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Joint Optoelectronics Research Scheme (JOERS) Conference

J.F. Blackburn

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Summaries of the information on 33 JOERS programs made available at the conference are given. Also given are summaries of nine of the ten papers presented. Since the objective of the conference itself was to summarize the scheme's programs, this report, provides a reasonably comprehensive picture of the UK's status in optoelectronic technology.

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JOINT OPTOELECTRONICS RESEARCH SCHEME (JOERS) CONFERENCE

Organized by the Department of Trade and Industry, this conference, held in June 1988, was attended by 166 delegates (by invitation) from within the UK.

The objective of the meeting was to summarize the progress of the Joint Optoelectronics Research Scheme (JOERS), which began in 1982 with a budget of £25 million (about $46 million). This allocation was committed to 21 collaborative projects involving 15 companies and 23 educational institutions. A second phase was launched in March 1986 with a funding of £11.25 million ($21 million), allowing for 10 additional projects.

A number of projects from the first stage of JOERS have been completed. The program has led to increased collaboration between industry and universities leading to a better understanding and appreciation of each others' work and needs; maintaining research in optoelectronics where it might not otherwise have taken place; and success in the research itself which may lead to exploitation by private industry.

Clearly, the evidence from this conference is that the JOERS Program has had and is having an important and useful impact on British technology. One major benefit is that of the large-scale cooperation between British industry and British Universities on a well-defined technological objective. This has worked very well in this case and has lead to other programs like LINK and Alvey.

Important developments in optoelectronics have been made as a result of JOERS that certainly would not have been made as early as they were without JOERS and may not have been made at all. As stated by Dr. Goodfellow, the UK now has three major metalorganic chemical vapor deposition equipment manufacturers, and several chemical reagent manufacturers resulting from the JOERS program.

The exploitation of advanced epitaxial growth technologies in the UK owes much to the JOERS program.

PROGRAM SUMMARIES

The summaries following are abstracted from handout material.

Long-Wavelength Optical Fibers

This program, involving British Telecom Research Laboratories (BTRL) and STC Technology LTD, was completed in April, 1987. Its objective was to assess the feasibility of producing optical fibers with losses significantly below those achievable in single-mode silica telecom fibers (0.15 dB/km at 1.55 μm). To achieve this it is necessary to consider materials which transmit to significantly longer wavelengths than silica so that advantage can be taken of the reduced Rayleigh scattering, which has a λ-4 dependence on wavelength. Among the most promising are fluoride gases, which have theoretical losses at an order of magnitude lower than silica in the waveband 2.5 to 3.5 μm.

Facilities were established at both industrial partners to produce high-purity samples of fluorozirconati glasses. Studies of the thermal stability of these glasses at the Department of Electrical and Electronics Engineering at Sheffield University enabled the optimum compositions to be established. Long lengths of multimode fiber with good dimensional control can be produced. Fiber losses have been reduced to well below 100 dB/km achieved at BTRL, close to the world best of 1 dB/km. A good understanding of the loss mechanisms in these fibers has been obtained, enabling a realistic estimate of the minimum achievable losses to be made: 0.03 dB/km at 1.55 μm. Significant progress was made in reducing the extrinsic absorption losses, in particular the fundamental water peak at 2.9 μm. A study has been made at the Warwick University Materials Lab of alternative oxyhalide glasses. However, these are not competitive with fluoride glasses as low-loss fiber materials.

Semiconductor Waveguide Integrated Optics Base Technology

This program was conducted by BTRL and Plessey Research Ltd.

Currently many laboratories are developing integrated optical components using lithium niobate and other nonsemiconductor materials. eventually, integrated optical components using semiconductors may give superior performance, cost, and reliability because optical sources (laser and light emitting diodes), photodetectors, and electronic components may be integrated monolithically with the optical waveguide devices.

This JOERS project was to study technical aspects crucial to the development of semiconductor integrated optics such as dry etching techniques, selective area epitoxy, novel waveguides, and theoretical assessment techniques.

The most significant development has been the demonstration of very low loss waveguides in GaAs and InP materials systems. Losses of less than 1 dB/cm have been obtained for single-mode waveguides in both. This puts the UK in the lead in this field. A nondestructive method

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of measuring loss developed as part of the project has been invaluable in allowing the low loss measurements to be accurately made.

Theoretical studies have resulted in a variety of computer programs, for use in microcomputers, being distributed to the collaborators for device design.

Theory and Technology of Quantum Wells in Semiconductors for Optoelectronics Applications

BTRL, Plessey Research, and GEC Research participated in this program. It involved materials growth and assessment, experimental measurements, and theoretical studies of quantum well structures in a number of different III-V materials systems of relevance to optoelectronic devices. The overall aim of the measurements and theory is to gain an understanding of carrier lifetimes.

Quantum well samples with various well and barrier widths have been grown in the GaAs system by all three collaborators and supplied to Essex for measurement. The measurement facility developed at Essex includes equipment for measuring photoconductivity at magnetic fields up to 7 T with 100-ps laser pulses at temperatures down to 2K, in addition to facilities for measuring optical absorption and photoluminescence, and clean-room specimen preparation. The optical measurements indicated the presence of quantum wells very clearly, however the photoconductivity measurements showed a highly complex behavior suggestive of a dominant role being played by defects and asymmetries in the growth process which are often masked by doping.

Quantum well samples of interest for application in long-wavelength optical communications have been grown in the InP/Ga InAs and GaInAs/AlInAs/InP systems at Plessey, in GaInAs/AlInAs at BTRL, and in GaSb/AlGaSb at GEC. In-house assessment facilities of the collaborators confirmed the existence of quantum wells in all these materials samples, with the BTRL samples showing well widths down to a single monolayer of GaInAs as evidenced by low-temperature photoluminescence. Measurements on these samples at Essex were delayed but have now begun.

At BTRL significant progress has been made in understanding the polarization dependence of optical gain, the nonradiative Auger recombination which can hamper laser operation, and the nonlinear optical properties of quantum wells. Plessey has developed a comprehensive theoretical model for quantum well lasers and has incorporated into it the BTRL Auger transition rates as well as results on intervalence band absorption from Durham University. The effects of electron-electron scattering and of carrier capture dynamics were included to obtain an improved agreement with experimental data. At GEC the theoretical work has concentrated on band structure calculations for the antimonides and for superlattices in order to obtain an understanding of the role of tunnelling as current/voltage characteristics.

Metalo-organic Chemical Vapor Deposition (MOCVD) Growth and Assessment Of Indium Phosphide Based Optoelectronic Materials

The aim of this program was to develop the MOCVD of InP-based mixed III-V Materials to the stage where advanced and sophisticated heterostructure multilayers can be prepared reproducibly over wide doping concentrated ranges and then be precisely characterized and specified for optoelectronic functions. The participants are Plessey Research, BTRL, STC Technology, St Andrews University, Queen Mary College (London), University of Manchester, and University of Oxford.

Safety purification and handling of Group III and Group V precursors have been pursued at Queen Mary College and St. Andrews University and prototype and manufactured materials evaluated in the industrial laboratories. Adducts, metal-amines, diphos adduct compounds – in addition to conventional trimethyl metal compounds and triethyl-diphos materials – have been prepared in purified form. Technology transfer to UK manufacturers of key processes has been done, and consistent high-quality Group III precursors are now available for UK industry and for export. Some progress has been made on Group V precursors as well.

In epitaxial growth, four methods have been assessed: growth from adducts, *in-situ* formation of adducts, direct growth without adduct formation at atmospheric pressure, and direct growth at low pressure. Binary, ternary, and quaternary combinations from the GaAl InAsP system have been prepared and state-of-the-art purities, compositional control, lattice matching, and efficient photoluminescence have been achieved. Those achievements result from the improved reagents and also improved gas handling manifolds, improved reactive cell design and better pressure control.

Lattice-matched GaInAs/InP, GaInAsP/InP, AlInGaAs/InP structures have been prepared in single-layer form and in multiquantum well structures. Materials have been effectively tested in device demonstrators and 1.7 kA/cm^3 1.3-m lasers, 97-percent quantum efficiency 2-m detectors, high gm FET's, and quantum well lasers have been developed by the industrial partners.

Metallurgical characterization using TEM, SEM, cathodo-lumi·escence and x-ray analysis has measured the structural quality and enabled the origins of defects to be found. It has identified the effects of cyclical parameter variation during growth, as well as interesting compositional-dependent effects such as spinodal decomposition and interface roughness between particular ternary compositions.

Langmuir-Blodgett and Related Polymer Films for Optoelectronics

The collaborators in this program are GEC Research, BTRL, Plessey Research, and the Universities of Lancaster, Durham, and Hull.

Certain classes of organic materials provide some of the highest optically nonlinear coefficients. Single-crystal organics are being studied separately in the JOERS but this project concentrates on thin organic films and seeks to take advantage of two particular aspects of film technology. First it may be possible to avoid the cancellation effects that occur in crystals for some of the more promising molecular structures. Secondly, thin organic film technology should be particularly suitable for fabrication of planar devices and for developing hybrid or monolithic integration of optoelectronic circuits.

The main emphasis is on the Langmuir-Blodgett (L-B) films, offering the advantages of close control of film thickness, composition, and order with the flexibility to incorporate a wide range of functional molecular groups and properties.

A wide range of high-coefficient organic molecules have been synthesized, many of which have proved suitable for L-B deposition. Automated L-B troughs have been developed allowing disposition of multilayers > 1/m thick. Extrinsic sources of optical loss have been minimized, enabling total losses as low as 10 dB/cm, depending on film composition. Detailed structural analysis of the films has established that molecules may pack with very large (40 degree) tilt angles from the normal to the plane. Symmetrical ψ decomposition has proved to be dominant, and to overcome this, decomposition of alternate layers of different molecules have been developed. Second harmonic generation from the multilayers can be significantly in excess of the sum of the effects from single layers. Current exploitation of these effects has led to second harmonic generation of 50 times the value for lithium niobate, with considerable scope for further optimization.

Work on polymer films has concentrated on guest/host systems with high electro-optic-coefficient molecules as the guest in a host of cost PVDF copolymer film. Stable internal fields of ≥ 1.1 degree v/m have been established, leading to second harmonic generation of 6.1^{-8}esu, the highest value published to date. Optical loss is as low as 5 dB/cm at a wavelength of 0.633 μm and is dominated by the host material. It is expected to be 1-2 dB/cm at λ = 1.3-1.5 μm.

Molecular Beam Epitaxy (MBE) Growth of III-V Materials for Advanced Optoelectronics Technology

The participants in this program are BTRL, GEC Research, and the Universities of Glasgow and of Manchester.

The aim of the program is to establish an MBE growth capability so that the geometric advantages of the technique can be exploited in III-V materials for advanced optoelectronic technology. Targets are: control of composition, thickness, and doping; heterojunction formation and assessment; and layer growth for device fabrication.

At BTRL work has continued on the GaInAs and AlInAs ternary alloy systems for telecommunications applications at 1.3 and 1.5 μm. State-of-the-art material is now routinely produced on 2-inch InP wafers with excellent uniformity across the wafer. Effort has concentrated on improving interface sharpness for application in MQW lasers. Single quantum well structures have been produced where PL line widths at 4 K are an order of magnitude narrower than previously reported. A quantum well 6 angstroms in width is clearly resolved, and emission from this well was observed at 897.3 nm. Similarly, results of modulation-doped hetrostructure results indicate that the interface is of extremely high quality, yielding a 1.2 K mobility in excess of 170,000 $cm^2V^{-1}S^{-1}$, the longest yet reported for this materials system.

At GEC the impetus has been to find a suitable n-type dopant for GaSb and AlGaSb. Work has concentrated on the chalcogens S, Se, and Te and it has been shown that Te is the most suitable in terms of electrical activation and the depth of the donor below the conduction band for AlGaSb. This study has then been applied to the growth of GaSb/AlGaSb laser structures which consist of a GRINSCH type structure with x = 0.45 in the cladding layers graded to x = 0.3 before the active region. The active region has an MQW stack of GaSb/AlGaSb (where x = 0.3). Increased luminescence has been observed in GaAlSb layers by optimizing the growth conditions. A study of GaAsSb of various composition has been made for TEM analysis. The University of Manchester, in collaboration with GEC, has investigated the incorporation of S into SaSb using an electrochemical cell. Here the emphasis has been directed towards *in-situ*-deposited epitaxial aluminum contacts, which yielded excellent Schottky barriers. The University of Manchester has also established the growth and doping conditions of InAsSb lattice matched to GaSb; this is a materials systems which is important for operation at 3 μm. At the University of Glasgow, before a fire destroyed the MBE facility in mid-1986, a thorough investigation of undoped and n-type InP had been undertaken to optimize the electrical and optical properties. The 77 K Hall data for InP-doped n-type at $2x10^{15}cm^{-3}$ had μ = 42,5000 $cm^2V^{-1}S^{-1}$, and was the best reported for this material grown by MBE from solid sources.

Anisotropic Fluorophors for Electro-optic Displays

The participants in this program were GEC Research, BDH LTD and the University of Leeds.

Liquid Crystal Displays (LCD's) have low power consumption and excellent contrast in bright ambient light. However, they suffer from a dull appearance and poor legibility in dim ambient lighting, and have a restricted angle of view compared to emissive displays. The aim of the program was to investigate the use of dyes with anisotropic fluorescence to enhance the brightness of the LCD's, especially when viewed under low-light levels, thus combining the visual appeal of emissive displays with the benefits of LCD technology.

The perylene diesters have been shown to be suitable fluorophors. A wide range of these which combine a high order parameter and high fluorescence efficiency with good photostability have been identified and synthesized. An energy transfer mechanism was identified in which invisible ultraviolet radiation is absorbed by the LC host, and its energy is transferred to the dye, which subsequently becomes fluorescent. The dyes have been purified, and show improved photostability to uv radiation. Different LC hosts have been designed that are suitable for twisted nematic displays and for other types of fluorescent displays. The dye/host mixtures have been characterized and incorporated in demonstrators. These have dark segments on a bright green background, and exhibit a good contrast ratio and a hemispherical viewing angle.

Components for Coherent Optical Systems

The participants in this program are BTL, Plessey Research, and the Universities of Glasgow and of Cambridge.

Special emphasis will be given to techniques compatible with very high capacity transmission rather than high sensitivity at currently achievable capacities. The relative improvements in receiver sensitivity of coherent detection over direct detection tends to increase with rising receiver bandwidth. Also, to realize the ultimate transmission capacity of monomade fiber it will be necessary to multiplex and demultiplex many closely spaced laser frequencies, and for this, coherent techniques should prove essential. Four schemes for coherent detection are being considered: optical phase lock loop; multipart detection; Costas loop receiver; and synchronous detection by applied local oscillator modulation.

The Cambridge group is concentrating on optical multiport detection. Both experimental and theoretical work has been carried out on four-port homodyne receiver systems. Also multiport detection techniques have been used to investigate the spectral characteristics of lasers for coherent systems. A measurement system has been assembled using components provided by Plessey and is being used to assess the characteristics of single-mode DFB lasers.

The Glasgow group has progressed in both theoretical and practical aspects of Costas loop homodyne receivers. A Costas loop was implemented but difficulties were experienced in achieving lock – attributable to the broad linewidth of the lasers being used. An analysis of the effect of loop propagation delay on phase error and loop stability was carried out. This indicates the need for narrower-line-width laser sources in order that the loop delay does not severely degrade receiver performance.techniques for producing single-mode narrow-line-width laser sources suitable for homodyne type systems, and theoretical studies of novel quasi-homodyne receiver concepts. Laser sources considered have been DFB lasers, both with and without an external form of cavity, and a multimode Fabry-Perot laser combined with a fiber grating external cavity to provide mode selection and line narrowing. The latter shows promise of development of a stable narrow-line-width semiconductor laser source, and line widths down to 3 kHz have been obtained.

The STL program involves experimental and theoretical studies of the three-port phase-diversity detection scheme developed there. Initial results have been reported on the performance of a system employing non-line-narrowed DFB lasers and wide-deviation FSK signaling.

Programmable All-Optical and Optoelectronic Devices and Their Applications

The participants in the effort are GEC Research, STC Technology, British Aerospace, Plessey, RSRE, Kings College (London), Heriot-Watt University, Paisley University, and Manchester University.

The aim of the project was to investigate and develop spatial light modulators and signal processing devices, which exploit the basic parallelism of optics, and to investigate their implementation into a practical laboratory system for two-dimensional optical signal processing of images and input data as a basis for future business.

In spatial light modulators, materials and devices have been developed including: BSO/liquid crystal devices; Si photodiode/LCD; electronic addressing/LCD; and InSb and photochromic Fabry-Perot devices.

In nonlinear optics a greater understanding of four-wave mixing has been developed together with its adaptation and control. The theory and practice of optical and optothermal nonlinearities have been developed with particular emphasis on two-dimensional arrays of switching devices.

The design of real-time optical image correlators has been optimized. The project has designed, evaluated, and copied CGH's, and constructed a dedicated optical plotter. CGH systems have been applied to image preprocessing and laser-beam profile modification. Finally, two demonstrators have been designed and built, one optically addressed and one electrically addressed.

Organic Electro-optic and Nonlinear Optical Materials

Organizations involved in this study were ICI, GEC Research, BDH, Plessey Research, University of Strathclyde, Queen Mary College (London), University of Manchester, and Heriot-Watt University.

The aim of this program was to produce improved material for the manufacture of commercially important optoelectronic devices.

The work has been that of molecular modeling and design, synthesis, and characterization, and initial device technology investigations. Much of the theoretical modeling has been done by the universities, the indicated molecules being synthesized by the chemical companies with characterization and guidance on device parameters supplied by the electronic companies.

Over 100 compounds have been screened and about a dozen identified as having favorable properties.

The production of single crystals and thin films from these compounds has been difficult but not unsuccessful. One disappointment was the tendency for molecules with higher second-order nonlinear coefficients to crystallize into centro-symmetric and hence inactive forms. Some of the significant achievements of the program are:

- Computer programs have been developed to calculate molecular nonlinear optical coefficients and to relate molecular response to that in a crystal. These programs have identified many useful compounds and provided a reliable guide to the synthesis work.o Over 100 compounds have been synthesized and screened.
- Standardized laser characterization facilities have been set up.
- A compound patented within the project has been shown to have a powder SHG 500 times that of urea, making it comparable with the best materials reported in the literature.
- A technique for growing thin-film single crystals from the melt has been developed.
- Large single-crystals of $X^{(2)}$ materials have been grown.
- A process for the manufacture of nonlinear waveguides in polymeric substrates has been patented.
- Thin-film waveguides of both $X^{(2)}$ and $X^{(3)}$ materials have been made and characterized.

Polymer Optical Fibers with Low Loss

Participants in this program are GEC Research, ICI, Westland Helicopters, Lucas Aerospace, University of Southampton, and the London School of Polymers.

This 3-year program has attempted to build up the understanding and skills required to make a polymer optical fiber with losses below 0.1 dB/m and has included the following stages:

- Materials selection, characterization and synthesis
- Fiber processing
- System studies.

Procedures for the purification of styrene and acrylate monomers and their subsequent bulk polymerization have been examined and adapted to allow fiber production direct from the reaction vessel or to make preforms for subsequent fiber drawing. This involved the setting up of a pilot plant suitable for making up to 400-m lengths of 0.5-mm-diameter fibers.

Optimum results have been obtained with PS cored fiber and an ethylene vinyl acetate copolymer (EVA)-based cladding. Losses of below 0.3 dB/m were achieved. The inability to achieve losses lower than 0.2 dB/m is attributed to inadequacies in the core cladding procedures, and this requires further investigation.

The preparation of the novel polymers, based on fluorine chemistry, proved more difficult than expected. Although many of the problems associated with their synthesis have now been overcome they were not produced in sufficient quantities to enable fiber to be made and evaluated.

Techniques for the characterization of optically *transparent polymers* and of fibers have been studied and procedures established. System studies have been undertaken and demonstration systems set up. In addition, a number of sensor applications have been studied.

Alternative InorganicMaterialsforOptoelectronics

Participants in this effort are: GEC Research, Plessey, University College (London), University of Sussex, University of Oxford, and Queen Mary College (London).

The program was designed to achieve improvements in established materials, provide materials presently unobtainable with required quality, and identify alternative properties for specific device applications.

The principal topics of collaboration have been:

- Production of light guides
- Photorefractive materials
- Metallo-organic compounds
- Fabrication techniques for optical components
- Measurement and theory of optical properties
- Thin-film deposition.

The main achievement include:

- Growth and characterization of bismuth titanium oxide and doped sillenite crystals
- Hydrothermally deposited single-crystal, low-loss, high-damage-threshold optical guides
- Amorphous, planar guides deposited by plasma-enhanced CVD
- *In-situ* guide formation by ion-implantation techniques
- Thin-film lithium niobate deposition by LPE
- Deposition of PLZT thin films by RF sputtering
- MOCVD deposition of lithium tantalate and lead titanate thin films
- Development of a high-rate ion milling process for silicon
- New techniques for high precision
- Optical loss and refractive index profile measurements

- A theory describing the origin of optical rotation in crystals
- A high-precision, high-spatial-resolution optical microscopy method for mapping and imaging optical-retardation/optical-anisotropy distributions.

Liquid Crystal Polymers and Optical Memories

Participating organizations here are: GEC Research, Laser-Scan Laboratories, and the University of Hull.

This project is concerned with investigating novel materials and their possible use in optical storage applications.

Materials development and evaluation has concentrated on the synthesis of polymer liquid crystal materials. A range of over 20 new polymer compounds has been developed and characterized for liquid crystal behavior.

Investigation into suitable mounting formats for the materials has been undertaken, and a reliable method of fabricating experimental samples already devised. Equipment has been developed to evaluate the temporal thermo-optic response of the materials, and this has led to novel equipment and measurement techniques.

Scanning laser equipment has been constructed to characterize the writing and readout performance of the materials. Potential applications for the materials have been identified, and evaluation and development of new laser deflection methods to exploit these applications is underway.

Optical Guiding Elements Using Liquid Crystals

Working on this project are: GEC Research, BDH, and University of Southampton.

The work of this project has concentrated on the following four areas:

- Optical and electrical characterization of liquid crystal materials
- Design and synthesis of improved liquid crystal materials
- Development of compatible waveguide technology
- Device design and implementation.

Basic optical parameters of many existing display mixtures were evaluated. This included measurement of optical attenuation, refractive index, and birefringence at 660 nm, 850 nm and 1300 nm. The most useful of the existing materials was identified in this way. Design guidelines for the synthesis of new, improved mixtures were established.

One of the problems identified was the high refractive index of liquid crystals. This makes them incompatible with silica optical fibers and waveguides. New additives for use with hydrogenated liquid crystals have been synthesized to produce liquid crystal mixtures with refractive indices of less than 1.456.

Waveguide structures have been based on the concept of using the liquid crystal as an overlay on an inorganic substrate. Thus light is guided in a low-loss inorganic material and interacts in a controlled way with electro-optic liquid crystal . This technique permits optimization of device parameters.

Three complementary waveguide technologies have been used. Potassium-ion exchange has been used with glass substrates and plasma-enhanced vapor deposition with silicon substrates, and several novel optical fiber manufacturing techniques have been developed.

Early in the project a simple planar optical switch was demonstrated. Subsequently an optical phase modulator was reported. A 2x2 cross-over switch is now under development.

Novel Active Micro-optic Device

Participating organizations are: GEC Research, Gooch and Housego, and the University of Oxford.

In this project a major part of the effort has been devoted to the design and fabrication of acousto-optic filters for scene analysis in the visible and near- infrared. A one-dimensional electro-optic filter has been successfully completed and work started on liquid-crystal-filled Fabry-Perot cavities. An optical switch with exceptionally low loss and high isolation has been demonstrated.

GEC Research and Gooch and Housego have designed two acousto-optic timeble filters (AOTF's) for operation in the visible (400-800 nm) and infrared (700-1400 nm) wavelength regions. They operate on the principle of acousto-optic diffraction in an optically anisotropic medium. The spectral bandpass of the filter can be timed over large optical regions by changing the frequency of the applied RF signal. The AOTF has a low fractional bandwidth, $\Delta\lambda/\lambda$, with a large angular aperture. The noncolinear interaction geometry was chosen in order to make the spectral line-width relatively independent of the angular divergence typically present in the incident beam. Tellurium dioxide was chosen as the acousto-optic medium for its high efficiency of interaction.

An infrared device was fabricated and a visible range device is nearing completion. The IR filter has been tested over the range 700-1100 nm, and a fractional bandwidth of 0.014 has been measured. The wavelength shift caused by angular detuning of the filter is in the region of 7 nm for 3 degrees.

The University of Oxford has developed a model of isotropic acousto-optic diffraction in two dimensions. It allows the input beam shape and acoustic distribution to be specified in detail, even in the high efficiency case. Multiple scattering, Fresnel diffraction and higher orders are included. The program is being run with realistic device data to predict beam quality and intermodulation behavior. Transducer design and anisotropic interaction are under study. The program should be useful in the design of novel devices as well as the understanding of existing measurements.

Electro-optical programmable filters being developed are electro-opt'ᴗ adaptation of fixed filter structures and rely on in.ᵕᵕ.erence – e.g., Fabry-Perot etalon or polarization ᵕ aversion such as (Solc filter effects). An electro-optic analogue of a birefringent Solc filter has been developed called an electro-optic programable filter (EOPF) using a birefringent crystal and 144 control electrodes placed on a 50-m pitch.

The major advantages of this type of filter are low drive power, flexibility of passband synthesis and fast tuning over a wide spectral range. The one- dimensional nature of the aperture of the device is appropriate for imaging systems based on linear arrays of detectors. The minimum fractional bandwidth is proportional to the square of wavelength and varies between 10 nm at 465 nm to 40 nm at 1000 nm.

Work on electrically tunable and switchable Fabry-Perot filters using nematic and smectic liquid crystals has begun and the initial results are favorable.

In the work on a moving dielectric switch a dielectric liquid is induced to move between the plates of two adjacent capacitors when a voltage is applied. The dielectric liquid acts as an index-matching fluid between to prisms on which the transparent electrodes of the capacitors have been formed. When the liquid sits between one set of capacitor plates, perfect index matching enables an incident light beam to propagate through the prisms undeflected. In the absence of the liquid dielectric, when bias is applied to the other set of electrodes, the beam is totally internally reflected, through 90 degrees, thus forming a beam deflection switch.

Devices have been fabricated with switching times down to 2 μs transmission losses through the switch of less than 0.4 dB and isolation between the two parts of better than -50 dB (measurement limited). While the existing switch could be used in a simple two-way bypass switch, it is possible to construct 4x4 cross bar switches using the same techniques.

Advanced Fiber Measures

Participants in this completed program were: Plessey Research, GEC Research, STC Technology, BICC Research and Engineering, York Technology, and University of Southampton.

The aims of this program were to advance fiber technology, advance fiber measurements, and avoid duplication and encourage cross-fertilization within the UK. The work concerned the application of fibers for advanced telecommunicatons and in sensors and signal processing. The program was completed in June 1987.

Some specific technical achievements of the program:

- Microbending Studies. STC achieved improved understanding of the microbending loss mechanisms in single-mode fibers by investigating the coupling from guided- to cladded-mode occurring when a short length is periodically deformed by a mechanical grating. BICC investigated the microbending losses in cabled fibers by coating them with helically wound fine wires in order to impress microbending of a known pitch.
- Propagation constant/interferometric measurements. Plessey developed a scanning interferometer capable of measuring the wavelength variation of the propagation constant of a fiber and its chromatic dispersion.
- Ultimate loss limits. York Technology investigated the potential use of Fourier Transform Spectroscopy (FTS) for measurement of very small fiber losses. The main conclusion was that the signal-to-noise advantage of FTS was lost due to the demands on control of the optical path ditterence in the interferometer.
- Cut-off. It was shown by GEC that the equalization wavelength of a fiber could be used to predict the absolute cut-off wavelength.
- Mode field radius. All members of the study measured the mode field radius of single-mode fibers as a routine assessment or to develop new techniques. Plessey demonstrated the far-field mask technique that was capable of directly measuring the so-called Petermann II spot-size. BICC built equipment to measure the mode field radius using the transverse off-set technique and the far-field variable aperture technique. A fiber with a significantly non-Gaussion mode (dispersion shifted fiber) was measured by all members and their results reduced to the Petermann II definition. The comparison showed an error in the BICC apparatus when large NA fibers were used, which was solved by using parabolic mirrors to perform the far-field imaging. The remaining results were the same to within ±3.5 percent.
- Polarization Measurements. Plessey extended their scanning interferometer to measure the group delay difference between the two polarization modes of highly birefringent fibers. The result could be obtained at a single wavelength by using a white light source and FTS. A similar technique was used to measure the polarization dispersion of km lengths of standard telecom fibers, giving values of about 50 fs/km. The Southampton group developed an apparatus for measuring fiber polarizers which is capable of measuring extinction ratios down to -51 dB. STL, working with Southampton used their impressed grating with highly birefringent fiber to produce a wavelength-dependent polarizer.
- Time Dispersion. STL produced two different apparatuses to directly measure the time dispersion in km lengths of SM fiber. The use of pulsed semiconductor lasers in place of pulsed Raman laser was investigated, and equipment usable in the field was developed.
- Stress in Fibers and Preforms. Southampton and York Universities collaborated to modify existing transverse refractive index profiling equipment to measure the

axial stress on the preforms of birefringent fiber. The result agreed with theoretical stress profile.

Advanced Fiber Waveguide Devices II (AFWD)

Organizations participating in this program are: Plessey Research, BTRL, GEC, STC, Southampton University, and St Andrews University.

The objective of this program is to continue the study of single-mode fiber-based components, building on the work of the AFWDI program with an emphasis on very fast (sub-nanosecond) nonlinear signal processing, including digital computing and in nonlinear fiber function generally.

The program began June 1987 as a follow-on to AFWDI, with the same partners.

Active Optical Switching and Logic

Participating in this effort are: BTRL, STC, University of Cambridge and the University of Bath.

The objective of the program is to study the possibility of achieving by means of integrated optics based on semiconductor laser structures a range of switching and logic function such as cross-point switch, three- and four-point couplers, matrix switch, and pulse regenerator, and orgates, inverter, amplifier, and termalility.

At BTRL preliminary predictions of bistability occurring at power inputs of the order of microwatts with switching times in the order of nanoseconds have been confirmed by background experimental measurements. The early work was confined to transmission through an amplifier but more recently an analysis has been made of corresponding effects occurring in reflection from the device. In this configuration a wide variety of nonlinear and bistable effects has been predicted, including a new butterfly hysteresis loop not widely known hitherto. Perhaps the most useful attribute of reflection-mode nonlinearities is that both NAND/NOR and AND/OR gate characteristics can be achieved in principle on a single device, depending on the conditions of drive current and wavelength detuning.

STL has concentrated on the fabrication of special laser structures designed to explore the potential of such devices for fast pulse generation, bistability, and spatial switching. Twin-ridge waveguide lasers have been made using ion beam etching techniques to penetrate the p-side metalization, and these devices have been supplied to the Cambridge group. Recently, ridge waveguide lasers with very high quality curved ridges have been made by wet chemical etching, curves with radii as low as 300 m are achieved before the performance begins to degrade significantly.

The Cambridge people have made progress using twin-stripe lasers from STL and four-contact devices from BTRL. An aim in the twin-stripe laser work was to demonstrate transverse modal bistability whereby the electron density in the laser has been minimally altered (enhancing the speed of response); and a first demonstration of this concept has been made.

The Bath Group is working with theoretical modeling of spatial switch structures and with fabrication of multistrip and multisegment lasers operating at 850 nm. The spatial switches studied have been the optical disc resonator and the active directional coupler, and in addition to theoretical calculations, microwave simulation of these structures has been done.

Optoelectronic Sensors

GEC Research, Thorn-EMI, York Technology, University College-London, King's College-London and Southampton University are the principles in this program, which aims to identify and develop novel optical sensing techniques, including both intrinsic and extrinsic fiber sensor development. This involves measurement and signal processing.

By making fibers out of doped glasses, various parameters may be investigated using nonlinear effects in fibers. The Stark effect gives a variation in fiber spectral attenuation with applied electric field. The Zeeman effect works similarly for a magnetic field. The dependence of polarization rotation on an applied electric field for a given length of fiber is also under investigation.

The distributed temperature sensor based on Raman backscatter has been subject to more rigorous characterization, mainly through component development. Alternative connector configurations are being investigated as is the use of a pulsed fiber laser source.

An extensive program on doping techniques for fibers to develop fiber components and intrinsic sensors is under way. Holmium- and neodymium-doped fibers have been demonstrated in a distributed temperature sensor configuration.

A doping-induced nonlinear effect, 2 photo absorption, allows the potential development of optical fiber correlators, distributed sensors and modulators.

High-rejection fiber wavelength filters have also been demonstrated. Second harmonic generation in fibers has been shown useful for the conversion of fiber laser output to visible light.

An evanescent field sensor (using a hollow-center fiber) for gas analysis has been modeled.

Thermal annealing of bow-tie fiber for magnetic field sensor developments has been examined. Results indicate that the sensitivity of such a sensor using the birefringence effects in bow-tie fiber may be enhanced by an appropriate annealing cycle for the metal coating on the fiber, which provides the sensitivity to the magnetic field. Coatings are also being investigated to allow or provide a temperature compensation for birefringent fibers.

A distributed sensor based on high birefringence fiber is under examination. It is a single-fiber interferometer using single-mode fiber dual moded at 850 nm.

A multisensor network has been built consisting of several electrical sensors powered, read, and activated by light under a central controller. The system has two buses connecting sensors to the controller, a databus and a power/address bus. The sensors remain in a passive state until polled for their data by the controller.

Comparison of various techniques to multiplex vibrating sensors down a common fiber link are underway. Three-sensor multiplexing using FMWC techniques is one of several methods being investigated.

Advanced Assessment for III-V Materials

The principles in this effort are: GEC, BTRL, Plessey, STC, and the Universities of Hull, Manchester, and Oxford. The objective is to assess the type of III-V semiconductor structures which are required for advanced optoelectronic devices and which are now being produced as a result of recent advances in growth techniques. In particular this requires:

- The determination of composition profiles through thin or graded layers, and the width of heterointerfaces between layers, using x-ray diffraction, secondary ion mass spectrometry (SIMS) photoluminescence, and photovoltage profiling
- The profiling of dopant and trace impurities across such structures, using capacitance-voltage techniques, SIMS and Hull profiling
- The measurement of band edge discontinuities at heterojunction, by photoluminescence, internal photoemission, and capacitance-voltage techniques
- The investigation of deep levels, both within layers and at interfaces between them, using deep-level transient spectroscopy, photocapacitance, photoluminescence, and optically and photovoltaically detected magnetic resonance.

BTRL has performed the first in-depth characterization of AlInAs and GEC is providing the first detailed compositional map of AlGaSb by Raman spectroscopy. GEC has developed a technique for compensation profiling and BTRL has extended the usefulness of photovoltage spectroscopy in ternary systems and to multi-quantum well characterization. A full study of the various numerical techniques for solving Poisson's equation has been undertaken at Manchester and applied successfully to an understanding of the behavior of deep levels in bipolar structures. C-V profiling of InP-based materials is being done at STL and Hull University and is providing fundamental material parameters from Magneto-optical experiments.

The importance of photoluminescence as a standard characterization technique tool has been consolidated, and Raman spectroscopy is proving very valuable for investigatin strain in heteroepitaxial layers and BTRL is obtaining period lengths in multi-quantum wells by observing the folded acoustic modes that occur in these repetitive structures.

Advances made on the structural aspects include the preparation of photolithographically defined needles at Plessey for use by the Oxford group in their pulsed-laser atom probe system. State-of-the-art SIMS at BTRL has improved the detection limits and quantification of key dopants in III-V compounds. X-ray diffraction analysis has been extended to unstrained (GaInAs/InP) and strained (InAs/GaAs) superlattices. Progress at STL includes Auger Profiles on InP-based materials.

Digital Optic: Applications to Computing and Communications

GEC, Plessey, STC, University College (London), Imperial College, and the University of Cambridge are the participants in this program.

Two potential attractions of optical logic are parallelism and speed. But optical fibers are already in use for intersystem communication and a number of the new generation of digital electronic machines have optical backplanes linking processor and memory boards within a single system. It is possible that optics will permeate all levels of computing systems, making extensive use of electrical intervention where this can aid sensitivity and faster electronic-to-optical interfacing. Properly directed research should offer solutions to some of the major problems that confront computer system designers at present, such as clock skew, interconnection bandwidth, and memory access. In this program the natural parallelism and wide bandwidth available from simple optical systems will be exploited in a number of ways for providing space wiring between logic planes such that novel system architectures can be implemented.

Hybrid electro-optic devices offer the possibility of exploiting electronics and optics for those functions in which each excels. The intimate involvement of electronic components implies easy interfacing to electronic processors, and by linking these concepts, the workers plan to realize the potential that optics offers. This relates to speed at the frontiers of electronics or beyondoperating on optical input and output data streams using parallel arrays of up to 10^4 elements, each having a large number of possible interconnections. Applications include signal processors, intelligent reconfigurable interconnects, and communications terminals and switches. The research output will be optical processing devices, an insight into algorithms and appropriate architectures, and the technology for optical wiring. The program will deal with systems architectures devices and subsystems, and interconnection technologies.

During the first phase of this program improvements have been made in both the production and assessment of the multi-quantum well and superlattice materials required for devices construction. Initial prototypes of both liquid crystal and PLZT-based spatial light modulators have been assembled. Performance specification tables are being produced for each device.

The architectures and algorithms section of the program has concentrated on the identification of suitable areas for the introduction of optical technologies and on the definition and implementation of the two simulators required for future assessments. Closely coupled to this, investigations have begun on the various optical interconnection technologies to assess their practicality and to identify any constraints these may impose on the architectures.

Organic Electro-optic and Nonlinear Optical Materials

Participanting in this program are ICI, GEC, Plessey, BDH, Strathclyde University, Queen Mary College (London), University of Manchester and Heriot-Watt University.

The program continues the work carried out under the previous project of the same title (page 4, above). The main emphasis of this continuation is on practical device technologies. A number of demonstrator devices will be made. The main program items are:

- Design, synthesis, and characterization of organic nonlinear materials
- Fabrication of thin films
- Optical waveguide definition
- Metalization and encapsulation
- Manufacture and testing of demonstrator devices

Specifications for a number of devices which use the unique advantages of organic materials have been produced.

High-Performance Spatial Light Modulators

GEC, STC, and the Universities of Edinburgh and Manchester are the participants in this program, which has two independent parts, each to produce and demonstrate spatial light modulators (SLM's) with framing speeds of up to 10 kHz. One SLM is to be optically addressed and the other electrically addressed. Both devices are to be operated in the reflection mode and are intended for use as inputs to optical correlators and other processors and display applications.

The program started in April 1987 and has progressed as follows:

- The optically addressed device will comprise an Si photoconductor light blocking layer and a dielectric mirror together with a smectic liquid crystal electro-optic layer. Initial work has concentrated on development of the α Si deposition technology and cell construction techniques. For the former, very high-resistance (pn1010cm), highly productive uniform layers of α Si have been deposited. A major effort has been directed to the construction of thin (about 2 μm extremely uniform about 0.1 μm variation) cells that are required for use with smectic C liquid crystals.
- The drive arrangement for the final SLM has been investig: ed and a possible scheme identified. A drive box capable of generating the required pulses to further test the same scheme is being constructed.
- A proof of principle device has been constructed. The device demonstrates the first smectic C device, produced on the high-performance SLM project, providing an optically addressed SLM function.
- For the electrically addressed devices the drive circuitry is currently being designed in CMOS. There are no immediate results to be reported.

Integrated Optical Device Technology

Participants in this project are GEC, Plessey, STC, University of Glasgow, and University College (London).

The aim is to develop advanced integrated optic concepts for guided-wave electro-optic and nonlinear optical device functions. It builds on a successful previous JOERS project, "Lithium Niobate for Integrated Optics," by considering device structures and concepts with increased sophistication and complexity. The primary effort concerns structures in lithium niobate. Electro-optic device concepts are studied for high-speed modulation and intracavity laser control elements. Nonlinear applications of integrated optics technology in harmonic generation and parametric interactions form a major element of the program. The design and fabrication technology for filters, couplers, and reflectors envisaged, including direct application to the electro-optic and nonlinear optic device concepts, are identified above.

At the time of reporting, the program had been underway for only 4 months, and progress had been confined to establishing designs for waveguide and electrode structures; photolithographic masks; theoretical modeling of intercavity structures, modulators, and gratings; initial evaluation of overlayer grating fabrication techniques; and theoretical and preliminary experimental assessment of nonlinear waveguide formats.

Theory and Characterization of Advanced Photodetectors

Plessey, GEC, St. Andrews University and the University of Sheffield are the participants in this program for the evaluation of advanced detector structures for high-speed, high- sensitivity applications, and falls into the categories of experimental characterization and theoretical modeling.

The investigation will include PIN devices without gain and a range of avalanche photodetectors based on bulk and MQW structures in the InP-based material systems. Establishing techniques for high- speed measurements of long-wavelength devices forms an essential part of the program.

The modeling activities will cover a diverse range, including the response characteristics on PIN devices at high speed, gain-bandwidth effects in APD's and lucky drift and Monte Carlo analysis of avalanche processes in MQW structures.

Key achievements to date are:

- Demonstration of ava anche multiplication in InP/InGaAs MQW structures
- One-dimensional electric field/ionization integral simulation for InP/InGaAs SAM APD's established
- Equivalent circuit model of high-speed PIN devices qualified based ITO/GaAs high-speed photodiode experimental data
- Fabrication of GaInAs photoconductive sampling gates for long wavelength initiated
- Impulse measurement on GaInAs photodiode have been carried out and shown to be limited by sampling scope response.

Integrated Optics Base Technology

Participanting in this program are Plessey, BT, STC, University of Glasgow, and University of Sheffield.

The program carries out precompetitive research on monolithic optoelectronic integration to demonstrate such technology in various integrated waveguide elements. It will build on the JOERS program, "Semiconductor Waveguide Integrated Optics Base Technology," with emphasis on InP-based long-wavelength materials.

The aim will be to demonstrate the ability to make the elements of semiconductor-based waveguide device – such as bends, tapers, mirrors, couplers, and waveguide selector elements – together with the measurement and assessment of the performance of these devices. In parallel with the device fabrication and assessment activities, processing technologies will be studied, which are seen as essential for the processing of the complex structure necessary for an integrated opto-electronic circuit.

The development of dry processing techniques to reproducibly pattern InP-based ternary and quaternary material is seen as an essential requirement in fabricating the demonstrators. Processes involving both plasma and ion beam techniques have been identified in achieving these aims and they are now being optimized on specific device structures.

Low-loss waveguides fabricated in the quaternary/InP system have been demonstrated and a study of fabrication techniques for buried waveguides initiated. Progress on in-situ SIMS sampling to assess depth location during etching has reached the stage where individual quantum well layers can be identified.

Advanced MOCVD Technology for III-V Optoelectronic Materials and Heterostructures

Plessey, STC, Epichem, Loughborough Consultants, University of Manchester, Queen Mary College, and University of Oxford, are the participants in this program which will cover:

- The preparation of advanced III-V heterostructures
- The synthesis and evaluation of novel precursors, and the characterization of their chemical behavior
- Semiconductor evaluation.

Progress to date includes:

- The preparation at STC of the highest purity InP ever prepared anywhere by a technique developed at Epichem was used.
- Excellent AlInAs prepared at Plessey with high crystallinity (x-ray diffraction) low carrier concentrations, and increased intensity luminescence.
- First quaternary layers of GaAlInAs prepared at Plessey.
- Further improvements in GaInAsP growth at both STC and Plessey.
- Quantum wells in GaInAsP/InP.
- Advances made at Queen Mary College on triethylindium and triethylgallium diphos adducts and information transferred to Epichem for commercial exploitation.
- Incorporation of As in InP at Manchester.
- Continued progress in the characterization of electrical, optical, and structural properties of materials at high resolution at the Universities of Manchester and Oxford.

Long Wavelength Fluorophors for Liquid Crystal Displays

Participants in this research are BDH, GEC, and the University of Leeds.

The passive operation of conventional liquid crystal displays (LCD's) is responsible for their desirable characteristics of low power consumption and absence of wash-out in strong light, but also for their poor visibility under low ambient light. A further disadvantage of LCD operating modes is a viewing angle characteristic inferior to that of competing technologies. The use of anisotropic fluorescent dyes as guests in a liquid crystal solvent provides a switchable emission of light under UV excitation, and the resulting display enables these problems to be overcome. This project aims to provide and characterize dyes suitable for this type of display which emit in the orange/red region of the spectrum, and to construct demonstrator devices using optimized display cells, hosts, and dyes.

The University of Leeds is synthesizing prospective fluorophors and tailoring the molecular structure to optimize solubility and order parameters. Products are tested for these properties, and the excitation and emission spectra are measured.

BDH is carrying out extensive tests of stability on dye/host systems and is developing new liquid crystal host mixtures needed for fluorescent displays. The scale-up of dye synthesis and provision of intermediates is also being carried out at BDH.

GEC is evaluating fluorescent LC solutions and investigating their use in different display modes. Test and demonstrator devices are being made together with their necessary drive electronics, and the effects of different lighting and viewing conditions are being established.

Four different fluorophor systems have been selected for initial exploration, and samples of each have been synthesized. Structural classes denoted I and II show poor photo chemical stability, although reasonable values of order parameter and solubility could be obtained. Structural class III dyes appear most promising: their stability is better and may be further improved by use of an appropriate stabilizer. Optimization of the solubility and order parameter has been done. Class IV provides dyes of improved stability, but these compounds show low solubility and further exploration is needed.

Successful operation of these displays relies on an intermolecular energy transfer from a UV absorber to the fluorosphor molecule in order to obtain a large cumulative Stokes shift. This phenomenon has been demonstrated to occur with high efficiency in red fluorophor systems. New energy transfer agents have been found which greatly widen the scope of LC materials which can be used. The influence of host on display lifetime is being studied, initially using model green fluorescent dyes, and the work will shortly be applied to red systems.

Low birefringence and negative anisotropy hosts have been formulated to allow phase change and reverse contrast device modes to be explored. Test devices have been constructed which have good appearance. The construction of multiplexable displays using supertwist technology is under development.

Active Optical Switching

Participants in this program are Plessey, STC, the Universities of Bath and Cambridge. This program, which began in August 1987, is a follow-on to the "Active Optical Switching and Logic" program. It concentrates on optical space switching technologies using III-V semiconductor materials, a prominent emphasis being the use of active gain media either to achieve the switching directly, or to compensate the losses of passive (e.g., electro-optic) switches.

The main approaches being assessed are:

- Use of a configuration of independently addressable active waveguide sections to provide a "through" or "cross" state depending on whether various sections are pumped (i.e., transparent) or not (opaque)
- Use of enhanced electro-optic-type effects in an interferometer-based switch. Gain blocks will be integrated to compensate for losses
- Active resonator-controlled crosspoints using a disk resonator to direct the light
- Diffraction-coupled active waveguides to distribute light to various ports in a controlled manner.

Thin-Film Electroluminescent Flat Panel Display Technology

Pilkington Brothers, GEC, Thorn EMI, RSRE, and the Universities of Durham, Essex, Manchester, and University College-Cardiff are the participants in this 3-year research program which aims to establish a dc electroluminescent displays (DCTFEL) technology base within UK industry.

In the initial phase the RSRE process for the formation of a prototype device based on sputter deposition of Mn-doped ZnS into cadmium stannate as the transparent conducting layer on glass will be repeated by the participants. Semiempirical approaches to lifetime improvement from the present hundreds of hours are underway. This includes variation in the deposition parameters and driving conditions and correlation with analysis of failure mode.

The work at RSRE and the universities is directed to gaining a better understanding of the basic physics of device operation and the causes of failure. Cardiff is studying barrier heights and the reactions which occur between ZnS and a variety of transparent conducting materials using a variety of sophisticated surface analysis techniques. The Durham and Manchester groups are studying trap distribution within the ZnS layer. Durham has also carried out a preliminary study of the variations in structure of a deposited Mn doped ZnS film. Essex is undertaking a theoretical study of hot electron transport in ZnS and is applying filament formation theory to a possible microstructural extension to breakdown theory.

Interactive DC Power Electroluminescent Display Devices and System

Phosphor Products, TI Research, and Thames Polytechnic are the principles in this investigation.

A program directed at optimizing the conventional phosphor material has yielded steady improvement in results, reproducibility, and understanding of the processes. More radical approaches to phosphor preparation to facilitate manufacturing are being pursued. In devices, an interlayer has been introduced which decreases forming time and improves the uniformity of the display. Many adhesives for affixing the backup have been evaluated and two preferred materials have been determined. Investigations have been based on a display of 640 columns by 256 rows capable of displaying 2000 characters. Displays of this format can now be readily manufactured with acceptable performance.

A method for predicting long-term display performance by admittance spectroscopy has been determined and is now being validated. An experiment to improve reproducibility by correlating display performance with manufacturing variables has been completed.

A new set of row drivers, recently adopted, has given an increase in display brightness and uniformity. A radical approach to column drive is underway, using a constant current device. Investigation has shown that forming to higher voltages and consequent high-voltage running has a beneficial effect on contrast, brightness, and stability. This has been adopted as standard.

A 128 switch based on the 2000 character display has been designed as well as its associated software.

Liquid Crystal Silicon Matrix

Participating in this effort are GEC, Lucid, BDH, and the Universities of Cambridge and Liverpool.

The aim of the project is to develop the technology for a thin, flat electronic display including graphics facility, full color, grey scale, and user interaction. Polysilicon TFT's will be used as the active switching components. Yield optimization and larger scale processing techniques form as essential part of the program. The target for the end of the program in late 1988 is to demonstrate a prototype display of intermediate size and complexity and a fully specified process for size A5 display. The necessary steps to scale the technology to produce A4-size display will also be included.

A new polysilicon deposition process has been developed which allows growth of films with fewer defects then obtained with conventional technology. This improved material coupled with an optimized fabrication process has led to the production of high-performance transistors (on/off ratio higher than 105, threshold voltage 8 V) which are adequate for the peripheral shift registers. A new active matrix circuit has been invested which eliminates line faults due to shorted transistors.

A new liquid crystal material suitable for use in an active matrix-addressed dyed phase change (DPC) display with 5 V rms operation has now been developed. A production-compatible fabrication technique for DPC displays has also been developed. Significant progress has been made on the areas of TFT gate insulator material, liquid crystal cell fabrication techniques, chip-on-glass drive circuitry, and the processing of A5-size displays.

Development of Large Panel Storage Displays Based on Ferroelectric Liquid Crystal

BDH, STC, Thorn-EMI, RSRE and the University of Hull are the participants in this 3-year program.

The objective is to exploit the novel properties of ferroelectric smectic liquid crystals to provide a new type of liquid flat panel display having:

- Large arrays of addressable pixels and large areas
- Great simplicity of panel construction
- Fast switching speed
- Low voltage operation.

The overall objective is to develop and demonstrate a large (more than 10-inch diagonal), complex (more than 300,000 pixels) ferroelectric storage display with a total line address time within the 64 available with TV video signals.

Test devices have been built to establish that ferroelectric smectic storage displays can operate at high resolution at the speed required for video images.

These properties have been demonstrated using small laboratory test devices, with about 4,000 pixels, but these have been used to simulate the behavior of large screens, with greater than one million pixels.

Video line address times (which require large matrices of pixels to switch in 32 μs per line) are achieved with these first-generation materials at temperatures greater than 35°C. Subsequent generations of materials which are capable of faster operation at lower temperatures are well advanced.

Work on spatial averaging and temporal averaging methods for achieving grey levels is underway, and the development of both conventional (microdot color screens) and unconventional (frame sequential) methods of rendering colored images.

The project is on schedule and approaching a key decision point concerning the potential *manufacturability* of display panels with 2-micron-thick liquid crystal layers.

CONFERENCE PAPERS

Opening Speech

Read by Mr. John Butcher, MP, Under Secretary of State for Industry and Consumer Affairs

This Joint Optoelectronics Research Scheme (JOERS) program was launched in 1982 and is the first major collaboration between companies and educational institutions under the scheme. As such it is a trailblazer. The program has been company led from the start with university participation. The government has played an administrative role.

The program has been selective in choice of material for R&D. The objective has been to meet industrial needs--the need for basic marketing and manufacturing techniques, for example. It has been critical to the success of precompetitive research in the photoelectronics industry. Commercial exploitation is now beginning, for example, STC-manufactured semiconductor lasers.

There is a clear need for collaboration in R&D at the national level and at the European level. The role of government is to break down the barriers to collaboration. Companies need to pay attention to technical and marketing skills in order to satisfy market needs. They must convert the results of research into products. The government is keen to see more partnerships among companies. Within my department, Mr. Butcher said, are JOERS, LINK, Alvey and the follow-on to Alvey.

The Europeans, look toward a single European Market in 1992, and we must build greater technical strength in Europe through international alliances like ESPRIT and RACE. National programs need to support European collaboration.

The Industrial Experience of JOERS

Read by Dr. David Kennedy, Manager, STC Optical Devices Division

The mission of the JOERS program is to carry out the research optoelectronics needs to develop products for the market. This requires early introduction of technology and innovation. The issues at stake are invention and the exploitation of the results.

Optoelectronics requires working with electronics and the phased introduction of optics into electronic systems. In communications, optical transmission is already widely used for long lines, and links to the users are planned. ICL, for example, has pioneered optical links between its mainframe computer and peripheral equipment. The final step needed is optical processing of information. The world market for optoelectronic devices will reach £2 billion (about $3.7 billion) by 1992 with £1/2 billion in Europe alone. Optointegrated circuits will account for £1 billion.

Among the achievement of the JOERS program are:

- Raising the level of knowledge
- Direction of funding and other resources
- Achieving valuable university support
- Raising the university skill base relevant to industry
- Fostering experience in collaboration between companies and between companies and universities.

In the past industry and universities operated independently of each other. Now there is much greater appreciation of each for the other's contributions. The importance of the exploitation of research results is now better understood by both.

Industry has a continuing need for skilled graduates. The meeting of this need has been aided by the JOERS program. More careers are now possible in industry. There is great value in collaboration at the precompetitive level between competing companies. Small companies gain because of the increased flexibility available. The mission of JOERS is precompetitive research. There is no long list of products to be developed.

The Academic Experience of JOERS

Presented by Professor Eric Ash, Rector, Imperial College of Science and Technology

JOERS is a first in major collaboration between industry and universities. There was an earlier consortium on gallium arsenide.

In its first committee meeting the JOERS committee debated various issues in the presence of all interested parties. There was considerable discussion on intellectual property rights and on university overhead expenses in connection with the program. Perhaps the biggest mistake was in having no standard form of agreement among the parties. The same problem arose in the Alvey Program, resulting in serious delays.

As viewed by the university the major benefit of the program has been an increase in motivation to work with industry. The work has been very successful, with interaction extending beyond the immediate program. Some examples of successful collaboration efforts are: semiconductors waveguides with very low loss, formation and dry etching of gallium arsenide, and joining of waveguides.

Of the several impacts on the universities, three principal ones are:

- There was more a redistribution of funding than an overall expansion.
- Universities began thinking about intellectual property rights. The person responsible for an invention holds the property rights but gives a license to the partners in the enterprise.
- Problems of overhead expenses are the same in universities as in industrial laboratories.

The UK Optoelectronic Mission to Japan

Read by Mr. John Fairclough, Chief Scientific Advisor, Cabinet Office

It is recognized in the government that collaboration is at the heart of the future and this recognition helps to set the agenda for technology.

The visit to Japan was designed to improve industrial and commercial relations with Japan. The targeted discussion was chosen to be optoelectronics. The objective of the visit was to look at Japanese capabilities in this field and to understand their willingness to collaborate on a mutually profitable basis. The participants in the visit included government officials and representatives of five UK companies and two universities. The itinerary included visits to Japanese universities, industry, ministry of Trade and Industry, a science and technology agency, one government laboratory, and one university department.

The Japanese optoelectronics industry in 1987 had a production of about £5.3 billion (around $9.6 billion). Of the total production, 30 percent resulted from optoelectronic components, 57 percent from optoelectronic equipment and 13 percent from optoelectronic systems. An important factor in the Japanese market for optoelectronic equipment was the establishing of a national optic fiber network by NTT. Another factor was the influence of the consumer market for optoelectronic products.

In 1986, Japan's gross expenditure on R&D was 8,415 billion yen (about $66.7 billion) or 2.51 percent of the nation's GNP. However 80 percent of the funds come from industry and only 20 percent come from the government. The UK spends 2.3 percent of GNP for R&D and 46 percent of this comes from the government. In Japan only 3 percent of government research expenditure is on defense, whereas in the UK the figure is 52 percent.

Japanese companies expend much effort in reducing the time between discovery and use. There are two Japanese companies operating 24 hours/day working on 10-gigabit diodes. There is very strong competition between Japanese companies. World competition is second to internal competition.

We conclude that the Japanese are, in general, very little ahead in technology but they are ahead in the exploitation of technology. For example, erasable optical disks are on the market from SONY. The Japanese companies are driving hard for high-resolution television. Shortly, liquid crystal displays will replace cathode ray tubes. In optical fibers the Japanese are not as far ahead as the UK in the use of monomode. They are doing well in molecular beam epitoxy.

The Japanese have highly developed informal communication within their laboratories. Much of their research is defensive as a result of fierce competition.

The period 1979-86 has been a period of collaboration in precompetitive research, including joint research in optoelectrics. A collaborative laboratory is more aggressive technologically. The government provides the capital equipment and the companies finance the operation including the furnishing of competent personnel.

On the questions of international collaboration, the Japanese have a desire to internationalize research. There is an awareness in Japanese industry of the need to collaborate with companies in Europe. They have a high regard for UK capabilities and the feeling is that now is the time to collaborate. In the UK JOERS has been a good stepping stone toward collaboration, but the UK must continue to develop collaborative relationships.

Looking to the single European market of 1992, Fairclough said, we must engage in early collaboration in order to be effective in Europe.

Semiconductor Optoelectronic Materials

Read by Dr. R.C. Goodfellow, Manager, Optoelectronic Materials and Integration Technology, Plessey Research

At the start of JOERS in 1984 the industry standard method for the preparation of optoelectronic device materials was liquid phase epitoxy. Molecular beam epitoxy (MBE) and metalorganic chemical vapor deposition (MOCVD) were emerging as powerful techniques for complex compound semiconductor materials structures. The UK efforts on MOCVD and MBE were fragmented, with several advanced centers in metallurgy, metalorganic chemistry, and optical and electrical materials characterization pursuing diverse objectives.

In 1985 two JOERS consortia were formed, one addressing MBE and GaAs-based materials with two industrial and two university partners, and the other addressing MOCVD and indium-phosphide-based materials having three industrial and five university partners.

The MBE program has studied advanced quantum well and superlattice structures incorporating antimony for GaAs/GaAsSb structures and explored the powerful *in-situ* monitoring possibilities of the technique. Since that time, two major SERC initiatives have also concentrated on MBE for advanced quantum well and "low dimensional" studies. A UK company is now a world supplier of MBE equipment, and the MBE technique has become a popular route for the exploration of new devices and materials concepts.

The MOCVD position has advanced considerably, mainly as a result of the JOERS consortium, and the UK is now frequently acknowledged to be a current world leader. The UK now has three major MOCVD equipment manufacturers and several chemical reagent manufacturers who offer proven high-purity metalorganics, and UK electronics companies are actively exploiting the processes. Key developments which made possible the advances were: the fast switching manifolds which enable abrupt interfaces to be achieved while separating the arsenic and phosphorus gas handling; ingenious purification techniques for the metalorganics including the "diphos route"; a novel ultrasonic monitoring cell for organometallic gas phase composition control; and the thorough study and comparison of the four alternative approaches to growth.

The increased complexity of material structures means that the assessment and validation of multilayer structures is complicated. New, more powerful techniques have become a necessity. The JOERS advanced assessment program has resulted in a specialist community of experts addressing optical, electrical, metallurgical, and chemical analysis techniques. Already, practical metallurgical and chemical analysis processes have been established and are in routine use.

The optical systems up to 1985 have used discrete optoelectronic components which are small-area devices, less demanding on uniformity and yield. The more advanced systems and low-cost systems planned for the next 5 years demand a higher yield of components to tighter specifications, a higher level of integration, and integrated optical signal processing. These requirements translate into larger areas, greater complexity, better reproducibility, and tighter quality assurance. The semiconductor materials technology R&D carried out under JOERS has enabled UK industry to establish major roles in the RACE program for a pan-European broadband network in the coherent optical system, customer access connection, and low cost component areas.

In summary, the JOERS program's impact on the UK semiconductor optoelectronic materials position has been to transform an ensemble of highly competent but fragmented groups into effective interacting communities, thereby accelerating the exploitation of the advanced epitaxial growth technologies.

Semiconductor Optoelectronic Device Technology

Presented by Dr. P. A. Kirkby, Technical Strategy Manager, STC Technology

The JOERS projects in semiconductor optoelectronic device technology are aimed at developing understanding and control of the physics and technology for the next generation of semiconductor optoelectronic devices. These devices will be the key components for the next stages of the penetration of optics into electronics. The majority of projects are aimed at integrated components for optoelectronic switching networks which will have the capacity to handle information at rates well beyond the limits of today's purely electrical systems. It is widely anticipated that by the mid-1990's these optoelectronic switching networks will form the basis of communication networks bringing broadband services to business and domestic subscribers. Small versions of these networks confined to equipment ranks or even within individual electronic units are also expected to overcome the present severe communications problems in parallel processing computers and enable much more powerful fifth-generation computers to be developed.

There are many different potential approaches to solving the severe problems of switch capacity that occur at the nodes of complex broadband networks. These range from all-electronic switching with optical interconnection to all-optical switching with optical logic for routing. The JOERS program, in conjunction with in-house and ESPRIT and RACE projects, has enabled the major UK electronics companies to research the options in greater depth and breadth than would otherwise have been possible. The collaboration has also provided valuable cross fertilization and new university-industry links. This will pay off not only in direct component developments but also in the development of the complete systems.

The JOERS I projects on semiconductor waveguide integrated optics-base technology and active optical switching and logic and their JOERS II successors are making good progress towards the development of electrically controlled optical space switches. The use of semiconductor materials for integrated optics offers the prospects of size reduction and integration with lasers, detectors, and transistors. There are, however, significant technological difficulties to overcome in order to demonstrate feasibility.

The first target is low-loss transmission through single-mode semiconductor waveguides. Work at the University of Glasgow, Plessey, and BTRL has put the UK in a world-leading position with losses below 1 dB/cm in both GaAs and InP materials systems. A key part of the work has been the development of new dry etching techniques using low-pressure ionized gas plasmas. Novel gas combinations and electrode configurations have given sufficiently smooth and vertical waveguide sidewalls to reduce scattering and achieve these results. The work is now being extended to curved waveguides, mirrors, Y-junctions, and crosspoints necessary to make a 2x2 crosspoint switch. The target is to demonstrate such a switch within 1 year.

Determining the best way to use the rapidly developing optoelectronic technology in the heart of computers and telecommunications switches has been the major aim of the Digital Optics project. University College with materials support from Sheffield University have demonstrated new types of optoelectronic logic switching elements based on the recently discovered quantum confined Stark effect semiconductor light modulators. Plessey and STC are pushing ahead to make arrays of such devices. The close involvement of computer system architects and device technologists in the project is helping to define more clearly the areas in which optical interconnection can provide an overall system benefit. These ideas will form the basis for major UK projects in optoelectronic computing and switching in the 1990's.

Liquid Crystal Displays

Presented by Dr. J.C. White, Head of the Optical Devices Department, Thorn-EMI.

The range of display technologies have been researched under collaborative JOERS projects including electroluminescent, active-matrix liquid crystal and ferroelectric liquid crystal displays.

Active-matrix and ferroelectric technologies are both contenders for video TV applications with the former already available in the marketplace. This presentation concentrates on the more speculative area and the use of a new type of liquid crystal display exploiting ferroelectric LC materials.

The program of interest is the JOERS Alvey Project LM8/11/5, "Large Panel Storage Displays Based on Ferroelectric Liquid Crystals."

Collaborators in the work are:

STC Technology Ltd. (Harlow), Thorn EMI CRL. (Hayes), BDH Ltd. (Poole), RSRE (Malvern), and the Department of Chemistry, the University of Hull.

Overall Objectives: Ferroelectric liquid crystals make possible a new generation of liquid crystal flat panel displays with a unique capability of rapidly addressing very large arrays of picture elements, while avoiding the complexities of active-matrix addressing. The program aims to establish a world lead in this technology by adopting the following ambitious device objects:

- To develop and demonstrate a rectangular ferroelectric liquid crystal display with a screen diagonal in excess of 10 inches, with greater than 300,000 picture elements, and with a line address time compatible with the requirements of video images
- To develop techniques to enable these displays to render images in color, and with grey scale. To demon-

strate the principles of these techniques by building engineering demonstrators.

While these project objectives have been stated largely in device terms it is recognized that the program is driven specifically by developments in liquid crystal materials.

Nonlinear Optical Devices

Read by Mr. S.C. Gratze, Manager, Optical and Microwave Devices Division, GEC Marconi Research Center.

Defining Nonlinear Optics. The term "nonlinear optics" is applied to a variety of optical phenomena in which the propagation of light can vary by external influences.

Light can interact directly with light via the nonlinear optical properties of the medium in which it is traveling. These properties arise from a variety of optoelectronic effects ranging from photo-refraction to third-order (atomic) susceptibility. These interactions can be used to: generate second harmonic radiation, (e.g. green light from a 1.06-m infrared laser) or to shift the frequency of an optical signal for use, for example, in coherent communications. They can also be used to amplify weak optical signals to aid their transmission or detection or to reflect them in phase conjugated form (as is being investigated for novel laser sensor and communications concepts).

"Nonlinear optics" also includes the interaction of light with applied electric fields, from dc to microwave, via the Pockels or the Kerr effects. These effects result in a change of the refractive index of the electro-optic medium employed. The resultant optical phase shift can, if required, be converted to amplitude modulation or polarization rotation. Devices based on these effects include optical modulators (both temporal and spatial), optical switches, and tunable optical filters.

A third type of interaction is that between ultrasound and light, where the acoustic waves change the local refractive index to form phase gratings corresponding to the wave-fronts. These gratings act like holograms to diffract the light, and the effect is used to produce beam deflectors, modulators, and tunable optical filters.

In this presentation, contributions to nonlinear optical device technology from three JOERS projects is illustrated by presenting both the achievements of the projects and the subsequent use of the JOERS technology base. There are several other projects which have made important contributions to nonlinear optics but time does not permit the inclusion of any details of the result to be included. In particular, major advances have been made in spatial light modulator[1] technology and in tunable optical filters[2] and these are referred to in the conclusion of this presentation.

Integrated Optics In Lithium Niobate. Lithium Niobate, which currently offers integrated optical devices with the highest performance and greatest complexity, has been the subject of two JOERS projects, Lithium Niobate Integrated Optics, LM8/03/100, and Integrated Optic Device Technology, LM8/03/137. Plessey, STL, Barr and Stroud, GEC, University College London, and, the Universities of Glasgow, Sussex, and Surrey contributed to these projects. The major outputs have been the development of high-quality lithium niobate in 3-inch diameter boules, the establishment of new and improved integrated optic process technology, enhanced device designs, and better measurement techniques. These achievements and their subsequent applications can be illustrated by examining the increase in performance of wideband integrated optic modulators, the use of integrated optical components for sensor applications, and the complexity of optical switching components which have now been demonstrated.

Organic Materials. The Organic Electro-optic and Nonlinear Optical Materials Project, LM8/03/112, seeks to exploit the large nonlinear optical coefficients of organic materials, their molecular design flexibility, and their potential for new dimensions in device fabrication techniques. ICI Plessey, GEC, BDH, BTRL, UMIST, Herriot Watt, Strathclyde, and Oxford universities and Queen Mary College (London), have all participated. Techniques have been developed to design nonlinear optical molecules and predict their performance which has led to the synthesis of many new nonlinearoptics moieties. Experimental techniques have been developed to characterize the resulting materials both optically and crystalographically, permitting the most attractive candidates to be grown in single-crystal form for use in experimental devices. A selection of the materials which have been developed will be presented and their application to prototype devices indicated.

Summary and Conclusions. The JOERS projects indicated have established the enabling technologies for integrated optics in lithium niobate and organic materials for electro-optic and nonlinear optic devices. Other projects developed electrically and optically addressed spatial light modulators and acousto- and electro-optical tunable filters. In doing this the projects have generated many processes, designs, and concepts for enhancing the utility of a wide range of devices. This technology and device expertise is now being built on to develop practical, high-performance devices for a wide variety of optical communications, optical signal and data processing, and optical sensing applications. The projects have also contributed to the availability of engineers and scientists with the necessary expertise to continue to exploit optoelec-

1 Spatial light modulators are optical devices which impress a pattern, such as an image or data, across the spatial cross section of an expanded laser beam. They can be applied to a variety of optical processing or computing functions as well as to optical switching, image filtering, and projection displays.

2 Tunable optical filter can transmit specific optical wavelengths that can be changed or programed at will and can provide simultaneous filtering of a whole scene.

tronics. As a result, the UK has a capability in these technologies which is fully equal to the best in the world.

There are compelling reasons for now giving priority to systems/applications pull rather than to technology push. Principal among these are that the increased functionality now being achieved results in more applications-specific devices and that the optimum and most cost-effective use of optoelectronic technology can often only be properly judged in the context of real systems. To continue to succeed in the future we must maintain the technology base and design capability at the world state-of-the-art level and use these to develop devices to full commercial viability and with increasing functionality. Most importantly, the exploitation of the devices in as wide a range of system applications as is possible must be strongly encouraged.

The Future Importance of Optoelectronics

Presented by Professor J.E. Midwinter, British Telecom Professor in Optoelectronics, University College (London)

During the 1980's, optoelectronics has moved from being a technology that was only used when it was designed to interface between an optical scene and an electronic system, to one that is increasingly chosen on its own merits in preference to electronics, even through electronics could carry out the required function. Examples of the former applications are:

- Cameras
- Visible and infrared detectors
- Lasers and displays.

In the latter case, we have optical fibers replacing metal cable, and compact disc ROM's starting to invade the territory previously held by magnetic recording media. In the future, we see this trend intensifying as optical technology penetrates more deeply into the infrastructure of information communication, storage and processing. Key examples are likely to include:

- Optical I/O for wafer-scale circuits
- Optical "wiring" overlaid on wafer scale circuitry
- Optical self-routing networks (photonic switching)
- Ultrafast multiplexing, coding and preprocessing
- Optical association memories and pattern recognition systems.

Thus optoelectronics is moving inexorably from a purely interface technology to one that will be the key to the successful implementation of a very wide range of information systems.