INTEGRATED LENSES FOR MICROFLUIDIC SYSTEMS

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Abstract: *Greater integration of optical devices is required in microfluidic systems for on-chip functionality, with lenses being key components. In this paper several candidate lens types are compared and simulations are presented which show that the paraxial kinoform lens offers optimum performance for efficiency and compactness in weak guiding systems.*

1. Introduction

The *lab-on-a-chip* offers great benefits in terms of reagent and sample consumption, speed, precision, and automation of analysis, and thus cost and ease of use, resulting in increasing use of microfluidic approaches for chemical analysis, and flow cytometry in particular [1]. The use of light for detection of particles and chemical species within these systems is widespread because of the sensitivity and specificity which can be achieved. Nonetheless, full integration of optical functions within microfluidic chips is in its infancy [2].

Approaches to miniaturising macro lenses described in the literature concentrate on the use of refractive lenses to improve fluorescence measurements. Such lenses have been shown to enhance performance [3], with reduction of aberrations being achieved using compound lenses [4]. Such unguided systems are limited by the high on-chip losses incurred. To optimise overall on-chip losses, lenses can be integrated into the waveguide system [5], also allowing realisation of improved on-chip detection optics [6]. Ideal refractive lenses have either an elliptical or hyperbolic form, for negative or positive lenses respectively [7], so that a single lens rather than a compound system is expected to give good aberration-free performance and will be more compact. The planar fabrication technology used for the lab-on-a-chip also allows for simple replication of diffractive lenses, with kinoform profiles offering the greatest efficiency [8, 9].

In this paper, the design and simulation of kinoform lenses for further miniaturisation and integration of micro-flow cytometers is described. Weakly guiding waveguide systems are targeted as they exhibit the benefits of good coupling to single-mode fibre, low Fresnel reflections and greater fabrication tolerances for single mode operation, when compared with high-contrast waveguide systems.

2. Design of waveguide lenses

The principal objective is to design a one-to-one imager lens with a spot-size of order 2 μm to image the output of a channel waveguide into the middle of a microfluidic channel, and to collect through another lens, as shown in Fig. 1. Etched regions with no waveguiding must be minimised to reduce diffractive losses, leading to the choice of a negative lens design.

In common with the refractive lens, the kinoform lens profile can be derived analytically from Fermat's principle, while also incorporating the diffraction of a Fresnel zone plate (FZP), which treats the kinoform as a family of curves, one for each zone for positive lenses [8, 9], but does not provide an explicit design procedure for how to divide the curves. We therefore applied a similar method to negative lenses where the family of curves are ellipses and the zone locations are defined in the same way as for an FZP to design an elliptical kinoform. The paraxial kinoform may be obtained by using commonly-used approximations [8]. McGaugh et al. [9] introduced the different design method of taking dividing the family of curves and we applied that too to the negative lens. The candidate lenses considered here are the elliptical refractive lens, the elliptical kinoform, the paraxial kinoform, and the McGaugh kinoform. A comparison of the lens profiles is given in Fig. 1, where on the left is the typical configuration of a microfluidic chip with the integrated optics. The centre of the lens region is expanded on the right to show candidate lenses superimposed for comparison. The area between the lens' boundaries is the etched region defining the slab waveguide regions.

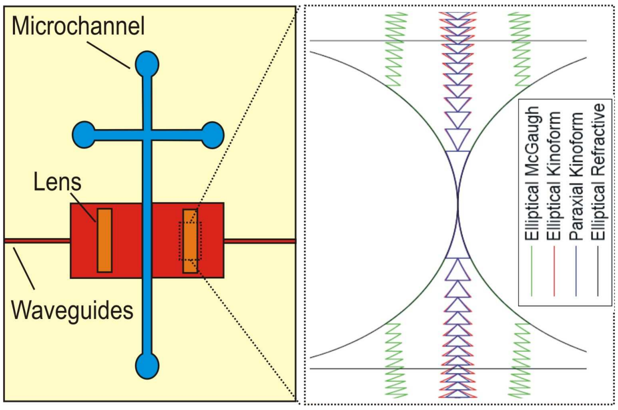

Fig. 1. Schematic of a microfluidic chip and comparison of the lens' profiles.

There are two shortcomings in the analytical design: firstly, the analytical model does not take into account the effect of diffraction in the lens itself leading to errors at the output boundary and, secondly, the model is based on the approximation that a spherical wavefront is incident on the input lens boundary. Numerical simulations are presented below to provide accurate comparisons of the candidate lenses.

3. Simulations and discussion

The effective index method was used to transform the 3D waveguiding problem to a 2D problem and the beam propagation method was used to simulate the candidate lens pairs and their coupling into a collection waveguide after focussing in the centre of the fluidic channel. The figure of merit is the power coupling efficiency given by the square of the overlap integral between the field incident on the waveguide input and the modal field.

The optical properties used were those of 2 µm square cross-section SiO_2:GeO_2 channel waveguides buried in silica with refractive indices of 1.474 and 1.458 respectively at 633 nm wavelength, for lenses designed for operation with a focal distance (distance between centre of the lens and the object or image plane) of 2000 µm.

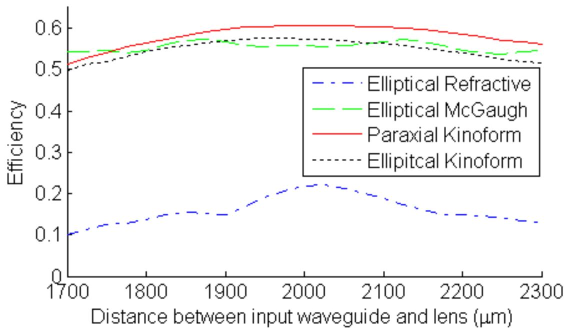

Fig. 2. Comparative single lens efficiencies as a function of input distance from the design focal distance of 2 mm.

Fig. 2 shows the efficiency of the single candidate lenses implemented as the separation between the input waveguide and lens is varied along the optical axis and the peak efficiency is taken along the optical axis with no microfluidic channel in place. The paraxial kinoform design is found to be the most efficient of the lenses and the refractive lens is found to underperform the kinoforms. This is because the paraxial design results in the thinnest lens, so that the geometrical optics approximations used in the analytical design models are more valid. The variation in efficiency of the paraxial kinoform lens with distance between the channel waveguide and the lens, f_1, and with distance between the lens and the middle of the microfluidic channel, f_2, is given in Fig. 3. The focus is in the middle of a microfluidic channel of 20 µm width filled with water. This shows that the paraxial design has excellent tolerances to axial offsets in fabrication. Fig 4 presents the lens pair efficiency with fluidic channel width, showing that good efficiency is maintained for a wide range of fluidic channel widths, allowing high tolerance and system scalability.

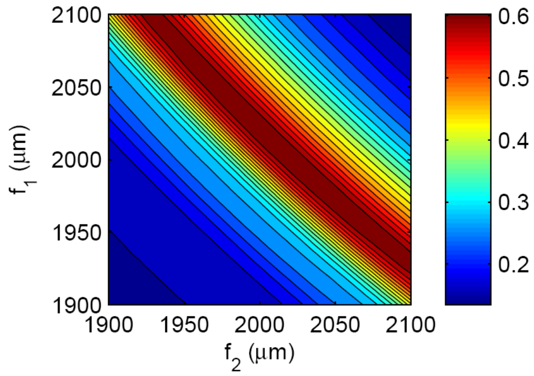

Fig. 3. Efficiency of paraxial kinoform lens as lengths f_1 and f_2 are varied.

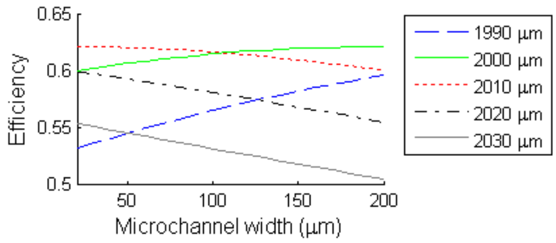

Fig. 4. Lens efficiency at f_2 versus channel width for several f_1 distances.

4. Conclusions

Kinoform and refractive lenses have been compared for use in micro-flow cytometers. The paraxial lens shows the best performance for imaging the mode profile of a 2 µm waveguide in the centre of a microfluidic channel in terms of throughput efficiency and size, and shows wide tolerances to fabrication errors and applicability to a wide range of microchannel widths without redesign.

References

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