Microlens array for enhancement of irradiance and fill-factor recovery in image detectors

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Abstract – *We present the result of calculations of the concentration factor C obtained by plano-convex microlenses, either in direct or reverse format, mounted in front of a detector array. C factors in the range 20 to 40 are demonstrated feasible with lens spacing of 70 μm and detector size 10 μm.*

1 INTRODUCTION

The concentration concept is important for recovery of the fill-factor of small-size individual photo-detectors in an array of pixels, for example when processing circuits are integrated around the photo-sensitive area [1] like in time-resolved spectroscopy, gene sorting and 3-D imaging. Concentration is based on the principle of acceptance invariance [2], by which the product of area A and solid angle Ω within which rays are propagated or treated by an optical element like the one shown in Fig.1, is a constant, or:

$$A_i \Omega_i = A_o\Omega_o \qquad (1)$$

Then irradiance (or power per unit area) E = P /A can be increased if we trade area for solid angle. As shown in Fig.1, if we want to decrease the area from input to output, we have to increase the solid angle accordingly. This implies that the objective lens used in front of the detector should be not the maximum aperture. More in detail, let us write the concentration C ratio of the output to input irradiance as:

$$C = E_o/E_i, = (P_o/A_o) / (P_i/A_i)$$
$$= A_i/A_o \quad \text{when } P_o= P_i \text{ (no power loss from input to output)} \qquad (2)$$

Recalling also the invariance of radiance R=P/AΩ [2], even in the case $P_o \neq P_i$, we can write:

$$C = E_o/E_i, = (R_o\Omega_o) / (R_i\Omega_i)$$
$$= \Omega_o/\Omega_i = [n_oNA_o]^2 / [n_iNA_i]^2 \quad \text{when } P_o> P_i \text{ (if any loss from input to output)} \qquad (3)$$

In Eq.3, NA= sinα is the numerical aperture, α being the half-cone angle of the ray bundle, and $n_{i,o}$ is the index of refraction of the input/output medium.
As we can see from Eqs.2 and 3, we can obtain a concentration either limited by area ratio or by the solid-angle (or numerical aperture) ratio. Thus, the general trend of a C vs NA diagram for any optical concentrator is of the type depicted in Fig.1 (right).

2 ANALYSIS

Now, about concentrators we may use prism-like elements [3,4] which have NA_o~1 and may reach theoretically high values of effective concentration (up to 100 and more). However, in the application at hand, calling for arrays of individual elements of 40-70 μm in diameters, such micro-prisms are difficult to fabricate. Instead, the micro lens array is a viable concept from the fabrication point of view [5,6].

We have therefore considered arrays of micro-lenses suitable for obtaining C factors in the range of 20 to 40. Two versions of the simple plano-convex lens have been considered, the normal lens with all the space to detector filled by material with index n, and the reverse lens, as it is shown in Fig.2. The reverse arrangement was interesting because it doesn't require exact thickness control and thus is easier to fabricate.

A computer ray-tracing subroutine has been written to follow ray trajectories across the lens down to detector and calculate concentration. Input bundle of rays was varied from NA=0 to 0.4.
Results are presented in Fig.3, as plots of equi-concentration lines drawn in an NA-vs-distance plane. Lens thickness was varied from 7.5 to 35 μm. Only the results for lens thickness yielding the largest concentration are shown. As it can be seen, the inverted lens can give C=25 for a marginal NA=0.05, and more realistically a low C=8 at NA=0.15 (or F#=3.3). This modest result is interpreted as the effect of more pronounced aberrations

together with the n=1.0 index of refraction in the back of the lens, which reduces the n·NA product available. On the other hand, the normal plano-convex lens has a high C=40 at NA=0.05 a good C=20 at NA=0.15 (F#=3.3), and also has an adequate latitude of distance (about ±5 μm at distance=85 μm).

3 CONCLUSIONS

We have demonstrated that concentration of irradiance of a factor about 20 can be obtained for a photodetector of 10 μm diameter with a 70 μm diameter microlens.

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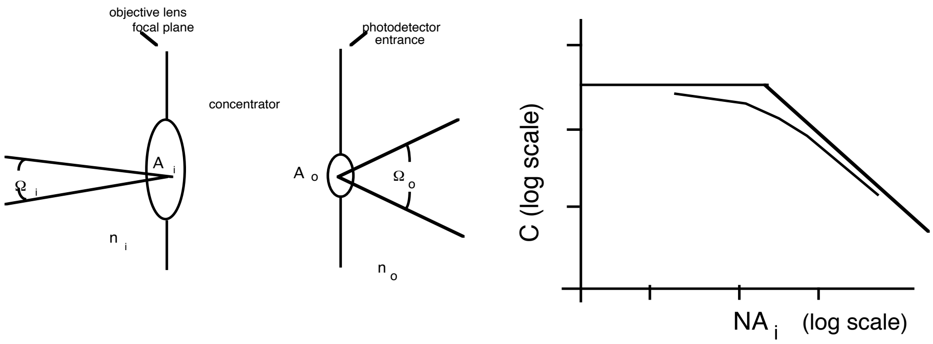

Fig.1 (left) Illustrating the invariance of acceptance AΩ between input and output planes of a concentrator (right) The general dependence of the concentration factor versus numerical aperture of incoming ray has two asymptotes corresponding to Eq. 2 and 3.

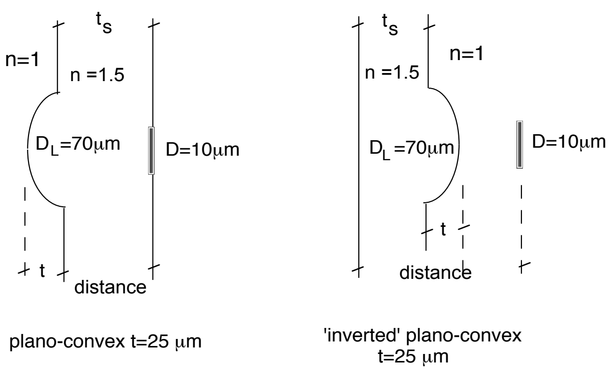

Fig.2 Two cases of lens concentrators considered: normal plano-convex lens (left) and inverted plano-convex (right). The former has the material with n=1.5 extended down to the detector plane, so that the distance shall be controlled to achieve optimal concentration, whereas the latter has air in between and thus the lens thickness doesn't need be controlled, an important feature for construction of the concentrator array.

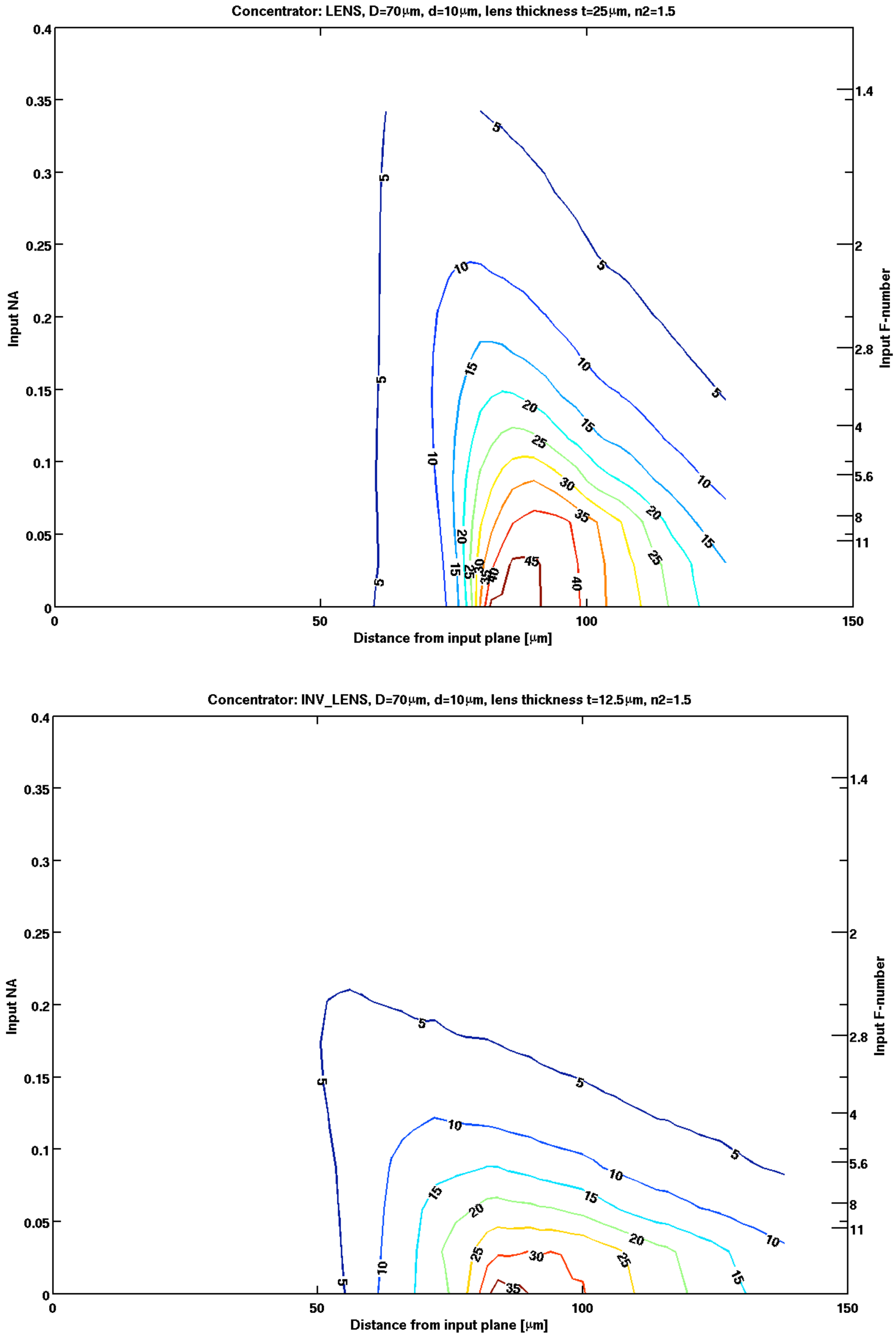

Fig.3 Concentration factor versus distance of lens from focal plane (see Fig.2). In both diagrams input and output diameters are D=70 μm and d=10 μm. Index of refraction is n=1.5. Top diagram is for the normal lens, bottom for the inverted lens. Optimal thickness of meniscus is 25 μm for the normal lens and 12.5 μm for the inverted. Performance is seen to be much better in the former case, as it may be qualitatively expected.