Coherent optical systems implemented for business traffic routing and access: the RACE COBRA project (invited)

Citation for published version (APA):

Bachus, E. J., Almeida, T., Demeester, P., Depovere, G. F. G., Ebberg, A., Rui Ferreira, M., Khoe, G. D., Koning, O., Marsden, R., Rawsthorne, J., & Wauters, N. (1996). Coherent optical systems implemented for business traffic routing and access: the RACE COBRA project (invited). *Journal of Lightwave Technology*, 14(6), 1309-1319. <https://doi.org/10.1109/50.511663>

DOI:

[10.1109/50.511663](https://doi.org/10.1109/50.511663)

Document status and date:

Published: 01/01/1996

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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Coherent Optical Systems Implemented for Business Traffic Routing and Access: The RACE COBRA Project

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(Invited Paper)

Abstract—The RACE COBRA consortium has performed four field trials to verify the suitability of dense WDM combined with heterodyne detection (for which the term CMC, “Coherent Multicarrier” is used) for different network applications. The main advantage in using heterodyne detection is the simple access to individual optical channels by only switching local lasers to the desired channel. Heterodyne detection acts as a perfect optical filter. Thus, a plurality of dense spaced optical carriers can be placed, e.g., within one WDM window. The additional freedom in the channel multiplex provides some advantages which are shown in the demonstrators: A routing flexibility in the RENO (Reconfigurable Node) cross-connect demonstrator supporting STM-16 at Philips Research in Eindhoven. A routing flexibility in the demonstrator at BBC in Kingswood Warren, UK, supporting uncompressed HDTV communication in a studio environment. By shifting switching functions to the terminals, the network is kept completely passive. This is also obtained in the local area videoconference trial at CET in Aveiro, Portugal, using high quality standard TV and in the BCPN trial at KPN Research in Leidschendam, NL, where ATM-streams are supported for multimedia services. The paper outlines the demonstrator concepts as well as some subsystems and key components developed by the consortium.

I. INTRODUCTION

ONE OF the objectives of the RACE program was to promote the competitiveness of the community's telecommunications industry, operators, and service providers in order

Manuscript received April 28, 1995.

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Publisher Item Identifier S 0733-8724(96)04779-2.

to make available to final users the services which will sustain the competitiveness of the European economy. The COBRA consortium reflects this objective by including among its partners two network operators and one service provider, as well as three industrial partners and two research institutions. The consortium was therefore in a position to investigate from many aspects the potential of innovative systems for short and medium term IBC (Integrated Broadband Communication) implementation.

Since IBC was first defined as the objective for the RACE program, there has been an important shift in perception. The orientation of the work has shifted from “Exploring Options” under RACE Phase I to “Preparing for Implementation” under Phase II. Work carried out in the COBRA project is aimed toward this latter exercise. Emphasis is placed on the exploitation of the optical frequency domain by coherent techniques, but other technologies are used as well where appropriate. Examples are the use of ATM in the KPN Research field trial, the coexistence of the WDM system in the TV studio BCPN, and the use of SDH interfaces and optical space switches in the optical RENO cross-connect demonstration.

II. COBRA CONSORTIUM AND RACE CONTRIBUTIONS

The RACE Phase II project R2065 COBRA (Coherent Optical systems implemented for Business traffic Routing and Access) covered the period of 1992–1995. The project participants are Philips (prime contractor), the Heinrich-Hertz-Institut (HHI), GEC-Marconi Materials Technology Limited, Siemens AG, Interuniversity Microelectronics Centre (IMEC), British Broadcasting Corporation (BBC), Centro de Estudos de Telecomunicacoes (CET), and PTT Telecom, NL (and KPN Research as a subcontractor). Since 1994, the Project Leadership has been subcontracted by Philips to the Eindhoven University of Technology.

COBRA was a follow-up of the RACE Phase I project CMC (Subscriber Coherent Multichannel System). In the CMC project, an important highlight was the design and construction of an engineered CMC distribution system. In the COBRA project, the knowledge and techniques developed in the CMC project were further enhanced and four different but

complementary multiwavelength systems were implemented in field trials.

The activities in COBRA have been split into different working groups: the WG Implementation coordinated the implementation of the demonstrators, the WG Technology specified the components and the link to the overall RACE program was established through the WG Systems. A public deliverable, the "COBRA-Report on Flexible Broadband Networks" was issued annually by this working group [1]–[4]. In these reports, the progress of the COBRA project was outlined and updated each year. Each COBRA Report also contains a summary of worldwide progress and trends in the area of multiwavelength networks and dedicated components.

The Working Group Systems also participated in a number of RACE activities such as the Project Line 1 (PL1) meetings and associated workshops, and Sub Technical Groups (STG's), which have been set up to draft specifications, and to provide essential inputs which are now included in the RACE Common Functional Specifications (CFS's) and in standardization proposals submitted to ETSI (European Telecommunications Standard Institute).

Cooperation with other RACE projects has been set up. The COBRA demonstrator at BBC shared the physical network simultaneously with the demonstrator of the RACE project WDM. The network of the COBRA CET demonstrator permits the operating status of the demonstrator to be assessed by collecting information on the status of each network element. This specific activity has been performed in close cooperation with RACE project ICM. Also a Techno-economical analysis was carried out with assistance of RACE projects TITAN and INTERACT.

III. OPTICAL NETWORK TRENDS AND COBRA

The aim of this chapter is to point out main features of the COBRA concept for the optical networks in the demonstrators.

A. Trends Toward High Capacity

10 Gb/s transmission systems are already commercially available. The next generation of WDM systems focusing on four or eight wavelength channels within the EDFA band are under development. Impressive advances on the laboratory level have recently been shown: the transmission of 400 Gb/s using optical TDM-processing techniques [5] and the arrival at the 1 Tb/s bound through multiplexing of wavelength channels (55×20 Gb/s [6] and 10×100 Gb/s [7]). The question arises, where the limit will be. In [8] the ultimate Shannon limit for the full band between $1.3 \mu\text{m}$ and $1.6 \mu\text{m}$ is estimated at 300 Tb/s. Pushing toward this frontier is of course an attractive approach. A distinct approach is to take an advanced but already engineered technique and to demonstrate various network applications. This was done in the COBRA project and is outlined in the following chapters.

B. The COBRA Concept

COBRA used a multiwavelength technology known as CMC (Coherent Multicarrier) developed in the RACE phase I project R1010 [9] which is based on optical heterodyne detection.

In a heterodyne receiver, the incoming signal is converted into a microwave signal by combining it with the light of a local oscillator laser at a slightly different frequency. The resulting intermediate frequency (IF) signal in the microwave region can be processed by conventional techniques which are well known from radio systems. The local laser frequency is locked to the signal light frequency by an automatic frequency control loop. Up to now this is the usual control scheme and also applied within COBRA.

The first obvious advantage offered by heterodyne detection is the high sensitivity of the receiver (and a corresponding long transmission span). With a sufficient amount of local oscillator power, a heterodyne receiver offers a sensitivity close to the shot-noise-limit. Meanwhile, this advantage has partly been eroded since the introduction of optical fiber amplifiers. The sensitivity of an optical direct detection receiver equipped with an optical fiber preamplifier approaches the sensitivity achieved with a heterodyne receiver.

1) Heterodyne Detection: A Perfect Optical Filter: The major advantages, however, offered by a heterodyne receiver are the selectivity and the tunability. A heterodyne receiver acts as a nearly perfect optical filter with very attractive features. The optical filtering function of the heterodyne receiver is determined by its electrical filter in the IF branch. In contrast to optical filters used in direct detection systems, multipole electrical filters of excellent passband characteristics are easily implemented in a coherent receiver. These nearly ideal optical filtering characteristics will be extremely useful when selecting a single optical channel from a high number of densely spaced channels transmitted on a fiber. A narrow channel spacing is advantageous, especially in the case of systems using a number of concatenated optical fiber amplifiers. As the frequency response of an optical fiber amplifier is not ideally flat, every additional amplifier reduces the available bandwidth leaving only a few nanometers in some cases.

Finally, the heterodyne receiver can be switched electrically to any desired frequency channel by changing the frequency of the local oscillator. Tuning can be performed very quickly compared to thermally or mechanically adjusted optical filters. A tuning range of more than 10 nm (>1 THz) [10] and a passband of around 1 GHz can be realized simultaneously. In contrast to preamplified direct detection systems, heterodyne systems can be operated over the entire wavelength range of the optical fiber (e.g., from 1300 nm to 1600 nm) and are not restricted to the passband of a particular optical amplifier. Note that the tuning range of semiconductor lasers is very large in principle. A continuous tuning of 242 nm ranging from $1.32 \mu\text{m}$ to $1.562 \mu\text{m}$ has already been shown in [11]. Some recent advances in CMC technology are reported in [12]–[20].

In our terminology, the term CMC (Coherent Multicarrier) is used for (dense spaced) optical carriers (which all have to fulfill certain coherence-conditions) combined with heterodyne detection. Channel selection (which is a switching function) is performed within the receiver. Thus, in any cases, the optical path is terminated by the corresponding transmitter-receiver pair. (If one wishes to route transparent optical WDM channels through a network, frequency selective all-optical devices like multiplexer, filter, router, and frequency converter are

Fig. 1. Hierarchical structure of multiplexing. The COBRA project aims at the potential of the carrier "pipes" and the interaction with the others.

indispensible). Most of the key technical problems associated with heterodyne detection have already been addressed and solved during recent years [21], [9], [22], [23], [24]. The technical advantages of coherent systems are evident; however, it still remains to be shown that these systems are economically competitive compared to other solutions. A step toward cost reduction is the monolithic integration of a heterodyne receiver front end on a single chip [25], which has also been one activity within the COBRA project.

2) *Illustration of the Multiplexing Concept:* A layered transport network architecture for SDH has been commonly accepted and will be standardized by ITU [26]. The ITU-T recommendation G.803 also explicitly states, that "the necessity of an explicit description of a WDM layer in the transmission media layer is for further study." The concept can be extended with new layers representing optical multiplexing and cross-connect functionality as proposed in [27], [28], a WDM layer and a CMC layer. The additional CMC multiplexing explored by the COBRA consortium is illustrated in Fig. 1.

The style of this figure differs from that commonly used (showing the layered areas) in order to illustrate the fact that a WDM-channel is a bundle of CMC-channels, each CMC-channel a bundle of TDM-channels which itself may split into the layers of SDH and ATM.

Physical and logical topology of a network need not to be identical, and can be optimized independently. Logical reconfiguration of a network (for example, in the case of varying traffic or service demands), is possible without changing the physical topology. Furthermore, optical multicarrier technology can also attribute to network survivability, by offering a very flexible way of rerouting traffic. For these purposes the RENO's (see Ch. IV-A) act as optical carrier cross-connects providing a means for flexible optical network reconfiguration.

3) *Main Features of the COBRA Concept:* The main features of the COBRA concept shown in the demonstrators are summarized in brief:

- A fine granularity of wavelength channels. The channel spacing can be performed close to the bandwidth of the channels.

Fig. 2. The four COBRA demonstrators and the network segments covered by these demonstrators.¹

- A dedicated wavelength channel for each application. This is shown for the transport modules of SDH (STM-1, STM-16), for uncompressed TV and HDTV distribution and for ATM-streams.
- COBRA networks are based on the broadcast-and-select principle. "Broadcast" by means of star-couplers, "select" by tuning of receivers.
- Optical paths are always terminated by the corresponding transmitter-receiver pairs. Each receiver performs a fully electrical regeneration of the digital signals (3R).
- No optical filters or multiplexers are used for discriminating individual CMC channels.
- Simple upgrading is possible by adding just more carriers (within the range of tunability and power budget).
- Unlimited cascability is possible through modular sub-networks. The resulting multihop network is of course not all-optical.
- The optical COBRA networks are circuit switched networks (packet switching with CMC is indeed an important option for further investigations).
- Emphasis is laid on demonstrating practical applications including the management of the demonstrator networks.

IV. THE COBRA TRIALS

The demonstrators have been chosen to illustrate different aspects of an overall communications network. The RENO demonstrator is a part of the core network, forming the switching centres at which SDH traffic is routed [29]. The three other demonstrators address three types of BCPN, each with specific customer requirements (Fig. 2).

The individual demonstrators are now outlined by short descriptions and figures followed by a table summarizing their main parameters.

A. The RENO Core Network

The general structure of a single RENO (Reconfigurable Node) is shown in Fig. 3. The maximum number of fibers and carriers per fiber is assumed to be N and M , respectively. The

¹The drawn lines in the figure are indicating optical connections, not necessarily single fibers. A connection may consist of a single fiber (duplex mode) or two fibers (simplex mode).

Fig. 3. General structure of the RENO's (Reconfigurable Nodes). CT_x is a Coherent Transmitter at a fixed optical frequency, CR_x is a Coherent Receiver switchable to any of the M carriers ($K \leq MN$).

Fig. 4. The RENO core network demonstrator.

incoming carriers are transferred through the RENO to the outgoing fibers via space switch matrices and CR_x - CT_x pairs ("C" stands for coherent) performing the wavelength translation. Also add-drop-functions are implemented. The transmitters have a fixed wavelength, the receivers are tunable (it has to be mentioned here that a plurality of different node-architectures are possible to obtain the same functionalities). A part of a core network based on RENO cross-connects is depicted in Fig. 4. The nodes are interconnected by unidirectional optical fiber links. Generally, such nodes will be located in major cities, also interfacing via dedicated optical links to the local exchanges (LEX's). In the demonstrator all CT_x and CR_x are working at 2.5 Gb/s for transmit and receive STM-16 signals of the SDH [30], [27]. In [31] it is shown that the SDH management facilities can be used to locate errors (monitoring) and to transport network information across the optical layer (signaling). In [28] it is shown how signaling and surveillance facilities can be achieved through the addition of a low bitrate signal to each wavelength channels.

The RENO demonstrator is restricted in terms of available hardware (4 wavelengths for 3 RENO's), but illustrates the full capability of the RENO concept.

A typical feature of the RENO network is the possibility to adapt the traffic per fiber to changes in the actual short-term traffic demand [32]-[35]. Each transmitter can be allocated to any trunk. This is cost effective, because reductions in hardware requirements can be made through statistical traffic analysis, the number of CR_x - CT_x pairs being determined using standard network planning techniques. Spare CR_x - CT_x pairs

may also be present to allow extra capacity for special events. These may also be used for replacing any CR_x - CT_x pair that has become unavailable. In the case of a connection failure between two nodes, the total traffic between the two nodes may be easily rerouted via one or more other nodes of the network. This avoids the necessity for extra optical switch hardware and links.

Some nodes will in practice only interface with a small number of other nodes, and will consequently only have a limited number of CR_x - CT_x pairs. Upgrading may be achieved by simply adding extra hardware modules (optical switch, tunable receiver, and transmitter), assuming that large enough optical splitters and couplers were initially installed. Performance studies which calculate the wavelength requirement and the survivability for realistic networks are published in [33], [34].

B. Broadband Video Multi Access—The BBC TV Studio Network Demonstrator

The objective of the BBC Demonstrator was to show an application of CMC technology in broadband routing—the transport of full-band television signals in a studio center. A coherent transmission layer has been specified and developed to determine the potential capacity of a practical network, and to show that coherent techniques are an effective means of extending close-spaced WDM. It is estimated that coherent techniques could increase the capacity of a conventional WDM system by about a factor of eight.

There is a requirement in a TV studio center to interconnect technical equipment on, say, an hour-by-hour or day-by-day basis, to draw together the technical facilities for a particular program production. (This is distinct from the rapid synchronized switching required for editing and program "cuts"). The network must be nonblocking, point-to-multipoint, with the capacity for several hundred video, audio, and ancillary signals.

RACE Projects R2001 and 1036 have developed a network to meet these requirements based on a combination of close-spaced wavelength multiplexing and electrical multiplexing. This system, known as WTDM, provides only just enough capacity for a typical studio center. The work in COBRA shows the extra capacity and optical power margin offered by coherent techniques. This can be used for more signals, for HDTV as opposed to conventional TV signals, to increase network flexibility, or a combination of these. It has also been demonstrated that WTDM and CMC can operate on the same optical network. The ability to tune the CMC receivers eliminates some of the high-speed electrical switching that would be needed in a WTDM network.

The typical demonstration is shown in Fig. 5. The coherent layer itself consists of three sets of 2.5 Gb/s transmission hardware (one each from GMMT, Philips and Siemens), and a central controller (developed by HHI and GMMT, and known within the project as the wavelength manager). The nominal channel spacing of the coherent transmitters is 0.25 nm (about 31 GHz), adjustable for experiments, grouped around 1553 nm. The WTDM lasers operate at 2 nm intervals from 1530

Fig. 5. The BBC Studio demonstrator: A merge of the RACE WTD and the COBRA project. HDTV studio terminals in the COBRA part are communicating at the STM-16 line bitrate of 2.5 Gb/s (uncompressed digitized video channels in the payload). All the COBRA CMC channels fit into a single WDM slot of the WTD testbed.

nm to 1560 nm. The coherent transmitters and receivers are connected to the WTD network's central optical star by additional 4×4 couplers, and in this arrangement replace the 1552 and 1554 nm channels. Program signals are connected to the network via SDH multiplexing equipment developed in R1036, and audio, TV, and HDTV interfaces developed in R1081. The bit rates of these signals range from 3.072 Mb/s to 1.152 Gb/s.

The system was originally demonstrated during September 1994. This demonstration linked a series of technical areas at the BBC's Research and Development Department in Surrey, UK, and was held as part of the Department's biannual "open days." COBRA equipment was used to convey signals ranging from audio to uncompressed HDTV over an existing optical network. The equipment was reassembled in March 1995 at RAI (Italian, State Television) Technical Research Center Turin, and a further trial was conducted in autumn 1995 at the main studios of NRK (the Norwegian State Broadcaster), Oslo. These last two events were collaborations with RACE 2001, WTD Pilot.

C. Videoconferencing in Aveiro Town—The CET Demonstrator

The COBRA demonstrator implemented by CET in Aveiro aims at assessing the viability of videoconference services by means of coherent techniques for the transmission of digitized standard video signals over a PON with a star topology. Coherent equipment is used which was developed under the R1010 project and designed for the distribution of high quality video channels at 140 Mb/s [36], [37].

The field trial is based upon a standard singlemode fiber passive optical network (PON) transmitting video signals between three sites (CET, Telecom Shop and Telecoms Institute) Fig. 6. The PON is configured as a star scheme with one duplex fiber cable per user. For the purposes of system control, one output of the central four-by-four star coupler is monitored by an optical spectrum analyzer, allowing measurement of optical power and frequency stability.

The optical network is supported by an N-ISDN network running in copper symmetrical pairs. This network uses the

Fig. 6. The CET demonstrator designed for 140 Mb/s point-to-point videoconferences. The network is controlled via the ISDN Network by the Central Control Unit (CCU). Remote management of the demonstrator is performed by the TMN platform which has access to a Managed Information Base (MIB).

ELDIS Local Digital Exchange developed by CET and interconnects the Control Unit with each of the users premises. There, an ISDN phone set is connected to a PC featuring an ISDN card and through which both digitized voice/sound and control signals are to be passed. The network permits the remote management of the demonstrator by a PON TMN platform which has access to a Managed Information Base (MIB) located in the COBRA Control Unit (CCU). The CCU contains updated information on the status of each network element. The functionalities of this platform include alarm management and configuration monitoring. This activity has been performed in close cooperation with R2059 ICM.

The CET demonstrator was installed in the Aveiro town area using the existing duct and cable network infrastructure from Telecom Portugal. The distance between each of the users and the control center (CET) is not greater than 3 km. Bidirectional interactive videoconference services (both point to point and point to multipoint) are available to business users, allowing telelearning/training and joint business meetings to be held. These define the requirements for the remote control of terminals.

In a realistic environment with a large number of users, a number of questions arise, answers to which are difficult to find from a small size demonstrator. These include spectrum management aspects, arbitration of the videoconferencing session, PON monitoring and alarm processing issues as well as delays introduced by network control. In addition, if less optical carriers are available than the total number of users, congestion is likely to occur and must be accommodated. These issues are studied using a network model with at least 100 users and a smaller number of available optical carriers. The results obtained complement the tests of the demonstrator.

D. Multimedia Communication in Leidschendam—The PTT-BCPN Demonstrator at KPN Research

It is generally expected that a future business customer premises network (BCPN) must deal with a large variety of broadband services, each specified by a different bit rate and traffic characteristic. In future BCPN's several connection types (like point-point, multipoint-multipoint, and point-

Fig. 7. The concept of the PTT-BCPN demonstrator at KPN Research Leidschendam, showing coarse WDM, CMC and ATM multiplexing (TR_x = transmitter and receiver working at $\lambda = 1.3 \mu\text{m}$, CTR_x = coherent transmitter and receiver in the $1.55 \mu\text{m}$ waveband). The network can be upgraded by alocal ATM switch (dashed lines).

multipoint) must be supported, besides which, the total network capacity is expected to increase significantly. Since it is at present almost impossible to foresee which applications will become prevalent, advanced BCPN's must have great flexibility and must be able to supply a high transport capacity.

Coming back to Fig. 1 showing the multiplex hierarchy, the demonstrators described so far are transporting their services on a corresponding single optical carrier. A higher granularity is obtained in the PTT BCPN demonstrator by introducing ATM multiplexing on each individual carrier [38]–[40]. Thus, the stations in Fig. 7 are individually linked by circuit switching through tuning of corresponding CT_x - CR_x pairs. Each carrier is transporting data at the STM-1 line rate of 155.52 Mb/s. The multimedia terminals of the linked stations are now communicating via additional TDM multiplexing, which is chosen here as ATM multiplexing in order to obtain a flexible granularity and to interface the future B-ISDN standard.

The basic idea of this concept is as follows:

- 1) By multiplexing a bundle of ATM circuits onto an optical carrier the concept "ATM optical path" introduced by Sato *et al.* [41] is realized as a measure to obtain very high capacity networks based on ATM.
- 2) Since CMC switching allows for point-to-point as well as for point-to-multipoint connections and ATM multiplexing allows for addressing individual terminals, a high number of circuit configurations can be established without any ATM switch in the network (it has to be noted that an ATM switch is indeed not a part of the demonstrator).
- 3) By introducing ATM switches (a single centralized switch or many decentralized switches within the stations) the network can easily be upgraded to multipoint-to-multipoint connections without changing the physical topology (the PON) and the optical hardware. In the final test and evaluation phase of the demonstrators these issues will be addressed in more detail.

The hardware configuration of the PTT BCPN trial in Fig. 7 consists of five transmitters and receivers connected to each other by means of a passive optical star. The transmitters and

TABLE I

Short name of the trial	RENO demonstrator	BBC demonstrator	CET demonstrator	PTT demonstrator
Location of the trials	Philips Research Eindhoven, NL	Kingswood Warren, UK	Aveiro, P	KPN Research Leidschendam, NL
Application shown	Cross-connected core network	HDTV in a studio	Videoconference	multimedia, medical
Number of nodes in the trial	3 OCCs (potential: unlimited)	1 passive star	1 passive star	1 passive star
Number of terminals connected to the nodes in the trial	(3 for testing only)	5	3	4
Number of optical carriers and line transmitters realized	4 in total	3 per node	3 per node	4 per node
Demonstrator concept allows for	16 per link	8 per WDM window	128 per node	128 per node
Number of line receivers realized	4 in total	3	3	4
Number of potential line receivers due to power budget limit (without amplifiers)	16 per link	more than 100	more than 4000	more than 4000
Fibre length in the trials	60 km between OCCs	below 1 km	average 3 km	up to 50 km
OAM and signalling via	separate fibre network	separate electrical network	public ISDN	WDM overlay at $\lambda = 1.3 \mu\text{m}$
Optical center frequency in GHz	193036.5	193040.8	192150.0	192150.0
Carrier spacing in GHz	15	30	20	25
Frequency stabilization implemented	yes	yes	yes	no
Bitrate per carrier in Mbit/s	2488.32	2488.32	140	155.52
Service per carrier shown	routing of STM-16	one uncompressed HDTV in STM-16	one PAL video channel	ATM streams
Modulation scheme	CPFSK	CPFSK	FSK	FSK
Coding scheme	NRZ	NRZ	Manchester	Manchester
Level of demonstration	field trial	application pilot	application pilot	application pilot

receivers are distributed among four stations. Each station comprises at least one audio/video (de)coder and an ATM (de)multiplexer.

The use of a passive optical network implies that all information is sent to all subscribers. Therefore, in many applications, network security is important. Implementation of network security functions is introduced in the demonstrator at three levels: User authentication during call setup, exchange of encryption keys, and high-speed encryption of user data. Since encryption is performed on the ATM adaption layer, services at various bit-rates, multiplexed on a single CMC channel, can be encrypted separately. Dedicated hardware and software is part of the demonstrator in order to make encryption of the ATM data stream possible.

Network control is another important aspect in the BCPN concept. Network control includes three main aspects: Call-control, wavelength management, and security/key control. In the BCPN a direct detection overlay network on the same fiber infrastructure at $\lambda = 1.3 \mu\text{m}$ is used for the network control functions [42].

A third important aspect tested in the demonstrator is optical amplification. The optical amplifier (EDFA) will either compensate the splitting loss in the passive optical star or the loss in the length of installed fiber. In the demonstrator two configurations are tested successfully: Unidirectional traffic with a transmissive star and an unidirectional optical amplifier, and bidirectional traffic with a reflective star and a bidirectional optical amplifier [43], [44].

E. COBRA Demonstrators Overview

The table on the following page summarizes main parameters of our demonstrators. Also, some technical details which

Fig. 8. The Wavelength Manager for controlling coherent transmitters.

are not explicitly mentioned in the foregoing chapters are listed here.

V. SUBSYSTEMS AND COMPONENTS

This chapter summarizes some CMC related hardware developments within the COBRA project.

1) *The Wavelength Manager*: In WDM and CMC networks a wavelength manager in general is responsible for three functions:

- 1) Monitoring the status of all WDM/CMC channels
- 2) Stabilization of the transmitter frequencies
- 3) Switch-off a transmitter which fails.

Since the temperature stabilized transmitter lasers are operating within their predefined windows and with very low intrinsic frequency drift, all demonstrators have been working during the demonstration periods without the explicit necessity of additional control. However, for large networks with a large number of carriers, and in order to maintain a high reliability, wavelength control is indispensable. The wavelength manager developed in the COBRA project is described in detail in [45]. It consists of a commercial high resolution scanning Fabry–Perot spectrum analyzer featured with a galvaton reference (Kr-line at 1547.825 nm). The total absolute accuracy of transmitter frequency control is within 2.5 GHz, the relative accuracy is below 200 MHz.

The wavelength manager was implemented in the demonstrator at BBC controlling the transmitters as shown schematically in Fig. 8.

2) *Laser With 1600 GHz Tuning Range*: BH-TTG lasers, fabricated by an all-MOVPE process, have been developed with an active region comprising six strained quaternary quantum-wells. An optimized n -contact geometry (double-sided arrangement) is used. By applying either forward or reserve bias to the tuning region, the continuous tuning range has been extended to the record value of 13.2 nm (1.6 THz). An output power level above 1 mW can be maintained over 12 nm tuning range, with the linewidth remaining below 30–40 MHz [10]. Work has been carried out on TTG-structures with current blocking layers for improved current confinement and therefore enhanced output power.

3) *Lasers With Flat FM-Response From 0 to Above 3 GHz*: A new type of laser has been developed that solves the problem of the low-frequency dip in the FM-response

of conventional lasers. This QCSE (quantum confined Stark effect) TTG (tunable twin guide) laser shows an extremely flat FM-response from dc to 3 to 4 GHz and allows simultaneously wavelength tuning [46]. Two versions—with polyimide layer for lowest capacitance and without polyimide but very small contact pads—have been produced.

4) *Common Laser Designs for Transmitter and Local Oscillator*: The QCSE-TTG laser has been found to be suitable for both the transmitter and the receiver local oscillator. For all types of single and double-section DFB lasers investigated, it appeared very difficult to meet the linewidth specification in combination with the low and high cut-off frequency specifications for the FM-response. A three-section tunable DBR laser has however been found to be successful, and also able to function as both transmitter and local oscillator [47]. For the transmitter, the FM-response of the modulated Bragg section was flattened to 2.5 GHz by means of an external electronic equalization circuit.

5) *Integrated InP-Based Polarization Controller*: An integrated InP-based polarization controller having the “semi-insulating embedded ridge structure” has been developed [48], [49]. The structure is fabricated in three epitaxy steps and by a combination of wet and dry chemical etching. A special procedure was developed, resulting in a completely flat regrown structure. Electrical measurements on the regrown structure showed leakage currents to be negligible.

6) *Micro-Optical Polarization Hybrid*: A novel fully packaged micro-optical polarization diversity hybrid, showing high performance and being extremely fabrication and alignment tolerant was designed. The design employs highly parallel glass plates, which result in parallel and equidistant input and output beams, thereby eliminating critical fabrication and alignment procedures. At the target wavelength of 1550 nm, typical fiber-to-fiber insertion loss is 0.7 dB, balancing is 50 ± 3 , polarization extinction ratios are better than >25 dB, and measured back reflection is smaller than <-58 dB. Wavelength insensitive behavior has been observed, resulting in a wide useable spectral operating range in excess of 90 nm. The packaged hybrid is robust, reliable, and allows for low-cost fabrication techniques [22]–[24].

7) *Low-IF Receiver Design Implemented*: A CPFSK receiver has been developed for 2.5 Gb/s NRZ with an IF of 2 GHz and an IF bandwidth of 4 GHz [18], [50]. This receiver uses a new concept, based on the suppression of the “double-IF” signal which is generated in the frequency demodulation process. The concept is especially attractive when combined with electrical dispersion compensation techniques.

8) *Multichannel EDFA Developed for Bidirectional CMC Operation*: An erbium-doped bidirectional fiber amplifier has been developed and tested [51]. It was found that the saturation of the amplifier is homogeneous, i.e., only dependent on the sum of the two bidirectional input powers. Besides, the crosstalk from reflections and backscattering, and the influence of gain saturation and noise processes was being examined. From this analysis, it came out that large reflections, even when causing laser action at 1531 nm, only slightly influenced the coherent bidirectional transmission at 1560 nm. It was also found that the crosstalk from Rayleigh backscattering between

Fig. 9. Schematic view of a fully integrated polarization diversity heterodyne receiver.

counterpropagating signals was increased when the gain was larger than the transmission loss after the EDFA. By a combination of experiment and simulation, it is predicted that up to 10 000 155 Mb/s channels can be amplified simultaneously, which corresponds to a total transmission capacity of over 1 Tb/s. Simulations show that in this case the access shot noise from the amplified channels has a significant influence in the system performance.

9) *Fully Integrated Heterodyne Receiver OEIC*: Within the COBRA project an OEIC concept has been developed that integrates the basic elements of an isolator-free heterodyne receiver: a four section DBR local laser, a 3 dB coupler, balanced photodiodes, and a JFET. In the meantime, the HHI has upgraded this device to a fully packaged polarization diversity receiver and has carried out first system experiments. Since this is a breakthrough in component technology with the potential of mass production supporting the introduction of coherent multicarrier technology in the future, a brief outline of this device is given here. On a single 2-inch InP-wafer a number of 100 heterodyne receiver chips of size 9×0.6 mm shown schematically in Fig. 9 can be produced. The process based on selective area MOVPE involves 23 lithographic and seven epitaxial growth steps for the integration of 17 different photonic elements [25]. A first packaged device was tested at 140 Mb/s exhibiting a sensitivity of -34 dBm ($\text{BER} = 10^{-9}$) and a polarization dependence below 0.5 dB [52].

VI. CONCLUSION

The implementation and the test of the four COBRA trials has been finished by end of 1995. The consortium has promoted coherent multicarrier technology and has gained expertise ranging from components technology to practical applications on a service level. The trials are covering different network segments for the evaluation of specific practical aspects. The RENO demonstrator shows that the flexibility of today's SDH-based core networks can be increased by CMC technology. The demonstrator in the BBC TV studio has proven the high capacity of an internal passive optical network and the simplicity to access ultra-broadband sources. The videoconference trial at CET demonstrates a fastidious service with real users in an operational environment and the trial at KPN Research a high capacity business customer network supporting ATM based multimedia communication.

ACKNOWLEDGMENT

This paper is written by the members of the Working Group Systems of the COBRA project. However, we wish to acknowledge the work of all our colleagues within the consortium. We also acknowledge the support of our individual companies and the support by the Commission of the EU within the RACE phase II program. We thank B. Mikulski for performing the manuscript and G. Reise for the drawing the figures.

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