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Published

2013

Journal Title

Journal of Lightwave Technology

DOI

https://doi.org/10.1109/JLT.2013.2246138

1.5 Gbit/s multi-channel visible light communications using CMOS-controlled GaN-based LEDs

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Abstract—**An on-chip multi-channel visible light communication (VLC) system is realized through a blue (450 nm) GaN-based micron-size light-emitting diode (μLED) array integrated with complementary metal-oxide-semiconductor (CMOS) electronics. When driven by a custom-made CMOS driving board with 16 independent parallel data input ports, this μLED array device is computer controllable via a standard USB interface and is capable of delivering high speed parallel data streams for VLC. A total maximum error-free data transmission rate of 1.5 Gbit/s is achieved in free space by modulating four μLED pixels simultaneously using an on-off key non-return to zero modulation scheme. Electrical and optical crosstalk of the system has also been investigated in detail and the further optimization of CMOS design to minimize the crosstalk is proposed.**

Index Terms—**Multi-channel, parallel data transmission, spatial-multiplexing, visible light communication (VLC), micro light-emitting diodes (μLEDs), complementary metal-oxide-semiconductor (CMOS).**

I. INTRODUCTION

High-performance III-Nitride light-emitting diodes (LEDs) have the capability of efficiently generating light across the visible spectrum, which enables a variety of applications such as signaling, displays and solid-state lighting [1] [2]. For general illumination, high power III-N-based white LEDs have shown superior capabilities over incandescent and fluorescent lamps in terms of efficiency and other attributes [1]. In addition to their appealing lighting properties, another promising application of LEDs is for visible light communication (VLC) [3] [4]. It is possible to achieve LED illumination and optical data transmission simultaneously, providing energy-efficient light sources with data encoded in them for dual applications. LED VLC has attracted much interest recently, as it is believed that this technology could provide new data transmission capacity and be widely used in future wireless systems [5]. Furthermore, by exploiting the low-loss transmission window in polymer optical fiber (POF), LEDs emitting at blue and green regime could be used for POF-based optical communication as well. Recently, 1.07-Gb/s data transmissions over a 50-m SI-POF fiber has been successfully demonstrated using a specifically designed cyan LED device [6].

However, the modulation bandwidth of conventional commercial LEDs for lighting is generally low [7] [8] and to improve the performance of these low-bandwidth transmitters for VLC, various advanced modulation and demodulation schemes, such as the orthogonal frequency division multiplexing (OFDM) modulation technique, have been proposed and developed [9] [10]. Recently, we have demonstrated that GaN-based micron-size LEDs (μLEDs) have very wide modulation bandwidths [11], which makes them ideal high-speed data sources for optical data transmission [12].

To significantly increase VLC data transmission capacity, optical wireless multiple-input multiple-output (MIMO) systems have been developed [13]-[15]. The idea of optical wireless MIMO is to modulate a number of individual light sources simultaneously for data transmission, thus realizing high-speed parallel data streams for communication. An optical MIMO system could greatly enhance the system data transmission capacity compared with a single-input/single-output system, and thus has drawn much attention recently [16]. Most of the current optical MIMO systems are based on separate LED devices.

In an earlier paper, we have reported a complementary metal-oxide-semiconductor (CMOS)-controlled μLED array, allowing individual μLED pixels from the array to be readily controlled via a simple computer interface while retaining high modulation bandwidth (up to 185 MHz) [11]. Although the CMOS chip was not designed for the purpose VLC, 512 Mbit/s data transmission based on a single pixel from such a CMOS-controlled μLED array was demonstrated. In this work, we further investigate the modulation capability of CMOS-controlled multiple μLED pixels in parallel with independent data input per pixel and demonstrate, for the first time, an easily-controlled on-chip optical multi-transmitter VLC system based on a single μLED array device. By simultaneously modulating four 450 nm-emitting 99×99 μm^2 CMOS-controlled μLED pixels using on-off key (OOK) modulation scheme, non-return-to zero (NRZ) data streams at a bit rate of up to 375 Mbit/s per pixel has been achieved. Error free operation, defined as a Bit Error Ratio (BER) of less than 1×10^{-10}, is confirmed for all of the data channels, giving a total bit rate of 1.5 Gbit/s. This establishes a baseline demonstration of the interest parallelism of these μLED arrays and opens the way to further multi-channel scaling.

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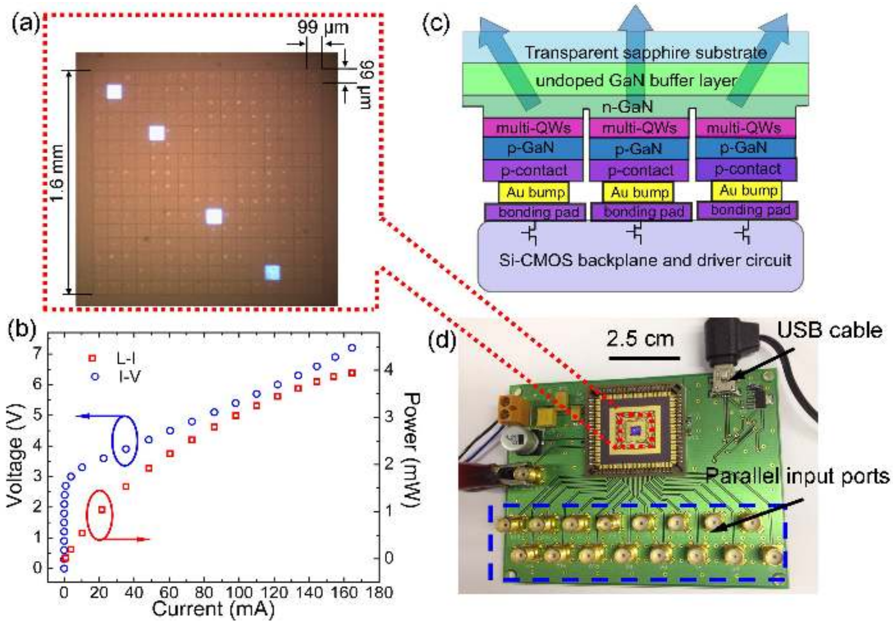

Fig.1. (a) Microscope image of the whole CMOS-bonded µLED array with four individual pixels in operation. (b) Characteristic I-V and L-I curves of a standard CMOS-bonded µLED pixel. (c) Illustration of flip-chip bonding between µLED matrix array and CMOS driver array using Au bumps. (d) Image of the CMOS driving board with parallel data input ports highlighted by the blue dash.

II. DEVICE STRUCTURE AND FABRICATION

The 450 nm blue µLED array device reported here was fabricated from a commercially-available multi-quantum-well (MQW) LED wafer grown on a c-plane patterned sapphire substrate. It has similar epilayer structure and processing steps to those reported previously [11] [17]. The array device consists of 16×16 individually addressable uniform-sized square LED pixels on a 100-µm center-to-center pitch and each pixel is 99×99 μm^2 in area with a 1 µm separation [Fig.1 (a)]. Every pixel of the µLED array shares a common n-contact, and can be individually addressed through its independent p-contact. Due to the flip-chip format of the device, light is extracted through the transparent and polished sapphire substrate. Fig. 1 (b) shows the current-voltage (I-V) and optical power versus driving current (L-I) curves of a typical µLED pixel driven by CMOS under direct current (DC) at room temperature.

The CMOS driver chip used here, which is a 16×16 array of individually-controllable 100×100 μm^2 driver cells on a center-to-center pitch of 100 µm, was designed to match the layout of the 16×16 µLED array. Each CMOS driver cell contains a 60×60 μm^2 bonding pad and dedicated driver circuitry. To achieve electrical connection between the µLED array and CMOS electronics, each µLED pixel is flip-chip bonded onto a corresponding CMOS cell [Fig.1 (c)]. Each CMOS driver cell functions as a high-speed digital switch to control the output of the µLED pixel according to the state of input trigger signal. The CMOS driver will be switched on when the input trigger signal reaches the logic threshold of the CMOS electronics and a bias is then applied to the corresponding µLED pixel. The optical output of the µLED is determined by the applied bias and its I-V and L-I characteristics. In this way, each µLED pixel can be OOK modulated according to the state of input signal. In addition, a CMOS driving board was developed to make each CMOS/µLED unit easily controllable via a simple computer interface. There are sixteen independent input ports on the CMOS driving board, allowing each column in the µLED array to be modulated simultaneously but with independent data patterns. Fig.1 (d) shows the layout of the CMOS driving board and corresponding data input ports. More details about the design and function of the CMOS electronics can be found in our previous publications [11] [18].

III. EXPERIMENTAL RESULTS AND DISCUSSION

The modulated light beams from the µLED pixels were focused onto a high speed alternating-current (AC)-coupled silicon photo-detector using a 0.68 numerical aperture lens. By adjusting the positions of the lens and photo-detector, µLED pixels were separately aligned with the detector for light output measurement. In the current system, although only one µLED pixel is aligned to the photo-detector at one time, the detector could also receive optical signals from other active µLED pixels. This causes the optical crosstalk and this can be measured using the method described next. With one µLED pixel turned on, its emission beam was aligned to the photo-detector and its optical output power was measured. The

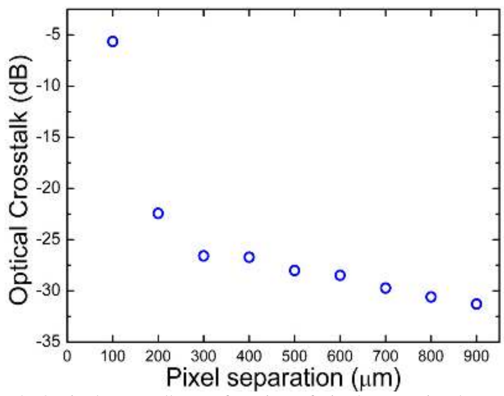

Fig. 2. Optical crosstalk as a function of pixel separation between the aligned pixel and other non-aligned pixels.

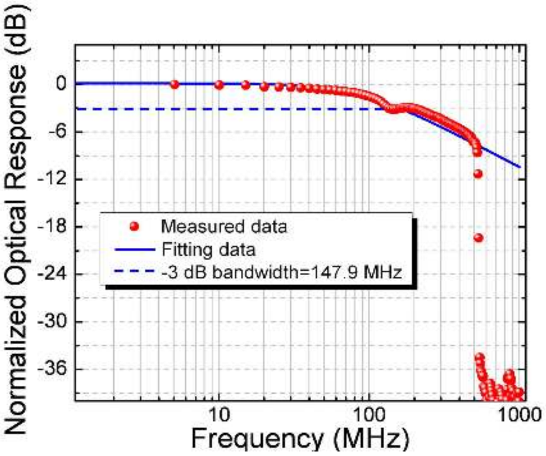

Fig. 3. Frequency response curve of a typical CMOS/μLED pixel, with a forward bias of 6.5 V. The optical -3 dB bandwidth is 147.9 MHz.

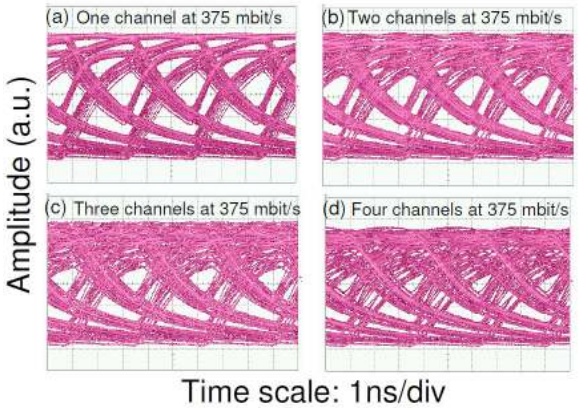

Fig. 4. Eye diagrams of a typical CMOS/μLED pixel when it is modulated at 375 Mbit/s in (a) one channel, (b) two channels, (c) three channels and (d) four channels. The applied bias is 6.5 V.

pixel was then turned off and without changing the alignment of the photo-detector, adjacent non-aligned pixels were switched on individually and the optical power coupled to the photo-detector was recorded. The optical power from the aligned μLED pixel was then compared with the optical power received from the other non-aligned μLED pixels, and thus, the optical crosstalk could be quantified. Fig.2. shows the optical crosstalk (in dB) as a function of the center-to-center pixel separation between aligned μLED pixel and other non-aligned μLED pixels. As shown in Fig.2, when using the μLED pixels next to each other (pixel separation 100 μm) for parallel data transmission, the optical crosstalk is approximately -6 dB, which could influence the system performance. However, when the pixel separation reaches 200 μm and above, the optical crosstalk is less than -25 dB. Therefore, in our present system we can effectively neglect optical crosstalk by selecting the active μLED pixels with a minimum spatial distance of 200μm. The optics used in the current system was chosen for characterizing the performance of the CMOS/μLED pixels, and it is noted that the optical crosstalk will vary depending on how the light is collected at the detector. By using specifically designed optics, such as integrated micro-lenses [19], it should be possible to modify the beam profile from the μLEDs and thus reduce the optical crosstalk between two adjacent pixels in due course.

The frequency response of a single CMOS/μLED pixel was measured by the silicon photo-detector and a network analyzer. The output from the network analyzer was combined with a DC offset to reach the logic threshold of the CMOS electronics and then sent to the CMOS driving board through the parallel data input to modulate the corresponding μLED pixel. The optical response of the μLED pixel was then detected by the fast photo-detector and the electrical output of the detector was fed back to the network analyzer. Fig.3 shows the frequency response of a representative μLED pixel at an applied bias of 6.5 V. From this measurement, the optical -3 dB bandwidth of the μLED pixel CMOS combination was found to be approximately 150 MHz. As shown in Fig.3, there is a sudden drop in the frequency response at around 500 MHz, which is due to the digital characteristic of the CMOS circuit. The present CMOS drivers are not able to be switched on and off in response to very high-frequency signals, therefore, they are effectively in the off state above 550 MHz. To test the bandwidth uniformity of the μLED array, fourteen pixels along the diagonal of the array were sampled and the optical -3 dB modulation bandwidth was measured to be 145 MHz ±10 MHz for all of the pixels. A detailed investigation of the frequency response of other CMOS-bonded μLED devices and the corresponding method to fit the frequency response curve has been reported earlier [11]. The bandwidth of CMOS-controlled μLED is lower than the 'bare' μLED (unbonded device) driven directly with a high-speed probe [12], which is largely due to the frequency response of the CMOS driver itself and the high modulation depth of the CMOS driver output. However, it is expected that an optimized design of the CMOS driver would enable much higher bandwidth.

Data transmission was carried out using four individual μLED pixels. The reason that four μLED pixels was chosen to carry out the data transmission measurement is that we believe using four μLED pixels is enough to prove the concept of parallel data transmission using this CMOS/μLED device and allow issues such as crosstalk to be examined. In this data transmission measurement, four separate data sources with a common clock frequency were used. The four data signals were all OOK-NRZ pseudo-random binary sequence with a standard pattern length of 2^7-1 bits and a peak-to-peak voltage swing of 0 to 2V. The data signals reaching the logic threshold of the CMOS electronics were sent to the CMOS chip through four parallel inputs to trigger four independently-addressable CMOS drivers directly, and in this way, the four corresponding μLED pixels could be modulated simultaneously with different data patterns. The spatial separation between the modulated μLED pixels was kept above 600 μm and in this case, the optical crosstalk in this multi-channel system is less than -25dB (Fig.2), thus negligible.

A typical eye diagram from an individual pixel (aligned to the detector) modulated at 375 Mbit/s and with a 6.5 V applied bias is shown in Fig. 4 (a). The eye diagrams of this aligned pixel when two, three and four μLED pixels are modulated simultaneously at 375 Mbit/s with a 6.5 V applied bias are shown in Fig. 4 (b), (c) and (d), respectively. It can be noted that the eye quality degrades with increasing number of modulated pixels (channels), indicating the presence of electrical crosstalk, as the optical crosstalk is negligible in this configuration.

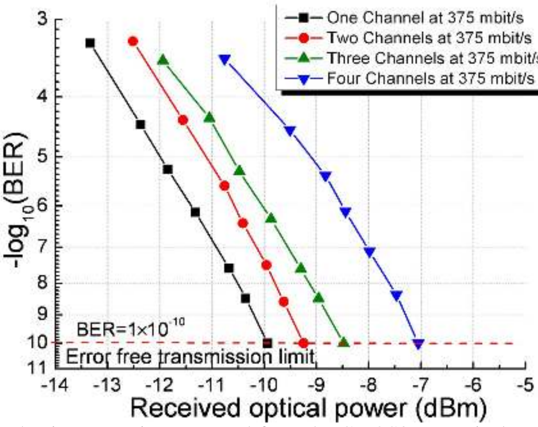

Fig. 5. Bit-error ratios measured from the CMOS/µLED pixel at 375 Mbit/s, with one channel, two channels, three channels and four channels in operation, as a function of received optical power at the detector.

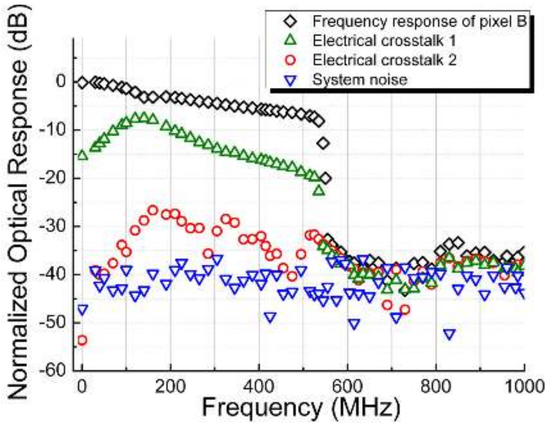

Fig. 6. Frequency response curves of a typical CMOS/µLED pixel under different operating conditions. The blue data points represent the system noise. The red data points represent the electrical crosstalk caused by mutual inductance/capacitance. The green data points represent the electrical crosstalk caused by "Ground bounce" effect. The black data points represent the frequency response of the µLED pixel under 6.5 V applied bias voltage.

The BERs were measured as a function of received optical power for the cases of one, two, three and four active µLED pixels. For our system, error-free transmission, defined as a BER value lower than 1×10^{-10}, could be achieved for a bit rate of up to 375 Mbit/s per pixel with four pixels modulated simultaneously, giving a total bit rate of 1.5 Gbit/s from the whole device. Fig.5 shows the BERs versus received power under different modulation conditions. To achieve the same BERs at the same bit rates, higher received optical power is required as we increase the number of modulated pixels as anticipated from the eye diagrams. Compared to the case of one modulated pixel under error-free transmission, there was a power penalty of 0.69 dBm, 1.46 dBm and 2.88 dBm for two, three and four pixels being modulated respectively. This power penalty is largely attributed to electrical crosstalk in the CMOS drivers, which will be discussed in detail in the following. By aligning the detector to other µLED pixels, our measurement showed that the BER characteristics of other pixels were very similar to the investigated µLED pixel, as would be expected.

Inter-channel crosstalk is an important issue in MIMO systems as the unwanted interference between channels can degrade the overall system performance. As such, the magnitude and origin of the electrical crosstalk on our CMOS/µLED device was investigated. It was found that the isolation resistance between two pixels on a 'bare' µLED array (without being integrated with a CMOS chip) is very high, suggesting that the electrical crosstalk comes from the integration with the CMOS electronics and the driver board. To investigate the electrical crosstalk happening/rising during multi-channel operation, two representative pixels with a spatial separation of more than 600 µm from the CMOS/µLED array, denoted hereafter as "pixel A" and "pixel B", were chosen. Fig.6 shows the frequency response of the CMOS/µLED system under a number of different drive conditions. For all these measurement, pixel B was always aligned to the AC-coupled photo-detector. The blue data points (inverted triangles) shown in Fig.6 represent the system noise floor, which was measured by only turning on pixel B in DC and aligning its output to the AC-coupled photo-detector. The black data points (diamonds), which are at around 40 dB above the system noise floor, show the normalized frequency response of pixel B when it is modulated alone by sending signals from the network analyzer to data input port B. It is very similar to the frequency response curve shown in Fig.3, as would be expected. The red data points (circles) shown in Fig.6 are the frequency response of pixel B when operated in DC mode alone, whilst the network analyzer is connected to data input port A but pixel A is not turned on. There is a slight increase in the system response above the noise floor possibly caused by the mutual capacitance/inductance between driver electronics, which could give rise to signal feedthrough from one channel to another [20]. However, this level of crosstalk (-25dB) is not large enough to explain the power penalties shown in Fig.5. The green data points triangles) shown in Fig.6 are the frequency response of pixel B when it is in DC operation and pixel A is turned on and modulated. In principle, if there is no electrical crosstalk between the two pixels, the frequency response of pixel B should be always at the same scale as the system noise floor (blue data points) no matter the state of pixel A, since the AC-coupled photo-detector will not respond to the DC output from pixel B. The observed rise of the frequency response from the AC-coupled detector indicates that pixel B has been modulated by the electrical crosstalk brought by modulating pixel A. As shown by the green data points, this electrical crosstalk causes pixel B to be modulated to a magnitude (-10 dB) which could influence the data transmission process. Analysis indicates that this electrical crosstalk is caused by the power routing resistance between CMOS drivers. When one pixel is in operation, turning on another pixel will induce a small global voltage drop due to the power routing resistance, leading to a lower bias to the first pixel. Turning off the second pixel, the first pixel will recover to its initial bias and output power. Thus, when the second pixel is OOK modulated, the absolute bias applied to the first pixel will fluctuate and this gives rise to the electrical crosstalk. This effect is known in the CMOS industry as the "Ground Bounce effect" [20]. To minimize the electrical crosstalk in high data rate CMOS driver circuits, it is therefore essential to reduce the power routing resistance, e.g. by using thicker and wider metal power tracks in the CMOS chip (the metal track resistance of the current CMOS driver is estimated to be 0.43 Ohm).

IV. CONCLUSION

We have reported the characterization of a single on-chip multi-transmitter VLC demonstrator system based on four pixels in a 16×16 CMOS-controlled GaN-based μLED array. When four pixels are modulated simultaneously, error-free data transmission of up to 375 Mbit/s per pixel can be achieved, giving an aggregate parallel data transmission rate of 1.5 Gbit/s, with a power penalty of 2.88 dB compared to a single-channel operation. Analysis suggests that on-chip crosstalk, brought by modulating multi-pixels simultaneously, induces the reduction of signal quality in the multiple-channel system, such that more optical power (power penalty) is required to be received by the detector to compensate. We have identified the origins of electrical crosstalk, in particular the "ground bounce" effect caused by a relatively high power routing resistance, and proposed ways to reduce these issues in future CMOS driver designs. By addressing the origin of electrical crosstalk, it should be possible to increase the total data transmission rate by increasing the bit rate per pixel, increasing the number or channels, or both. Assuming that electrical crosstalk greatly reduced/eliminated and 375 Mbit/s error-free data transmission per channel with 16 simultaneous data inputs, an overall data rate of 6 Gbit/s could in principle be achieved by the whole μLED array. Furthermore, the parallel data transmission results reported here were achieved by using OOK modulation, and we believe the data rates could be further increased by using complex modulation and encoding scheme, such as OFDM and multi-level pulse amplitude modulation. The results reported here highlight the potential of such a CMOS/μLED device as a easily-controlled and highly-integrated multi-channel optical data transmitter, allowing (in this case) up to 16 channels, each capable of transmitting data at hundreds of Mbit/s, for parallel data transmission.

ACKNOWLEDGEMENT

This work was supported by UK EPSRC under 'HYPIX' project. The authors acknowledge Dr Bruce Rae for designing the CMOS chip.

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BIOGRAPHY

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In 2007 he joined the Institute of Photonics as a Ph.D. student where the focus of his Ph.D. was on the application of AlInGaN-based micro-LEDs for time-resolved fluorescence lifetimemeasurements and optical communications. He currently works as a Research Associate in the Institute of Photonics where his research primarily focuses on the application of AlInGaN-based micro-LEDs and hybrid organic/inorganic LEDs for optical communications.

David Massoubre received the Ph D. degree in photonic from the University of Paris-Sud, Paris, France, in 2006. His thesis work covered saturable absorption in semiconductor material and all-optical regeneration of long-haul optical transmission.

He has since worked as a research fellow for the Institute of Photonics at the University of Strathclyde, Glasgow, U.K. His current research is on the design, fabrication and use of GaN-based micro-LEDs for applications including visible light communication, bio-sensing and hybrid organic-inorganic devices.

Andrew Cogman, biography not available.

Erdan Gu received the Ph.D. degree on thin film physics from Aberdeen University, U.K. in 1992.

He has been working in the Institute of Photonics (IOP), University of Strathclyde, Glasgow since July 2002. He is an Associate Director and a Research Team Leader at the Institute. In 1992, he was appointed as a research fellow in Cavendish Laboratory, Cambridge University, U.K. In Cavendish Laboratory, he worked on epitaxial magnetic film growth, micro-magnetic structures and spintronic devices. In 1997, he joined the thin film group, Oxford Instruments plc, U.K., as a Senior Research Scientist working on superconducting device research and development. In the Institute of Photonics, he is working and playing a leading role in a range of research projects on micro/nano photonic materials and devices, micro/nano optoelectronics, diamond optics and photonics, hybrid organic/inorganic optoelectronic devices and micro-systems. He is the author of over 200 journal papers.

Robert Henderson is a reader at the School of Engineering in the Institute for Microelectronics and Nanosystems, University of Edinburgh. He obtained his PhD in 1990 from the University of Glasgow.

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Anthony E. Kelly, biography not available.

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