Chapter

All Optical Signal Processing Technologies in Optical Fiber Communication

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Abstract

Due to continued growth of internet at starling rate and the introduction of new broadband services, such as cloud computing, IPTV and high-definition media streaming, there is a requirement for flexible bandwidth infrastructure that supports mobility of data at peta-scale. Elastic networking based on gridless spectrum technology is evolving as a favorable solution for the flexible optical networking supportive next generation traffic requirements. Recently, research is centered on a more elastic spectrum provision methodology than the traditional ITU-T grid. The main issue is the requirement for a transmission connect, capable of accommodating and handling a variety of signals with distinct modulation format, baud rate and spectral occupancy. Segmented use of the spectrum could lead to the shortage of availableness of sufficiently extensive spectrum spaces for high bitrate channels, resulting in wavelength contention. On-demand space assignment creates not only deviation from the ideal course but also have spectrum fragmentation, which reduces spectrum resource utilization. This chapter reviewed the recent research development of feasible solutions for the efficient transport of heterogeneous traffic by enhancing the flexibility of the optical layer for performing allocation of network resources as well as implementation of optical node by all optical signal processing in optical fiber communication.

Keywords: defragmentation, format conversion, grooming, multicasting, optical signal processing, semiconductor optical amplifier, wavelength conversion

1. Introduction

In recent years, with the proliferation of cloud computing and high-definition media streaming increasing the use of communications and information technology in photonic infrastructure. Fiber capacity crunch concerns are driving optical networking toward a spectral-efficiency-conscious design philosophy. Moreover, as the number of various high-capacity services increases such as video delivery service and data centers, transport network flexibility will become important, resulting in the demand of elastic transport optical networking [1–5]. Key methods for empowering the elastic/flexible optical system are: single SDN XCVR, BW increase, flexible spectrum approach, Multicore fiber using the SDM technology. Nonetheless, it would be cost-restrictive to convey an entirety set of advances.

Therefore, in the next generation optical communication, optical nodes will need to allocate resources in an elastic and effective way to professionally provision high and low data rate signals [6]. To represent this evolving network scenario, an elastic network is proposed and demonstrated, providing elastic resource allocation in spectrum as a means to address the disparity between required and allocated bandwidth. By using this technique it is possible to assign a customized bandwidth per channel depending on specific requirements. Elastic allocation in the spectral domain implies that the standard 50-GHz ITU grid is not used and a continuous spectrum can be allocated to accommodate high-capacity channels with large bandwidth requirements. Also, channels that require lower bandwidths can be accommodated more efficiently by using narrower channel spacing as long as the performance is not compromised. Next generation optical networking is expected to cope with a number of challenges, especially in terms of elastic optical nodes [7], as there is always a need of increasing flexibility in the allocation of spectral and temporal resources so that they are able to efficiently support on-demand services and functionality.

Apart from the obvious advances in capacity and performance, it is clear that with each progressive stage of evolution of the optical node, additional flexibility has been introduced, e.g. the introduction of wavelength granularity, the ability to add/drop individual wavelengths, reconfigurability, etc. Other types of functionality may also add flexibility to the system, e.g. wavelength conversion (WC), format conversion (FC), multicasting (MC), regeneration, etc. In [8] a broadcast and select node based on bandwidth-variable wavelength selective switches (BV-WSS) was proposed. However, the very nature of this architecture will restrict upgradeability and will limit support for evolving requirements and new functionalities, e.g. optical signal processing. However, in Reconfigurable Optical Add Drop Multiplexer (ROADM) architectures [9] it is difficult to introduce additional functionality due to the fact that several wavelengths are simultaneously switched over the same port. On the contrary, OXCs support additional functionality more naturally as wavelengths are split and switched individually. Thus, modules with the required functionality to operate on individual wavelengths can be positioned in the right place within the OXC. However, the requirement for a particular signal processing function is often uncertain, e.g. it may be required for some wavelengths at some time period and for other wavelengths at a different time period. Therefore, modules that provide a per-channel functionality are generally deployed for all wavelengths as there is no possibility of sharing them among several optical paths inside the OXC. A better solution would enable modules to be shared, thus improving modules' utilization and reducing the amount of modules required to satisfy a given demand for the offered functionality, i.e. better hardware utilization and efficiency.

WDM networks utilize routing and wavelength allocation (RWA) algorithms to find available resources for new requests. However, in elastic optical networks the problem is more difficult due to the new flexible spectrum allocation, where elastic spectrum bands rather than single wavelengths are considered. For new requests with specific bandwidth requirements, routing and spectrum allocation (RSA) algorithms need to identify sufficiently wide spectrum slots that are available from source to destination. Furthermore, as channels are added and removed, they leave behind noncontiguous slots of free spectrum. Although these fragments may add up to a considerable amount of bandwidth, new channel requests may be blocked due to the lack of sufficient contiguous spectrum [10]. Spectrum fragmentation may be prevented to some extent by introducing appropriate policies in RSA algorithms. Alternatively, techniques to defragment the spectrum may also be utilized, e.g. using wavelength conversion.

Another issue of optical node is that, it should manage transport of blend of suppliers' traffic facilities for legacy signals, core traffic and multiple format signals with variable bit rate. Thus, flexible optical nodes will ought to assign resources in an adaptable and proficient way to back a blend of super-channels and lower speed channels. The nodes' density will mainly influenced on the link interoperability between segments (i.e. core segment: need signal processing and to support super-channels, metro segments: might carry legacy 10 Gb/s [11] links).

To address increasing traffic growth, the most straightforward and economical way in which this can be done is to deploy additional 10G wavelengths. Thus, new 10G wavelengths are placed 50 GHz, according to the standard WDM grid, until the available bandwidth is exhausted. However, the maximum capacity that can thus be provided is 800 Gb/s (i.e. 80 × 10 G using only the C band), which is already in sufficient for heavily used backbone network links. Furthermore, providing additional capacity in this manner is highly inefficient in terms of the spectral resources that are consumed. The immediate solution to this problem is to deploy 100 G links, despite their higher cost compared to 10 × 10 G. 100 G is more spectrally efficient than 10G as it can fit in a standard 50-GHz WDM slot, advance modulation formats (like DP-QPSK), coherent detection, extensive use of Forward Error Correction (FEC) and electronic impairment mitigation. However, this solution is expected to be viable only for the short and medium terms. For super-channels at 400 Gb/s [12], 1 Tb/s [13] and beyond [14, 15] will occupy broader spectrum, require more complex multilevel modulation formats with higher OSNR and consequent shorter reach which neither fits within the existing ITU grid nor is supported by conventional optical network infrastructures. For instance, optical cross-connects and ROADMs allocate only discrete 50-GHz slots of bandwidth due to their internal WDM (de)multiplexers. Channels that require wider bandwidths are severely distorted if passed through such devices. Therefore, in order to efficiently support high-speed channels, a flexible bandwidth infrastructure is required.

In spite of the increasing popularity of elastic optical networks, there has been very little work focusing on elastic node architectures. Therefore it is critical to investigate the details of realizing optical networking solutions toward flexible and efficient allocation of network resources. Further, provide fully functional intelligent infrastructure for simultaneously supporting the switching and transport of combination of high-capacity super-channels and lower bit rate channels [16]. How elastic nodes support dynamic and on-demand provisioning of functionality, such as spectrum defragmentation, wavelength conversion, regeneration, grooming, format conversion, time multiplexing, etc. leaves the door open for future research.

2. The roadmap toward elastic optical networks

A number of different industry surveys indicate the global IP traffic is increasing at a startling rate i.e. more than 30% per year [17] and estimates that by 2025 the Internet will burn 7% of the 2010 global electricity supply [18]. This heralds the start of a huge wave of data driven mainly by broadcasting or multicasting, streaming of IPTV, high-quality videos using ultrahigh-definition (4 k _ 8 k pixels) videos and rich media files that clients migrating to an all smart phones and tablets, enabling video to be consumed more conveniently stored in cloud architecture such as Microsoft Azure or Apple's iCloud via network connections anywhere, anytime.

To cope with this expected growth in traffic volume technological advances to date have allowed an increase in DWDM data rates to higher than 100 Gb/s per optical carrier, but these technologies will soon be close their practical or theoretical limits. To offset this growing trend and the consequences of unbridled demand, research efforts are focused on the ways to improve the efficiency of these networks, often by leveraging photonic alternatives to provide improved performance [19]. The evolution of optical nodes and networks has been characterized by continuous enhancements in the parameters listed in **Figure 1**. These parameters are inter-dependent and their relative temporal evolution, combined with the related network economics, will dictate the exact network evolution, assuming maturity of the available technology. For an optical network to accommodate all the above requirements, it must transparently transmit, switch channels (e.g. wavelengths,

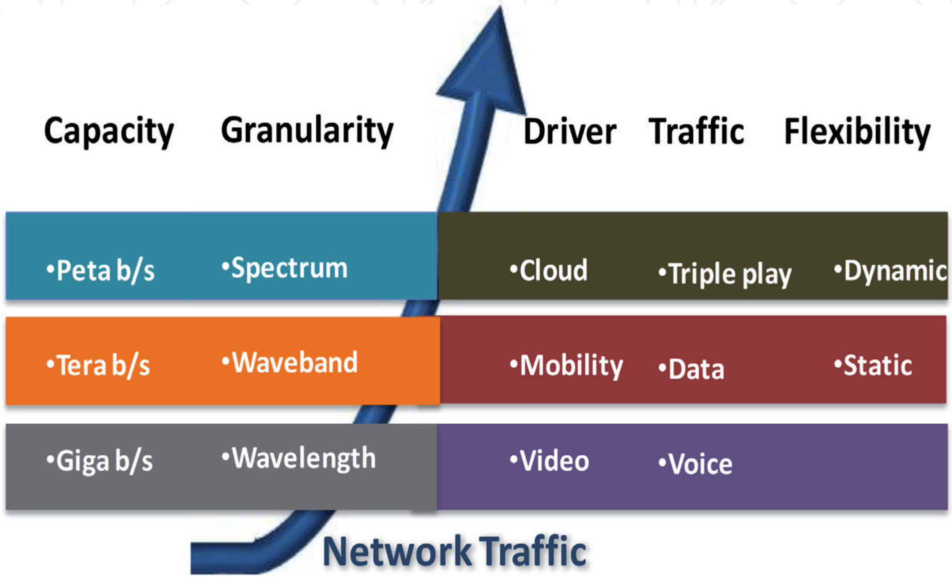


Figure 1.
Vision for a transparent reconfigurable optical network: it is the relative development of the each of five parameters with respect to time and that will dictate the network evolution.

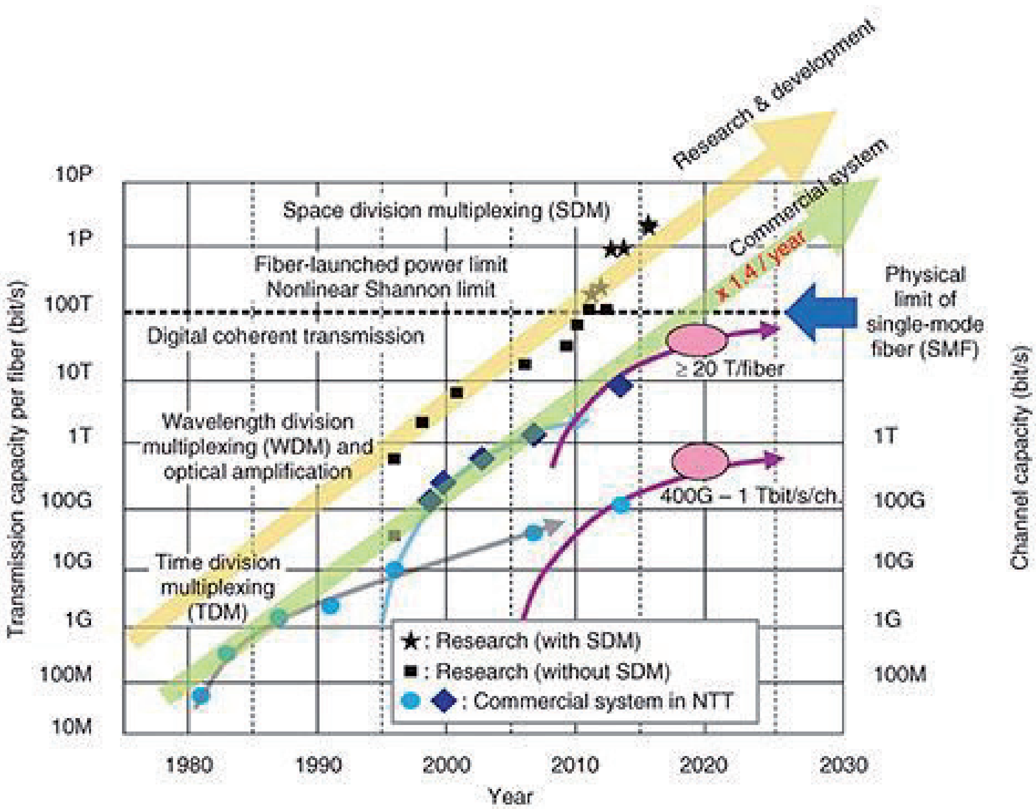


Figure 2.
Evolution in optical transmission technology [22].

wavebands, sub wavelength channels) and provide on-demand bandwidth in a scalable and reconfigurable fashion [20].

The graph (**Figure 2**) shows that the evolution of transmission capacity x fiber link has been growing over the years. The optical fiber bandwidth utilization approaches its peak limit quickly. Given the potential for such capacity crunch, the research community has concentrated on finding alternatives that make the most of the scarce network resources and meet the consistently expanding traffic requests [21]. In such context, adaptability or reconfigurable capability of networks will become more and more critical and hence spectrum efficient optical networking techniques have been introduced as a way to offer efficient utilization of the available optical resources. The place to start is with the transport network, which forms the foundation of elastic networking.

Currently, all deployed optical transport technologies are mainly based on a fixed grid 50 GHz or 100 GHz/frequency grid standardized by ITU-T and the same modulation technology has been used for optical signals at the same bitrate regardless of the transmission distance. In this scenario, the system is reaches its limits in terms of both capacity and flexibility [10, 23, 24] as higher capacities per fiber have been achieved by improving the spectral efficiency (SE) through increasing the bitrate per channel while keeping or even narrowing the channel

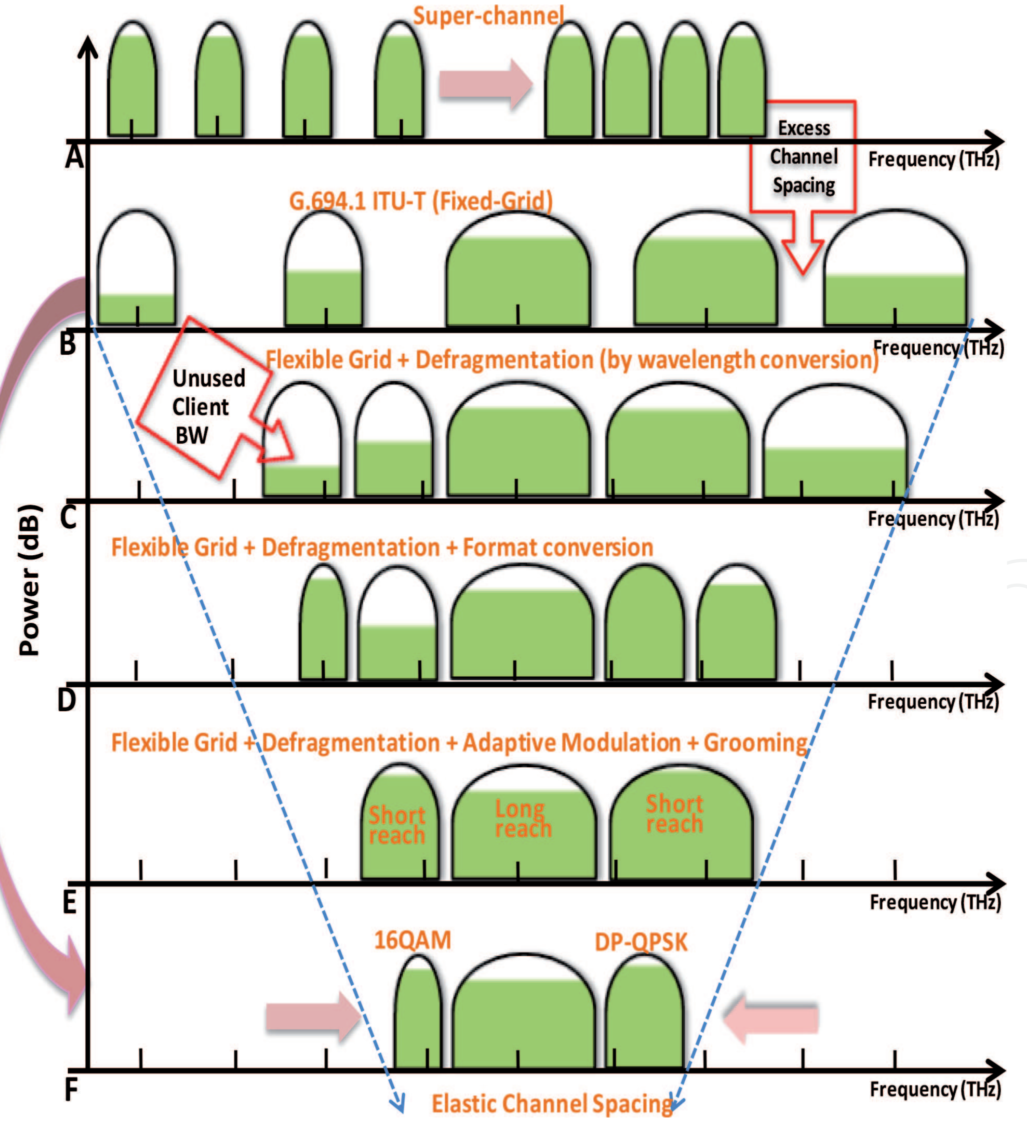


Figure 3.
Roadmap toward elastic spectrum by all-optical signal processing based on transmission distance and user traffic volume [27].

spacing. In order to fully realize the vision of elastic optical networking, network operators have migrated to flexible transport technology solutions capable of supporting grid spacing flexibility. Opportunities for exploiting underutilized spectral resources are shown in **Figure 3**. The essence of elastic optical path network yields highly-efficient optical path accommodation. The resulting spectral savings is achieved by taking advantage of the spectral resources that had not yet been fully utilized, thus results in an increase in network capacity [25]. Let us consider an example in which mixed-rate with different modulation format traffic is transported in a single fiber. For spectrum A, four 100-Gb/s optical channels headed for the same destination. These can be combined them into a tightly spaced 400-Gb/s superchannel and transported as a single entity by eliminating the unnecessary spacing between the channels. Spectrum B shows the ITU-T fixed grid with excess channel spacing. In the next step (spectrum C) implement a flexible grid by using the all optical processing technique i.e. defragmentation. For client traffic that does not fill the entire capacity of a wavelength, the elastic optical path network provides the right sized intermediate bandwidth [26] by format conversion through adaptive modulation represented in spectrum D. This makes the unused client bandwidth available for use. The wavelengths routed in the same direction, grooming is performed as illustrated in spectrum E. Finally in spectrum F, for shorter optical paths, which suffer from less SNR degradation, employment of more spectrally efficient modulation format, such as 16QAM or DP-QPSK, further combined with elastic channel spacing, where the required minimum guard band for wavelength routing is assigned between channels is performed [25]. In this way, elastic optical path networks accommodate a wide range of traffic in a highly spectrally efficient manner [26].

3. Optical switching paradigms

To appreciate the benefits and challenges of all optical networking, it is instructive to review switching in the optical layer. In this section, we first discuss the carrier perspective on the design, functionality and application of switching technology.

Ongoing years have exhibited the constrained versatility of electronic switching changing to acknowledge transport systems. In reaction, all-optical switching/processing has been recognized as a candidate arrangement to empower high-capacity communication within the future. One of the elemental challenges is to proficiently bolster a wide range of traffic configuration, driving the requirement for hardware that is affordable to construct and deploy [28]. The purpose is to identify the key switch technology which can be used in the gridless elastic network scenario.

3.1 Switching technology

With the growth of network traffic due to continue to meet the insatiable consumer demand for transmission bandwidth, the need for more flexibility and better control over network capacity which drives the need for switching in the optical domain is apparent [29]. **Figure 4** shows a potential photonics switch evolution. The switch fabric circuit is the fundamental building block of the next generation optical network, distributing all network traffic from ingress ports to egress ports and also providing the functionality of sharing the spectrum in the time domain with respect to sub wavelength switching. The performance of switch fabrics is very critical in network applications. Efficiencies must be delivered via the use of switch management which is autonomic and guided by intelligent software algorithms.

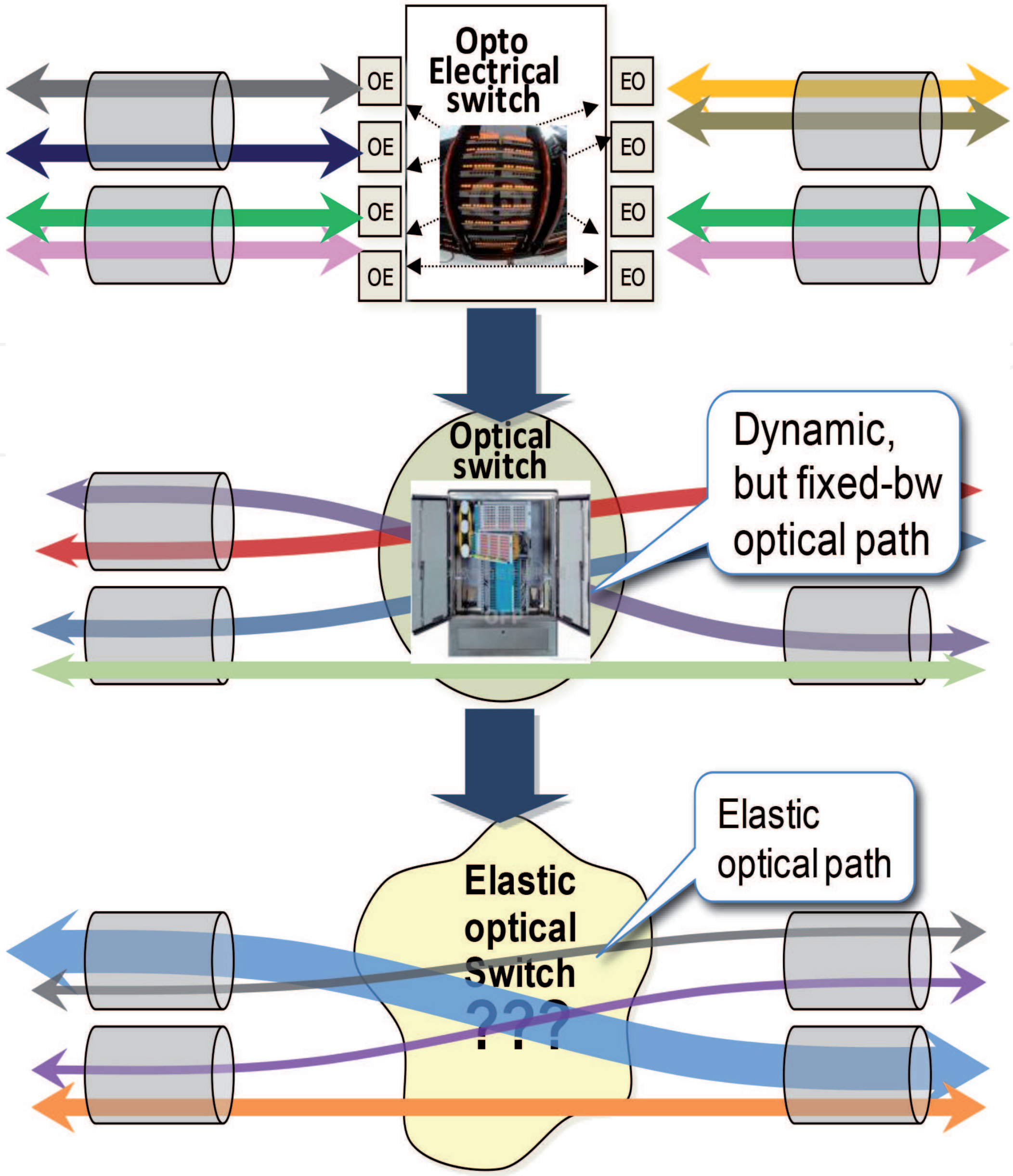


Figure 4.
Photonic switch evolution [27].

As mentioned elastic optical communication are based on the principle that the bandwidth of fiber can be partitioned dynamically into adaptable size spectrum slots. The size and state of each space are generally customized to the prerequisites of a particular (group of) channel(s) in order to achieve effective network-wide transport. This fine slicing and shaping of passbands is achievable with spectrum selective switching (SSS) devices feature a fine spectrum granularity that facilitates the employment of customizable filters with variable bandwidth, e.g. from 10 GHz to 5 THz in 1-GHz increments, and attenuation, e.g. programmable from 4 dB to 30 dB in 1-dB steps [30].

A few optical switch technologies are shown in **Table 1** that can be used in elastic networks. The combination of gridless spectrum switching and rapid time switching devices advances empowers the provisioning of a wide range of optical bandwidth granularities [6]; however, they do not have a large port-count, which makes them incompatible for connecting devices in an elastic optical node. Fast switching are more easily achieved with semiconductor optical amplifiers (SOA) or electro-optic materials such as LiNbO3 or PLZT. Large port-counts are usually implemented with 3D-MEMS [38] or direct beam-steering devices [39] (achieves lower insertion

Material	Cons	Pros
PLZT [31]	Coupling loss	High-speed switching (<5–10 ns), low driving voltage (5–10 V)
LiNbO3 [32]	Polarization dependence	Fast response (<10 ns), low voltage (3 V)
SOA [33]	High PDL, wavelength dependence	Fast response (3 ns), no insertion loss, low power consumption
Directional Coupler [34]	High insertion loss	Fast response (~100 ps), low cross talk
Polymer [35]	Slow response (>1 ms), medium power consumption	Low loss (<0.5 dB/cm)
Silica (PLC) [36]	High power consumption	High extinction ratio
MEMS [37]	Slow response (~10 ms), high voltage (50–200 V)	Scalability, small cross talk

Table 1.
Optical switch technologies.

loss than 3D-MEMS [40]), they have a slower response than fast switching devices, on the order of 10 ms.

4. Need for elastic optical node in optical fiber communication

Recent developments in optical networking have enabled elastic allocation of spectral resources in a gridless manner in order to accommodate high-speed and variable-bitrate signals and achieve high spectral efficiency [41]. For instance, in [42] the spectrum sliced elastic optical path network centered on OFDM, alters signal bandwidths by changing the number of sub-carriers in the transmitted OFDM channel. Other elastic networks based on single carrier (SC) adapt the transmission modulation format in order to mitigate losses or transmit at higher data-rates by exploiting the high OSNR margin [8] with a tradeoff between transmission range and spectral efficiency (SE). Such demonstration requires optical communication infrastructure with the suitable functionality in order to operate [8], frequency/time/space multiplexing, spectrum defragmentation, wavelength conversion, multicasting, format conversion, etc. However, it would be cost-prohibitive to deploy a complete set of technologies and infrastructure to fulfill the requirements for all possible signals and traffic profiles. Instead, emerging technologies need to co-exist with existing ones and provide a smooth migration path where old technology can be gradually replaced. Also, in the context of dynamic optical networks the required services functionalities might change overtime as channels with specific transport and switching requirements are setup and terminated. Providing efficient support for this combination of dynamic requirements with static optical node architectures is a major challenge, which may not be achievable or cost effective [8]. Thus, a new type of flexible and evolvable optical infrastructure needs to be developed in order to enable flexible allocation of resources, and provide any switching and processing capability on demand.

The network scenario considered herewith takes into account the potential applicability of all-optical processing techniques in the network domain. **Figure 5** depicts a case within this framework which consists of four stages which can be placed in diverse geographical sites, i.e. arbitrary input traffic 12.5/42.7/170.8/Gb/s transmitters (WDM domain), an all-optical processing node, field transmission (dark fiber) and receiver. Upon entering the all-optical processing node and to

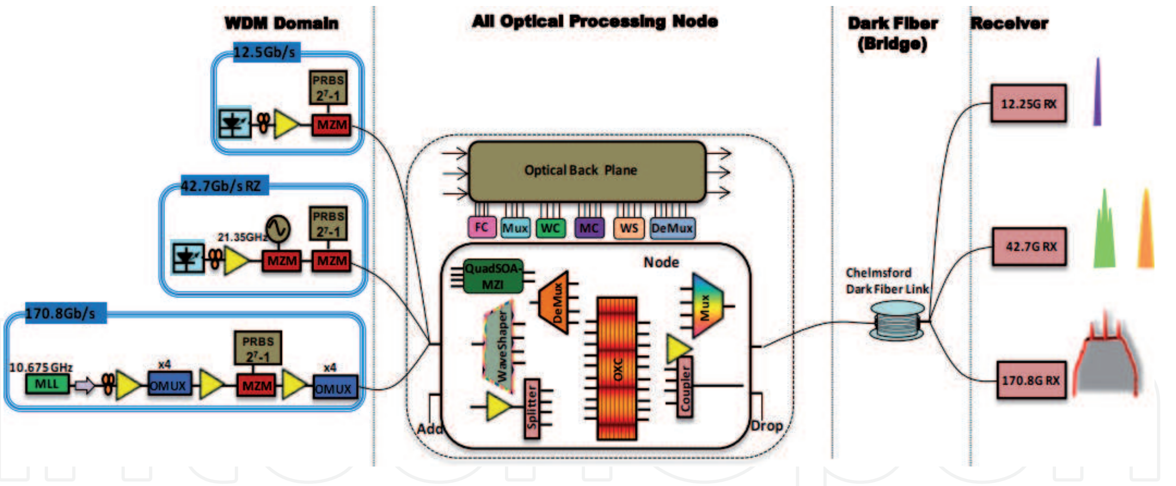


Figure 5.
Network scenario and switching node architecture. Four network sections are highlighted: transmission, all-optical processing in flexible architecture adaptable node (FC, format conversion; WC, wavelength conversion; WS, WaveShaper; MC, multicasting; OXC, optical cross connect), dark fiber, receiver [7].

deliver the optical routing function, all the WDM signals are routed through the 96 × 96 3D-microelectromechanical systems. The optical cross connect architecture consist of subsystems such as Quad Semiconductor Optical Amplifier-Mach-Zehnder interferometer, 200 ms LCoS based SSS [43], wavelength/waveband AWG, (De)-Multiplexer, optical power couplers/splitters and EDFA are interconnected using a 96 × 96 3D-microelectromechanical systems optical switch. The grooming node delivers required real time all-optical processing [44] functionalities, arbitrary spectrum switching and time-domain sub-wavelength switching [45]. It also considerably improves the efficiency and elasticity of the optical node and offers support for current and future data-rates with transparent facilities with low power consumption. All the traffic after node is routed over a dark fiber link, and performances are evaluated by means of BER measurements [7].

5. Key functional building blocks for next generation elastic optical network: wavelength conversion, format conversion and multicasting

The foundation of a photonic network's physical layer is transmission technology in the links and switching technology in the nodes. Different optical multiplexing techniques and modulation formats such as differential quadrature phase shift keying (DQPSK) and quadrature amplitude modulation (QAM) can increase the transmission line rates per fiber to more than 100 Tbit/s [46]. Now research effort are targeted at the Optical Transport Network layer switching where optical processing in the network node allows highly efficient use of capacity, and the abstraction of client data rates from the super-channel data rate. Since some of the networking functions are difficult to carry out electrically, novel processing schemes are required. All-optical processing techniques remove the need for optical-to-electrical conversion, and electronic processing, resulting in optically transparent networks [47]. **Figure 6** illustrates the key issues relating to the component and subsystem requirements for the main parts of the future all optical network [48]. As discussed earlier, flexibility is the important issue that will drive optical subsystem research and development over the next few years.

One of the challenges being faced by the elastic network is bandwidth assignment and channel numbering for different bit rates. When increasing number of channels, the spectrum gets fragmented as channels are added and removed leaving behind noncontiguous empty slots. When high bandwidth requests arrive there may

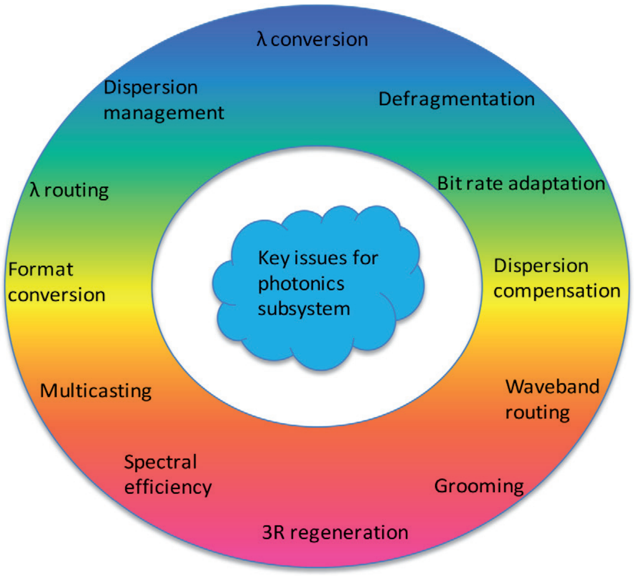


Figure 6.
Key issues of future photonics subsystem [27].

not be sufficient contiguous bandwidth to accommodate them, resulting in blocking [49]. Techniques for spectrum defragmentation involve relocation of existing wavelengths by means of wavelength conversion. Providing such functionality to those channels that require it, and doing it in an efficient manner, is a major challenge. This holds true for other types of functionality such as time multiplexing, format conversion, regeneration, etc. Importantly all-optical modulation format conversion is likely to be used for future all-optical networks in order to add the optical network flexibility [50, 51]. In these networks, systems deployed in different regions could have different bit rates and modulation formats depending on the network size. Therefore, a critical requirement will be the transparent interconnection of these different network islands, which should take place by all-optical means at the network gateways [52].

Transparent optical multicast by multiwavelength conversion has revealed a brand-new way for performing data multicast function directly in the optical domain without passing through any electronics. It provides new visions of optical network designs in terms of optical network switching and forwarding efficiency, transparency, and effectiveness [53]. One-to-many or multichannel wavelength converters are very attractive because they could potentially reduce the number of converters in a routing node without adding more complexity in the switch design. Applications for optical multicast include teleconferencing, video distribution, multiparty gaming and global enterprise virtual private networks (VPNs), etc. [54].

6. All optical converters

The implementation of simple converters can be considered an enabling technology for taking the full advantage of the wavelength dimension in WDM networks. A straightforward implementation of a converter would be a detector followed by an electronic amplifier and a transmitter with the desired new output format/wavelength. However this principle suffers from both a high component count and a high power consumption making the approach impractical for use in large optical switches. Therefore, much attention has been devoted to the realization of all optical converters exploiting the properties of nonlinear devices relying on mechanisms such as cross gain modulation (XGM), cross phase modulation (XPM) and four-wave mixing (FWM) in nonlinear devices [55].

6.1 Cross gain modulation (XGM)

In its general form the principle of operation of the technique is that an optical input signal to be wavelength converted is used to saturate the gain of an active nonlinear element and thereby modulate a continuous wave (CW) signal (pump) at the desired output wavelength [49, 56–58] as shown in **Figure 7**.

Several approaches have emerged to implement all optical wavelength conversion using XGM in SOA, but its conversion speed is determined by the carrier dynamics [59], which are governed by slow interband carrier recombination [60]. Some indicative examples include the work presented in [61] where a 1.2 mm long SOA is used for 40 Gb/s conversion with 1.5 dB power penalty. In [62] a 2 mm long SOA is used for achieving 100 Gb/s wavelength conversion based on XGM. In [63] 80 Gb/s conversion with reportedly low penalty has been achieved.

XGM WCs are attractive because of their simplicity and high conversion efficiency, and the conversion can be made independent of the polarization of the incoming signal. The XGM converter has a number of shortcomings, such as (bit stream) data polarity inversion and the relatively large chirp of the output signal due to the large gain modulation. Finally other than wavelength conversion, XGM has been used for many functions like: format conversion [64], multicasting [65] and header processing in packet switches [66, 67].

6.2 Cross phase modulation (XPM)

In XPM, phase change of the nonlinear element is used rather than the gain change. The optical input signal power controls the phase difference acquired by a pump along the two arms through the refractive index of the nonlinear element [68]. There are number of interferometric configurations that have been used for XPM, some of these are shown in **Figure 8**. A very promising method is XPM in delayed interference signal wavelength convertor configuration (DISC) [62, 69]. 3R regeneration with DISCs has been demonstrated in [70] and a Michelson's interferometer (MI) [71], Mach-Zehnder (MZ) [72]. Some of the first implementations to appear using the interferometric technique is Terahertz Optical Asymmetrical Demultiplexer (TOAD) [73] configuration for the MZI where high-speed operation has been achieved [75].

These converters can perform ultra-high bit rate operations, e.g., demultiplexing from 250 Gb/s [76]. Configurations like the TOAD or the Ultra-fast Nonlinear Interferometer (UNI) [77] have been used mainly for optical processing functions other than wavelength conversion. For instance, UNI configurations have successfully been used in [78] for optical packet switching and in [79] for clock recovery.

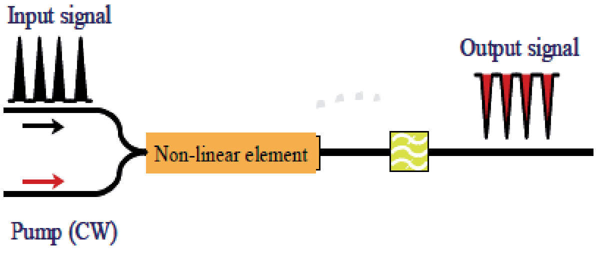


Figure 7.
Schematic of wavelength conversion by XGM in nonlinear medium [27].

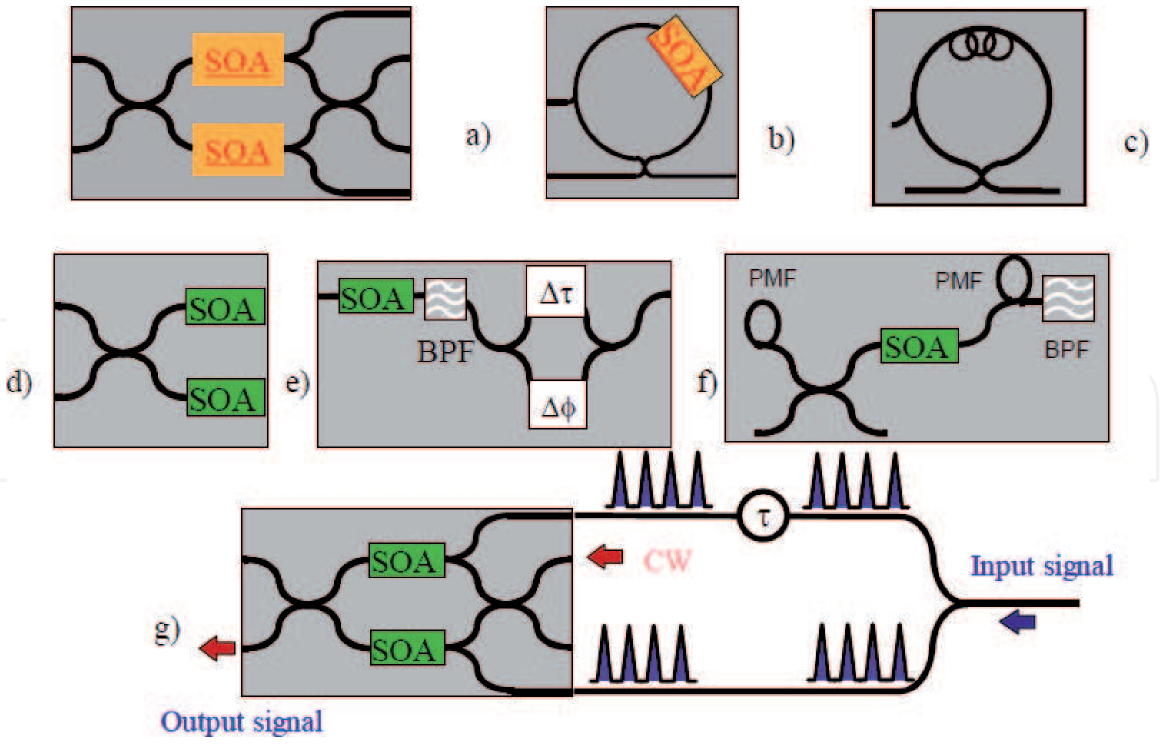


Figure 8.
Different interferometric configurations that have been used as optical gates (a) MZ, (b) TOAD, (c) NOLM, (d) MI, (e) DISC or (f) UNI and (g) push-pull [74].

The use of SOAs is favored over the other elements mentioned above by virtue of compactness and the potential for amplification in suitable all active configurations [56].

The most promising implementation is based on Mach-Zehnder (MZ) structures, their compactness and broad range of functionalities give a very versatile, and thereby a very cost effective device. Nevertheless, owing to the carrier recovery time, the operating bit-rate of the MZ is limited, like the XGM gates. To tackle this problem push-pull configurations have been suggested where, by applying phase changes in both arms [56], the performance can be significantly enhanced [80, 81]. This configuration has been used in a number of different signal processing applications such as demultiplexing [81], regeneration [82], add-and-drop multiplexing [83], regenerative add-and-drop multiplexing [84] and format and wavelength conversion [85]. In fiber-based devices, the nonlinear loop mirror (NOLM) is of particular interest [86, 87]. Due to the inherently ultra-fast response of the Kerr nonlinearity, the NOLM is capable of performing a number of fast bit-level processes e.g., 640 to 10 Gb/s demultiplexing [88], regeneration [89], simultaneous 10 Gb/s wavelength conversion and regeneration [90], and clock extraction [91]. Other than in interferometric configurations, phase modulation can be translated into power modulation by a simple notch filter like that in [92] and XPM can be achieved. XPM in fibers has been used in other configurations to provide 160 Gb/s conversion and 3R regeneration [93] and low penalty wavelength conversion [94]. Recently Raman enhanced self-phase modulation in fibers attracted a lot of attention as an ultra fast technique with noise suppression capabilities [95], however the method is still immature. Generally, nonintegrated devices suffer from stability problems and encounter control issues.

6.3 Wave mixing based: four wave mixing (FWM)

The linearity of the optical reaction is lost when a high-power optical signal is introduced into a fiber. Four wave mixing is a sort of optical Kerr impact, happens when light of two or more unlike wavelengths is launched in a fiber, offering ascend to another wave. When two pump photons are formed, two photons are created: the first one at the signal frequency, the other one at a complementary frequency called idler as shown in **Figure 9** [96, 97]. A schematic of the FWM process, that takes place in nonlinear media, is shown in **Figure 10**. The beating of two distinctive frequency waves modulates the medium's polarization and generates a grating. The input wave interaction with the gratings leads to new components of the frequency. The cause of FWM in SOAs [98–102], is linked to interband and intraband carrier dynamics, while in passive devices and fibers it is because of the induced polarization of the medium under an electric field. The major disadvantage of FWM is its low efficiency, which results in low power FWM products. The main parameter that affects both the efficiency and optical signal-to-noise ratio (OSNR) is the unsaturated gain [68, 103], which can be enhanced by utilizing either longer SOAs, with a smaller active layer [104] or different structures such as multiquantum well devices [103]. The use of an assisted beam has been suggested for the enhancement of the FWM efficiency in [105, 106].

Another disadvantage is that FWM is normally polarization sensitive. The problem has been tackled by using dual-pump configurations [107, 108]. In [109] a 80 nm conversion bandwidth was achieved by dual pump configuration at 2.5 Gb/s. In [110] an almost constant efficiency (<3 dB variation) over a 36 nm wavelength conversion of a 10 Gb/s channel, was achieved.

Due to the nature of the nonlinearities, four wave mixing is very fast. In [111] a multiplexed channel of 100 Gb/s was converted over a range of 3.2 nm by a 2 mm SOA. In addition to converting high bit rate pulses [112–114], the method has been utilized to convert modulation formats [115, 116]. Very fast FWM conversion has been applied as in the demonstration of a 6.3 GHz clock extraction from a 400 Gb/s signal [117], 100 to 10 Gb/s demultipler based on photonic downconversion for a stable add/drop operation [118]. Regenerative properties of wavelength converters based on FWM in a semiconductor optical amplifier have also been demonstrated in [119].

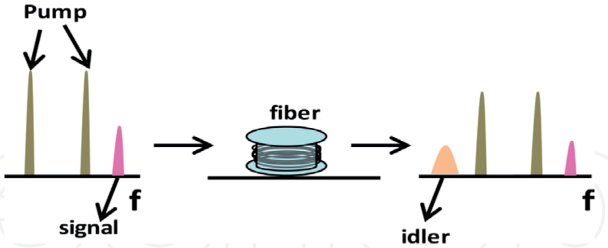


Figure 9.
FWM effect in the spectral domain after the propagation of the signal and the two pumps in DSF fiber [27].

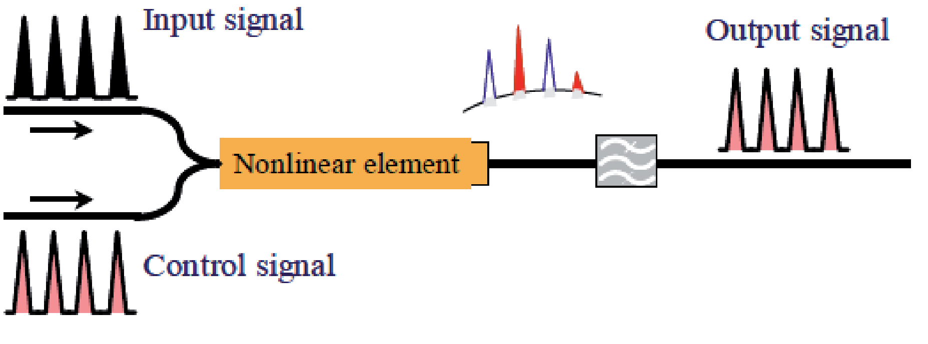


Figure 10.
Mixing of a control and input signal for a four-wave mixing based gate [27].

Another advantage of FWM is that it supports the simultaneous conversion of multiple wavelengths. This has been demonstrated in [48] where 26 WDM channels were simultaneously converted in a highly nonlinear, specially designed fiber. In [101, 120] multichannel SOA based FWM is investigated. In [65, 121] it has been used for multicasting. In a highly nonlinear fiber for FWM was used to demonstrate simultaneous conversion of 200 Gb/s [122] and 32 × 10 Gb/s channels [123].

FWM is a very promising technique, but due to the complexity of the configuration for polarization insensitive operation or wide tunability it will probably be used only for converters operating at 100 Gb/s and beyond.

7. All optical signal processing functionalities survey

Many efforts have been put in the past years to design and implement the entire collection of subsystems required for enabling high speed all-optical routing and switching by all-optical signal processing exploiting a variety of nonlinear media [124]. Significant examples are, format conversion by cross phase modulation at 40 Gb/s based on single SOAs [125] and 160 Gb/s all-optical OOK to DPSK format converter based on HNLF [126]. Both the schemes require high input power, i.e. high clock power in the first case and high input power, 20 dBm for the HNLF, making their operation expensive in terms of energy consumption. Coupling loss of 8 dB between the lensed fiber and the waveguide is reported in [127], as reverse biased silicon-on-isolator p-i-n rib waveguides is wavelength converted via FWM. In [128], demonstration of FC NRZ-DPSK-to-RZ-DPSK, NRZ-DPSK-to-RZ-DPSK and NRZ-to-RZ in a PPLN waveguide by using SHG/DFG, while all-optical wavelength MC based on combination of XGM and XPM in a QD-SOA is presented in [129]. Here the detrimental effect of FWM coherent cross talk on the conversion is identified as the major drawback, responsible for degradation when using four equally spaced channels. Recently, T-H Cheng et al. demonstrated the multicasting in a HNLF loop mirror using FWM at 10 Gbit/s, but using three-pump lasers. In [130], demonstration of Grooming Switch for an OTDM Meshed Networking was reported, however OTDM-to-WDM would need thermally stabilized packaging and the light-paths in the WDM-to-OTDM must preferably be made of waveguides rather than fiber. Each of the demonstration could not support simultaneous MC, FC and WC of multiple modulation format signals to groom OTDM signals in a gridless elastic communication [7]. **Table 2** summarizes the devices used in all optical processing functionalities to date.

The suitability of optical wavelength converters for future networks will be judged on specific criteria that these must fulfill [56, 60]. In particular, modules will ideally have to simultaneously present the following characteristics: compactness (can be integrated in a single substrate with the other switch modules), operation at low optical/electrical powers with high dynamic range, polarization insensitivity, complete transparency to bit-rate (>100 Gb/s) and format or easily adjustable, induce minimal transmission power penalty (small chirp, amplitude distortion and extinction ratio reduction, and large OSNR) to a signal and thus can be cascaded, provision of amplification and (ideally) regeneration and wide conversion bandwidth (tunability) without the need of filtering.

The fundamental idea, common for all technologies discussed here, is the exploitation of the physical properties of a nonlinear element to perform optical processing. The main nonlinear elements are: SOA-MZI, PPLN and HNLF. SOA based devices have the added advantages of compactness and low energy requirements to trigger nonlinearities. Fibers have an instantaneous response to pulses but on the other hand have limited nonlinearity, even in specially designed photonic crystal fibers, hence long lengths and high injected powers are required for efficient operation [74].

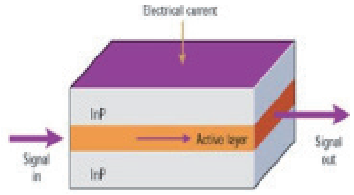
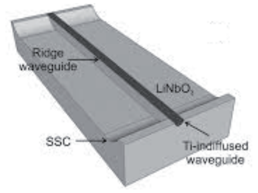
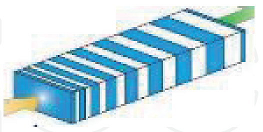
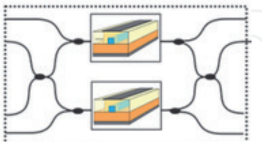
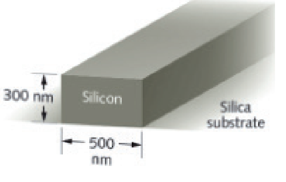
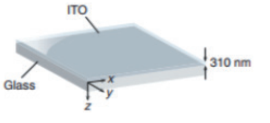
Reference	Device	Reference	Device
[131]	SOA  	[132]	Adhered ridge waveguide 
[133]	PPLN 	[134]	SOA-MZI 
[135]	Chalcogenide microstructured fiber  	[136]	HNLF 
[31]	Silicon nanowaveguides  	[137]	ENZ 

Table 2.
Major technologies devices for all-optical processing reported to date.

8. Conclusion

Exploring methods for the processing of signals in the optical domain, the chapter includes the solutions for the efficient transport of heterogeneous traffic by enhancing the flexibility of the optical layer in allocating network resources as well as for the implementation of an adaptable infrastructure that provides on-demand functionality according to traffic requirements. Further provides a comprehensive review of the state-of-the art of optical signal processing technologies and devices. It presents breakthrough solutions for enabling a pervasive use of optical signal processing to overcome the capacity crunch in optical fiber applications. The chapter content ranges from the road map toward elastic optical networks, optical switching paradigms, need for elastic optical node and application that support gridless node in optical communication having the ability of repositioning signals in a fragmented spectrum by all-optical signal processing functionalities such as MC, spectrum defragmentation, FC, WC and grooming of high speed signals in order to maintain a proficient resource utilization.

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