High-Speed Integrated Transceivers for Optical Wireless

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ABSTRACT

Optical wireless LANs have the potential to provide bandwidths far in excess of those available with current or planned RF networks. There are several approaches to implementing optical wireless systems, but these usually involve the integration of optical, optoelectronic, and electrical components in order to create transceivers. Such systems are necessarily complex, and the widespread use of optical wireless is likely to be dependent on the ability to fabricate the required transceiver components at low cost. A number of U.K. universities are currently involved in a project to demonstrate integrated optical wireless subsystems that can provide line-of-sight in-building communications at 155 Mb/s and above. The system uses two-dimensional arrays of novel microcavity LED emitters and arrays of detectors integrated with custom CMOS integrated circuits to implement tracking transceiver components. In this article we set out the basic approaches that can be used for in-building optical wireless communication and argue the need for an integrated and scalable approach to the fabrication of transceivers. Our work aimed at implementing these components, including experimental results and potential future directions, is then discussed.

INTRODUCTION

The provision of voice, data, and visual communications to mobile users has become a key area of research and product development. In indoor environments the market for radio wireless networks is growing rapidly, and although data rates available with RF wireless LANs are rising, there is an increasing mismatch between fixed and mobile networks. Fiber optic LANs will be carrying traffic at data rates of tens of gigabits per second in the near future, whereas data rates of tens of megabits per second are difficult to provide to mobile users. In this regime we believe that optical channels, offering terahertz of bandwidth, have many advantages.

Provision of high-bandwidth indoor optical wireless channels is an active area of research [1–3]; in the next section the basic approaches and problems are introduced.

OPTICAL WIRELESS SYSTEMS

APPROACHES TO OPTICAL WIRELESS COVERAGE

There are two basic approaches to implementing optical LANs.

Figure 1a shows a diffuse network. A high-power source, usually a semiconductor laser, is modulated in order to transmit data into the coverage space. Light from this wide-angle emitter scatters from surfaces in the room to provide an optical ether. A receiver, consisting of an optical collection system, a photodetector, an amplifier, and subsequent electronics, is used to detect this radiation and recover the original data waveform. The diffuse illumination produces coverage that is robust to blocking, but the multiple paths between source and receiver cause dispersion of the channel, thus limiting its bandwidth. The commercial networks that have been demonstrated largely use this approach and provide data rates of approximately 10 Mb/s to users, as dispersion caused by multipaths is not a problem at these speeds.

The alternative approach is to use directed line-of-sight paths between transmitter and receiver, as illustrated in Fig. 1b. These can provide data rates of hundreds of megabits per second and above, depending on the particular implementation. However, the coverage provided by a single channel can be limited, so providing wide area coverage is a significant problem. Line-of-sight channels can be blocked, as there is no alternative scattered path between transmitter and receiver, and this presents a major challenge in network design. Multiple base stations within a room can provide coverage in this

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case, and optical or fixed connection could be used between the stations.

WHAT MIGHT OPTICAL WIRELESS OFFER?

The provision of coverage using radio channels is relatively straightforward in comparison to optical channels, for several reasons. The scattering and diffraction involved in the radiation propagation allows large-area coverage using a relatively simple antenna. The resulting low levels of radiation can then be detected with extremely sensitive (compared to a conventional optical system) coherent receivers. Diffuse optical wireless systems have similar coverage attributes, but do not have the advantage of receiver sensitivity. The disadvantage of both these systems is that while coverage is straightforward, available bandwidth is limited, largely due to regulation in radio and multipath dispersion in the optical case.

Systems that use line-of-sight channels are not in general bandwidth limited by the propagation environment; it is the provision of coverage that is problematic. Sophisticated transmitters and receivers are required in order to maintain the narrow line of sight channels, as the location of transmitters and receivers change or an alternative line of sight is required as one is blocked.

It is our view that in the near term systems that use line-of-sight channels, despite the problems of blocking, are likely to find application because of their ability to provide bandwidth. In the longer term the goal must be *optical radio*, combining the coverage attributes of radio and the bandwidth of the optical system.

In the next section some of the basic design constraints and their influence on our preferred system topology are discussed.

CONSTRAINTS AND DESIGN CONSIDERATIONS

At the transmitter the major constraint is that the source must emit optical power that meets eye safety regulations. Typically optical wireless systems work in the near infrared regions (700–1000 nm) where optical sources and detectors are available at low cost. The eye is particularly sensitive in this region, so additional measures, such as the use of source arrays, can be taken to ensure eye-safe emission.

At longer wavelengths (1400 nm and above) the regulations are much less stringent, making operation in this regime attractive. The range of source geometries in this regime is limited at present to in-plane semiconductor lasers or LEDs, and potentially more useful two-dimensional arrays of sources are yet to become available.

Daylight and artificial lighting is often orders of magnitude more intense than the optical transmitter power allowed by eye safety regulation, so steps must be taken to filter out the unwanted optical noise this causes. Filtering at the receiver can be both optical, in order to narrow the optical bandwidth, and electrical, in order to filter out the noise from this ambient illumination.

There are a number of other constraints at the receiver; reducing the effects of these is where, in our view, the major research issues lie. A receiver would ideally have high optical gain, that is, a large collection area and the ability to focus the light onto a small photodetector. As the receiver and transmitter change their locations, the angle from which light enters this receiver system will change, so the ideal receiver will also have a wide field of view.

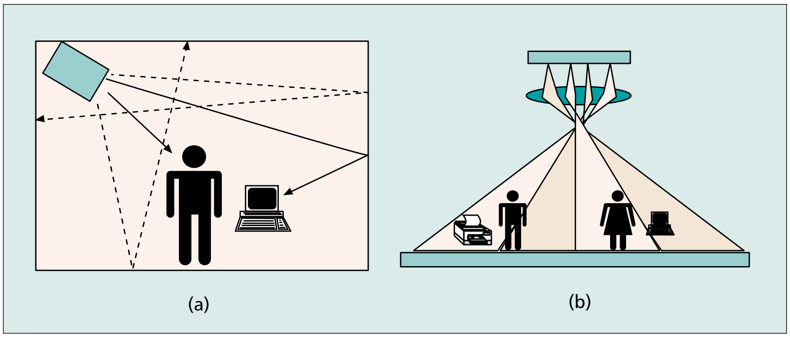

Figure 1. *a) Diffuse optical channel; b) line-of-sight optical channe1.*

The constant radiance theorem sets limits on optical gain, depending on the etendue of the detector, so a large overall photodetection area is required to maximize this. The attendant capacitance of the detector is a major problem for optical wireless as it limits receiver bandwidth and provides a major design constraint. Segmentation of the detector into an array of smaller detectors allows this to be decreased, with increasing bandwidth and other advantages.

Photocurrent from the detector or detector arrays is then amplified, usually with a transimpedance amplifier. The availability of detector structures and suitable preamplifiers optimized for optical wireless, rather than optical fiber communications, provides a practical constraint we are presently addressing; this is discussed in later sections.

As previously mentioned, the other major problem for optical channels is blocking. Line-of-sight channels are required for high-speed operation and are necessarily subject to blocking. Within a building networks must be designed using appropriate geometries to avoid blocking, and multiple access points to allow complete coverage.

All of these constraints and the need to provide reliable coverage will necessarily lead to complex transceiver components, and it is our view that designing to be scalable and use potentially low-cost integration is vital if systems are to be widely applicable. A number of U.K. universities are currently involved in a U.K. government funded program that aims to demonstrate integrated transceiver components for a high-speed wireless network.

In the next section an overview of the system topology and work within the program is presented.

CELLULAR ARCHITECTURE

Figure 2 shows the system under development. A base station is situated above the coverage area; 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 minimizes power transmitted, as sources not pointing at a terminal can

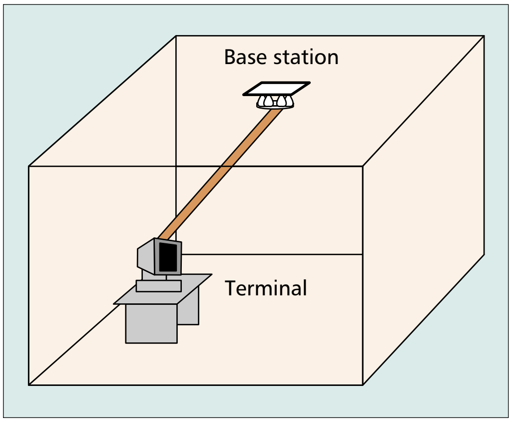

Figure 2. *A line-of-sight optical wireless system.*

be deactivated, and offers the potential for each source to transmit different data. The sources are arranged on a hexagonal grid, and the coverage pattern on the floor of the room therefore consists of a hexagonal pattern of cells.

Each terminal within the space has a lens system that collects and focuses the beam of light onto a particular detector within a close-packed array of hexagonal detectors. 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 base station). The system is therefore a combination of a tracking transmitter and tracking receiver. This has the potential to maximize the power available at the receiver (compared with combinations of tracking and nontracking components). Each detector has low capacitance and a narrow field of view, thus increasing channel bandwidth and reducing the effect of ambient illumination. This is also known as an imaging diversity or tracking receiver [4] as a particular portion of the coverage angular space is imaged to a particular point on the array. Figure 2 shows the downlink; there would be an identical set of uplink components in order to provide a bidirectional channel.

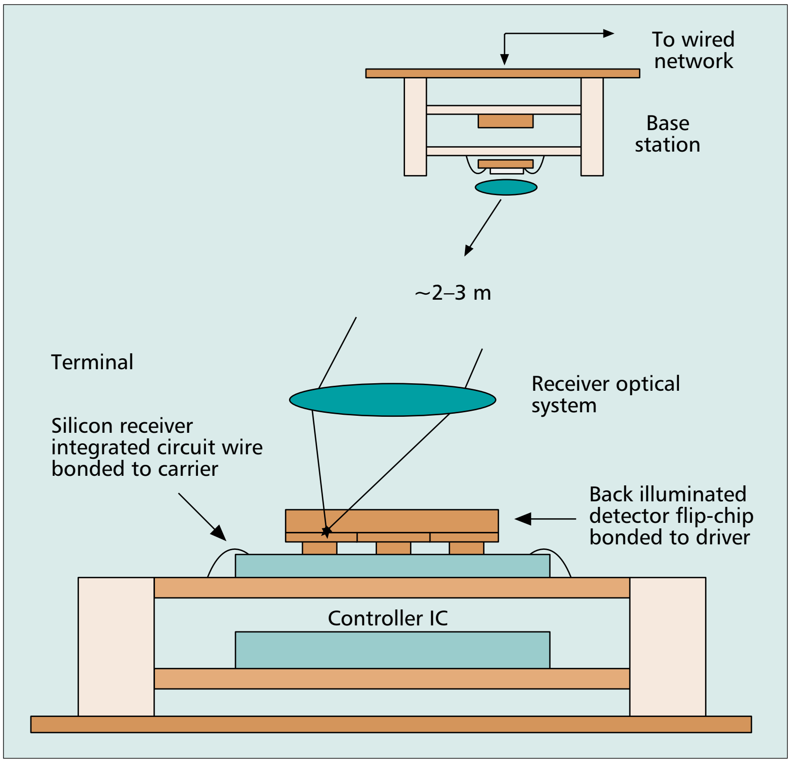

Figure 3. *A schematic of the transceiver integration scheme (shown for a single-direction link only).*

COMPONENTS AND INTEGRATION

APPROACH TO INTEGRATION

Figure 3 shows a schematic of one set of transceiver components (in this case the downlink) and 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 complementary metal oxide semiconductor (CMOS) integrated circuit. This contains the necessary control and driver electronics for the transmitter elements. A similar approach is taken at the receiver: an array of detectors is flip-chip bonded to a custom CMOS receiver integrated circuit, which contains an array of receivers that amplifies incoming signals and recovers the required data.

Particular features of this approach make it potentially amenable to large-scale integration:

- Scalability: Flip-chip bonding of drivers and receivers directly under the detector arrays within the area required ensures that the basic driver and receiver units are scalable to large numbers of detectors. This integration can take place on a wafer scale.
- Functionality: The CMOS process used for the electronics allows complex digital control circuitry to be integrated with the analog receiver and transmitter electronics.
- Cost: Electronic circuits use a low-cost CMOS process, and optoelectronic devices can be produced and tested on a wafer scale.

Work has been focused on developing a system with seven transmitting and seven receiving channels, operating at a wavelength of 980 nm. Transmitters and receivers are designed to transmit 155 Mb/s data that is Manchester line coded before transmission.

The number of channels is chosen to be the minimum to demonstrate tracking functions, and a more practical system would have a much larger number of channels. This operating wavelength is chosen as substrate emitting devices are available and detectors are relatively straightforward to fabricate. Later demonstrations will focus on operation at wavelengths longer than 1400 nm in order to meet eye safety regulations.

The following sections detail aspects of the systems and component design.

OPTOELECTRONIC DEVICE DESIGN

The system requires two-dimensional arrays of surface emitters that emit through the semiconductor substrate, thus making devices suitable for flip-chip bonding. Both vertical cavity surface emitting lasers (VCSELs) [5] and resonant cavity LEDs (RCLEDs) [6] are appropriate for this application, and both are well-developed technologies at 980 nm. For the optical wireless application RCLEDs offer a simpler structure

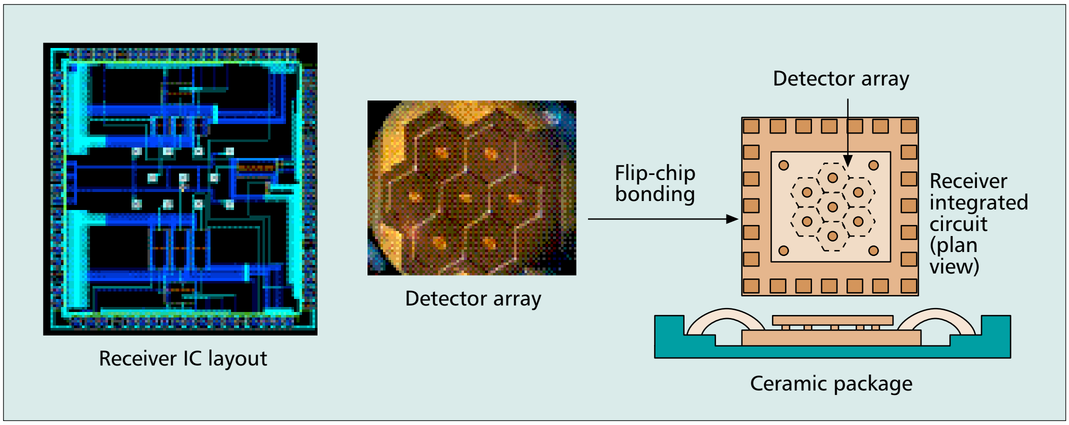

Figure 4. *The flip-chip integration path for transceiver components.*

The silicon circuitry must perform two sets of functions. Each emitter must have a drive circuit, and each detector a receiver. This type of function is "local" to each channel, but there are also "global" system functions that involve control, data recovery, and arbitration.

than a VCSEL with sufficient modulation bandwidth, and these are used for the initial 980 nm demonstrator. Device arrays that emit up to 1.5 mW with good modulation performance at 310 Mb/s have been developed under this program, and while not eye-safe, these devices provide a usable component that allows testing of the integration processes. VCSELs or RCLEDs operating at wavelengths beyond 1400 nm are likely to become the preferred source for this application, but these are not yet readily available.

The system requires a close packed array of hexagonal detectors that are illuminated through their substrate, and low-capacitance InGaAs PIN photodiodes are grown for this application. The bandwidth of the detector is determined by the carrier transit time across the depletion width and the capacitance of the structure, and it is possible to balance these effects for a particular photodiode. In the case of these epitaxially grown structures the limit in practice is the width of the intrinsic region that can be reliably grown. The structures used here have measured capacitances on the order of 24 pF/mm^2 and responsivities of ~0.4 A/W at 980 nm, and will also operate at 1500 nm when sources become available. In the longer term significantly lower capacitance detectors should be possible if these growth constraints are removed.

ELECTRONIC DESIGN

The silicon circuitry must perform two sets of functions. Each emitter must have a drive circuit, and each detector a receiver. This type of function is "local" to each channel, but there are also "global" system functions that involve control, data recovery, and arbitration [7]. Our approach is to use a CMOS silicon process to fabricate these circuits as this allows high-level digital control functions to be integrated with the receiver and other analog circuitry at low cost.

A number of different receiver and transmitter components have been fabricated and are reported in [8, 9]. The receivers use trans-impedance amplifiers that are optimized for high input capacitance. (Measured bandwidths of 160 MHz have been demonstrated for ~10 pF of input capacitance. When receiving data these show good eye diagrams at 200 Mb/s with 1 µA of received average photocurrent.) Novel transmitter designs that incorporate current peaking and current extraction have been developed. These deliver up to ~100 mA of drive current, and measurements indicate that the integrated transmitters should be able to modulate RCLEDs at the required 155 Mb/s Manchester coded data rate.

OPTICAL SYSTEMS DESIGN AND SYSTEM INTEGRATION

Figure 4 shows the layout of the integrated receiver silicon and detector array, and how these will be flip-chip bonded and packaged. The resulting packaged receiver is then integrated into the required lens system, and similar for the transmitter. Figure 5 shows the optical system in its optomechanics.

The optical system can be thought of as performing a position-angle mapping at the transmitter and the inverse mapping at the receiver. Transmitter optical elements are relatively straightforward to design, and the system is largely constrained by the receiver. Theoretical considerations allow an estimate of the maximum optical gain that can be obtained at the receiver. In practice designing systems that approach these limits is challenging, and in our case further constrained by the use of commercially available lenses in the first demonstration system.

STATUS AND CONCLUSIONS

Optical wireless systems offer the promise of extremely high bandwidth subject only to eye safety regulations, and the increased congestion and sometimes cost of the RF spectrum makes this resource increasingly attractive. This article describes an approach to fabricating optical wireless transceivers that uses devices and components that are suitable for integration, and uses relatively well developed techniques to produce them. The tracking transmitter and receiver components currently being assembled have the potential for use in the architecture described in this article as well as in other network topologies.

All of the individual optical, electronic, and optoelectronic components have been fabricated and successfully tested, and we are in the process of undertaking the flip-chip bonding required for the integrated components described here. Promising initial results indicate that a scaled version of this demonstrator should

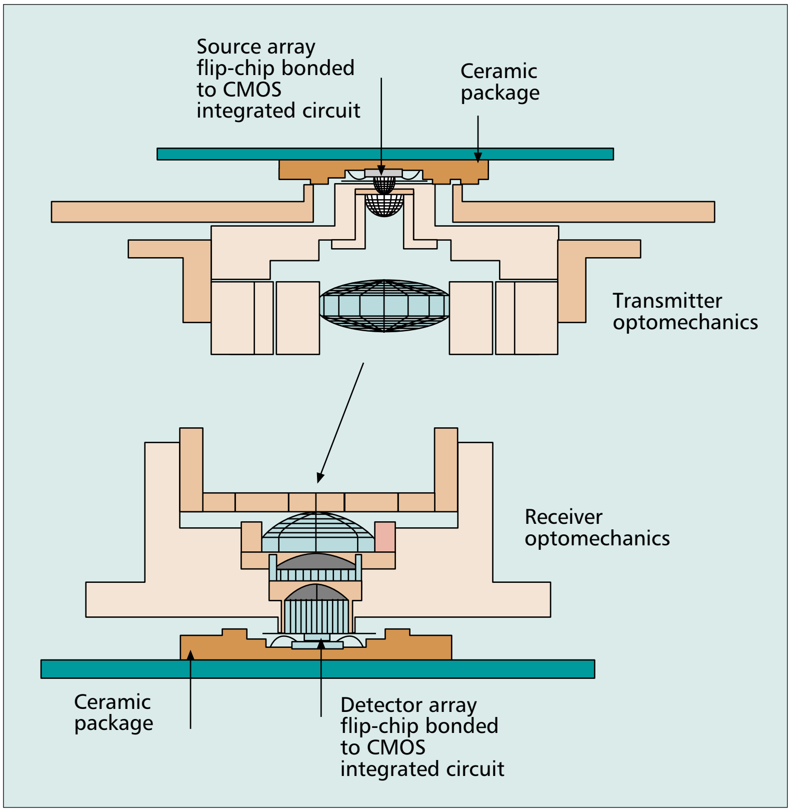

Figure 5. *Demonstration system optomechanics.*

allow high-bandwidth optical wireless channels to be used in a wide range of environments and applications.

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