Coherent System Tests of Experimental Retroreflectors with Very Wide Field of View for Free-Space Optical Communication

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Abstract

This paper reports the development and testing of novel retroreflectors and optical phase modulators for use in retroreflective optical communication systems. For the first time, practical measurements on a three-element retromodulator array based on high index corner cubes confirm a planned hemispherical field of view. Graded-index sphere lens structures have shown promise for making low-cost retromodulators compared to those using corner cubes, as well as providing performance benefits. Diffraction-limited optical performance has been produced in these lenses for the first time, with apertures similar to those of the corner cubes used in this work. Retroreflective communication range would be quadrupled compared to a uniform sphere lens of the same size.

Keywords: Retroreflectors, free-space optical communication, Graded-index, sphere lenses, corner-cubes

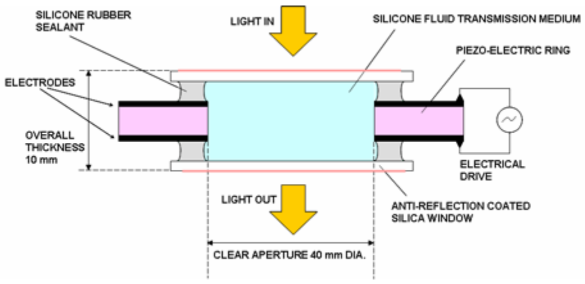
Introduction

This paper reports the development and testing of novel retroreflectors and optical phase modulators for use in retroreflective optical communication systems. For the first time, a three-element retromodulator array is demonstrated with a complete hemispherical field of view. Applications include surveillance and asset tracking, remote sensing, tagging and optical IFF. Also, large-aperture, diffraction-limited graded index sphere lenses are reported for the first time, leading toward future low-cost retromodulators.

The feasibility of retroreflective optical communication has previously been established by analysis of optical power budgets and key components [1-3]. It will be important for retromodulators to have a wide field of view in order to make such systems practical and affordable. We have previously discussed retroreflectors based on high-index corner cubes [4], concluding that a refractive index near to or greater than three might be acceptable for use in few-element arrays covering usefully large fields of view. This paper reports the first demonstration of a three-element array of retromodulators with a collective field of view covering more than a hemisphere. We have also suggested [3,4] that graded-index, spherical (GRIN-sphere) lenses might offer much less variation in reflected power with changing angles of incidence, as well as cost advantages compared to corner cubes. Diffraction-limited lens apertures of at least one centimetre will be required to support communication ranges of kilometre order. Moderately sized GRIN-sphere lenses may in principle achieve this by suppressing the most problematic feature of conventional sphere lenses, that is, their strong spherical aberration. Fabrication of lenses of the required size and quality are reported for the first time in this paper.

Novel phase modulators

Coherent systems in principle offer the highest detection sensitivities for optical communication and can employ phase modulation. Novel phase modulators were devised for use with corner cubes so that the low phase-front distortion, wide aperture and field of view of the final retromodulator assembly would be optimised at low cost, while permitting the best possible communication bandwidth and requiring very low power electrical drivers. These phase modulators were designed as variable-thickness windows to be placed in front of the corner cubes. Piezo-electric actuation was chosen to minimise power consumption. For convenience, a separate modulator was used in front of each reflector. A schematic view of the modulator structure is shown in the figure below.



Structure of phase modulator

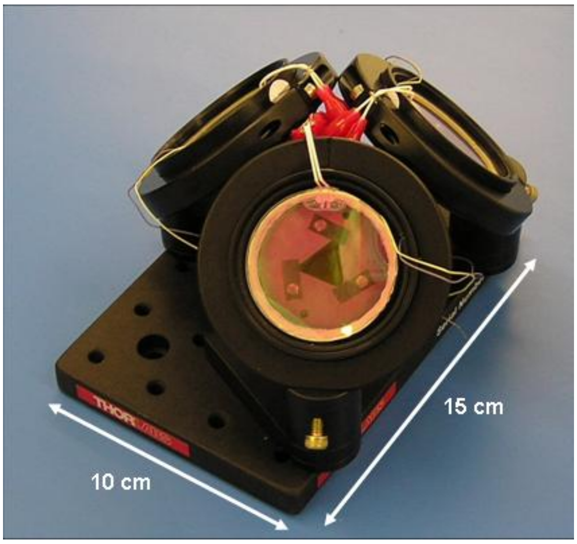
The simplicity of the structure permits very low polarisation and wavelength sensitivity, together with very low insertion loss. The single-pass, on-axis loss at the operating wavelength of 1320 nm was confirmed to be 0.13dB. Silicone oil was chosen as the filling fluid as it offers a very wide temperature range between its freezing and boiling points (-70^{o}C to > 120^{o}C), together with low viscosity, which was expected to benefit the frequency response of the device. The measured frequency response shows some structure due to non-optimally damped mechanical resonances in this simple design, but extends to approximately 450 kHz. The phase modulation coefficient varies across the useful frequency band from 0.02^o/V up to 0.25^o/V at normal incidence. Another benefit of this structure is that it provides increasing phase modulation amplitude for larger angles of incidence. This helps to compensate for the inevitable reduction in retroreflection efficiency of the corner cubes with increasing angle of incidence.

Corner cubes

Gallium phosphide was identified as being potentially useful for fabrication of corner cubes with adequate field of view for the retromodulator array [3,4]. The refractive index is 3.07 at 1320 nm. This leads to a power penalty in the far field of just under 7.6dB at 45^o angle of incidence and 13.2dB at 63.4^o. These power penalties should be acceptable within an overall power budget, if compensations could be made elsewhere in the system design.

Retromodulator array

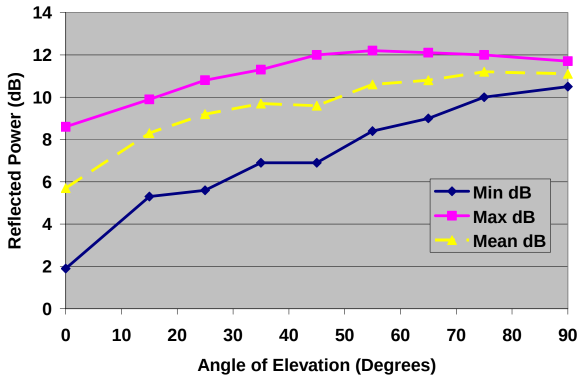
A retromodulator assembly was constructed by mounting a phase modulator directly in front of a corner cube. The mechanical structure was made from standard catalogue parts, with no attempt at this stage to miniaturise the overall size. An array of three retromodulators was then built, with an angular spacing between each of 120^o in the plane of the mounting base. The axis of each retromodulator was set at 45^o to the plane of the base in order to optimise performance over a hemispherical field of view. The finished array is shown here.



Three-element retromodulator array
Coherent system demonstration

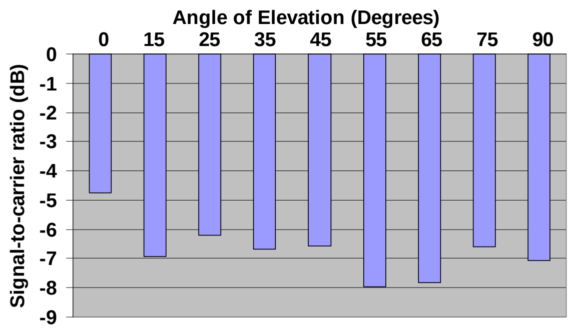
A coherent system demonstration was performed over a range of ~30m using an existing 1320nm coherent laser transceiver. The range was limited by the transceiver design and site availability and not by the performance of the retromodulators.

The projected beam was set to diverge in order to cover the entire retromodulator array, which was mounted on a motorised rotating platform with controllable elevation of the platform plane. Data was recorded for full rotations of the array at a range of different platform elevations from 0^o-90^o with respect to the line of sight to the transceiver. The power reflection performance of the array was first measured using an optical power meter placed immediately in front of the coherent receiver. Retroreflected power was detected for all orientations of the array within a hemispherical field of view. The figure below shows the minimum and maximum instantaneous received powers in dB referred to an arbitrary reference level, for a full set of angles of elevation. The signal variation reduces as expected when the angle of elevation of the plane of the rotating platform is increased from 0^o to 90^o. The difference between the best and worst possible reflected powers within the entire hemispherical field of view is 10dB.



Reflected power variation with angle of elevation of retromodulator array

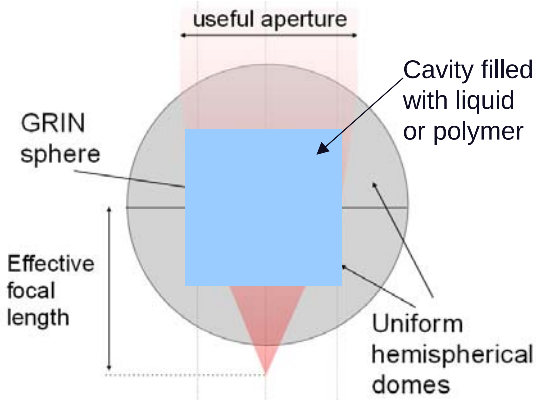
Finally, the modulation performance was measured in order to confirm the overall communication capability of the array. The phase modulators were driven at a frequency convenient for the existing transceiver, 18.1 kHz. The intermediate frequency waveform from the coherent receiver was captured and processed in software to generate spectrograms of the received signals. Modulation sidebands were seen around Doppler-shifted carrier signals from each corner cube reflector. Strong short term variations due to speckle were reduced by post-processing, including threshold and moving-average computation in appropriate frequency bands and rotation ranges. Results are shown below as mean sideband-to-carrier ratios for each elevation. The results confirm the wide field of view of the modulators and also tend to support the expectation of improved modulation amplitude at higher angles of incidence.



Variation of mean sideband-to-carrier ratios with angle of elevation of array

GRIN-sphere lenses

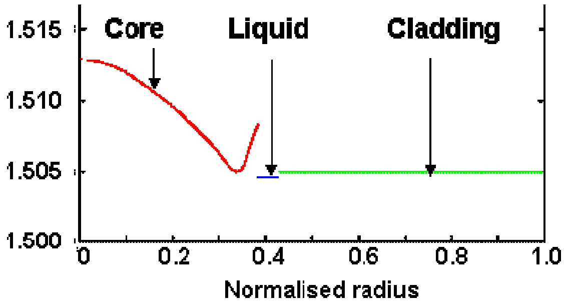
The potential advantages of using graded-index sphere lenses for retroreflective communication are also being examined. Experimental GRIN-sphere lenses have been fabricated through diffusion and ion-exchange in glass. The low aberration of the GRIN-sphere lenses was intended to be produced by using a variation on a Luneberg index profile [5]. This requires the graded-index core to be clad by a layer of uniform index. The structure chosen offsets the spherical aberration produced by the cladding layer against that produced by the core [6]. The lens was planned to be assembled from three pieces, with the central graded-index sphere located inside two hemispherical domes and an intermediate layer of a refractive index selected to provide minimum overall spherical aberration. A diagram of the lens structure is shown in the figure below, together with the lens design parameters.



Feature	Value
Physical diameter	25.4 mm
Effective aperture diameter	13.2 mm
Effective focal length	17.35 mm
Optical performance	Diffraction limited
Operating wavelength	1320 nm

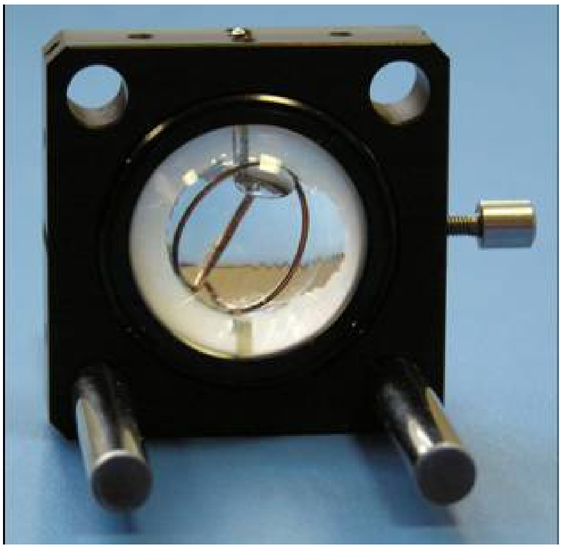
GRIN-sphere lens structure and design parameters

Suppliers of graded index components provided specialist assistance with optical materials design, fabrication and supply [6,7]. A representative refractive index profile of the lens assembly at 1320nm is shown below.



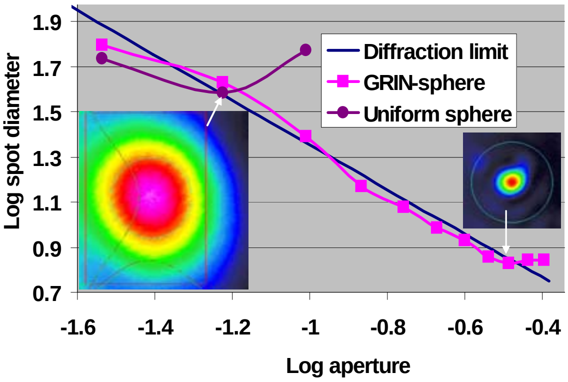
Measured refractive index profile of experimental GRIN-sphere

Cladding hemispheres were assembled with the GRIN-sphere core using a wire spacer and circular mounting rings to hold all three elements precisely concentric with respect to each other. Finally, the cavity was filled with refractive index liquid. The figure below shows the complete, mounted assembly.



Practical GRIN-sphere assembly

Using a ray tracing analysis, the lens was predicted to have diffraction limited optical performance over 28% of its physical aperture at 1320nm. Measurements of the variation of the focussed spot size against aperture either met or slightly exceeded the performance predictions. Example results are shown below, together with those for a uniform sphere of the same size for comparison.



Measured transverse spherical aberration

Based on the measurement results, the diffraction limited aperture expressed in conventional lens terminology is f/2.2. The physical aperture is very similar to that of the high index corner cubes made in this work. Also, the achieved performance is within a factor of two of the best theoretically possible with the materials used and should allow retroreflective communication over four times greater range than would a uniform sphere lens made from the cladding glass only.

Conclusions

This paper reports the development and testing of novel retroreflectors and optical phase modulators for use in retroreflective optical communication systems. For the first time, practical measurements on a three-element retromodulator array based on high index corner cubes confirm a planned hemispherical field of view. Graded-index sphere lens structures have shown promise for making low-cost retromodulators compared to those using corner cubes, as well as providing performance benefits. Diffraction-limited optical performance has been produced in these lenses for the first time, with apertures similar to those of the corner cubes used in this work. With these GRIN-sphere lenses, retroreflective communication range would be quadrupled compared to a uniform sphere lens of the same size.

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