic amplification characteristics, attractive in metropolitan networks, even though the properties are not as good as those of fiber amplifiers'.

4.2.2.2. 3R WDM regeneration. Full (3R) or partial (2R) optical regeneration could become a disruptive technology, if its cost-effectiveness and efficiency are demonstrated [10].

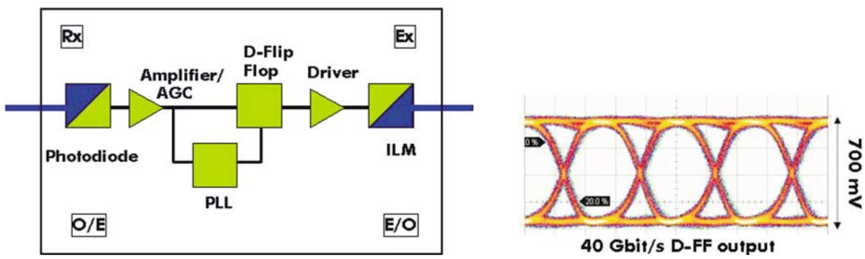
In present repeaters (Fig. 5), or in an optical cross-connect, transponders are accounting for a large share of the total cost. Replacing present transponders by optical regenerators (Fig. 6) could save much of the system cost, and allow more compact and integrated components [10]. This potential advantage would be expected to increase as bit rate increases, or if an optical regenerator could be designed able to operate on a wavelength multiplex. This would represent as much a disruptive technology as optical amplification has been in the past. Major progress has been accomplished in this area in recent years: for instance (Fig. 7) 2R at 40 Gbit/s with non-linear Mach–Zehnder interferometers based on SOA [11], and more recently with saturable absorbers. Semi-conductor saturable absorbers have allowed to double the transmission range of 20 Gbit/s signal, from 3400 to 6800 km [12].

Optical clock recovery (OCR) for 40 Gb/s data stream have already been demonstrated by using for example self-pulsating lasers [13]. OCRs operating at 80 and 160 Gbit/s appear as a realistic target [14].

4.2.3. Duplexor access terminals

The best of wired and wireless technologies must be generated in order to improve the access to private and business users. Low-cost evolutions of opto-electronics devices are required for making FTTX viable in the *access network*. In the FSAN (full-service access networks) initiative, simultaneous emission/reception is anticipated, using both 1.3 and 1.55 µm wavelengths at 155 Mbit/s or higher. Lasers able to operate without Peltier cooler over a large temperature range are required for such applications. Obviously cost is mainly dependant on the integration technology. While the micro-optics approach, relying on the assembly of discrete components, allows the sensitivity requirements to be reached, a more promising solution is expected from the integration of the active devices on a SiO_2/Si mother board.

Another solution involves the monolithic integration of the laser and photodetector. Such a device has been demonstrated [15], able to fulfill FSAN B specifications, at 155 Mbit/s. Providing further progress is accomplished, in terms of crosstalk, and thus sensitivity, this solution could help to bring FTTH closer to reality.



(a) (b)

Fig. 5. O/E/O interface: (a) standard 3R regeneration approach; (b) 40 Gbit/s output signal from a HBT InP D-Flip–Flop circuit (Alcatel R&I).

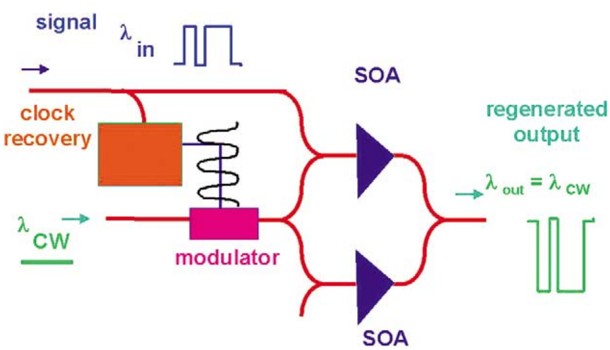


Fig. 6. 3R all-optical regeneration set up: a cw laser at λcw is modulated with the clock signal recovered from input signal at λin; the SOA-based Mach–Zehnder interferometer (MZI) regenerates the input signal at λcw; a second stage MZI can convert the signal back to λin and restore the incoming polarity.

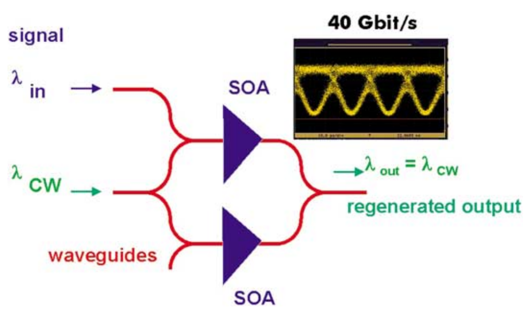


Fig. 7. Integrated SOA wavelength converter: 40 Gbit/s converted signal from 1552 nm to 1560 nm.

4.2.4. Radio components

Beyond FSAN, other network architectures are worth being investigated, for instance mixing optical and wireless technologies to bring large bandwidth to the customer. Delivery by a more flexible and powerful wired infrastructure will be needed for the wireless connections. The demand for more capacity will result in smaller radio cells, more efficient use of the limited number of available radio channels and the introduction of intelligent networks combining optical fibre network feeders with smarter antennas and higher radio carrier frequencies.

Simultaneously, very compact opto/radio converters should be developed to bring broadband to an increasing number of mobile terminals.

4.3. Disruptive technologies

While the developments mentioned so far are expected to result from the evolution of already mastered technologies, new possibilities are offered by technologies which are still in their infancy and could bring real breakthroughs.

4.3.1. Photonic crystals

Such artificial material structures, acting for light the way a semiconductor acts for electrons, could be used to control the optical properties of materials and thus to open new applications or functionalities. One of the keys in this is to use wavelength-scale confinement of optical signals, which calls for the use of high refractive index contrast structures, such as, for example, photonic crystals. These structures require an accuracy of at least an order of magnitude smaller than the wavelength.

Many challenges are still to be addressed, but encouraging features have been highlighted on preliminary samples, in terms of a drastic miniaturization of optical circuits and enhanced dispersion properties. Dispersion engineering could be tailored for achieving very compact integrated dispersion compensation functions.

4.3.2. Quantum dot technology

The evolution from a bulk, three-dimensional active layer structure to quantum wells already brought improved characteristics to lasers. With a dimensionality reduced to 1 or even 0 (quantum dots of a few 10 nm in diameter) a further improvement in characteristics is anticipated (in dynamic properties for instance).

It is worth noting the very high characteristic temperature (>200 K) recently measured on high performance GaAs 1.3 µm lasers [16]. Extension to 1.5 µm is the next challenge.

4.3.3. New materials

Opto-electronics material characteristics still limit device performance and functionality. It is very important to find ways of improving the characteristics of existing materials and to look for new materials, i.e., polymers that are promising for electro-optical modulation at 40 Gbit/s and above.

As far as III–V materials are concerned, much attention is presently paid to materials and heterojunctions with improved thermal stability, emitting at 1.3–1.6 µm. Such materials would largely simplify the attached electronics or could avoid the use of an expensive Peltier cooler. Low band-gap nitrides grown on GaAs substrates appear as good candidates for this application.

Similar investigations are carried out in the companion III–V microelectronics area where Sb-based materials are considered for their specific bandgap offset properties. In particular a higher cut-off frequency is expected from InP-based HBT (heterojunction bipolar transistor) incorporating a GaAsSb base layer which helps the injection of high speed electrons in the high breakdown collector. This HBT structure could provide a sound basis for the development of electronic ICs operating at 80 Gbit/s or even 160 Gbit/s which are presently beyond the capability of currently available technologies: at least in the next decade, OTDM techniques are expected to be used for ultra-high bit rates, quite likely bringing new concepts for transmission.

4.3.4. New concepts

Many new concepts able to generate disruptive technologies or technical approaches are presently considered in research laboratories. One example is given by Inter-sub-band transitions in quantum wells which offer sub-picosecond relaxation times and large non-linearities which could be very useful to implement broadband, ultra-fast and highly efficient all-optical switches; first investigations within the 1.2–1.6 µm range on AlAsSb-based structures are very promising [17].

5. Conclusions: faster, better, cheaper

Components are crucial enablers of other economic activities for delivering competitive, efficient and reliable products and services in a timely manner. With the development of WDM and high capacity links and generalized broadband access demand,

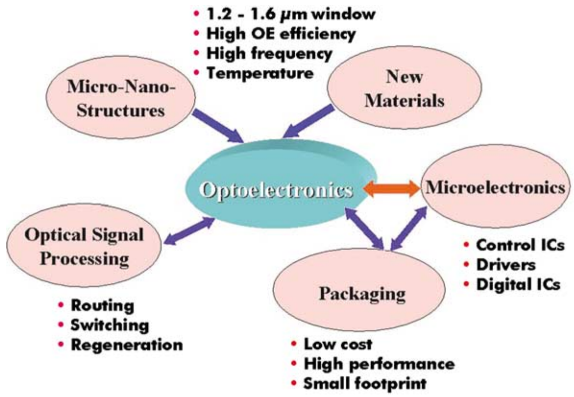


Fig. 8. Opto-electronics: an interdisciplinary field.

we are reaching a stage where further scaling will create opposite effects, such as growing energy consumption, complexity and costs. This implies work at the device level and at the ever growing level of function integration [18].

Advanced competitive products increasingly depends on excellence in designing and producing the basic building blocks. Opto-electronics is an interdisciplinary science which is increasingly linked with micro-electronics and micro-systems (Fig. 8).

The photonic industry is very new compared to Si microelectronics and has not reached the same level of maturity. The manufacturability aspects now need more attention from the research community in order to achieve the economics of scale which are necessary to make low-cost products. Competition towards high-speed IP services driven by emerging fiber-to-the-home (FTTH) markets would bring incentive for cost effective systems offering.

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