PHOTONIC TECHNOLOGIES AND DEVICES FOR MULTI-WAVELENGTH NETWORK APPLICATIONS[1]

F. Testa, S. Merli
Ericsson Telecomunicazioni, Roma
G. Randone, S. Rotolo
ITALTEL, Milano
E. Vezzoni
CSELT, Torino

Keywords: photonic technologies, broadband services, telecommunication networks, optical networks, MWTN - MultiWavelength Transport Networks, wavelength multiplexing, optical overlay, optoelectronic integrated devices, transport capability of networks, layered networks, optical integrated devices, $LiNbO_3$ acousto-optic tunable filters, optical waveguides, spatial switches, practical examples, space switch matrices, semiconductor optical amplifiers

Abstract: Fast and quick growth of potential need for broadband services which may be offered by public network operators to business and residential users cannot be easily satisfied by a simple evolution of current electronic technology. In principle, photonic technology is ready to offer a huge increase in the overall transport capability of present networks, by using both the wavelength multiplexing principle and the optical overlay concept. A practical exploitation of these principles still needs a large amount of theoretical modelling and experimental work, along the guidelines which have been carried out within the RACE project "MultiWavelength Transport Network", where an optical network test bed has been fully implemented by using state of the art optoelectronic integrated devices. Results of this work will be presented here, with special attention to those aspects which need further improvement, and where different solutions may offer better alternatives.

Fotonske tehnologije in elementi za uporabo v večvalovnih komunikacijskih mrežah

Ključne besede: tehnologije fotonske, servisi širokopasovni, omrežja telekomunikacijska, omrežja optična, MWTN omrežja transportna večvalovnodolžinska, multipleksiranje valovnodolžinsko, prekrivanje optično, naprave optoelektronske integrirane, zmogljivost omrežij transportna, omrežja slojevita, naprave optične integrirane, $LiNbO_3$ filtri akusto-optični uglašljivi, valovodi optični, stikala prostorska, primeri praktični, matrike komutacijske prostorske, ojačevalniki optični polprevodniški

Povzetek: Današnja standardna elektronska tehnologija ne more več slediti hitri rasti potencialnih potreb za uslugami, ki jih upravniki javnih komunikacijskih omrežij ponujajo poslovnim in osebnim uporabnikom. V principu pa je fotonska tehnologija že pripravljena ponuditi ogromno povečanje gostote prenosa podatkov preko obstoječih mrež z uporabo načela valovnega multipleksiranja in optičnega prekrivanja. Pred praktično uporabo teh načel bo še vedno potrebno opraviti veliko teoretičnega modeliranja in eksperimentalnega dela v skladu z navodili, ki so zastavljena v sklopu RACE projekta " Večvalovne komunikacijske mreže ", kjer je bila tudi izdelana testna optična komunikacijska mreža s pomočjo najmodernejših optoelektronskih integriranih komponent. Rezultate tega dela bomo predstavili v tem prispevku, kritično bomo poudarili stvari, ki jih je potrebno še izboljšati, oz. kjer drugačne rešitve ponujajo boljše alternative.

1. Fundamentals of optical networks

The large transmission bandwidth associated with single mode optical fibers has been the basic factor for allowing the development of SONET (Synchronous Optical Network, in USA and Japan), and SDH (Synchronous Digital Hierarchy, in Europe) transmission standard. As a consequence, it has been possible in recent years to promote a world wide set of uniform criteria for defining:

- the *synchronous multiplexing technique*, which allows the transport of signals with different bit rates, services and transmission formats;
- a very flexible and powerful control technique for network management, bit error rate monitoring, network maintenance and provisioning, by using the section and path overheads bits in the SDH data stream;

1 Following two papers already published in MIDEM in 1994 on photonic devices, this last contribution is dedicated to medium term system and network applications aspects, which have been studied and developed mostly within the RACE II Project MWTN.

- the definition of a world standard for the SDH transmission equipment, from the STM1 (155 Mbit/s) hierarchy, which allows the full compatibility of equipment from different suppliers, to be used in the same transmission link.

These standards are still implementing a traditional concept, where electronic coding is used for all control and routing purposes, and optical technology is only applied for transport functions.

Looking to the introduction of broad band services (B-ISDN), a large increase in the network transport capacity is foreseen. A long term evolution strategy should be defined which shall allow a full use of the available fibre infrastructure transport bandwidth, and in particular by studying a more flexible and powerful network node structure, able to use photonic options, in addition to electronic functions, to increase the data throughput and traffic handling capability.

Recent advances in photonic device technology offer many opportunities to increase the transport network capacity; among them, EDFA are the key devices able to expand both the network geographical size and optical transparency, and to recover the optical losses which may be intrinsic to the use optical functionalities in the network node operation./1/

Racc. ITU G.803 defines a "layered model" of the transport network /2/, and classifies the nodes in *local exchanges*, directly connected to the users, and *transit exchanges*, without direct connections. This scheme may be extended by defining a new "optical layer" constituted by optical nodes (Optical Cross-Connect) and fibres interconnecting them. This layer will be overimposed on the "electrical layer", in which we find, for instance, the DXCs (Digital Cross-Connects).

In the new layer, signals will be carried transparently without dependence on the transmission format; on these signals main "optical transport functions" will be exerted:

i. assignment of wavelength to different signals by means of suitable tunable and/or switched sources
ii. selection of signals by means of fixed or tunable optical filters

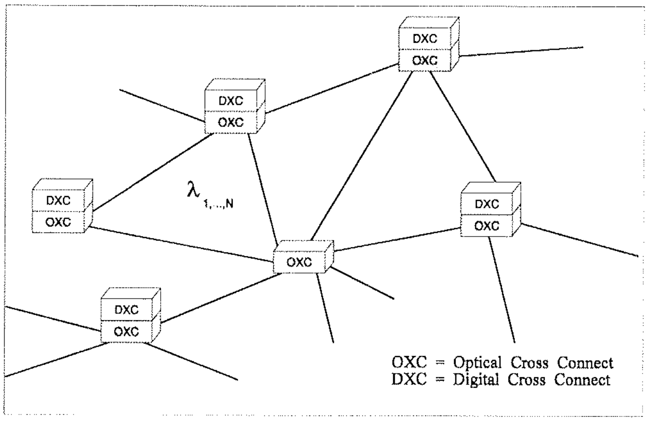

Fig. 1: "Layered" network: OXCs placed upon DXCs

iii. channels routing by means of spatial optical switching
iv. wavelength conversion
v. amplification by means of doped fibres or semiconductor amplifiers

Fig.1 shows the general scheme for a "layered" network.

A new and important feature is given by the capability of accessing the optical bandwidth to process signals by using the minimum number of optical-to-electrical-to--optical conversions.

On the basis of number of functions that will be exerted directly in the optical layer it will be possible to define a 'transparency degree" for the network, for instance with respect to the modulation scheme, data format and transmission speed.

Technology growth will allow the implementation of the "All-Optical Networks" /2/, in which, as a matter of fact, photonic devices will largely replace the electronic ones.

The introduction of such an optical layer in the telecommunication networks calls for the development of high performance, low cost components in order to make the optical transmission and routing functions cost effective with respect to more traditional solutions.

Some general considerations may be applied to the different applications.

In the range of data rates of 155÷622 Mbit/s, electronic equipment have been very well assessed: the ADMs (Add-Drop Multiplexers) and the DXCs (Digital Cross Connects), thanks to very large scale digital integrated circuits, can perform multi/demultiplexing, routing and switching in the electrical domain in a very efficient way.

At higher speed (2.5 Gbit/s, 10 Gbit/s, ...), quite essential for the B-ISDN, the realisation of very large ADMs and DXCs meets increasing feasibility problems in terms of physical dimensions, power consumption and costs.

On the contrary, at increasing bit rates, the implementation of optical routing functions becomes more convenient, depending on the high reliability of optical links and on the availability of a "new dimension", the "wavelength domain", in which performing network functions such as channel multi/demultiplexing and routing.

Let us consider optical filter devices, as an example, to select optical channels: the higher is the bit rate, the higher is the channel spectral width and, consequently, the easier is the technical feasibility of the optical filter.

2. Multi-wavelength transport networks: the MWTN project

The network proposed by the RACE Project R2028-MWTN (Multi Wavelength Transport Network) can be considered as a very good application of all the aforementioned concepts /3/.

Fig. 2 shows the OXC (Optical Cross Connect) node.

For each of the input or output fibres, the system carries 4 optical carriers (channels) spaced by 4 nm (1548, 1552, 1556, 1560 nm); each channel can then be substituted by a comb of 4 closely spaced optical carriers (0.1 nm), in order to further increase the overall capacity. In the "optical layer" channels can be transmitted, routed and amplified without any optoelectronic conversion.

A closer look at the OXC structure shows that optical amplifiers are located immediately at the input and at the output ports: they compensate for the path losses (a typical span of 50 km between two adjacent nodes is considered) and for the attenuation experienced by signals that have been filtered and spatially switched inside the node.

Optical multi-channel transmitters and receivers perform a suitable interface with the "electrical layer" (DXCs) and allow the drop/insert functions for channels relevant to the considered node; higher bit rates of the SDH hierarchy have been adopted: 622 Mbit/s and 2.488 Gbit/s.

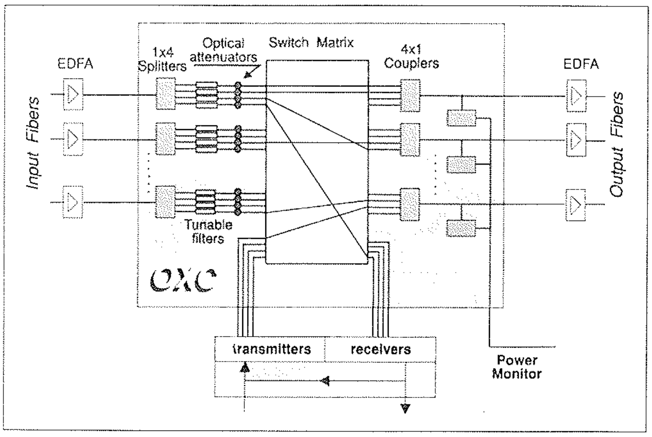

Fig. 2: OXC node proposed by the MWTN Project

3. Why optical integrated devices ?

Optical and optoelectronic integrated devices only can make cost effective the concepts related to a "layered network": they are essential to keep low the power consumption and the physical dimensions of the hardware.

Moreover, optical integration minimizes the number of optical interfaces between different devices: actually, fibre/device coupling introduces the more severe constraints in terms of attenuation and is the more costly step in the packaging process.

NxN waveguide spatial optical matrices, for instance, may be realized by interconnecting simple 2x2 switches in a specific multistage structure; monolithic integration is the only way to implement an efficient interconnection of the elementary bricks of the device.

The integration level of optical functions, both on semiconductor and on electro-optical materials, is very low if compared to that of electronic circuits. This is due to the larger dimensions of elementary component blocks and to a lower maturity of the photonic technology. Optoelectronic circuits are, anyhow, very valuable because transmission, more than logic, functions can be easily integrated. Another characteristic is related to the difficulty to obtain good yields and good performances because requirements for components such as sources, detectors, modulators, amplifiers, filters, couplers and switches are typically very stringent. In the following a brief review of more common integrated functions is given together with some implementation example.

4. Integration of optical functions

As far concerns laser sources, recently available DFB lasers are suitable for operation at 2,5 Gbit/s, with relatively low (0,1 nm) dynamic spectral broadening (chirp).

Moreover, the combined effect of chirp by the laser source and chromatic dispersion is often responsible of a bandwidth limitation; in this case, the useful bandwidth can be increased by using an external light modulator. Commercially available $LiNbO_3$ electro-optical modulators have 10 Gbit/s bit rate modulation capability, with almost negligible chirping, but require quite high driving voltages, which are not easily obtained at high bit-rate. Therefore it looks very promising the development of a monolithic integrated structure made by a laser coupled to a semiconductor electroabsorption modulator, which already shows high modulation rate, in excess of 10 Gbit/s, and low driving voltage (<5 Volt)./4/

Tunable sources are a critical component in multi-wavelength networks, where the wavelength of many optical carriers need to be quickly selected and switched in a tuning range several nm wide. Distributed Bragg Reflector (DBR) devices with multielectrode configuration are suitable to cope with the wavelength tuning requirement /5, 6/. The realization of DBR devices still remain a difficult technology development task, particularly in terms of yield, grating uniformity and layer thickness control. More sophisticated structures have been proposed to allow a wider tuning range, by using multiple DBR devices, integrated on a single substrate, with contiguous tunable ranges ($\Delta\lambda$ = 21 nm, /7/), Y shaped lasers ($\Delta\lambda$ = 50 nm, /8/), laser DBR with a non uniform grating period ($\Delta\lambda$ = 50 nm, /9/).

Semiconductor optical amplifiers, are ideal candidates to be combined in integrated monolithic devices to obtain a large variety of optical functions (splitting, combiners, filters and switches), with compensation of the relevant insertion losses. Optical non linear effects, as gain saturation and four-wave-mixing for instance, may be used to obtain high level functions; among them, wavelength conversion is a key feature for routing of optical channels through an OXC node.

Optical filters, in particular for high density WDM systems, are critical devices which must fulfil several tight specifications: high selectivity, low insertion losses, wide range tunability and low cost. An interesting example of a filter based on a diffraction grating will be described in the following paragraph. Normal DFB or DBR lasers, operating under laser threshold as a selective amplifiers, may be used as active filters, with optical bandwidth between 1 and 10 GHz. Multielectrode configurations allow a tuning range of the order of 2 nm with a relatively flat output level /10/. These filters are tunable with switching times of a few nsec.

Acousto-optical filters /11/ are based on channel waveguides realized on $LiNbO_3$; the operating principle is shown in Fig. 3: the optical input signal (with TE polarization state) is coupled to the acoustic wave, and its polarization state is converted to TM, which is transmitted through the TM polarizer at the output of the filter. Without the coupling with the acoustic wave, the optical wave is blocked by the output polarizer. The optical transmission characteristic of the filter is controlled by the frequency of the RF signal, which generates the acoustic wave. The central frequency of the RF signal is about 175 MHz for frequencies around 1552 nm, and 10 mW of RF power are needed to achieve a good acousto-optic coupling. The optical selectivity of the filter is of the order of 1 nm and a tuning range of a few tens of nanometers may be achieved by changing the RF signal central frequency. Simultaneous tuning on different wavelengths can be obtained by using different RF excitation frequencies. Switching speed for acousto-optic filters is of the order of several microseconds.

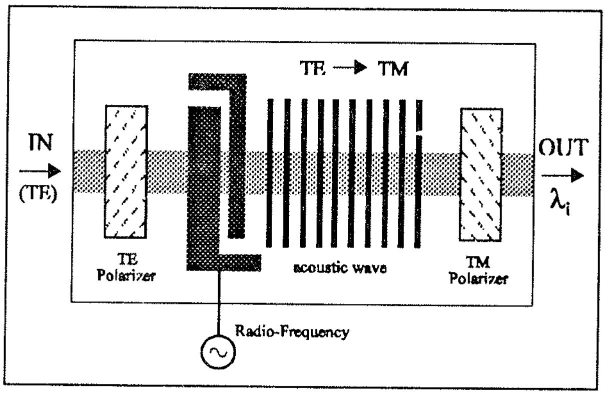

Fig. 3: $LiNbO_3$ acousto-optic tunable filters

Key components for the implementation of optical cross-connects are the space switching matrices, which may be realized starting with monolithic 2 x 2 elementary blocks. For this elementary unit, several design configuration (Fig. 4) have been already tested: a) the directional coupler, b) the Mach-Zehnder interferometer, c) the X junction, d) the optical gates.

In the first three devices, coupling or interference conditions are controlled by suitable voltages applied to the controlling electrodes; without bias, the optical signal coupled to the input port is transferred to the normal, or so called "bar", output port, while by applying the control voltage the signal is switched to the other "cross" output port. The fourth structure is based on semiconductor optical amplifiers which may be switched by current injection from a high absorbing state to a transparent state; therefore the optical path where the amplifier is located can be opened or closed by the control current, and any connection between input and output ports can be implemented. An added advantage of using optical amplifier is that optical gain may compensate the overall switch insertion losses.

The first three configuration, which make use of the dependence of the index of refraction from the electric field, may be realized on $LiNbO_3$, or semiconductor substrates. Recent experiments have shown the possibility to use, to the same purpose, a thermorefractive effect; therefore, Silica on Silicon or ion-exchanged-glass materials may be used as waveguide substrates. The semiconductor material, of the Multi-Quantum-Well heterostructure type, have the highest electro-optical coefficient, and are suitable for realization of very small elementary devices, which may lead to matrices with large number of stages.

The fourth structure can be realised only by semiconductor material.

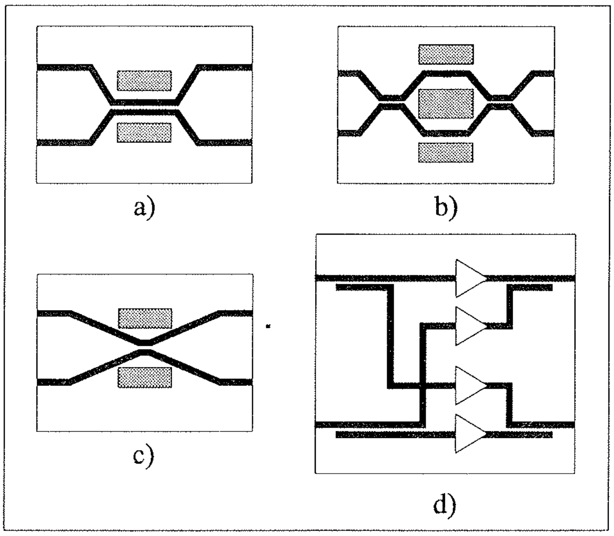

Fig. 4: Optical waveguide spatial switches with dimensions 2 x 2

Characteristic parameters of these devices are the insertion losses, operating voltages (currents), temperature stability, ageing, extinction ratio, switching time and noise.

Integration of optical and electrical functions on a single substrate is a further step toward the so called Opto Electronic Integrated Circuits (OEIC). Simple OEIC devices are for instance a laser with an integrated driver or a photodetector with integrated preamplifier; arrays of such simple OEIC have been implemented for multichannel operations, as for instance by the RACE 1027 Project /12/, where an array of 8 integrated detectors and preamplifiers has been realized on InP substrate, as an example of monolithic OEIC with several tens of elementary optical and electrical devices.

An important point to be noted here is that OEIC development is particularly useful in view of their capability to offer high speed performances, allowed by the very short electrical connections, reduced stray capacitances and other parasitic effects.

5. Practical example of integrated optic devices

Main manufacturing technologies for integrated optic devices should include Lithium Niobate, InP based heterostructure materials and Silica on Silicon.

Lithium Niobate technology is now relatively mature and a few devices are commercially available; among them high speed electro-optical light modulators, optical switching matrices and optical filters. Recent advances include the realization of active (Er doped) waveguides, which may allow the development of optical amplifiers and laser sources integrated in the $LiNbO_3$ substrate, to obtain a quite wide range of optical functionalities.

InP technology holds the most promising potentiality for a truly integrated optics approach, as it may allow monolithic integration of laser sources, modulators, photodetectors and semiconductor optical amplifiers, to achieve a high degree of integration with very complex functionalities. Most of these potentialities have been already tested with laboratory prototypes, and in fact two devices (a 4 x 4 space switch and a 4 channel tunable filter), realized for the optical cross-connect used in the MWTN experiment, will be described in detail in this paper. Process control and reproducibility to achieve reasonable yields still need a better assessment before the InP technology could be considered fully available for cost-effective industrial purposes.

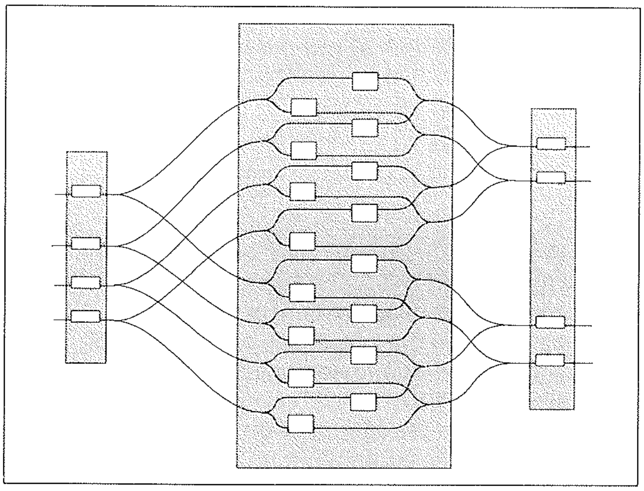

Fig. 5: 4 x 4 space switch matrix, based on semiconductor optical amplifiers

Silica on Silicon waveguide technology (which has been already described in this journal in detail, /14/) is suitable for a hybrid assembly opportunity, which may offer a good compromise between yields, complexity and cost, including the benefits of the mature and reliable Silicon process technology. A possible implementation of the optical cross-connect node for the MWTN experiment by using the SoS technology will be described.

5.1 InP 4 x 4 space switch, with active optical gates

The space switch matrix is the key functionality required for an optical cross-connect; the device described here, which is based on a single chip InP/InGaAsP integration of a passive waveguide optical routing network, 16 optical gates and 8 input/output semiconductor optical amplifiers (Fig. 5), may be considered a state of the art OEIC realization /15/, with characteristics well suited for an optical switch (low insertion losses, a few nsec reconfiguration set-up time, small (7 x 3 mm) dimensions).

The switching element in the matrix is a Y passive power splitter, followed by two semiconductor optical amplifiers; the optical signal path through the switch is controlled by the current injected into the matrix of optical amplifiers, which may be switched between off (absorbing) state and on (amplifying) state. The optical gain of the amplifiers can be used to compensate the splitting (3 dB) and excess loss of the splitters. The routing pattern through the full matrix implements a strictly non-blocking architecture. Further optical gain is provided by input and output buffer amplifiers, which allows compensation for fibre pig-tailing losses, bending losses and waveguide losses. The material growth process is based on a Metal Organic Vapour Phase Epitaxy, and the InGaAsP active material composition is chosen to operate around 1550 nm wavelength. Overall insertion losses (fiber to fiber) are less than 5 dB, and cross-talk extinction ratio better than 40 dB has been achieved. The device is somewhat sensitive to input light TE or TM polarization state, with differential losses between the two polarization states of the order of 6 - 12 dB. The level of current injection required to switch the gate amplifiers is of the order of 50 mA.

5.2 Multi-grating filters

Another device based on InP material technology is the multi-grating filter /16/, which allows the extraction of one or more selected wavelengths from a WDM signal. While still affected by relatively high losses and polarization sensitivity, these filters are easily controlled by current injection, with a good rejection factor and further monolithic integration capability. In Fig. 6 a scheme of a multi-grating filter is shown, designed for 4 channel selection, with wavelength at 1548, 1552, 1556, 1560 nm. The filter operation principle is based on a cascade of four DBR gratings, each one tuned to reflect one of the above wavelength, in such a way that, without bias, all optical channel are back reflected. To allow the transmission by the filter of one or more optical channels, the reflection band of the appropriate grating is shifted by current injection.

The structure of the multi-grating filter is based on a buried hetero-structure channel waveguide 0.2 μm thick and 1.3 μm wide, with intrinsic undoped InGaAsP active layer material, with 1,38 eV band gap energy at room temperature. The overall waveguide structure is identical to a laser structure with n and p doped InP cladding layers (Fig 6b). Gratings are etched 0.1 μm above the active layer with 60 nm thickness; each grating is 300 μm long, with 50 μm spacing between different gratings.

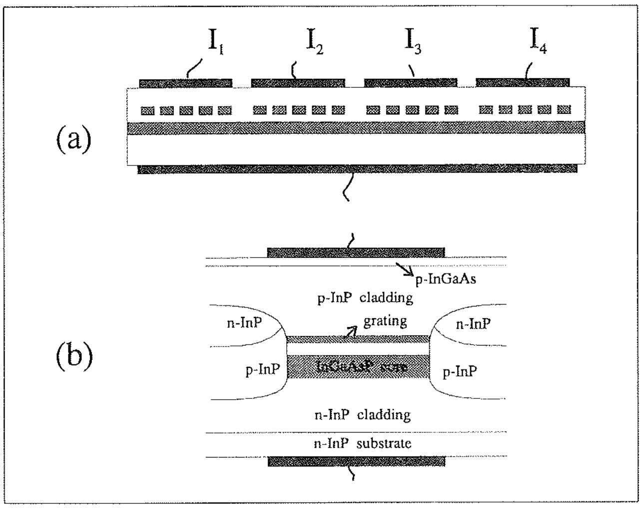

Fig. 6: Tunable multi-grating filter:
a) side view, to show the electrical contacts structure,
b) cross section view

Filter response has been measured by using the spontaneous emission from a fibre optical amplifier as a wideband light signal, with suitable polarizer to select TE or TM polarization state. Insertion losses (including pigtail losses of 6 dB for each chip facet) of the order of 25 dB have been measured for TE mode excitation, due to free carrier absorption and waveguide scattering losses. Transmission spectrum for the unbiased filter is shown in Fig. 7a, which shows a relatively flat response for the four gratings response. The transmission spectrum, with 2 mA current injected in the first grating electrode, is shown in Fig. 7b, and 2.6 nm shift in the transmission bandpass for the corresponding wavelength is clearly observed. With a TM polarized input light the effect is similar but the wavelength shift increase up to 4.5 nm with the same injection current. Therefore the input light need to be polarized to avoid cross-talk effects with the present device: an improved control of the polarization sensitivity of the structure is necessary, for instance by using a more symmetrical cross-section for the active waveguide, even if this may noticeably increase the complexity of the fabrication process.

The full cross-talk characteristic of the multi-grating filter, for a TE excitation, is shown in Tab. 1; the cross-talk is defined here as the ratio between the optical power transmitted by the active channel with respect to the

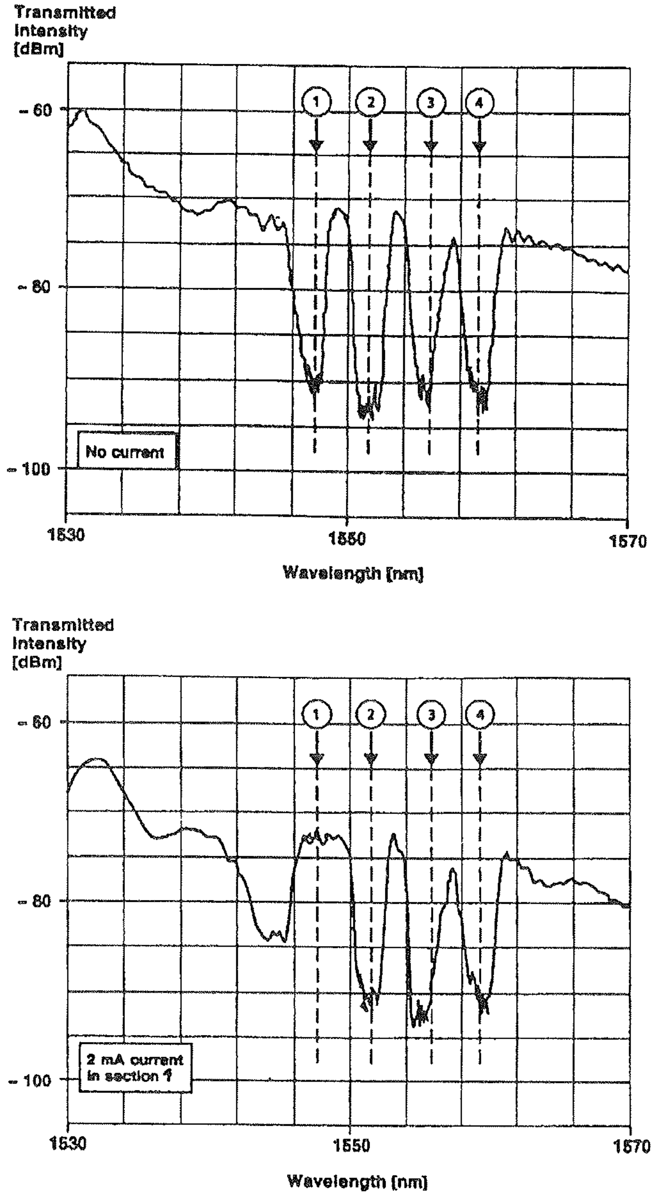

Fig. 7: Spectral emission from the Multi-grating filter. (Input light from the ASE emission by an EDFA) - a) without excitation
b) with 2 mA current injected in the first section electrode

power transmitted through the blocking channels. A quite large spread has been found in the experimental values, ranging from a minimum of 9.4 dB up to 19.4 dB. Reasons for these discrepancies are still not well understood, but may be due to non uniform coupling of different gratings with the active waveguide, which can be improved by a better control of the fabrication process. Even taking into account present limits, which could be off set by an optimized structure design and by some improvement in the process technology, the optical notch filter described here is well suited for multi-wavelength systems applications, and is a good demonstration of the potential of the OEIC InP based technology.

Selected channel	Channel cross-talk			
dB	1	2	3	4
1	-	18.5	19.4	18.2
2	11.8	-	19.4	15.9
3	11.0	11.0	-	15.9
4	10.6	11.1	9.4	-

Tab. 1 - Channel cross-talk ratio, for different channels of the multi-grating filter

5.3 A perspective evaluation of the Silica on Silicon technology

We conclude the description of possible technology solutions to implement an optical 4 x 4 wavelength routing node by considering a full use of SoS devices. In this case, known data and technical characteristics of elementary SoS devices will be used for modelling a few relatively more complex optical circuits, taking into account present technology constraints (the 4" wafer size, as a limit for the optical circuit practical dimensions, for instance). The results should be taken only as a design feasibility indication, but they clearly demonstrate the intrinsic technology potential for very low cost, good performances and simple construction practices. The optical routing node structure is shown in Fig. 8; it consist of four main building blocks, each one of which can be realized on a 4" Silicon wafer, with overall dimensions of each device not larger than 60 x 60 mm. This is fully compatible with wafer process capability currently available, even if process yield for a wafer size device has not been evaluated so far.

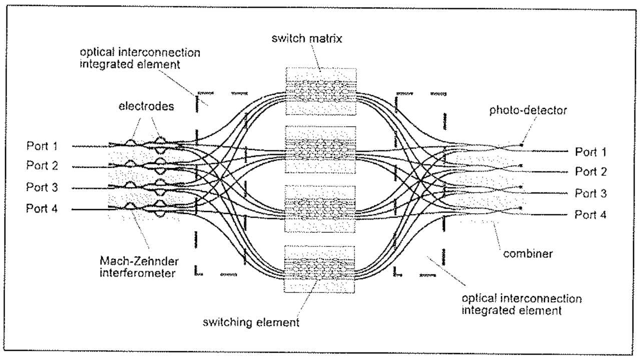

Fig. 8: Example of a 4 x 4 multi-wavelength routing node fully implemented with Silica on Silicon technology

Let us describe now each node building block in some detail starting from the input side:

4 channel WDM demultiplexer

The first device includes 4 identical WDM demultiplexers on a single substrate wafer; each demultiplexer is designed to separate the input multi-wavelength signal stream into four single wavelength output channel. A detailed description of the demultiplexer operation has been already reported in this Journal /ref. 14, pag. 155,156/; typical performances (already experimentally tested for a single device) are listed in Tab. 2.

insertion loss	2 dB
cross-talk attenuation	20 dB
spacing between adjacent channels	0.1 - 20 nm
temperature dependence	low
polarization dependence	low

Tab. 2 - Typical characteristics of a wavelength demultiplexer based on Silica on Silicon technology

Integrated interconnection element

As directly shown in fig. 8, the function of this element is simply to connect each wavelength channel output from the demultiplexers to the appropriate input of the switching matrices. Design constraints for such structure are related to the bending radius of the waveguides (which must be higher than 10 mm, to avoid attenuation) and the waveguides crossing angle (which should be not less than 15 degree, to avoid cross-talk). By using these simple design rules, the overall attenuation for each connection path, including fiber coupling loss, will be less than 1 db. This element is used twice in the optical node, as shown in fig. 8.

Optical switching matrices

The wavelength routing function is accomplished by four identical 4 x 4 optical space switches. Each space switch provides the routing of a single wavelength, by using a combination of balanced Mach-Zehnder interferometers, which can be switched between the "cross" and "bar" state by using the thermorefractive effect, induced by a small thin film heather deposited on one arm of the interferometer (for a more detailed description, see Ref. 14, pag. 157). The switching time which may be attained by the thermorefractive effect is of the order of a msec; therefore this type of space switch is suitable only for transport network applications, where low switching speed is generally adequate. Optical characteristics of the space switch are listed in Tab. 3.

insertion loss	3-4 dB
cross-talk attenuation	12-15 dB
modulation frequency	1 KHz
working principle	thermo-optical
control current	0-100 mA
temperature dependence	low
polarization dependence	low
optical bandwidth	>40 nm

Tab. 3 - Optical characteristics of a space switch based on Silica on Silicon technology

Optical combiner

The last building block for the node is an array of 4 x 2 optical combiners, where one of the output ports is used for output power control and monitoring. A small fraction of the light output is extracted from this channel waveguide by a 45 degree tilted mirror, directly etched into the waveguide, and coupled to a PIN monitor photodiode self aligned with respect to the mirror. Optical characteristic of this node output stage are listed in Tab. 4.

insertion loss	2 dB
intrinsic loss	6-7 dB
optical bandwidth	300 nm

Tab. 4 - Optical combiner typical characteristics.

ACKNOWLEDGEMENTS

The Authors wish to thank Dr. A. Fincato for his advice in writing the paragraph concerning the Silica on Silicon technology. Development of many components described in this paper has been in part financially supported by the E.C. RACE 2028 Project.

BIBLIOGRAPHY

/1/ A. Acampora, "Toward on All-Optical Telecommunications Infrastructure". Proc. EFOC&N, Heidelberg,1994.

/2/ S. Johansson et al., "An Optical Transport Network Layer; Concept and Demonstration". Ericsson Review, Aug. 1994

/3/ G. Hill et al., "A Transport Network Layer Based on Optical Network Elements". IEEE Journal of Lightwave Technology Vol.11, N°5/6, May/June 1993.

/4/ F. Devaux et al., "InGaAsP/InGaAsP Multiple Quantum Well modulator with improved saturation intensity and bandwidth over 20 GHz", OFC '92, PDP4, S. Josè, 1992

/5/ Y. Kotaki et al., "Wavelength tunable DFB and DBR lasers for coherent optical fibre communications", IEE Proceedings-J, Vol. 138, No 2, pp. 171-177, Apr. 1991

/6/ Y. Ogawa et al., "Tunable narrow linewidth MQW-DBR laser", Proc. 4th Optoelectronic Conference", pp. 60-61, Chiba, 15-17 Jul. 1992

/7/ U. Koren et al., "An integrated tunable light source with extended tunability range" Proc. IOOC '89, paper 19A2-3, Kobe, 1989

/8/ M. Shilling et al., "6 THz range frequency conversion of 2.5 Gbit/s signals by 1.55 μm MQW based widely tunable Y-laser", Proc. of 13th International Semiconductor Laser Conference, pp. 272-273, Kagawa, 21-25 Sept. 1992

/9/ Y. Tohmori et al., "Ultrawide wavelength tuning with single longitudinal mode by Super Structure Grating (SSG) DBR laser", Proc. of 13th International Semiconductor Laser Conference, pp. 268-269, Kagawa, 21-25 Sept. 1992

/10/ T. Numai, "1.5 μm Phase-Shift-Controlled Distributed Feedback Wavelength Tunable Optical Filter", IEEE J. of Quantum Electr., Vol. 28, no 6, pp. 1513-1519, June 1992

/11/ D.A. Smith et al., Appl. Phys. Lett., No 56, p. 209, 1990

/12/ W.S. Lee et al., "Monolithic 8 channel photoreceiver array OEICs for HDWDM applications" at 1.55 μm" Elettr. Letters Vol.28, 1992

/13/ H. Herrmann et al.,"Integrated optical, acoustically tunable wavelength filters and switches and their network applications", ECIO '93, Neuchatel, Switzerland, April 1993, pp.10.1-10.3

/14/ A. Fincato et al. "Glass on Silicon technology for optical interconnections.........". MIDEM, Vol 24, 3 pag 151 (1994)

/15/ M. Gustavsson et al. "Monolithically Integrated 4x4 InGaAsP/InP Laser Amplifier Gate Switch Arrays" IEEE Electronics Letters Vol.28,N°24 pp 2223-2224.

/16/ J. Weber "Four-Channel Tunable Optical Notch Filter Using InGaAsP/InP Reflection Gratings". IEEE Photonics Technology Letters, Vol. 6, N°1, Jan. 1994.

F. Testa, S. Merli
ERICSSON TELECOMUNICAZIONI,
R&D Department
Via Anagnina 203,
I-00040 Roma, Italy,
tel. +39 6 725 82413
fax + 39 6 725 83725

G. Randone, S. Rotolo
ITALTEL, Central Research Laboratories
Castelletto di Settimo Milanese,
Milano, Italy
tel. + 39 4388 7320
fax + 39 4388 7989

E. Vezzoni
CSELT,
Via G. Reiss Romoli, 274,
I-10148 Torino, Italy
tel. + 39 11 2285 281
fax + 39 11 2285 085

Prispelo (Arrived): 27.03.95 ***Sprejeto (Accepted): 05.04.95***