Variable-Focus Microlenses as a Potential Technology for Endoscopy

P. J. Smith, E. M. McCabe, C. M. Taylor, D. R. Selviah[†], S. E. Day[†] and L. G. Commander[†]

Department of Physics, Trinity College Dublin, Dublin 2, Ireland

[†]Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE

ABSTRACT

Using a new device which contains an array of microlenses whose focal lengths can be electrically varied, we have been able to control the input from one microlens to a single mode fibre using an applied voltage. For such a microlens array many closely-spaced focal spots can be generated in parallel, and electrically switched to address, potentially, an array of receiver fibres. We show how the particular switching characteristics of the device, whereby the lenses switch from diverging to converging, serves in turn to disperse light and to focus it into the fibre.

Keywords: Microlenses, Endoscopy, Direct View Microscopy

1. INTRODUCTION

The recent development of variable-focal-length microlens arrays[1,2] offers an interesting new method of switching on and off an array of optical probes with high light throughput, high extinction, and no moving parts. We have investigated the use of such an array of microlenses to address single mode optical fibres, potentially for endoscope and similar applications.

We have previously considered direct view (i.e. multi-aperture confocal) microscopes[3] in some detail. The combination of a microlens array and a coherent bundle of optical fibres is suggested as a way of creating a high-throughput switchable aperture array for a future multiple aperture instrument.

2. VARIABLE-FOCUS MICROLENSES

The variable-focus microlens element used is a combination of photoresist lenses and a liquid crystal cell. The lenses are made by photolithography, with a melting step to produce the lens shape. They are made on a glass slide which forms one side of a uniformly-spaced cell, with the lenses on an inside face. The inside glass faces are coated with an electrically conductive film, and the cell is filled with nematic liquid crystal. Thus, lensing occurs at the curved photoresist/liquid crystal interface.

A voltage applied across the cell electrically switches the crystal; this effectively varies its refractive index for light polarised in parallel with the crystal alignment. Hence, the lensing effect of the lens/crystal interface is altered, in this case varying the lens' focal length from negative (diverging) at 0V, with a switch to positive at around 2V, and a smoothly varying range of positive focal lengths for voltages above 2V. The positive focal lengths cover a range of 400μm. The microlens and crystal cell arrangement is shown in figure 1. Voltage is applied to transparent electrodes deposited on the inside cell surfaces, and the effect on transmitted (polarised) light is as shown.

There are a number of microlens sizes available to us, ranging from 25μm to 400μm in diameter. The arrays are square, and typically consist of 10×10 microlenses. The 200μm lens array was used in the course of this work; the focal length of the 150μm lenses is known from previous work[4] to be -910μm at zero applied voltage, to have a switch to positive focal length at 2V, and then to vary from 200μm to 600μm for voltages up to 11V. Switching speeds are relatively slow, especially across the diverging-to-converging lens transition, which corresponds to a major crystal reorientation; this is a drawback of a thick nematic liquid crystal cell.

Correspondence:
Email: smithpj@tcd.ie
Telephone: +353 1 608 2167
Fax: +353 1 671 1759

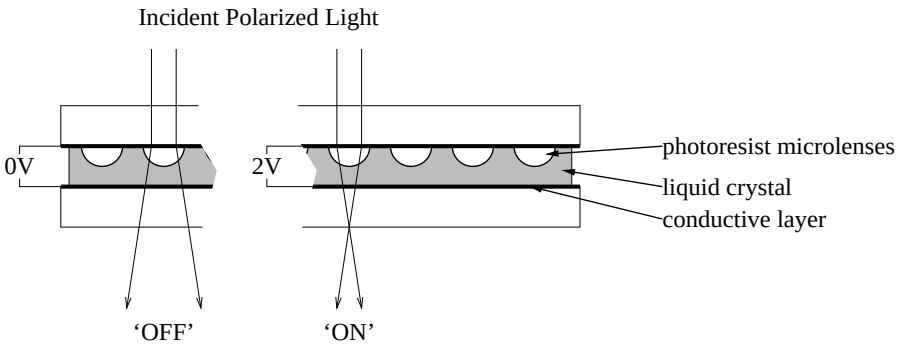

Figure 1. The structure of the microlens array/liquid crystal cell.

3. SWITCHING INTO SINGLE-MODE FIBRE

The system shown in figure 2 was used to test the microlens' ability to switch light into a single-mode fibre. A collimated, plane-polarised laser at 458nm is used to illuminate an area of the liquid crystal cell containing a microlens array. When an AC voltage above the (approximately 2V) crystal switching point is applied across the cell the microlenses converge the incident light to an array of foci. Unfortunately the focal length is such that these foci lie inside the cell thickness, and diverging light from each focus emerges from the cell.

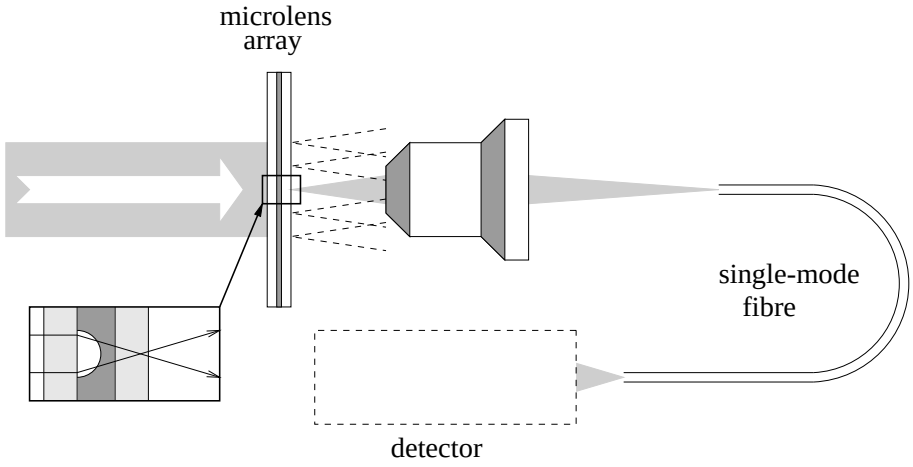

Figure 2. The microlens/fibre coupling test system.

The diverging light from the lenses is captured by a microscope objective and focussed to form an array of focal spots in a plane containing a single-mode fibre, which is positioned to collect light from one of the focal spots. As the focal length of the microlenses is varied the re-focussed light from the objective is most strongly coupled into the fibre at some particular applied voltage. More importantly, however, when no voltage is applied the lenses diverge light and there is virtually no coupling into the fibre.

There are two distinct switching mechanisms. Coarse optical switching is achieved when the microlens behaviour changes from diverging to converging, as the crystal itself reorients. At higher voltages there is a finer optical response as the crystal is affected increasingly strongly by the field. For efficient and highest-speed optical switching, it would be preferable to only couple in light for some narrow voltage band within the range of *converging* focal lengths the microlens exhibits above the major crystal switching point. This is because the crystal response is continuous, and hence faster, in this voltage region. Although the initial reorientation produces a dramatic optical effect, it is a relatively slow process.

Using a 5×, 0.12NA objective lens we were able to measure a sharply increased fibre coupling just above the main crystal switching voltage, with a further sharp drop in coupling due to focal length variation. Two quantities were initially varied to characterize the microlens behaviour: the voltage across the cell and the axial position of the collecting end of the fibre, i.e. the distance from objective lens to fibre.

The response of a photodetector at the free end of the fibre against both these variables voltage is shown in figure 3. In the figure, the distance scale is in millimetres, with *increasing* values as the fibre is moved *closer* to the objective. The vertical scale is measured in arbitrary units, based upon the output signal from a linear photodetector.

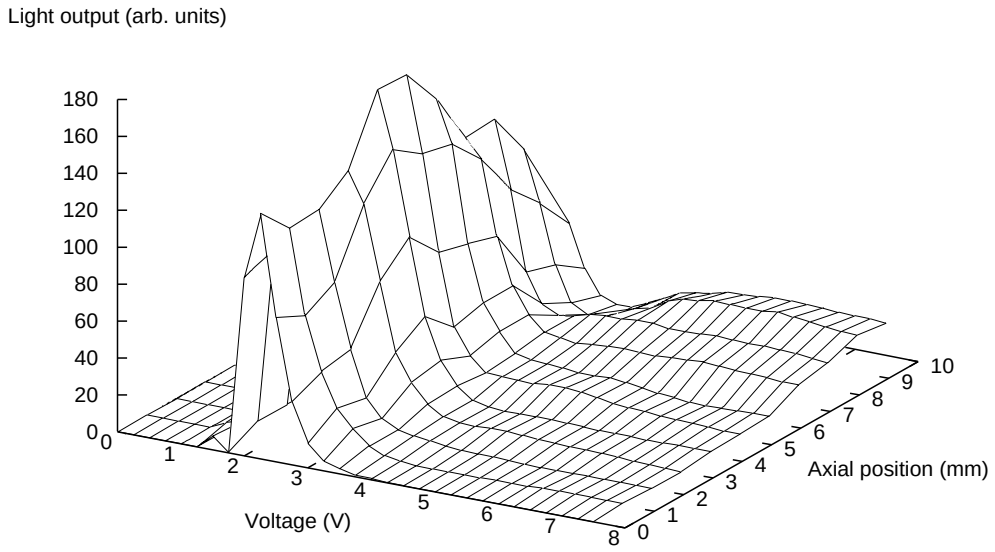

Figure 3. A plot of light output versus both the applied voltage and the axial distance of the fibre.

Clearly, there is a sharp peak in transmitted light at 2.25V, for all axial positions over the 1cm range tested. There is an optimum performance in the centre of the tested distance range. This is unexpected, as it implies that the sharp falloff with increasing voltage is not due to focal length change alone. Clearly, in this low-NA system, there is an axially-extended focal spot at 2.25V.

The shape of the light transmittance peak is seen in more detail in figure 4, which shows the area around 2-3V for the optimum axial distance. The response is sharp, with a $\sim$1V width; there was no measurable background at low voltages, and a contrast of 30:1–50:1 between the peak and the light level measured at higher applied voltages. This is approaching the 100:1 contrast ratio achieveable with another liquid crystal device we use for direct-view microscopy, a ferroelectric liquid crystal SLM.[5]

The distribution of light in the focal plane at the peak voltage was measured by scanning the fibre across the focal spots, and this is shown in figure 5. Although the sampling is not fine enough to show the shape of the light distribution in each focus, the width of a spot can be estimated at 40μm from this graph. Again, there is virtually no background light between the spots. The difference in height between the peaks is attributable solely to the coarse sampling; in reality, neighbouring focal spots are of similar peak intensity.

Photographs taken at the focal plane of the objective lens for diverging and converging microlens states are shown in figure 6. The first picture shows the distribution for a 1V applied voltage, below the crystal switching level. The

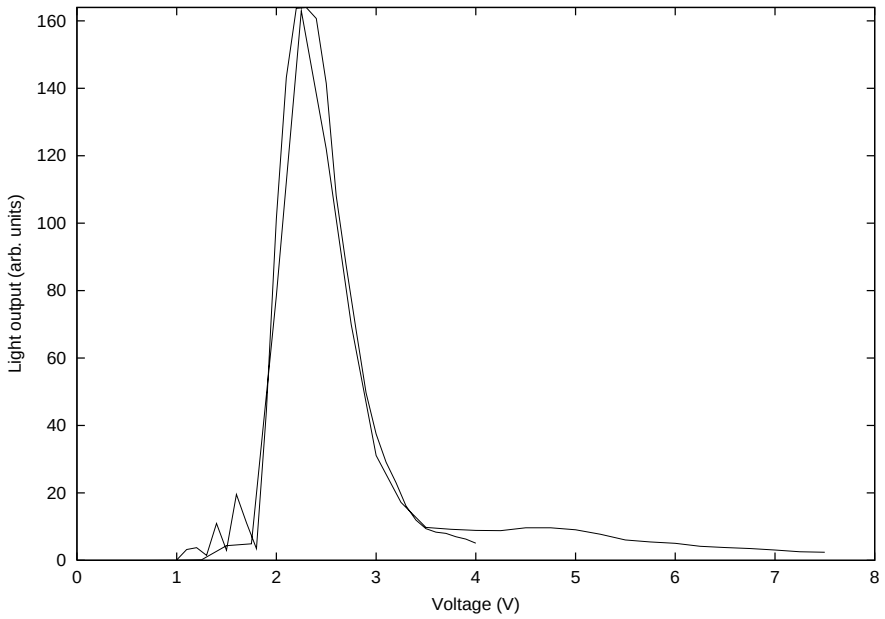

Figure 4. A higher resolution plot of light output versus applied voltage for the optimum axial distance.

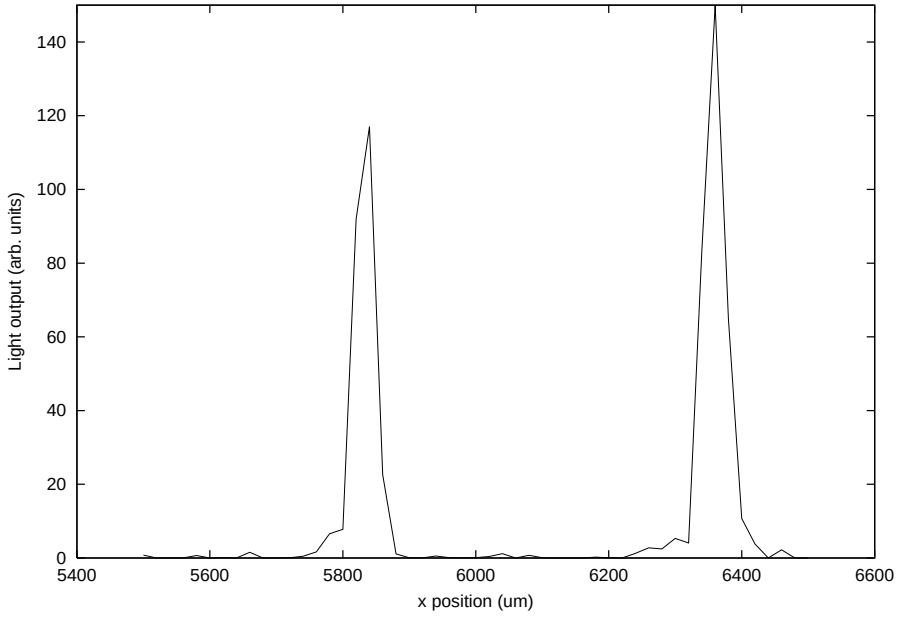

Figure 5. A transverse scan across two microlens focal spots.

second picture shows the optimally-focussed array at 2.25V, and the third the defocussed array at 3V. It is notable that an array of defocussed spots is actually visible in the 3V picture, but not in the 1V picture — illustrating that the focussed array in the 2.25V picture is bounded by a discontinuous effect at lower voltages, but a continuous effect at higher voltages.

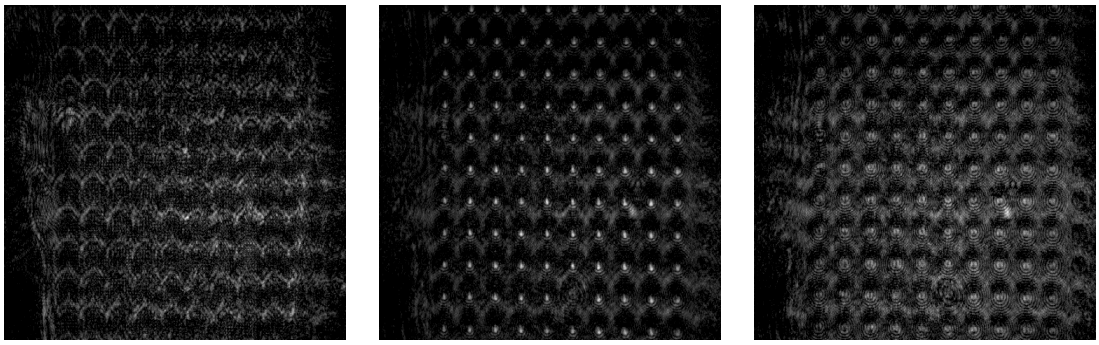

Figure 6. Photographs showing the microlens array output for diverging and converging modes. (a) taken at 1V, with lenses diverging, (b) taken at 2.25V, with lenses focussed, and (c) taken at 3V, with lenses defocussed.

4. A PROPOSED MICROLENS/IMAGE-FIBRE ENDOSCOPE

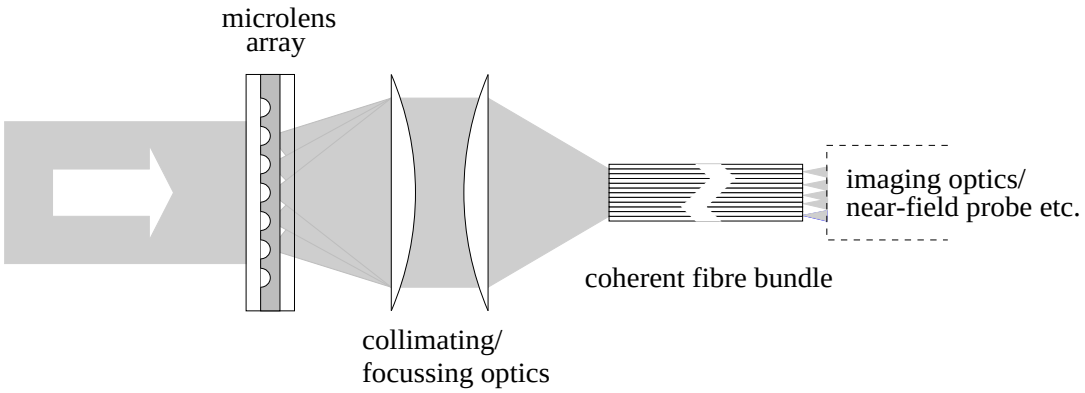

Figure 7. A proposed system using the microlenses to address a coherent fibre bundle.

Having demonstrated switching into one single-mode fibre, we propose to use the array of microlenses to do parallel switching of channels into a coherent fibre bundle, or 'image fibre'. A possible system is shown in figure 7. This will have the effect of generating multiple light outputs at the free end of the fibre upon application of the appropriate voltage to the cell. The shape of the input array will be retained through the fibre.

For full control of the outputs of this system we require individually-switchable microlenses, which calls for a liquid crystal device of much greater electrical sophistication. Microlens devices with patterned conductive elements, allowing some independence in microlens control, will be tested in the near future.

5. SUMMARY

Although we have shown that electrically-controllable microlenses have a promising application in switching light into optical fibre, experimental evidence suggests that the focal length variation is not, directly, the modulation mechanism but that the variation in numerical aperture plays a more important role. The modulation effect is available over a range of axial distances, and takes the form of a voltage 'window', within which light transmission occurs.

This has been successfully demonstrated for coupling light into a single fibre, and the next step to an endoscopy application is the use of a coherent multi-fibre bundle for collecting the light from the entire lens array, the work for which is underway.

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