

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

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Abstract

This paper reports the development of novel retroreflectors and optical components for use in optical communication systems designed to have a minimum of complexity at the remote end of an optical link. Practical measurements on initial samples of high index corner cubes and graded-index sphere lens structures have shown encouraging optical performance. The key property of GRIN-sphere lenses is that they can in principle suppress the most problematic feature of sphere lenses, that is, their strong spherical aberration. A ten-fold reduction in spherical aberration compared to a homogeneous sphere lens is predicted for an initial lens design.

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

Introduction

This paper reports the development of retroreflectors for use in optical communication systems designed to have a minimum of complexity at the remote end of an optical link. Applications include surveillance and asset tracking using small, low signature, low cost, remote sensor or tagging nodes. When retroreflective optical tags are used on vehicles or personnel, IFF capabilities will also be possible.

The feasibility and theoretical performance limits of possible systems have previously been established by considering optical power budgets and technical features of major system components [1-3]. It will be particularly important for the retroreflectors to have a very wide field of view to make such systems practicable and affordable. In a previous paper [3], analytical work showed that retroreflectors based on graded-index, spherical (GRIN-sphere) lenses can offer valuable technical advantages if they can be fabricated with

good quality, in suitable sizes and relative apertures. The conclusions from the power budget analysis indicated that lens apertures of at least one centimetre will be required to support optical communication ranges of kilometre order. The key property of GRIN-sphere lenses is that they can in principle suppress the most problematic feature of sphere lenses, that is, their strong spherical aberration. However, lenses of the required size and quality have never been fabricated, to the authors' knowledge.

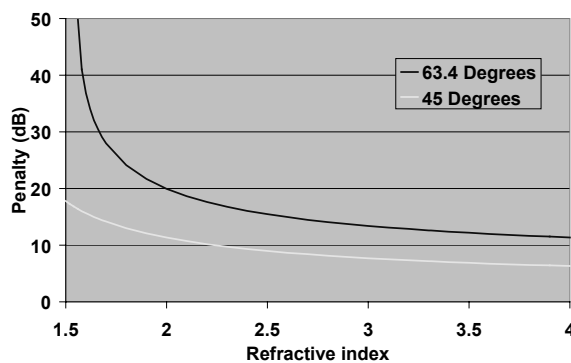
Corner cube retroreflectors represent a potentially more practical alternative to the use of GRIN-sphere lenses, but must be made from material which has a very high refractive index in order to meet the requirement for a wide field of view. This requires the use of materials with refractive index larger than that of any available optical glass. It is therefore necessary to examine whether this type of reflector can be produced with sufficiently low cost and high performance to be considered for use in commercial systems.

Corner-Cube Reflectors: Choice of Material

In order to choose the material from which suitable corner cubes should be made, the reflection performance at the edge of the field of view was considered. As the angle of incidence is increased from zero, the reflection efficiency will always reduce and will produce some power penalty which will vary with both the angle of incidence and the index of the body of the reflecting prism. In the figure below, the magnitude of this penalty is plotted as a function of refractive index for two particular angles of incidence near the edge of the field of view which might be required from a single retroreflector. The curves are predicted from the formula given below [3]:

$$\frac{P(\theta)}{P(0)} = \left(1 - \sqrt{2} \tan \phi\right)^2 \left(1 - \frac{\sqrt{2}}{3} \tan \phi\right)^2 \cos^2 \theta$$

where $P(0)$ is the on-axis reflected power, ϕ is given by $\phi = \sin^{-1}\left(\frac{\sin \theta}{n}\right)$ and n is the refractive index of the material of the corner cube.



Power penalty relative to on-axis reflection versus refractive index for corner cube reflectors at two different angles of incidence

The figure shows that the power penalty for an angle of incidence of 63.4 degrees exceeds 20dB for a refractive index of 2, which is approximately the highest index available from commercial optical glass

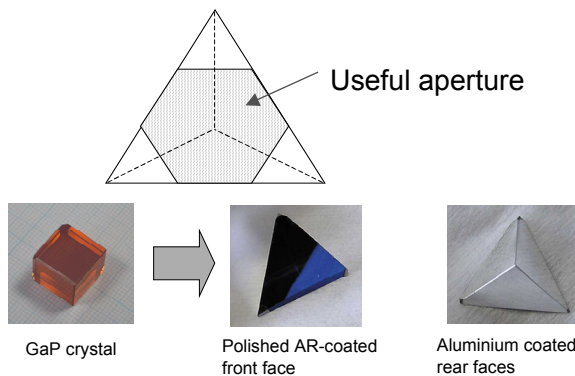
catalogues. Even for a refractive index of 4, which might be provided by a Germanium prism for wavelengths between about $2\mu\text{m}$ and $15\mu\text{m}$, the penalty is still greater than 11dB. If the maximum angle of incidence is constrained to be no greater than 45 degrees, the power penalty becomes more acceptable, but is still greater than 11 dB for a refractive index of 2. However, gallium phosphide was identified as being potentially useful. This material is usable through most of the visible region and for wavelengths up to about $4\mu\text{m}$. The refractive index is 3.31 at 633 nm. This leads to a power penalty of just under 7.2dB at 45 degrees angle of incidence and 12.6dB at 63.4 degrees. These power penalties might be acceptable within an overall power budget, if compensations could be made elsewhere in the system design.

Corner cubes: Practical Tests

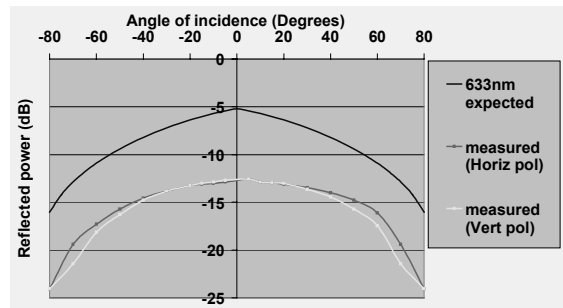
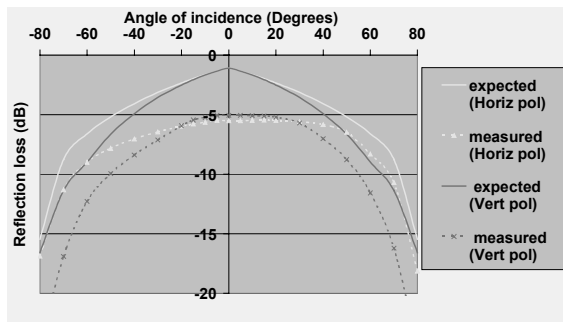
An experimental corner cube was made from gallium phosphide in order to confirm theoretical predictions and material suitability. A corner was cut from an undoped gallium phosphide cube of approximately 1 cm height and the cut face was polished to optical quality. A single layer anti-reflection coating was deposited on this face and the three rear faces were metallised in order to avoid reliance on total internal reflection at the largest angles of incidence. The useful aperture of the reflector was hexagonal, 10.6 mm across the opposite points, as shown in the figure on the next page. The figure also shows photographs of the starting cube and the finished front and rear faces.

Measurements of reflection efficiency were made at 633 nm and 1320 nm as a function of the angle of incidence on the front face of the cube. The antireflection coating was optimised for 633nm and was confirmed to provide less than 0.5% reflectivity at all angles of incidence up to 70 degrees. This coating was less effective at 1320nm and

led to a stronger polarisation dependence in the retroreflection measurements at this wavelength.



Practical Gallium Phosphide corner cube



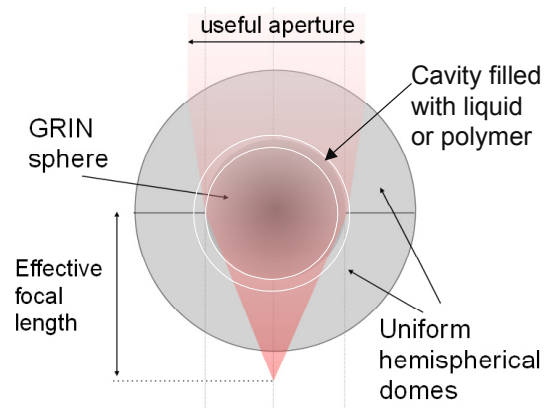
Reflection efficiency of Gallium Phosphide corner cube at 1320nm (upper curves) and 633nm (lower curves)

The measured results approximately confirm the shape of the theoretical variation of reflection efficiency with the angle of incidence. The expected on-axis losses were calculated from measured propagation losses in the gallium phosphide material itself. However, significant discrepancies exist between the expected and measured on-axis performance at both wavelengths. This was found to be due to

the use of the aluminium reflective coating on the rear faces of the cube. Subsequent diagnostic measurements and theoretical analysis showed that the optical behaviour of the interface between aluminium and gallium phosphide account for the observed losses to ~1dB accuracy. Future corner cubes will use different coating materials on the rear faces for better performance.

GRIN-sphere lens

Several possible approaches were considered for fabrication of experimental GRIN-sphere lenses. The approach selected for trial fabrication is based on 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 [4]. This requires the graded-index sphere to be clad by another of uniform index. This structure uses the spherical aberration produced by the cladding layer to counterbalance that produced by the core, a concept originated by Kikuchi [5]. The lens was accordingly planned to be assembled from three pieces, with the central graded-index sphere located inside two hemispherical domes, with an intermediate layer of a refractive index selected to provide minimum overall spherical aberration. A diagram of the proposed structure is shown in the figure below.



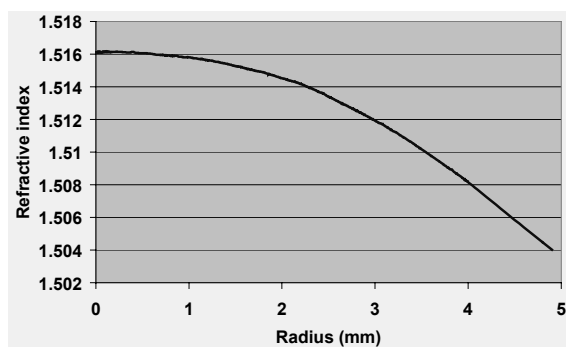
Proposed GRIN-sphere structure

The design was guided by the key performance requirements, including the physical diameter, relative aperture and operating wavelength of the lens. The resulting design parameters are given in the table below.

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 design parameters

Suppliers of graded index components were selected to provide specialist assistance with optical materials design, fabrication and supply [6,7] and experimental components were procured. A representative refractive index profile of an experimental GRIN-sphere is shown in the figure below. This was measured at 633nm, but the profile shown has been adjusted using the known dispersion of the glass to provide an estimate of the profile at 1320nm.



Measured refractive index profile of experimental GRIN-sphere

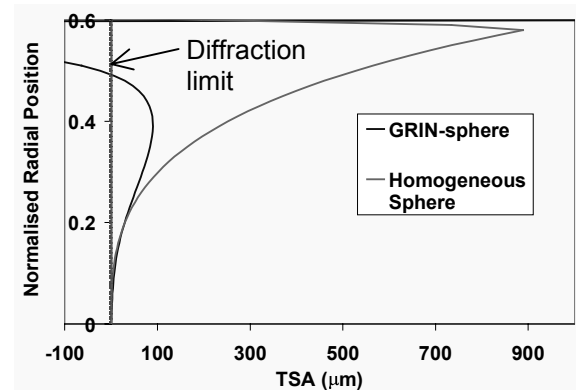
Cladding hemispheres were made from BaLKN3 glass and were assembled with the GRIN-sphere having the index profile

shown above. The figure below shows a partial assembly of one hemisphere with the GRIN-sphere, and the complete, mounted assembly including a spacer element to hold the sphere precisely concentric with the cladding structure.



Practical GRIN-sphere: Partially assembled lens (left); Complete, mounted assembly with spacer (right)

The optical performance of the finished lens at 1320nm was predicted using a ray tracing analysis. This facilitated an optimum choice of refractive index for the region between the graded index core and the cladding. The resulting prediction of transverse spherical aberration at 1320nm is plotted in the figure below as a function of the distance of an incoming ray from an axis passing through the centre of the sphere.



Predicted transverse spherical aberration

In the above figure, the vertical axis is scaled according to the radial position of incident rays as a fraction of the outer diameter of the cladding. Examination of these performance predictions shows that this initial GRIN-sphere lens should possess approximately ten times less transverse spherical aberration than a uniform sphere lens made from the cladding glass only. However, the thick line drawn over the vertical axis shows the extent of the aberration permissible for the diffraction limited case. The refractive index profile of the core must be improved in order to approach this limit more closely.

Conclusions

This paper reports the development of novel retroreflectors and optical components for use in optical communication systems designed to have a minimum of complexity at the remote end of an optical link. Practical measurements on initial samples of high index corner cubes and graded-index sphere lens structures have shown encouraging optical performance. Future work will incorporate developed versions of these components together with novel modulator components in experimental retroreflective optical links.

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