Micro-LED waveguide for fluorescence applications

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Abstract – **A micro-LED-coupled multimode slab waveguide is reported for fluorescence sensing. The device consists of a 1-dimensional micro-LED array coupled to a sub-mm polymeric slab for evanescent excitation of fluorescent analytes present on the surface. Proof-principle detection of semiconductor nanocrystals down to 0.2 pM/cm^2 is demonstrated.**

Keywords— fluorescence, quantum dots, GaN, LED

I. Introduction

Precision medicine at the point of care (POC) promises earlier diagnosis and more efficient treatment of patients. However, for widespread success it critically needs novel, cost effective, miniature diagnostic technologies that are simple to use [1]. One technological challenge is to translate the multiplexed biochemistry sensing capability of centralized laboratories, which enables an assessment of the biomarker landscape of a patient, into a small form factor, low weight and low power instrumentation that can be utilised both within and outwith clinical settings. Herein we report the concept of a slab waveguide fluorescence sensor using GaN micro-sized LEDs (µLEDs) that could contribute to address this challenge.

Fluorescence is a well-established biochemical sensing technique used for diagnostics [2]. The approach is based on biomolecular processes whereby analytes are captured on a surface and coupled to fluorescent tags. The latter are then excited using a laser or LEDs and the resulting fluorescence is measured to assess the presence and amount of the analytes. The issue of autofluorescence in biological samples (a source of noise that can severely reduce the limit of detection) can be mitigated by using evanescent waves to excite the labels in what is called total internal reflection fluorescence (TIRF) [3]. This can be realized with a waveguide structure [4]. As light undergoes total internal reflection in the waveguide, an evanescent wave is generated and probes only the region very near the surface of the waveguide (within a few tens of nm). The potential for miniaturisation of the concept for POC applications has been shown, for example in [5] where a laser diode was coupled in a glass plate that acted as the waveguide.

Here we utilise an array of µLEDs as the excitation source and polydimethylsiloxane (PDMS) as the waveguide material. PDMS makes a suitable cost-effective waveguide due to its high transparency in the visible spectrum. It is also often used for microfluidics and is therefore an attractive platform to directly incorporate micro-wells and channels into the waveguide structure. As opposed to previously reported POC TIRF platforms, the excitation sources are here directly butt-coupled to the PDMS waveguide as shown in Fig. 1(a), i.e. it does not require optics. The small size of LEDs enables efficient coupling to thin waveguides, with a maximum coupling efficiency of 92% for a 1 mm-thick waveguide. The butt-coupled/1D array geometry also permits near filling of the waveguide which is important for TIRF. In the following we give details about the device and describe the experiments carried out for proof-of-principle of this platform.

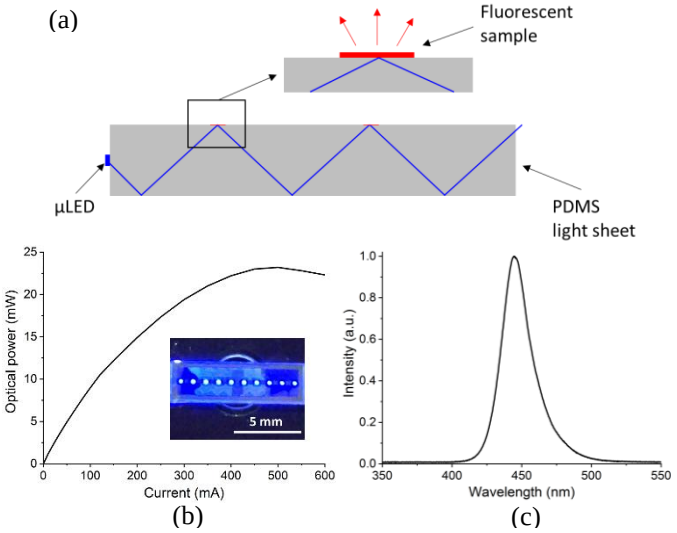


Fig. 1: A schematic of the sensor design (a) the current-optical power characteristics of the µLEDs, inset shows the 10 individual pixels with the device switched on (b) the wavelength spectrum of the µLEDs (c).

II. Materials and Methods

The µLED consisting of 10 pixels in parallel, each 100 x 100 µm^2 and separated by 720 µm, is utilised as depicted in Fig. 1. The µLED array has a turn-on voltage of 2.6 V. For the fluorescence experiments it is ran at a current of 120 mA producing a total output optical power of 10 mW for a peak wavelength of 444 nm.

The PDMS membrane (40 x 20 x 1 mm^3 in dimensions) was edge-coupled to the µLED and an imaging system consisting of an achromatic lens, filter and CCD were placed above the membrane, to filter scattered µLED light and image the fluorescence from the waveguide surface. The lens (focal length, 40 mm) was set 170 mm above the membrane, the long pass filter (cut-on wavelength, 500 nm) and the CCD (Thorlabs, DCU224M) were placed a further 40 mm away. The sensor exposure time was set to 100 ms with a gain of 1.

For the fluorescence proof of principle experiment, we have used colloidal quantum dots (CQDs). The CQDs were red emitting (630 nm) CdSSe/ZnS nanocrystals with a mean diameter of 6 nm. Multiple concentrations were obtained by diluting the CQDs in toluene. 2 µL of each concentration ranging from 1 mg/ml to 1 µg/ml were drop-coated onto a PDMS waveguide slab (40 x 20 x 1 mm^3 in dimensions). The toluene was then allowed to evaporate in air with the remaining CQD molar concentrations ranging from 100 pM/cm^2 to 0.2 pM/cm^2.

III. Results and Discussion

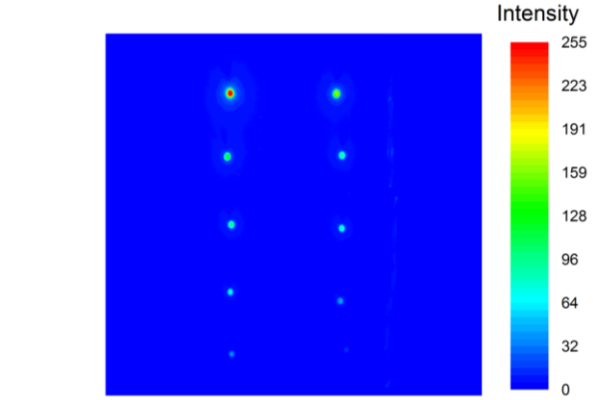
The pixel data from the CCD sensor was analysed to produce an intensity map shown in Fig. 2a. The fluorescent samples have a high pixel intensity compared to other regions of the waveguide surface. The pixel data is used to produce a plot of intensity versus concentration of the fluorescent sample which is shown in Fig. 2b. At the highest concentration of CQDs, 100 pM/cm^2, the sensor reaches its highest value of 253 counts, close to the sensor saturation level of 255. As expected, a decrease in CQD concentration results in a decrease in peak intensity with a minimum concentration of 0.2 pM/cm^2 being observed to have a peak intensity of 17. Below 1 pM/cm^2 the intensity can be approximated as varying linearly with the CQD concentration with a slope of 37 (see Fig. 2 inset). Above a concentration of 2 pM/cm^2 the response saturates and up to 100 pM/cm^2 the intensity trend is approximately linear with a slope of 2. The intensity data can be extrapolated to obtain a limit of detection. The average pixel dark value is 2 with a standard deviation of 1, therefore intensity values of 3 or less are associated to CCD noise. Extrapolating the plotted data suggests that a minimum limit of detection for the device would be 0.06 pM/cm^2.

The fluorescence measurement utilises a large focal length, producing an estimated collection efficiency of 2.5%. This efficiency could be increased by reducing the focal length of the lens/camera or by increasing the diameter of the collection lens, this would allow for an even lower limit of detection for the fluorescent samples. A lower limit of detection is also achievable by increasing the input optical power to the waveguide. An increase in the input light will increase the level of evanescent wave excitation, causing lower concentrations of CQDs to fluoresce.

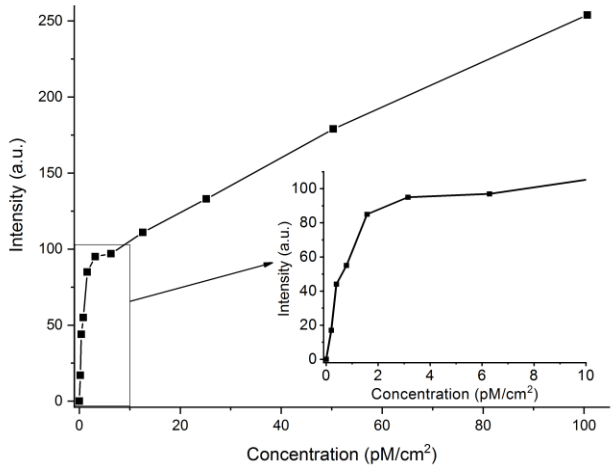
This proof of concept device uses a CCD sensor to obtain images of fluorescence at low CQD concentrations. The use of a CMOS sensor will greatly reduce the cost of the device and by implementing the changes discussed a reasonable limit of detection could be maintained.

IV. Conclusions

A proof of concept sensing device has been described. The device utilizes the evanescent wave excitation of fluorescent colloidal quantum dots on a PDMS waveguide with a µLED light source. The fluorescence is identified by a CCD sensor above the device. The pixel data is then utilized to determine the sensitivity and the limit of detection of the device. This approach produces a low limit of detection of 0.2 pM/cm^2.



(a)



(b)

Fig. 2: An intensity map of the pixel data showing each concentration spot (a) plot of pixel intensity versus CQD concentration, inset shows the trend in the lower concentration region (b).

Acknowledgment

We are grateful to the EPSRC, Fraunhofer UK Research Ltd. and the Centre for Doctoral Training in Medical Devices and Health Technologies. This work was supported by EPSRC grant EP/L015595/1. Supporting data is available: http://dx.doi.org/10.15129/e6d04c87-6d09-453a-bb90-c81583c41c4d

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