POLYMER MICROLENS FOR FILL-FACTOR RECOVERY: SPREAD IN OPTICAL PARAMETER OF FABRICATED SAMPLES

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Abstract: *We use a polymer microlenses array, made of 50-μm pitch, 32x32 elements, in connection to an array of as many 6-μm diameter SPADs (Single Photon Avalanche Detector). Aim is mitigation of the loss in sensitivity due to the area fill-factor, due to the small 7-μm size of the detector compared to the 50-μm pitch. The lens array is fabricated by polymer casting in a photoresist replica mold. Results about repeatability of concentration factor and back focal length ware reported. At a C factor of 30 and a focal length F=40 μm, the spread of concentration factor is < 6%, and the spread of BFL is <0.5 μm.*

1. Introduction

Pixel on-board processing of detector signal is not carried out in image detectors, because even a simple circuit may occupy a large area, spoiling the effective efficiency: if σ (A/W) is the spectral sensitivity, partial filling η of pixel area reduces the apparent sensitivity to ση, where $\eta=A_d/A_p$ is the fill factor, ratio of detector A_d to pixel A_p areas. If η is small (e.g. 0.01), on-board processing is impracticable.

This issue is particularly true for array of avalanche photodiode or SPAD (Single Photon Avalanche Detector), requiring a quenching circuit to recover fast from triggering after detection of a single photon initiating the avalanche. Additional processing circuits that can be integrated around the photo-sensitive area are: time sorters, time-of-flight rangefinders and spectrum analyzers, for applications in time-resolved spectroscopy, gene sorting and 3-D imaging [1, 10].

Taking advantage of acceptance AΩ conservation [2], we may concentrate the power collected on a large pixel area A_p in a smaller detector area A_d – provided allowing an equal increase of solid angle Ω, from input to output. The solid angle is $\Omega=\pi\ NA^2$, (NA= numerical aperture of the field-of-view of the receiver). Thus, to get a high C we shall trade the numerical aperture NA^2_L of the lens imaging the scene. Frequently, the objective lens NA is limited by other considerations, like layout, desired depth of focus, available size or weight, etc. Typical sizes involved in our design, based on a CMOS 120-nm technology, are: pixel size 50-μm by side, detector size 7.0–μm, number of individual SPADs 32x32. Thus we need an array of microlenses of 50-μm pitch (≈ diameter), and the achievable fill-factor recovery (area ratio) is 51 (40 after the π/4 square-to-circle fill ratio).

2. Types of Optical Concentrators

As the optical element of the array, we might use non-imaging prisms of different shape (cone, parabolic and tilted parabolic) [3,4] which theoretically reach high values of concentration (up to 100 and more) [5], but that are difficult to figure in the required shape on small diameters. Instead, as thermal reflow readily generates a spherical dome, fabricating micro-lens-array is a feasible approach [7-9] and can readily provide C-factors in the range of 20 to 40, adequate for a substantial recovery of fill-factor.

Before fabrication, we started assessing concentration performance, using a computer ray-tracing subroutine to evaluate the concentration factor of the a number of concentrators' design. As a typical result of simulations [6], the plano-convex lens attains theoretically a good C=55 at NA=0 and C=45 at NA=0.15 (corresponding to an objective lens F#=4), and also has an adequate depth of focus (about ±5 μm at focus distance=65 μm).

3. Experiment

Lens array fabrication by the replica casting of a polymer into a photoresist mold is described in [7-9], and a microphotograph is shown in Fig.1, left. By a separate assembly operation, the array is then baligned and glued onto the silicon chip carrying the SPAD array. Size of the lens array is 1.6x1.6 mm, to match a 32x32 SPAD array with pixel size 50μm.

The lens array has been first tested by a specially designed optical bench, comprising a variable input-beam NA objective and a scanning CCD array, interfaced to a PC. Results of concentration factor, measured on a typical sample of the fabricated lens array, along the Z-axis parallel to the optical axis of the lenses is shown in Fig.1 right, with NA as a parameter. Compared to theoretical value of 40 (at small NA), the measured concentration 30 is smaller, by a factor about 25%. Possible reasons, presently under investigation, are: defects at the spherical-to-plane edge of lens base; deviation from the spherical shape; residual scatter of the lens surface.

Anyway, the value of 30 at small NA is a good result, because it allows recovering of the same amount the quantum efficiency – no more penalized by the small area fill-factor, and this is the main conclusion of our R&D effort.

More important, the uniformity of C and the BFL, the back focal length, were assessed on a number of individual lenses inside a single array and along a number of arrays. Both C and BFL are important because they reflect in a spread of signal amplitude of detected signal. The statistical data about the two sub-classes (inter- and intra-array) were quite similar giving evidence to their belonging to the same population. In Fig.2 we report typical samples of iso-concentration C curves measured on stand-alone lens-arrays, plotted in a NA-z (numerical aperture versus distance along the optical axis) graphs. In Fig.3 we plot the BFL (back focal length) deviation as a function of NA. From these data, we find that the rms spread in concentration was $\sigma_C<6\%$, whereas the back focal length has a rms deviation $\sigma_{BFL}<0.5$ μm.

Compared to other lens array fabrication, e.g. ink-jet printing [8], with spreads reported 12% in diameter (24% in concentration), replica mold technique performs significantly better. Last, reproducibility of pitch (nominal 50-μm) is shown in Fig.4.

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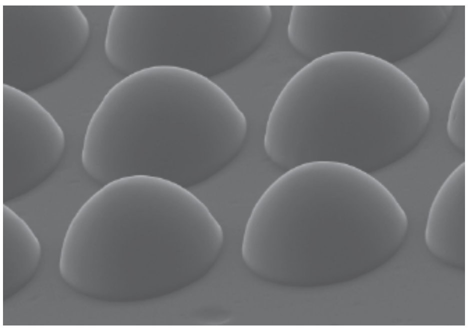

Fig.1 Microphotograph of plano-convex lens in the 32x32 array, 50-μm pitch, 46-μm diameter fabricated by polymer molding

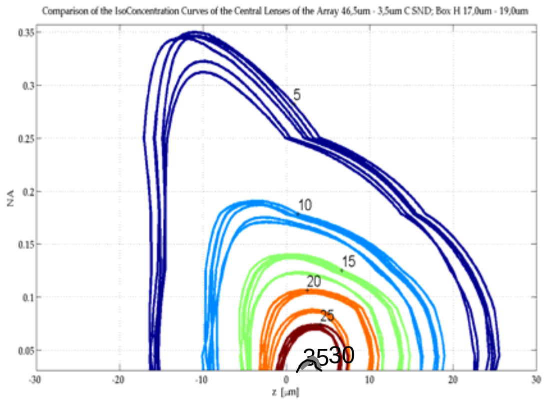

Fig.2 Examples of iso-concentration curves in a NA-z plot for the plano-convex lens array. The parameter is the value of concentration C. Horizontal scale is 10 μm /div., vertical scale 0.05/division.

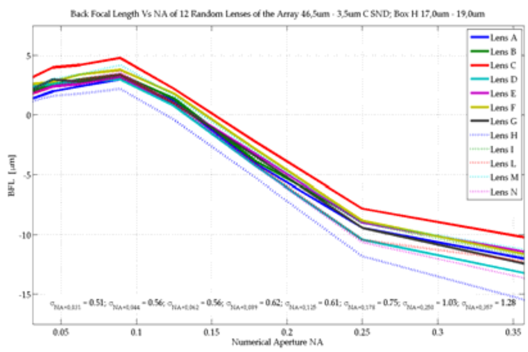

Fig.3 A few BFLcurves plotted as a function of numerical aperture. Horizontal scale is 0.05 /div., vertical scale 2.5μm/division.

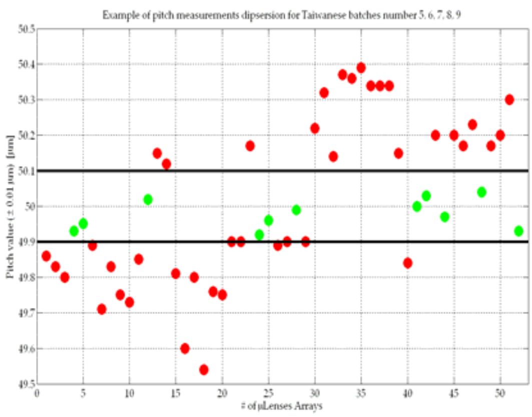

Fig.4 Pitch value dispersion for some of the 32x32 lens-array batches. Green circles are for samples with acceptable pitch (error <0.1-μm), red circles represent those with excessive pitch error.