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# Large Aperture Receiver Based on Co-packaged Micro-Lens and PD Arrays for Indoor GbE OWC Links

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***Abstract*** *A new concept of co-packaging of a bespoke micro-lens array on a 4×4 photodiode OWC receiver is demonstrated, leading to more than 3 dB improvement in received power efficiency for GbE application. The concept is scalable to higher speed operation and more compact OWC receivers. ©2022 The Author(s)*

## Introduction

Optical wireless communication (OWC) is considered a promising candidate for indoor communication and optical interconnects in data centers. This is based on the potential of light to encode higher data rates with lower transmission losses compared to mmWave and THz carriers[1]. Opposite to fiber optics, light in free space does not suffer from dispersion or wiring problems, making reconfiguration and routing easier to perform[2].

Multiple methods for high-speed OWC transmitters have been reported[3]. However, the research on high-speed OWC receivers is limited as the high-speed photodiode (PD) requires a small aperture (to restrict the capacitance) and, as a result, fails to capture enough light from free space to achieve high-speed (>1Gbps), error-free data transmission. Lenses can be used to collect more light[4], but standard lenses have large focal lengths, which leads to a reduced field view (FoV). Besides, packaging a lens with a diameter of a few millimeters and a PD with around tens of micrometers in size is challenging and sophisticated mechanics are needed to keep the alignment steady during vibrations and structure deformation. Micro-lenses are very useful in fiber optics and imaging, to increase the coupling efficiency of PDs[5] or the responsivity of imaging pixels[6][7]. Micro-lenses achieve a smaller focal lengths with a thinner profile, which ensures smaller aberrations and a larger FoV than standard lenses. Besides, micro-lenses can be integrated with PDs or on interposers with micrometer precision (contact lithography) resulting in a smaller and more stable structure. However, the size of a single micro-lens is also too small (<500 μm) to collect enough light for high-speed, error-free connections.

Previously, we have reported on the development of a 2-dimensional PD-array concept for OWC receivers with bonding wires[8]. These receivers can achieve a larger optical detection area while keeping the bandwidth the same as the single PD. However, because there are gaps between the PDs, the previous prototype lost around 6.5 dB of light collection efficiency due to the limited fill factor. In this paper, we introduce the concept of an array based on PDs combined with micro-lenses, which enables a faster OWC receiver with an improved light collection ability, compactness, and reduced packaging cost. To establish the validity of the concept we first simulate the gain from introducing the micro-lenses to the PD array and then verify these findings experimentally. For the simulation, a model was built on ZEMAX Opticstudio@ platform. For the experiment, a 1 Gbps OWC receiver with a larger light collection area and improved efficiency is used to verify the simulation. We also update the packaging technology of the OWC receiver with flip-chip technology on a silicon platform to further improve the high-speed performance of the packaged receiver[9]. The results show that the lenses packaged on a ϕ150 μm PD array can increase light collection by 3 dB compared to the PD array without lenses. Furthermore, the 4×4 PDs with microlenses show an FoV >23 degree (half-angle).

## System Setup and Simulation

The prototype of the receiver, shown in Fig. 1, has two parts. The first part is an array of PDs flip-chip bonded on a silicon interposer. The silicon interposer includes the patterned traces (based on previous scheme[10]) to connect the PD array. Through-silicon vias (TSV) are wet-etched on the interposer to maximize light transmission.

The second part is the photoresist micro-lens

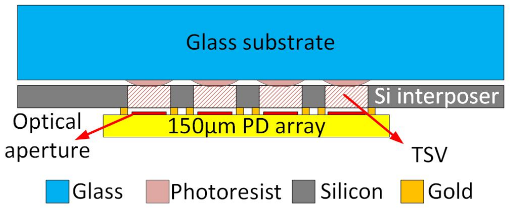


**Fig. 1:** Setup of prototype

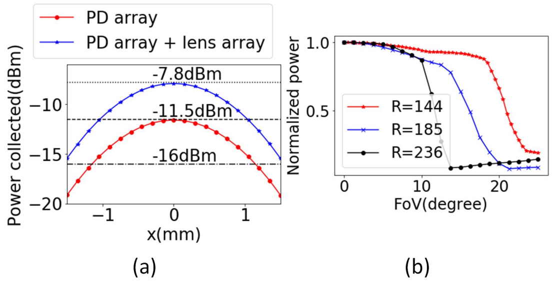


**Fig. 2:** (a) Position tolerance of system with R=236 μm lens and without lens; (b) Normalized optical power from receiver microlens arrays versus FoV

array, positioned upside down on the TSVs. The 240 μm diameter photoresist lenses are fabricated by reflow process on the glass substrate. The refractive index of the photoresist (n=1.55) and the glass substrate (n=1.44) are similar.

Using ZEMAX, the light source is a collimated 3 mm (taking its 1/$e^2$) Gaussian beam with a power of 0 dBm. One million beams are used in ray tracing to define the sum of energy received by the PD array. The power received versus the transmitter-receiver misalignment (at 0-degree FoV) is simulated to study the improvement achieved by adding micro-lenses into the setup. Additionally, lenses with different radius of curvature (ROC, represented by 'R' in this paper) have been simulated.

According to the simulation results, the light collection efficiency improves by 1.1, 3.0, and 3.7 dB by using lenses of R=144, 185, and 236 μm, respectively, compared to the model without lenses. That ϕ240 μm lens has filled up the gap of ϕ150 μm PD array (fill factor of receiver increased from 22% to 50%) is the reason why the gain of light collection efficiency is improved. The misalignment tolerance and FoV study are shown in Fig. 2, in which the line of -16 dBm (experimentally estimated) error-free threshold received power (by PDs) for 1GBps data transmission is annotated, together with the lines presenting the maximum power collected for the receiver with and without the lenses. It is shown that adding lenses improves the tolerance of transmitter-receiver alignment from ±1.1 mm to ±1.6 mm.

Simulation results verify that microlenses indeed improve the light collection ability of the receiver. Due to the upside-down configuration of the lens array in our setup, we experienced a total internal reflection of light at the edge of the micro-lenses with a smaller ROC which will reduce light transmission. Thus, the gain from the lens with a smaller ROC becomes smaller. By flipping the lens array to make sure that light first goes through the spherical surface and then the plenary surface, we can avoid this loss.

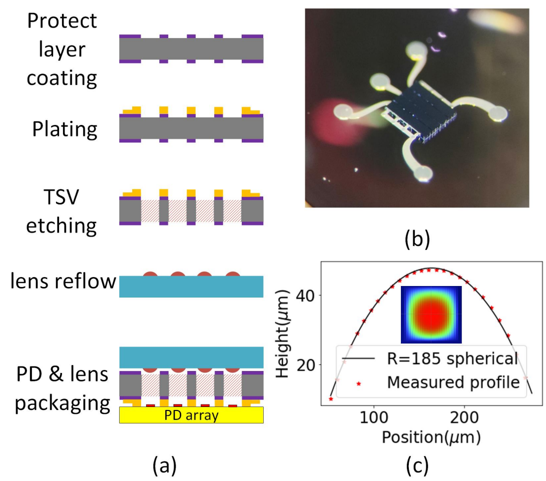


**Fig. 3:** (a) Process flow; (b) Packaged PD; (c) Picture and profile of R=185 μm microlens (Insert: 3D map of reflowed lens)

## Fabrication and Experiment

The schematic process flow of the Si interposer fabrication is shown in Fig. 3(a). Firstly, a $SiN_x$ hard mask is defined on both sides of the Si wafer. Afterwards, a seed layer (Ti/Au) for electroplating is evaporated on the top side of the wafer. Then the metallization for the PD array is patterned with contact lithography and subsequently realized by electroplating. After that, square holes in the silicon substrate are etched chemically from both sides of the wafer. Finally, a 4×4 PD array (Albis Optoelectronics) with the bandwidth of 1.8 GHz is flip-chip bonded to the silicon interposer. The receiver is fully packaged by wire bonding the silicon interposer on the PCB board on which packaged a commercial 10 kΩ 700 MHz trans-impedance amplifier(TIA), as Fig. 4(a).

The micro-lens array is made from AZ40XT photoresist. The pattern matches with TSVs layout (see Fig. 4(a)). The spherical surface is formed by reflowing photoresist cylinder. And the profile of the reflowed lens is measured with a DektakXT stylus profilometer, the results are shown in Fig. 3(c). The 3D and cross-section profiles indicate that the reflowed lens has almost a spherical shape.

The system built up to test this OWC receiver is

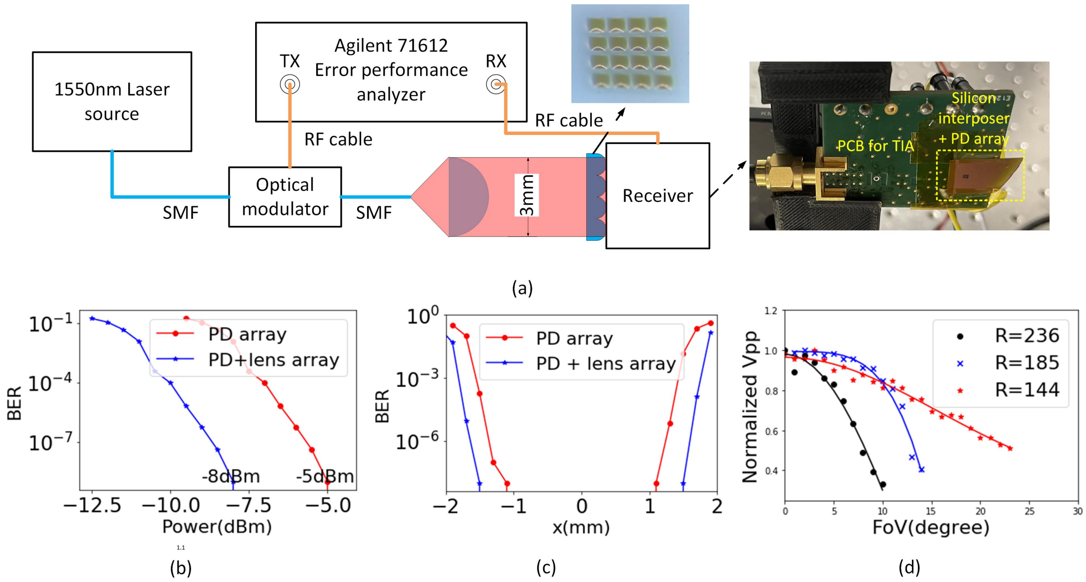


**Fig. 4:** (a) Experiment setup; (b) BER vs optical input for lensless receiver and receiver with R=236 µm lenses (c) BER vs. misalignment for lensless receiver and receiver with R=236 µm lenses; (d) Normalized voltage amplitude(Vpp) from receiver with microlens arrays vs. FoV

shown in Fig. 4(a). First of all, the minimum power required for error-free operations (BER$<10^{-9}$) for 1Gbps non-return to zero pseudo-random binary sequence (PRBS23) On/Off Keying signal is measured for systems with and without micro-lens array. The light source from the transmitter is a Gaussian beam with a waist of 3 mm and a power of 0dBm. From the minimum power required for error-free connection, we concluded that the gain from the microlens array is 1.1, 2.5, and 3.0 dB for R=144, 185, 236 µm lens, respectively, which is consistent with the simulation results. As stated in the simulation, the extra loss from lens arrays with a smaller ROC is not fundamental and can be eliminated easily with an optimized design. Moreover, the BER for 1Gbps data transmission is measured for different optical input powers using a receiver with a 236µm lens. The results are presented in Fig. 4(b) confirming a 3 dB improvement from lenses. Fig. 4(c) shows the BER depending on the relative transmitter-receiver positioning, the improvement in the received optical signal translates into an increased misalignment tolerance of the OWC communication link at 0 degree from $\pm$0.9 mm to $\pm$1.5 mm according to the measured data.

Additionally, the FoV is tested with this experiment setup, results are shown in Fig. 4(d). The hypothesis that as larger the ROC, as smaller the FoV is verified. In addition, the PD array integrated with the 144 µm photoresist micro-lens array achieves a half-angle FoV (3 dB decrease in power) of $>$ 23 degrees.

## Conclusion and Outlook

In this paper, we have extended our previous work by proposing a novel structure combining an off-the-shelf 4×4 PDs and a 4×4 micro-lens array. The simulation and experiment results have shown a more than 3 dB gain due to the use of the manufactured micro-lens array for GbE operations. Besides, the largest FoV achieved with photoresist micro-lenses is >23 degrees (half angle), which is smaller than the bare PD array but is acceptable for several use-cases including indoor OWC and outdoor fixed-wireless access.

In the future, we aim to follow up on this effort by co-integrating micro-lens with PD array on a single glass substrate. For the OWC receiver used in indoor applications where FoV is very important, we will provide more impact package modules (where PDs and micro-lens array are on the same interposer) to optimize the efficiency while keeping the satisfying FoV. Besides, it should be noticed that transforming the photoresist lens profile into the high refractive index substrate promises a larger FoV. More importantly, for applications where FoV is less crucial, thin micro-lens integrated with a PD array can significantly increase the fill factor of the PD array and realize even high-efficiency data transmission with even higher speed (>20Gbps).

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