Design and Simulation of a Planar Micro-Optic Free-Space Receiver

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Abstract: We propose a receiver design and simulation that optimizes a Si microlens array with micro-optic injection structures to selectively couple light into a waveguide and then to an edge-mounted detector to couple 2.5Gbps modulated input.

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1. Introduction

Short link free-space receivers provide digital communications for emergency response, multiple building corporate campuses [1,2], recent data center concepts [3], and can play a role in secured mobile UAVs. Constraints for the last two emerging applications include the need for small physical volume, real-time beam tracking to assist in setup, and sufficient temporal bandwidth for high-resolution video transmission. Any solution that requires a large focusing lens or a matrix of amplified detectors would impose significant complexity and cost, to include electrical power dissipation. We propose an alternative configuration derived from recent research on waveguide-based solar concentrators [4]. A microlens array and a shared waveguide direct incident light into a detector typically 50x to 500x smaller than the aperture, and uses a small lateral translation to select and maintain directional alignment.

Our waveguide concentrator homogenizes the input beam and provides disparate optical paths to the detector. This results in a path-dependent delay that limits the temporal bandwidth of the system. For sufficiently high-definition video transmission, we required the transit time through the waveguide to be compatible with a 2.5GHz signal modulation bandwidth, and a transmission wavelength of 1550 nm. In the following sections, we detail software simulations that optimize receiver variables for these constraints and demonstrate that such a planar receiver could efficiently collect modulated beams.

2. Planar Free-space Receiver Concept

The micro-optic waveguide concentrator is shown in Fig. 1. Input light is focused by each lens in a lenslet array onto a corresponding array of small reflective facets, micro-optic injection features that couple the reflected light into guided modes of the shared waveguide. The optical signal propagates through the waveguide towards a small exit aperture. A detector is mounted onto the waveguide edge.

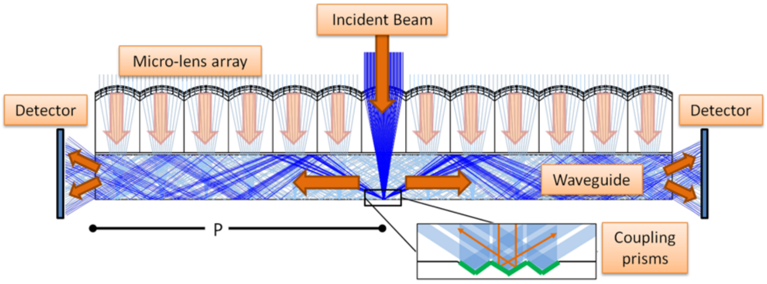

Fig. 1. Receiver diagram showing distribution of light towards the exit aperture

Once reflected by the couplers, rays guide via total internal reflection (TIR) unless they strike a subsequent prism which strip light from the waveguide. Summing the number of ray and surface interactions, we can calculate theoretical efficiency using the decoupling and positional efficiencies.

When the focal spots of the incoming light are misaligned with the features, light passes through the waveguide. As a result, translation between the two planar surfaces is adjusted to achieve peak coupling alignment. This type of micro-tracking, on the order of the spacing between injection prisms, allows lateral translation to replace conventional tip and tilt [5]. The angular separation between incident beams translates to a linear shift of the focal spots on the back of the waveguide defined by $y = 2F / (\# \tan \theta_\alpha),$ where θ_a is the acceptance angle of the microlens. This shift decreases the overlapping portions of the focus on the injection feature.

3. Design and Simulation

We created an analytical model of modal dispersion to build basic relationships between receiver geometry, material choice and bandwidth. The calculated transit times of individual rays through the model provided an impulse response for the waveguide. We then used non-sequential ray tracing in Zemax to evaluate microlens, waveguide, and injection feature designs. The merit function for optimization was based on the total output power coupled to the detector. The variables under consideration were the radius, conic, and aspheric terms of the lenslet array and the position, width, and height of the injection elements.

The design space was initially bounded by material selection and manufacturing limitations. The desire for high concentrations and large acceptance angles led to high index lenses and waveguide materials, specifically silicon at $\eta=3.48$ for the slab and microlens array, which is transparent at the 1.55µm operating wavelength. Minimizing total detector area and maximizing concentration required waveguide designs that were as thin as possible. We designed for Silicon on Insulator (SOI) material to decouple waveguide thickness from structural requirements. For example, the 250µm thick lens array and substrate are shown in Fig. 2. The substrate is separated from the lens substrate by a gap that can be filled with air or a fluid that is lower in index than the waveguide. The best overall performance was obtained with an optical coupling fluid, $n = 1.6$, to minimize geometrical lens aberrations. We chose a 10µm thickness for the optical cladding as a reasonable minimum thickness that still supports low waveguide reflection losses. The waveguide thickness was set to 30µm. We then chose a 10µm spacing of optical coupling fluid at $n = 1.46$ with interspersed SiO_2 beads sandwiched between the substrate and waveguide to provide wide-angle TIR guiding and structural support.

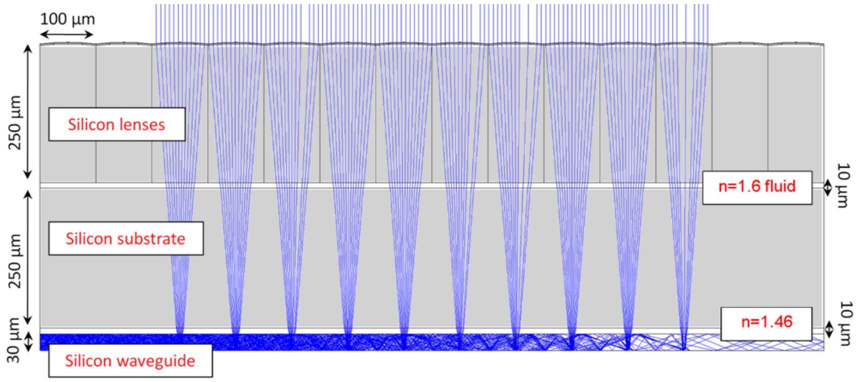

Fig. 2. Layout and ray path for optimized Si-based lenslet array and waveguide

With each iteration of material and geometry, we calculated the lens F/# and the injection geometry on the bottom of the waveguide. To generate the impulse response, we linked the optimized Zemax model to Matlab analytics using a set of database manipulation scripts that allowed all light ray paths to be imported into a Matlab structure [6]. Three 30µm x 3.33mm ideal detectors were assumed to cover the waveguide edge. The simulation sent a full-aperture beam of λ=1552nm rays to be incident on a representative three-dimensional lenslet array. On-axis incident rays were time stamped with an associated intensity at the detector and compiled into an intensity-based impulse response of the waveguide as a function of time. The shape of the impulse response is a direct result of the different optical paths through the waveguide. We convolved the impulse response with a 10-bit PRBS signal at 2.5 GHz to yield a simulated system eye diagram. The eye diagrams generated by various material and geometry combinations were compared until we identified a successful lens array, substrate, and waveguide candidate with a maximum 1 cm^2 aperture.

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5. References

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