This paper gives an overview of present status and future trends in Electro-optical communication systems and networks. Within the architecture of Electro-optical communication networks, three areas with a different type of research focus can be distinguished; the long haul links, the cross-connects and the access networks to the subscribers.

1 Introduction

Telecommunications networks are the largest and most complex artificial structures the human race has ever built and have gradually become an essential social and economic infrastructure. The worldwide demand for communication has consistently pushed the transport speed from merely 34 Megabit/s in the early eighties to 10 Gigabit per second today, i.e. a growth of a factor 10 each seven years. The growing demand for communication is mainly due to the trend towards globalisation and the evolution of the social structure of our society. Presently, we witness a revolution towards a global information society, which is most clearly visible by the very rapid introduction of the Internet, and of wireless communication equipment.

Traditionally, the telecommunications industry only provided lines connecting users. In the next millennium, telecommunications and information services are expected to evolve towards multimedia services which will be characterised by integration of the traditionally separated areas of telecommunications, computers, computer networks, and consumer electronics. The envisioned information-sharing systems for the next millennium will almost certainly require a several orders of magnitude higher network capacity and flexibility than currently available. This development will push the demand for network capacity well into the Terabit/s range.

It is evident that this transport capacity requires explorations of new ultimates in the technological platform of the communication infrastructure to overcome limits which soon will be imposed by electronics technology, which develops at a speed of a factor 10 in 12 years, i.e. approximately half the speed of the increase in the demand for communication capacity. Optical communication is emerging as one of the most important technologies of the future to serve the world-wide demand for capacity in communication by providing the technology for processing the huge amount of signals involved. In principle, optical techniques offer low-loss transmission over thousands of kilometres. Moreover, the bandwidth of an optical fibre allows the transmission of many different wavelengths simultaneously. It is thus envisioned that communication networks will eventually reach a capacity beyond the Terabit/s level, thus creating many new challenges for the required photonic components and network infrastructure.

Within the architecture of communication transport networks, three areas with a different type of research focus can be distinguished; the long haul links, the cross-connects and the access networks to the subscribers (see Fig. 1).
The challenge in the highest level of telecommunication architecture, the long haul links, is how to overcome limitations imposed by the fibre attenuation, non-linearity's and dispersion. Long-term research emphasises ultrafast and high-throughput photonic concepts to lead the transmission and switching capacity towards the Terabit/s domain. Optical cross-connects, covers topics in the intermediate levels of the telecommunication architecture. The challenge is to develop telecommunication nodes that have more throughput, are more reliable and have more speed. A main challenge at the level of the access networks is the development towards bi-directional broadband access to the subscribers. Cost aspects play a very important role here.

2. Long haul links

In the area of long haul links optical amplifiers, Wavelength Division Multiplexing (WDM) and Optical Time Domain Multiplexing (OTDM) are important research issues. Moreover, limitations imposed by the transmission medium are also subject of explorations. Cancellation of dispersion effects has encouraged researchers to investigate the potential of soliton propagation. Phase conjugation halfway a transmission path is another way of cancelling dispersion. A better understanding of the interactions between the transmission medium and the Electro-magnetic light wave is required to proceed towards an infrastructure, which provides the best conditions for an ultrashort pulse to propagate.

2.1 Wavelength Division Multiplexing, WDM

Optical fiber communication links are widely used nowadays for long distance communications, connecting nodes in optical networks. To increase the transmission capacity per fiber, Wavelength Division Multiplexing (WDM) has been introduced, using a number of different wavelengths to carry different data signals. At present, transmission systems with a speed of 10 Gigabit per second are being prepared for commercial use. At the same time, operational systems at the level of 2.5 Gigabit per second are also being upgraded by means of wavelength multiplexing, creating a system with a
capacity of 10 or 20 Gigabit per second using 4 or 8 wavelengths in parallel. Researchers are exploring higher speed at one wavelength as well as the option of more wavelengths in parallel, including concepts where high speed signals can be transferred from one wavelength to the other, using photonic wavelength converters. Typical examples of WDM systems are demonstrations by researchers of the Nippon Telegraph and Telephone (NTT) Company who reported on an experiment at a total capacity level of 1.4 Tb/s (Terabit per second), using 200 Gb/s (Gigabit per second) in the time domain and 7 wavelengths in parallel [1] and a 2.6 Tb/s using 132 channels with 20 Gb/s transmission capacity [2]. In the world, Japanese researchers are leading in these areas. Another example is a demonstration by researchers of Bell Laboratories, Lucent Technologies, showing 206 wavelength channels in parallel.

Today, the strategy for WDM light sources is to use laser diodes with different wavelengths for each channel. Novel concepts for multi-wavelength light sources may be explored. Breakthroughs in planar device concepts and technologies are needed to overcome the problems of accumulation of cross-talk, noise and signal distortion, occurring in large networks. Wavelength conversion and its role in signal regeneration have to be further explored. Novel amplifier concepts and materials have to be developed in order to broaden the usable wavelength window of 30 nm, which is presently set by the Erbium Doped Fibre Amplifier (EDFA). Novel host glass combinations should be explored and combined with suitable doping species. Generally, novel methods for the light amplification in the entire wavelengths area offered by the fibre should be explored.

2.2 Optical Time Domain Multiplexing, OTDM

Ongoing progress in photonic technologies will be exploited to further expand capacity and flexibility in the wavelength domain, involving high density wavelength division multiplexing (HD-WDM) techniques and wavelength conversion techniques. Photonic technologies will also be exploited to enhance transmission and processing speed in the time domain, involving all optical signal regeneration and optical time domain multiplexing (OTDM) and demultiplexing at a femtosecond timescale. This will lead towards the possible realisation of an all optical transport infrastructure with a terabit capacity approaching the fundamental maximum fibre capacity imposed by Heisenberg’s limit on the time-bandwidth product.

The transport system between the nodes has to benefit from ultrafast photonic devices emerging from research in materials and devices. Options for very high bitrate transmission systems in which the signals are multiplexed, demultiplexed to a lower bitrate and regenerated in the optical domain should be explored. The concepts should aim at transmission speeds of at least 40 Gigabit per second. When combined with wavelength division multiplexing (WDM), the total system capacity can easily exceed the Terabit per second level.

Key elements in time multiplexed systems are the generation of ultra short pulses, multiplexers, demultiplexers and timing extractors. Using those key modules, data can be transmitted, multiplexed to a higher bitrate, regenerated and received. For the manipulation of bitrates and timing, the potentials of using harmonics and subharmonics in combination with mode locked laser diodes (MLLD) and four wave mixing (FWM) in semiconductor optical amplifiers can be explored. In principle, it has been shown that the MLLD can be locked to an injected sequence of short optical pulses, which operates in its subharmonics. It has also been shown that the MLLD can be locked to the subharmonics of an injected sequence of short optical pulses.

Large subharmonic numbers will open ways to allow optical pulses with high repetition rates to be created from much lower repetition rates and also to extract an optical clock signal at very low rates from an incoming high bitrate optical signal. The combination of different frequencies can also be used to explore optical domain multiplexing in semiconductor optical amplifiers (SOA). Optical multiplexing methods using the four wave mixing (FWM) effects in SOAs has been shown. A possibility is to mix the low bitrate signal of one wavelength with a high frequency pulse train of another wavelength in the SOA, using a WDM device at the input of the SOA. The FWM in the SOA...
will create a modulated signal at the rate of the high frequency train.

As indicated earlier OTDM transport systems need generators for ultrashort optical pulses and optical domain demultiplexers. One way to generate ultrashort optical pulses is by the external modulation of a continuous wave optical source with a modulator. Fast modulators should be investigated in the area of semiconductor materials and devices. Optical time domain demultiplexing can be realised by means of a TOAD (Terahertz Optical Asymmetric Demultiplexer). The TOAD is commonly realised by means of a fibre loop the ends of which are coupled via an optical coupler. Optical signals coupled into this loop will be reflected. However, the reflection properties can be disturbed by inserting a SOA at an asymmetric position in the loop. A probe signal passing the SOA will disturb the symmetry of the loop and a particular signal will thus be passed and not reflected. Experiments have been carried out to demultiplex 40 Gbit/s to four 10 Gbit/s optical signals. Semiconductor versions of this TOAD configuration and to combine many TOADs locked to a single ring laser clock device will be investigated.

3. Cross connects

Optical fiber communication links are widely used nowadays for long distance communications, connecting nodes in optical networks. To increase the transmission capacity per fiber, Wavelength Division Multiplexing (WDM) has been introduced, using a number of different wavelengths to carry different data signals. Routing and switching in the nodes is performed electrically so in each node of the network all optical signals have to be converted to the electrical domain and vice versa. Electronic telecommunication nodes will not be capable to switch and route future Terabit/s data streams. Photonic routing and switching nodes must be developed capable to handle WDM and OTDM multiplexed signals. Photonic switching devices will therefore be used in many functional modules in the network, for signal modulation, regeneration, multiplexing and routing. Physical phenomena, which can lead to ultrafast wavelength conversion, are a subject for investigation. In parallel, the physical properties of the transmission medium have to be explored more accurately and have to be tuned where possible. Integrated optical cross-connect chips which consists of multiplexers, switches and demultiplexers are being developed now and will be commercially used over a few years.

The management of a multi-wavelength telecommunication infrastructure is a serious challenge. New approaches should recognise that the problem involves geographically distributed and complex control points and therefore deals with basic problems in network architecture and mathematical modelling of the network elements. When optical networks are becoming more and more complex, the use of optical laser neural network nodes can be an interesting solution.

3.1 Laser Neural Nodes

The Laser Neural Network (LNN) provides interesting options for the realisation of an optical network node. Neural networks are intrinsically suited for parallel operation [3]. A dedicated hardware configuration operating in the optical domain and the use of the ultrafast photonic components sections is expected to offer further improvements in the speed and capacity of telecommunication networks.

Generally, a first advantage of optical configurations is that light beams can cross each other in free space without interacting. In addition, all three dimensions can be used, which reduces the problem of interconnectivity and allows for larger and more complex configurations. Finally, optical domain systems are potentially much faster than electrical domain systems. Weighting and summation in the optical domain can be done very fast, while speed limitations caused by charge build-up, like in electronic based devices, are not present.

We first explored the potentials of a semiconductor laser as a key element in the optical neural
network, see fig 2. The longitudinal modes of the laser are used to represent neurons, and controlled optical feedback via an external cavity is imposed to each of the longitudinal modes. A bulk grating is used to separate the modes spatially in the external cavity. The optical power contained in each of the modes responds nonlinearly to the degree of optical feedback and the configuration thus behaves like a neural network. Controlled optical feedback is provided via a matrix of liquid crystal elements, which is inserted in the external cavity of the laser. One dimension of the matrix is used to input data and the other dimension is used to insert weight factors. In principle, the longitudinal mode patterns respond very fast on changes in feedback, because the phenomenon is based on intraband effects.

![Figure 2: Laser Neural Network.](image)

The current experimental configuration is only capable of handling input-output problems with small dimensions. Furthermore, the liquid crystal matrix limits the speed of operation. Strategy for future research is to find ways to further expand the LNN with a larger matrix, to improve the speed and to investigate how the LNN can be implemented as a node in telecommunication networks.

A first challenging step is to investigate how the speed of operation can be improved. It is necessary to replace the liquid crystal matrix with a faster device and to reduce the length of the external cavity. Next, a high-speed matrix, which can provide controlled feedback to the longitudinal modes of the laser, is required. The length of the external cavity will be reduced when the bulk grating used in the current experiment is replaced by a planar configuration. A shorter external cavity will allow faster operation of the LNN. LNN concepts where the diode laser can be integrated with planar gratings and a semiconductor matrix element have to be studied.

Several options for the realisation of the semiconductor matrix modulators are to be explored. In principle, high speed modulators can be inserted in the external cavity configuration. The modulators
can be based on electro-optical effects or opto-optical effects. An interesting option for implementation in the optical network is the hetero n-i-p-i structure with opto-optical modulation because of the possibility to operate the configuration fully in the optical domain. The semiconductor modulators can be combined with a phased array structure and the laser diode itself to form a monolithically integrated version of the LNN. Since a two-dimensional external cavity configuration and a two-dimensional matrix are needed, novel concepts in the integration method have to be found.

A second issue is the exploration of concepts of LNN based telecommunication nodes. Optical payload (data) to be routed or switched can be provided with an optical header. An optical header preceding the payload can be used to input the modulators in the LNN. The serial information in the header needs to be transformed into a parallel pattern, which can be used to influence the degree of reflection imposed on the longitudinal modes. One option is to use an optical gate that can select and route the header to an optical series-to-parallel converter that may consist of fibre delay lines. The output of the converter can be used to set the first dimension of a modulator matrix, which operates, in the opto-optical mode. Alternative methods need to be explored, the use of gated optical bi-stable devices may provide novel solutions for the processing of the header. Mode locked laser structures which can be switched on or off by an external optical trigger have to be investigated. The use of such devices to capture the bit pattern of the header will be explored. Each header contains information about routing, switching or management operation to be executed by the node. The induced longitudinal mode power pattern of the laser produces information needed for the node to execute the required operation. The laser can be learned to translate specific header patterns into specific longitudinal mode power patterns by appropriate training sessions, using the second dimension of the matrix as weight factors. In that way, the node can be ordered to perform switching and routing or to carry out operations necessary to manage the optical network.

3.2 Network Management with Local Intelligence

The physics of optical telecommunication networks differs fundamentally from the physics of electrical telecommunications networks. As a result of this the control and management of optical devices in telecommunication networks has become a new field of research. Optical Networks are potentially suited to cover geographical areas which extend well beyond traditional limits such as the borders of countries and the traditional reach of telecommunication network management. It is therefore meaningful to search for a network management concept that relies as much as possible on local intelligence.

In principle, the optical input and output signals of, for example, an optical amplifier can be used to examine the performance of the device. Simple operations, which can be carried out locally with these signals in order to obtain meaningful information, have to be investigated. Possibilities are cross-correlation operations between input and output signals or a simple subtraction between output and input. In case of the optical amplifier, the output signal can first be attenuated with the same amplification factor, to improve the sensitivity of the subtraction result to unwanted effects in the amplifier.

For a proper interpretation of the results of local measurements, it is required that a local intelligence containing an accurate model of the device is available. The model must be based on an accurate physical model, which can predict how the measured input signal is related to the output signal. The relationship is commonly non-linear and depends on a large number of material parameters and input functions of the device. In future, this strategy may lead to the co-design of hardware and software, similar to a trend in electronics called embedded systems. In this case, we can speculate on the onset of something, which may be called embedded photonics. Because of the ultrafast optics, dispersion may be critical and has to be compensated for. We will explore how dispersion management of the fibre links in dynamic network configurations can be realised, using intelligence in the network.

Investigates what physical models adequately and reliably describe, for example, an optical amplifier, in particular when the device is degrading have to be carried out. Usually such a problem is
formulated by a set of coupled non-linear differential equations. Numerical methods to rapidly solve these equations have to be investigated. Moreover, methods on how to find the parameters, which determine the performance of the device to be monitored, should be investigated. The challenge will generally be to find the proper minimum of a non-linear equation and to determine the changes in the model parameters. Finding a minimum may be done numerically by Genetic algorithms, Monte-Carlo or neural methods.

4. Access networks

Although the bandwidth demand of broadband services has been tremendously reduced by video compression techniques, the existing access network infrastructure represents a bottleneck for these services and for the access to the Internet. As the network evolution should be adapted to the service demand, hybrid fiber based architectures offer a high potential as a bridge or even an alternative to Fiber To The Home (FTTH). A fiber based alternative is Hybrid Fiber Twisted Pair were telephone lines are used in combination with digital signal processing techniques to transport for instance 50 Mbit/s over 300 m twisted pair. Also the Hybrid Fiber Coax (HFC) CATV networks can be used for broadband data transmission. A flexible alternative is the Hybrid Fiber Radio solution. An alternative for the use of glass optical fiber in the home environment could be the Polymer Optical Fiber (POF) which has no limitations in diameter of the fiber. Optical fiber made of this material can be made thick and robust compared with glass optical fiber and thin and more easy to connect compared with coaxial cable and twisted pair. Moreover, POF offers the same large bandwidths compared with multimode glass optical fiber.

4.1 Polymer Optical Fibers

Silica based single mode optical fiber is widely utilised in the long distance trunk area for giga bit per second transmission and beyond, because of its high bandwidth. On the other hand, use of the silica based multimode fiber is a recent trend in the area of local area networks (LANs) and interconnection. This is because the large core diameter of silica based multimode fiber of 50 and 62.5 microns relaxes the tolerance required for connection compared with the single mode fiber whose core diameter is only 5 to 10 microns. However, even with the multimode silica fiber, an accurate alignment in the connection is still required.

Large-core, high-bandwidth, and low-loss graded index polymer optical fiber (GI-POF) has been developed [4,5]. The large core diameter (200–1000 microns) of the GI-POF enables the use of inexpensive polymer connectors, which are prepared by an injection molding process, because a displacement of ±30 microns in the connection does not seriously influence the coupling loss. Furthermore, a large core of more than 100 microns could reduce the modal noise, which disturbs systems with multimode silica fibers [6].

Polymethyl methacrylate (PMMA) has been generally used as the core material of commercially available step-index POF. Its attenuation limit is approximately 100 dB/km in the visible region [7]. Therefore, the high attenuation of POF compared to the silica-based fiber has limited the POF data link length, even when the bandwidth characteristics are improved by the GI-POF. On the other hand, the development of the perfluorinated (PF) amorphous polymer base GI-POF [8,9] opened the way to high-speed POF networks. The serious intrinsic absorption loss due to carbon-hydrogen stretching vibration that exists in PMMA base POF is completely eliminated in the PF polymer based POF. The experimental total attenuation of the PF polymer based GI-POF decreases to 40 dB/km even in the near infrared region.

In table 1 some important world-wide record results on transmission via POF are shown.
Table 1

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Month-Year</th>
<th>Organisation</th>
<th>Bit-rate</th>
<th>Distance</th>
<th>Fiber</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1993</td>
<td>Essex Univ.</td>
<td>0.5 Gb/s</td>
<td>100m</td>
<td>PMMA SIPOF</td>
<td>650 nm</td>
</tr>
<tr>
<td>2</td>
<td>1994</td>
<td>Keio Univ.</td>
<td>2.5 Gb/s</td>
<td>100m</td>
<td>PMMA GIPOF</td>
<td>650 nm</td>
</tr>
<tr>
<td>3</td>
<td>1997</td>
<td>Fujitsu</td>
<td>2.5 Gb/s</td>
<td>200m</td>
<td>PF GIPOF</td>
<td>1300 nm</td>
</tr>
<tr>
<td>4</td>
<td>2-1998</td>
<td>Eindh. Univ.</td>
<td>2.5 Gb/s</td>
<td>200m</td>
<td>PMMA GIPOF</td>
<td>645 nm</td>
</tr>
<tr>
<td>5</td>
<td>8-1998</td>
<td>Eindh. Univ.</td>
<td>5 Gb/s</td>
<td>200m</td>
<td>PF GIPOF</td>
<td>1310 nm</td>
</tr>
<tr>
<td>6</td>
<td>10-1998</td>
<td>Eindh. Univ.</td>
<td>2.5 Gb/s</td>
<td>300m</td>
<td>PF GIPOF</td>
<td>645 nm</td>
</tr>
<tr>
<td>7</td>
<td>11-1998</td>
<td>Eindh. Univ.</td>
<td>2.5 Gb/s</td>
<td>550m</td>
<td>PF GIPOF</td>
<td>1310 nm</td>
</tr>
<tr>
<td>8</td>
<td>1-1999</td>
<td>Eindh. Univ.</td>
<td>2.5 Gb/s</td>
<td>550m</td>
<td>PF GIPOF</td>
<td>840 nm</td>
</tr>
<tr>
<td>9</td>
<td>2-1999</td>
<td>Lucent</td>
<td>11 Gb/s</td>
<td>100m</td>
<td>PF GIPOF</td>
<td>1300 nm</td>
</tr>
</tbody>
</table>

Experiments have been carried out with different polymer fiber and at various wavelengths. PMMA has a low loss transmission window at 570 nm and 650 nm. Owing to the availability of light sources, only the 650 nm window can be used, unless low cost 570 nm sources come available. As the fundamental attenuation of PMMA is limited to about 100-150 dB/km at 650 nm wavelength, a large extension in distance cannot be expected with this material.

Perfluorinated (PF) polymer based GI-POF has a low loss wavelength region from 500 to 1300 nm [10]. In experiment 8 at 840 nm a Vertical Cavity Surface Emitting Laser (VCSEL) has been used in combination with a Silicon APD receiver [11]. Potentially the attenuation of PF GI-POF can be as low as 10 dB/km for the 850 as well as the 1300 nm wavelength region [12]. As the attenuation of PF GI-POF at the 650 nm wavelength region is still about 110 dB/km, 300 m has been reached at this wavelength in experiment 6 [13]. In addition to the receiver sensitivity, we believe that both the method of excitation as well as the spectral characteristics of the exciting source plays a significant role. Semiconductor lasers subject to back-reflected waves in optical communication systems may undergo different and complicated state of behaviours. Unless the reflected light is well monitored, optical feedback is often detrimental because it enhances noise and introduces multiple nonlinearities in the emission characteristics which degrade the signal-to-noise ratio at the receiver. Another explanation for the present performance can be found in connection with the spectral characteristics of the exciting source. The dispersion is further avoided by the launching condition of our experiments [14]. In case of the 1300 nm experiments, the SMF pigtail of the laser source was butt jointed to the GI-POF only exciting a few modes. In case of the 840 nm experiment also only a few modes are excited because the exciting beam was nearly parallel, meaning that the numerical aperture was not overfilled. So, the fiber should exhibit less modal dispersion because the number of propagated modes is less than can be excited under full launch condition, and this may lead to a further bandwidth improvement.

4.2 WDM with GI-POF

WDM over a 100 meter PMMA based GI-POF has been realized with a 2.5 Gbit/s and a 600 Mbit/s channel [15,16]. The large core diameter of the GI-POF, which is 750 microns in this case, provides interesting options for the multiplexing of wavelengths at the transmitter side of the system. Light sources can be supplied in standard single mode fiber pigtailed modules, modules provided with step index multimode silica fiber pigtails or graded index silica fiber pigtails. In those cases, it is possible to simply butt joint a bundle of light source pigtails to the input of the GI-POF fiber. In our experiments, we used two multimode source pigtails that are butt-jointed to the entrance of the GI-POF. For the demultiplexer a Littrow configuration was used, which uses a grating as the main
wavelength-separating component.

Owing to the narrow transmission window of PMMA GI-POF, the WDM wavelengths must be relatively close together, which could result in more expensive devices. PF GI-POF has a broad transmission window as indicated before, so many WDM wavelengths can be applied over a broad wavelength range, which can be separated easily with low cost devices [17]. As a start to this development a WDM demultiplexer for splitting up the wavelengths 645, 840 and 1310 nm has been realized with planar interference filters. These filters consist of thin layers. The demultiplexer will be used in combination with experiment 6, 7 and 8 of table 1 for a 3 times 2.5 Gbit/s GI-POF WDM experiment.

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References

Berlin, Post Deadline Paper.


