Final report: Integrated optical wireless transceivers

Note: The report is common to all the grantholders. An appendix details the work of individual institutions, and factors that were particular to each.

Background

Wireless optical channels have the potential to offer wireless connection with data rates far in excess of those available using RF approaches. This is due to both the higher carrier frequency, and the limited availability of free spectrum in the crowded RF frequency regions. However, multipath dispersion, and limited receiver sensitivity when compared with radio LANs requires that line-of-sight paths be established between transmitter and receiver if high data-rates are to be achieved[1].

Provision of high bandwidth indoor Optical Wireless (OW) channels is an active area of research. Various approaches have been taking including tracking transmitters, angle diversity and imaging receivers. Providing coverage using line-of-sight channels usually involves some sort of tracking mechanism to align transmitter and receiver. Various approaches to this have been taken. BT labs demonstrated a 1d tracking system that used an array of lasers and detectors[2], and a similar system is reported in [3]. Kahn reported the design of a 2D-imaging receiver in [4]. The first experimental demonstration of a 2D-tracking system that uses an array of sources and an array of detectors is that by Parand at Oxford[5]. This is a hybrid integrated nine channel demonstrator that uses commercial parts, operates at 34Mb/s.

All of these involve complicated transceiver designs, where complex optical systems and electronic systems are combined to produce functions such as tracking and selective signal combination.

Key to the scaleability of these systems is the ability to integrate these components in a straightforward manner. The programme set out do this; aims are set out below.

Aims

1. To demonstrate compact potentially low cost optical transceivers for in-building free space networks.
2. To develop long wavelength (1500nm) emitter and detector arrays optimised for free space data transmission.
3. To evaluate the performance of such transceivers by transmitting ATM computer and video data at 155Mbit/s.
4. To investigate extending this architecture to a Gbit/s free space optical network.

Programme overview

System overview

Figure 1 shows the system demonstrator. A base station (BS) is situated above the coverage area, and this uses a two dimensional array of semiconductor sources that emit normal to their substrate. A lens system is used to map sources in the emitter array to a particular angle, thus creating complete coverage of the space. The use of an array of sources both minimises power transmitted, as sources not pointing at a terminal can be deactivated, and offers the potential for each source to transmit different data. Each terminal within the space has a lens system that collects and focuses the beam of light onto a particular detector within a detector array. The resulting electrical signal is amplified and a data stream is extracted from it. The detector array allows the angle of arrival of the beam to be determined, and hence the direction of the required uplink (from terminal to BS). The system is therefore a combination of a tracking transmitter and tracking receiver. This has the potential to maximise the power available at the receiver (when compared with combinations of tracking and non-tracking components). Each detector has low capacitance and a narrow field of view, thus increasing channel bandwidth and reducing the effect of ambient illumination.

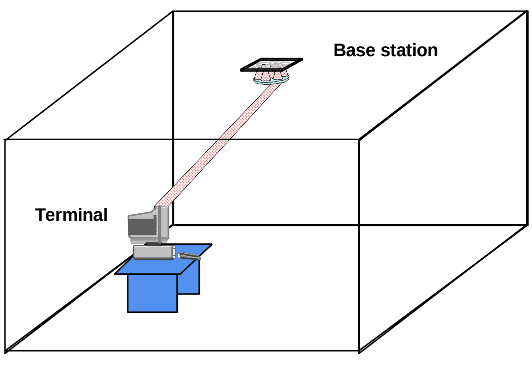


Figure 1. Optical wireless system

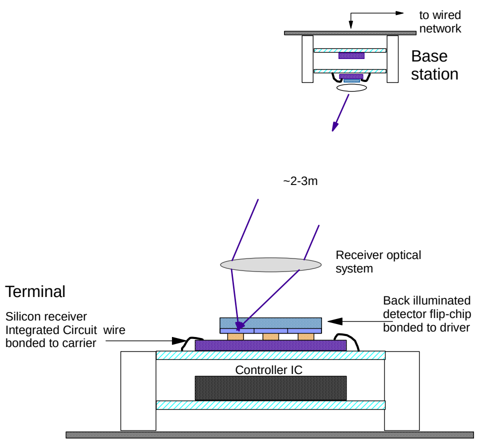


Figure 2. Wireless transceiver integration

Figure 2 shows the approach taken to integration. Arrays of sources that emit through their substrate are flip-chip bonded to arrays of driver electronics fabricated in a 'commodity' CMOS process. This provides the transmitter functionality, and a similar approach is taken with the receiver photodetector array. Flip-chip bonding of receivers directly under the detectors ensures the interconnect between them is local to each 'pixel' ensuring that the system is potentially scaleable. CMOS circuitry was used to allow future integration of digital control circuitry.

Programme approach

The major aim was to produce integrated link components, and all components are ‘custom’, so that a balance was struck between the risk of using novel individual components and achieving an integrated demonstrator.
One of the key issues for the programme was the choice of wavelength of operation. Eye-safety is a critical issue for these systems, and at wavelengths greater than ~1500nm the allowed emitted power for a point source is a factor of 20 higher than below this wavelength. There is a further constraint that substrate emission is required to allow flip-chip bonding.
Long wavelength surface normal emitters are still in early stages of development so emitters that operate at 1500 were developed as a separate exercise. Resonant cavity LED (RCLED) devices emitting at 980nm meet the geometrical constraint and were available, so these were chosen for the demonstrator work, although they do not strictly meet eye-safety limits. Detectors that operate at both 980 and 1500nm have been designed, to allow a long wavelength system to be built with no change in receiver.
The receiver is where the major system constraints lie. A receiver must have maximum optical concentration (the ratio of collection area to detector area), and this is limited by constant radiance (etendue) considerations. For a system with limited concentration ratio collected power becomes proportional to the area of detector, and the capacitance that this presents to the subsequent preamplifier. The capacitance of the photodiode then becomes critical, as well as the ability of the preamplifier to provide sufficient bandwidth with high input capacitance. This work is the first to address these problems and to develop devices optimised for these constraints.
Given the constraints of wavelength, device availability and the use of novel components for all aspects of the programme we took a staged approach to the work. A link budget model was produced and optical designs were simulated and realistic targets were set for receiver sensitivity and detector responsivity. Single channel LED drivers and Preamplifiers were designed to these specifications, fabricated and tested. Detector and RCLED arrays were also fabricated and tested, and results from these used to refine the system model.
In order to test these first devices wirebonding was used to integrate optoelectronic and electronic components. After performance of these was assessed a seven channel flip-chip integrated system was then targeted. At the present moment we await the final optoelectronic devices-all other components are complete. In parallel with this theoretical work on scaling the system was undertaken, using device results where possible.

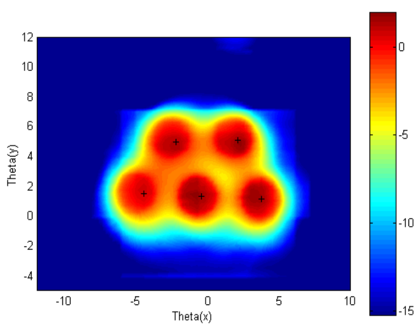
Results

System

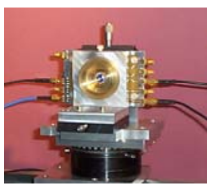
A complete end to end system optical model was developed, initially using calculated RCLED emission characteristics, in order to set a power budget and initial specifications. These were a system to transmit 155Mb/s Manchester data over a range of 2-3m, using a receiver with a sensitivity of –30dBm receiver and RCLED transmitters with >+1dBm output power. An analysis of scaling to higher data rates (1Gb/s) and larger coverage areas was also undertaken [6]. This identified a novel preamplifier design as well as an optimum detector size for this design, and showed that practical coverage areas were achievable at these data rates. This work is reported in [6], but will be reported in greater detail when the DPhil thesis associated with it is complete.

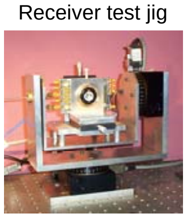
Optics

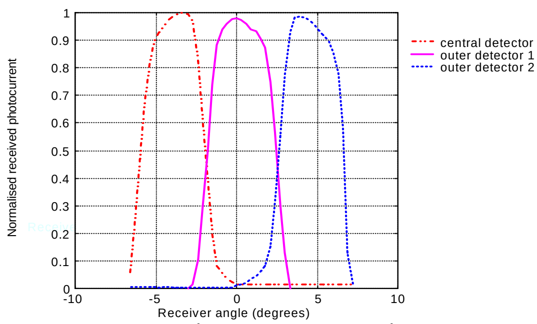
The transmitter forms an angle-position mapping, taking light from a particular emitter and directing if to a particular part of the coverage angular space. The receiver performs its inverse, focussing the light from a particular direction onto a single element of the detector array. The detailed design of the optical system is described in [7]. In order to test the performance of the optical systems arrays of sources and detectors were mounted onto the optomechanical systems and the system was tested without data modulation. Figure 3 shows an angle scan of transmitter illumination; the transmitter assembly is shown mounted on the measurement goniometer. The coverage map shows received intensity using a dB scale normalised to the maximum value vs. azimuth and elevation (in degrees). The receiver system is tested by illuminating the aperture of the receiver in a direction along the optical axis of the system, and then rotating the receiver and recording the signal from the central detector and two adjacent in the hexagonal array. As the angle is increased light should strike the outer detectors, thus demonstrating the angle position mapping. Figure 3 shows the receiver optomechanics and the plots of detected photocurrent as the angle is changed. These indicate the optics is performing to specification.



Transmitter illumination


Receiver test jig


Transmitter test jig



Receiver response vs angle

Figure 3. Optics and optomechanics.

Silicon

Transmitter

Figure 4 shows a block diagram of the RCLED driver circuit that is used to drive each source. The driver incorporates novel timing generators for charge injection and charge extraction to improve the optical source's turn-on and turn-off times respectively. Each driver is designed to source 100mA of current at 1.5V, which would yield the required 2.5mW with device efficiencies of around 1.7%. Single channel driver test structures have been designed and fabricated, and these were tested using an electrical model of an RCLED, and a separately packaged RCLED array. The electrical model used a 100pF capacitance in parallel with two diodes to provide the appropriate turnon voltage drop, and a series connected 1Ω resistor. The electrical model has been evaluated and has demonstrated similar electrical DC and transient behaviour to the RCLEDs. DC testing with the electrical model showed the devices could source the necessary current to drive and pre-bias the RCLEDs, and these could be controlled as predicted. AC tests with this model were also undertaken: the electrical output achieved rise and fall times of 1.0ns, with the novel timing generators operating as expected. Measurements of the optical outputs of packaged RCLEDs are currently in progress, so that the effects of injection and extraction on optical rise and fall times are yet to be confirmed [8].

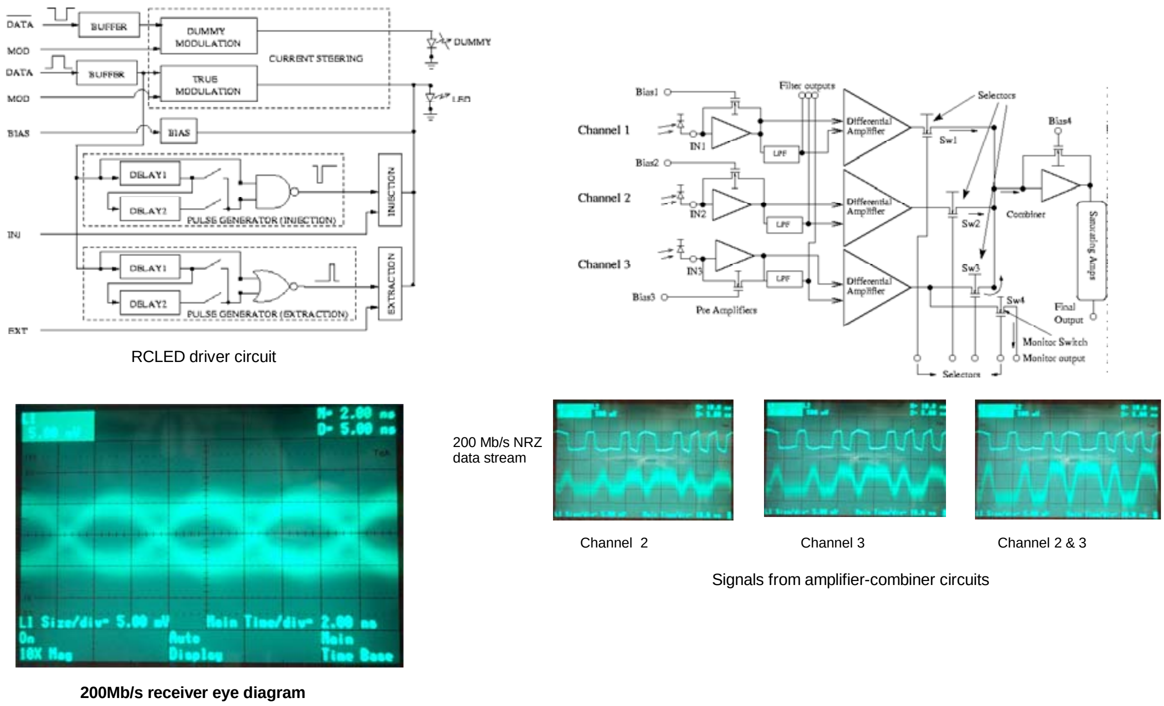


Figure 4. Receiver and transmitter

Receiver

A major effort has been the design of a transimpedance amplifier with target sensitivity of –30dBm at a BER of 10^{-9} and a bandwidth of 217MHz, assuming the total capacitance (including photodiode and any stray capacitance) at its input is ~10pF. Circuits that operate according to this specification with an input capacitance of 10pF have been fabricated and tested, and it has been shown that this bandwidth can be maintained over a range of capacitances from 2pF to 10pF. The noise performance of the circuits has been measured by comparing the output noise spectra with and without input signal, in order to remove the effect of measurement noise[9]. The measured input referred noise current density is $5.92\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$. At a bandwidth of 217MHz, using the measured detector responsivity of 0.39A/W, this implies a sensitivity of ~ -29dBm at 980nm. Detailed BER measurements will be undertaken on the flip-chip integrated structures in order to verify this.

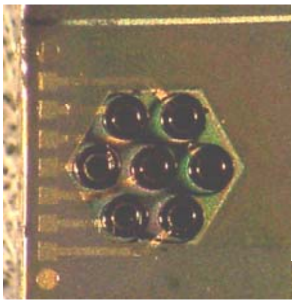
In order to recover data from the incoming optical power the signal from the desired detector or group of detectors must be routed to the data recovery circuit. A combiner circuit that allows arbitrary combination of signals from three preamplifiers has been designed and submitted for fabrication[10]. Figure 4 shows the operation of the combiner. Two individual received waveforms are shown, along with the combined signal. It should be noted that there is no output noise filtering to optimise the SNR at the detector output.

Optoelectronics

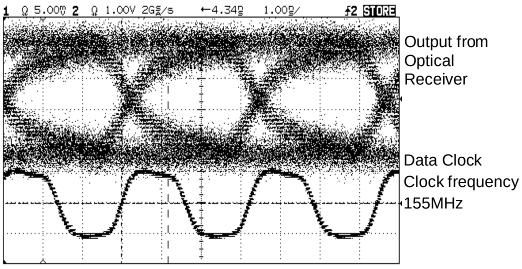
Emitters

3.1. Emitters

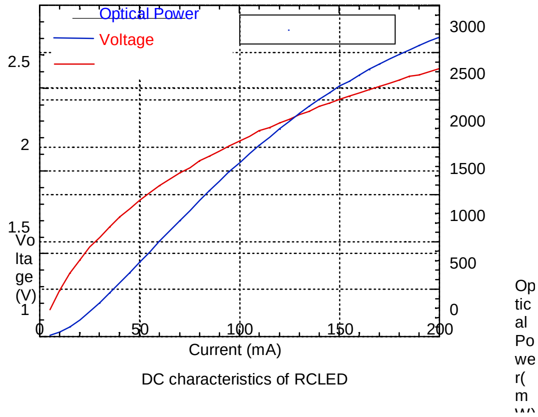
The system requires two-dimensional arrays of surface emitters that emit through the semiconductor substrate, thus making devices suitable for flip-chip bonding. Resonant Cavity LEDs (RCLEDs) offer sufficient modulation bandwidth for this application and have several characteristics that make them well suited to this application[11]. The beam profile emitted from the device can be tailored by offsetting the cavity resonance of the device from the peak emission wavelength of the material. This detuning causes a beam profile with peak emission away from the optical axis, which improves the illumination profile at the receiver plane. Material was grown by MOVPE at the University of Sheffield, and the wafers then mapped to allow regions with the correct detuning to be identified. These were processed into arrays using standard lithographic techniques. Devices of various sizes were fabricated on a 250µm and 400µm pitch. Figure 4 shows a typical 7 channel RCLED array. Detailed material and device structure is reported in [12].



Seven channel RCLED array



Eye diagram for RCLED



DC characteristics of RCLED

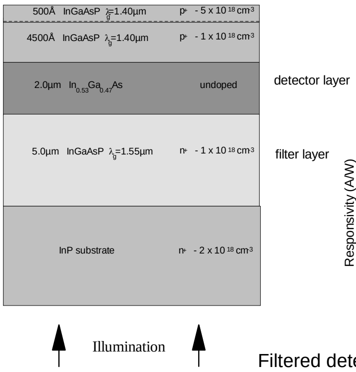
Figure 4. Resonant cavity LED array

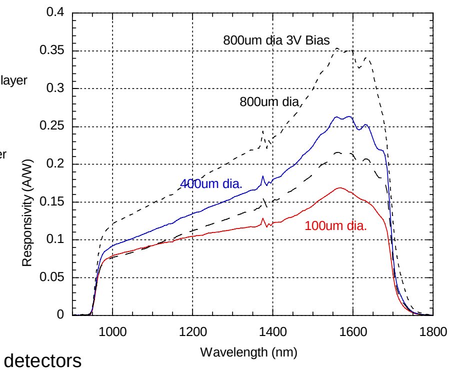
Several processing runs have been attempted in order to validate the approach to processing, using non-optimum parts of wafers from the MOVPE process. Figure 4 shows a typical device, eye diagram for 310Mb/s operation and DC characteristics. Device efficiency was approximately 0.6% for 100mA drive current, with output power of approximately 1mW and a slope resistance of around 3Ω for devices that gave the maximum output optical power. This performance is sufficient for the final demonstrator. Devices for this, that include necessary barrier metals for flip-chip bonding are currently being fabricated. These will use optimum material, so we expect improved performance.

Long wavelength RCLED structures designed for 1500nm operation have been grown in InGaAsP using MOVPE. Initial assessment of the wafer using photoluminescence has shown promising results, and these are awaiting processing into test structures for assessment.

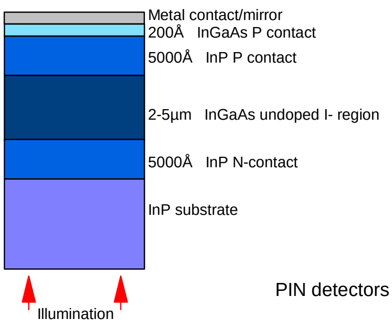
Detectors

Two detector approaches were investigated under the programme. Optical filtering is often used as a means of reducing noise from ambient light, and narrowing the optical bandwidth by integrating optical filters with the detectors was investigated. Figure 5 shows the initial structure that was evaluated. Light passes through the InP substrate, which filters all light with a wavelength shorter than 950nm. The thick InGaAsP (with a bandgap corresponding to 1500nm) filter layer absorbs all light between 950-1500nmm. The InGaAs detector layer then detects light and generates photocurrent for only a small wavelength range between 1500nm and the long wavelength cut-off for this material composition, which is at 1650nm. Simple large area devices have been fabricated using materials grown to this specification Figure 4 also shows a plot of responsivity vs. wavelength for this structure. There is some suppression of the responsivity in the band from 1000-1400nm, although more would be expected from calculations of the absorption of the filter layer. This is likely to be due to the diffusion of photocarriers from the filter layer and the InGaAsP p-layer into the I-region, from which they can be swept by the internal field to the contacts.

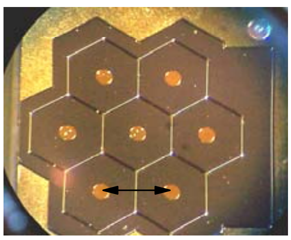




Filtered detectors



PIN detectors



500µm pitch array

Figure5 . Photodetectors

These structures are highly capacitive, and for the demonstrator a simpler PIN structure was designed. The detectors for the demonstrations are InGaAs/InP PIN diodes are grown on InP substrates by MOVPE, designed for substrate illumination and operation in the range from 980nm to beyond 1500nm. Devices are processed into close packed hexagonal detectors using standard techniques similar to those used for the emitters. Figure 4 shows a typical array.
Initially devices suffered from unacceptably high leakage currents, associated with etching the top p-contact to isolate individual detectors in the array. Etching through the I-region and passivating the etched surfaces reduces this problem substantially, but tracks cannot be run over these trenches, so contacts are made to individual devices using wire bonds. This will not be a problem for later flip-chip demonstrators, as contact will be made directly to the rear of these detectors.
Devices typically have a measured capacitance of 5.2pF (at 4V reverse bias) compared with a calculated value of 5.1pF for a fully depleted I-region. The slight discrepancy is due to the reduced bias voltage (4V) compared to that required to fully deplete the I region (estimated to be approximately 8V). Leakage current for these devices was in the range 2-140nA. The measured responsivity was 0.39A/W at 980nm, compared with a theoretical maximum of 0.79A/W. Two factors contribute to the reduction in responsivity: the InP substrate has significant absorption at this wavelength, and the Fresnel losses (~30%) as light enters the semiconductor substrate reduce the illumination incident on the PIN structure. An estimate of the likely reduction these two effects produce leads us to believe the detectors are operating efficiently.

Integration

Wirebonding between ICs and optoelectronic devices was used in the early stages of the project, in order to obtain the electronic results shown in the figures. However, this has extremely limited scalability and is only suitable for initial assessment. Flip-chip bonding allows attachment of the CMOS directly to the optoelectronic ICs, offering low inductance and capacitance, good thermal management and simplification of packaging. Figure 6 shows a schematic of the approach used for the seven channel receiver (a similar approach is using the transmitter). Connections are made around the periphery using wirebonds, and the pads in the centre of the IC are used for flip-chip bonding. Solder bumps were attached to the ICs using a Europractice post-processing route (these can be seen in the photograph of the receiver IC in figure 6), and optoelectronic devices incorporating the necessary platinum barrier layers. Parts are then aligned in a reflow-aligner and the resulting hybrid placed in an IC package. This is then mated with optical mounts of the type shown in figure 3. At the current time all these parts have been fabricated and are awaiting final assembly and link test.

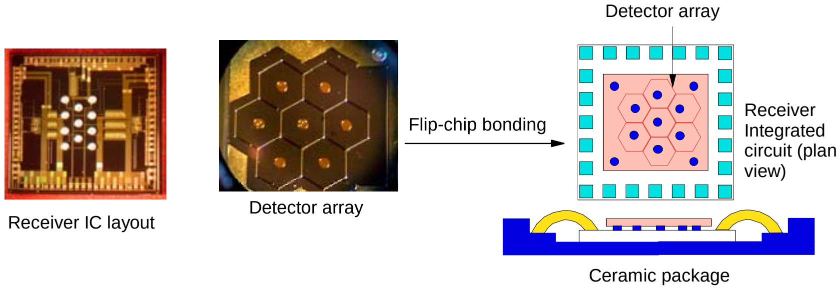


Figure 6. Integration of optoelectronic components, showing flip-chip compatible receiver array, detector array and packaging.

Programme review

Difficulties

The programme was impeded by two problems. Initially the emitters were to be fabricated using MBE at Imperial College, but continuing difficulties meant that an alternative design was used. MOVPE structures were grown at the University of Sheffield, and after initial metallisation difficulties devices with suitable output power were procured. There were also difficulties with detector processing, and modified structures had to be used to overcome high dark currents. The final set of devices (both emitters and detectors) require barrier metals to prevent Au contacts diffusing into solder bumps, and several attempts were made to obtain barriers with suitable adhesion. (This work was carried out at the EPSRC III-V facility in Sheffield).
We had hoped to obtain flip-chip bonding at GEC-MMT at Caswell, but this had to be changed when their priorities meant that this was no longer possible. A processing route using Europractice to obtain solder-bumped wafers, and aligning at Oxford has been developed.

Communication of research outputs

Members of the programme have presented papers at each of the last three optical wireless conferences. A poster or presentation was given at each of the last three EPSRC OSI workshops as well as the EPSRC review of laser research. Invited papers were presented at one US conference, and one in the UK, as well as several research seminars. We expect to publish journal papers on this work when the final demonstrator is complete, which should be within the next few months.

Collaboration and exploitation

Partners maintain contact with the BBC and Cablefree solutions, who take an active interest in this work. Cablefree are interesting in the application of these receivers in outdoor systems, and we have written (as yet unsuccessful) proposals with them. The BBC continue to be interested in Optical Wireless and the intended equipment loan will take place when the demonstrator is complete. BT have scaled work back in this area, although we continue to keep in contact. A patent resulting from this work has been filed by partners and is being pursued by ISIS, the innovations company of Oxford University.

Research impacts

The system demonstrator will be the first demonstration of an integrated system for optical wireless, and as such internationally leading. This is the first programme that has examined the optimisation of devices for optical wireless, and has developed silicon ICs and optoelectronic devices that are specifically for this purpose.

The work on CMOS ICs is novel, in that it receivers designed specifically for high input capacitance were implemented. This may also have impacts in low cost fibre-optics links, where large area detectors are used to match fibre diameters and to keep manufacturing tolerances small. The detectors grown in this work are not optimal, due to the problems of growing i-regions of the required thickness. In our view the near term impact of this work is likely to lie in outdoor optical wireless, where optimised detectors can offer significant performance benefits over currently available structures, and we are pursuing this approach in collaboration with Cablefree solutions. At the same time we are investigating the use of these receivers in a multichannel system. The long wavelength RCLEDs, if successful will allow the system to be scaled to higher (Gb/s) data rates whilst meeting eye safety considerations, and may also impact optical fibre link applications.

Overall, the programme has made significant advances in optical wireless systems, and individual subsystems and components have the potential to impact other free space and fibre optic applications.

Partner roles

Oxford. Programme management, system modelling design, optical and optomechanical design, optical device layouts and mask design, device assessment

Cambridge. Electronic design and test

Imperial College. Optoelectronic device design and wafer structure assessment

Huddersfield University, Test electronics design and fabrication, Component and subsystem testing

Institution specific information

The previous sections are common to all partners. In this section factors specific to each are described

Oxford University

Expenditure broadly followed expected patterns, except the need to divert consumables funds to partially purchase a flip-chip aligner.

Cambridge University

Imperial College

Huddersfield University

References

[1]A. M. Street, P. N. Stavrinou, D. C. O'Brien, and D. J. Edwards, "Indoor optical wireless systems-a review," *Optical and Quantum Electronics*, vol. 29, pp. 349-78, 1997.

[2]D. Wisely and I. Neild, "A 100 Mbit/s tracked optical wireless telepoint," presented at 8th International Symposium on Personal, Indoor and Mobile Radio Communications - PIMRC '97,proc. British Telecom Res. Labs. Ipswich UK

Waves of the Year 2000+ PIMRC '97. The 8th IEEE International Symposium on Personal Indoor and Mobile Radio Communications. Technical Program Proceedings (Cat. No.97TH8271). IEEE New York NY USA, vol.,pp.1232, 1997.

[3]V. Jungnickel, C. V. Helmolt, and U. Kruger, "Broadband wireless infrared LAN architecture compatible with Ethernet protocol," *Electronics Letters*, vol. 34, pp. 2371-2372, 1998.

[4]J. M. Kahn, R. You, P. Djahani, A. G. Weisbin, B. K. Teik, and A. Tang, "Imaging diversity receivers for high-speed infrared wireless communication," *IEEE Communications Magazine*, vol. 36, pp. 88-94, 1998.

[5]F. P. Parand, G. E. Faulkner, D. C. O'Brien, and D. J. Edwards, "Optical wireless testbed system using a multiple source transmitter and a segmented receiver to achieve signal tracking.," presented at Optical Wireless Communications IV,proc. SPIE, vol. 4350, 2001.

[6]E. B. Zyambo, D. C. O'Brien, G. E. Faulkner, and D. J. Edwards, "Design of a High speed wireless LAN at long wavelengths," presented at Optical Wireless Communications III,proc. SPIE, vol. 4214,pp.115-124, 2000.

[7]D. C. O'Brien, G. E. Faulkner, E. B. Zyambo, K. L. Jim, D. J. Edwards, M. Whitehead, P. N. Stavrinou, G. Parry, J. Bellon, M. J. N. Sibley, V. A. Lalithambika, V. Joyner, R. Samsudin, D. M. Holburn, and R. J. Mears, "High speed integrated optical wireless transceivers for in-building optical LANs," presented at Optical Wireless Communications III,proc. SPIE, vol. Proc SPIE 4124,pp.104-115, 2000.

[8]D. M. Holburn, R. J. Mears, R. J. Samsudin, V. M. Joyner, and V. A. Lalithambika, "CMOS 155-Mb/s optical wireless transmitter for indoor networks," *Proceedings of the SPIE The International Society for Optical Engineering*, vol. 4214, pp. 124-32, 2001.

[9]V. A. Lalithambika, V. M. Joyner, D. M. Holburn, and R. J. Mears, "Development of a CMOS 310 Mb/s receiver for free-space optical wireless links," *Proceedings of the SPIE The International Society for Optical Engineering*, vol. 4214, pp. 133-43, 2001.

[10]D. M. Holburn, V. A. Lalithambika, R. J. Samsudin, V. M. Joyner, R. J. Mears, J. Bellon, and M. J. Sibley, "Integrated CMOS transmitter driver and diversity receiver for indoor wireless links," presented at Optical Wireless Communications V,proc. SPIE, vol. 4873, 2002.

[11]E. F. Schubert, N. E. J. Hunt, R. J. Malik, M. Micovic, and D. L. Miller, "Temperature and modulation characteristics of resonant-cavity light-emitting diodes," *Journal of Lightwave Technology*, vol. 14, pp. 1721-9, 1996.

[12]D. C. O'Brien, G. E. Faulkner, E. B. Zyambo, K. L. Jim, D. J. Edwards, M. Whitehead, P. N. Stavrinou, G. Parry, J. Bellon, M. J. N. Sibley, V. A. Lalithambika, V. Joyner, R. Samsudin, D. M. Holburn, and R. J. Mears, "A high- speed integrated optical wireless system demonstrator," presented at Optical Wireless Communications IV,proc. SPIE, vol. 4530, 2001.