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Abstract: In this paper we report on the development and optical properties of nanostructured gradient index microlenses with good chromatic behavior. We introduce a new fabrication concept for the development of large diameter nanostructured gradient index microlenses based on quantized gradient index profiles and the use of nanostructured meta-rods. We show a dependence of the quality of performance on the number of refractive index levels and the lens diameter. Measurements carried out at 633 and 850nm show good optical properties and similar focal lengths for both wavelengths.

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References and links


1. Introduction

Gradient index (GRIN) components are a class of planar-surface micro-optical elements which produce the desired optical functionality by changes in the refractive index...
perpendicular to the optical axis [1]. The planar nature of GRIN lenses makes them an attractive approach for compact optical systems, since they can be easily integrated with fibers, detectors, sources and other micro-optical components [2]. In particular, they have been used successfully in the fields of optical sensing, optically interconnected computing and endoscopy [2–4].

There are several well-known standard methods of GRIN microlens fabrication (e.g. ion exchange, chemical vapour deposition (CVD), neutron irradiation) but they suffer from several drawbacks with the inaccuracy of the refractive index distribution being the most significant [1,5]. In addition, the gradient of refractive index achievable with the standard GRIN fabrication techniques is very limited, typically of the order of $\Delta n \sim 0.1$ per 250 $\mu$m [6]. A 1D multilayer GRIN, developed using chemical vapour deposition, has been demonstrated with a refractive index gradient of $\Delta n = 0.25$ per 6.5 $\mu$m [7].

Recently we have introduced a technology which allows the fabrication of 2D gradient index lenses with internal nanostructures and a very high gradient of refractive index [8]. These nanostructured micro-lenses are fabricated using a modified 'stack and draw' technique, similar to that commonly used for photonic crystal fiber manufacture. This method allows the creation of extremely large refractive index gradients ($\Delta n = 0.2$ per 5 $\mu$m). We have also demonstrated that a more general (i.e. non-radial) shaping of the refractive index distribution is possible. The successful fabrication of an elliptical lens has been reported [9] with diffraction limited performance. The functionality of the nanostructured GRIN lens can be described using standard gradient index models [10]. However it should be noted that the fabricated microlenses reported in recent works [8,9] were of a limited diameter (up to 20$\mu$m) which radically limits their area of application. These initial micro-lenses were fabricated using conventional preform assembly techniques, where individual rods (~10000 for a 20$\mu$m lens) of the basis glasses are placed in the appropriate pattern. Use of this technique to assemble a 100$\mu$m diameter lens is not feasible, as it would require the manual placement of 100,000-250,000 individual glass rods. However, the advent of robotic preform assembly methods may make this direct nanostructuring approach practical in the future.

In this paper we present our new approach to the fabrication of large diameter quantised gradient lenses with internal nanostructure. We compare the performance of the quantised nanostructured lens against an ideal continuous one. The fabrication method is reported and the focusing properties are measured for various wavelengths.

2. Design of quantised nanostructured gradient index lens

A nanostructured microlens consists of a matrix of parallel subwavelength glass rods of differing types. In the case considered in this paper, each of the two types is made from one of two glasses with different refractive indices that are thermally and mechanically matched. The rods are stacked according to a predetermined pattern and the subwavelength diameter of the rods produces a quasi-continuous distribution of effective (averaged) refractive index within the structure. The design algorithm uses the first order Maxwell–Garnet formula [11] where the effective refractive index of a certain point is calculated by averaging the refractive indices around that point (on the scale of the wavelength of incident light). The rod distribution is optimized by simulated annealing using a cost function which measures the difference between a target refractive index distribution and the current distribution of the effective refractive index. The design algorithm is described in [8] and the fabrication is based on the mosaic technique [12].

As a test structure, we selected a GRIN lens with a diameter of 100$\mu$m and a minimum and maximum refractive index of 1.5212 and 1.6068 respectively. An ideal GRIN lens of this diameter and refractive index gradient has a radial refractive index distribution given by

$$n = n_0 \left(1 - \frac{A}{2} r^2 \right)$$
and a gradient index constant \( \sqrt{A} \) of 6.53 1/mm, a full pitch length (distance for one full sinusoidal ray path = \( 2\pi / \sqrt{A} \)) of \( Z_{L} = 963\mu m \), a maximum acceptance angle of 63.3 degrees and an effective quarter pitch focal length \( (1/n_{0}\sqrt{A}) \) of 95.3µm. The f-number of the lens is \( f# = 1.05 \) and a diffraction limited focal spot of 1.97µm is expected for an illumination wavelength of 850nm assuming a near-axis approximation [1].

As mentioned above, the number of refractive index levels in the designed lens is restricted. To compare the performance of the designed lenses against an ideal lens we have performed a set of simulations using the fast Fourier transform beam propagation method (FFT BPM) [13].

![Diagram](image1.png)

**Fig. 1.** (a) Schematic of quantised nanostructured GRIN microlens consisting of 101x101 "pixels" with one of 7 discrete effective refractive index level structures formed by a nanostructured composite of two soft glasses. (b) Ideal continuous GRIN microlens.

The fabrication of nanostructured lenses with 32 refractive index levels would be extremely time consuming, impractical and not cost-effective. The practical technological limit of the proposed method is seven refractive index levels (Fig. 1) and to determine the maximum lens diameter capable of producing an acceptable lens, we investigated the variation of lens performance with decreasing lens diameter. The results of these simulations (Fig. 2) imply that the maximum lens diameter for good optical performance is on the order of 140-200µm.

![Diagram](image2.png)

**Fig. 2.** Improvement of focusing for a 7 refractive index level nanostructured GRIN microlens with a reduced diameter of (a) 500µm, (b) 250µm and (c) 140µm. Focusing behaviour of ideal continuous GRIN lenses with diameters of (d) 500µm, (e) 250µm and (f) 140µm. The wavelength of light is 850 nm.
3. Development of large nanostructured lens

Fig. 3. Structured GRIN microlens composed of 100x100 nanostructured rods of 7 types

The initial test nanostructured lens design was created using a hexagonal lattice of 100x100 nanostructured rods (metarods) ordered as shown in Fig. 3. Each of the metarods has a diameter of 1.2 µm and is composed of 50x50 rods of 20 nm diameter. There are 7 different types of metarod composed of different fractions of the glasses (NC21 and F2) to obtain different effective refractive indexes at a design wavelength of 850 nm. The effective refractive indices of the metarods are linear between \( n_1 = 1.5212 \) (pure NC21 glass) and \( n_7 = 1.6068 \) (pure F2 glass). Five of the seven rods were fabricated using the two fundamental glasses NC21 and F2 according to a pre-calculated pattern to ensure a uniform effective refractive index within every nanostructured rod (Fig. 4). NC21 is a silicate glass synthesized in-house at the Institute of Electronic Materials Technology (ITME) in Warsaw (\( n_{d,\text{NC21}} = 1.5212 \)). Both the NC21 and F2 glasses are thermally matched to allow a joint thermal transformation within the optical fiber drawing tower. The weight compositions of the NC21 and F2 glasses are as follows: SiO\(_2\) = 55.0%, Al\(_2\)O\(_3\) = 1.0%, B\(_2\)O\(_3\) = 26.0%, Li\(_2\)O = 3.0%, Na\(_2\)O = 9.5%, K\(_2\)O = 5.5%, As\(_2\)O\(_3\) = 0.8%, and SiO\(_2\) = 45.7%, PbO = 45.5%, Na\(_2\)O = 3.5%, K\(_2\)O = 5.0%, As\(_2\)O\(_3\) = 0.8%.

Fig. 4. Structures of five metarods composed of two fundamental glasses NC21 and NC25 according to the calculated pseudo-random pattern to ensure a uniform effective refractive index within each of the 5 nanostructured rods.

The nanostructured rods were fabricated by a stack and draw method using an optical fiber drawing tower in following manner:

1. Drawing of individual calibrated rods (1 mm diameter) of both thermally matched glasses - NC21 and F2 (Fig. 5(a)).

2. Assembly of 5 metarod preforms according to the calculated patterns (Fig. 4). Preforms are hexagonal without an outer tube (Fig. 5(b)).

3. Drawing of the series of metarods with a diameter of 0.5 mm (Fig. 5(c)).
Fig. 5. Schematic of the development of metarods: drawing of calibrated rods (a), assembly of hexagonal metarod preform (b), drawing final metarods (c).

The nanostructured GRIN lens with was fabricated by a similar stack and draw method using an optical fiber drawing tower in the following steps:

1. Assembly of the preform with 7 types of metarod according to the calculated pattern (Fig. 3). Diameter of the metarods is 0.5 mm. The structure is embedded into an NC21 tube. The free space between the tube and the hexagonal lens structure is filled with additional NC21 rods (Fig. 6(a), 7(a), 7(b)).

2. Drawing of the preform on the fiber tower, into an intermediate preform with a diameter of 3 mm (Fig. 6(b)).

3. Assembly of the final preform. The rod with lens structure is embedded in a thick walled NC21 tube with an outer diameter of 30 mm (Fig. 7(c)).

4. Drawing of the final preform on the fiber tower into the final structure with diameter of 1 mm. The lens structure has a diameter of 100 µm (Fig. 7(d)).

5. Cutting of nanostructured rod into appropriate lengths (quarter pitch lenses or other) using diamond saw (Fig. 6(c)).

6. Polishing of optical surfaces of the fabricated elements with fiber optical powders (Fig. 6(d)).

Fig. 6. Schematic of development of nanostructured GRIN lens: (a) assembly of structured lens preform, (b) drawing lens preform, (c) cutting and (d) surface polishing.

Fig. 7. Development of nanostructured quantised GRIN lens: (a) assembly of prefrom with metarods, (b) final preform of lens structure with the diameter of 60 mm, (c) intermediate preform with the diameter of 30 mm and (d) final microlens with the diameter of 0.1 mm.
The measurement of the internal structure of the fabricated lenses is difficult due to the very small feature size and low refractive index contrast of the structure. The use of standard methods for the measurement of phase shifts cannot be applied due to the small feature sizes within the microlens [14]. The final fabricated lens structure was verified with a phase contrast microscope (Fig. 8). A clear image of the ring structure that corresponds to the various effective indices is obtained. The diameter of the fabricated lens is 140µm.

![Fig. 8. A phase contrast microscope photo of developed nanostructured GRIN lens](image)

4. Numerical verification of performance of developed lens

Based on the design and final diameter of fabricated lens we have performed an FFT BPM simulation to verify the expected performance of the fabricated lens. The simulations were performed at a wavelength of 850nm. To identify the quarter pitch of the fabricated lens, we have performed simulations of light propagation through an infinite rod lens with a diameter of 100µm. The quarter pitch of the nanostructured microlens was determined to be 249µm (Fig. 9(a)) with a full width half maximum (FWHM) beam diameter at the focus of 0.7 µm (Fig. 9(b)). As a reference we performed simulations for a continuous (unquantized) lens with the same diameter. In this case the lens has a quarter pitch equal to 232µm (Fig. 10(a)) and a FWHM beam diameter at focus of 0.8µm (Fig. 10(b)). The relatively small difference between the two lenses shows that we can expect the nanostructured lens to perform in an almost identical manner to the ideal lens. It should be noted that the Airy rings are less intense in the case of the quantised lens (Fig. 9(b)) with respect to the ideal one (Fig. 10b)). This denotes a degradation of the expected performance of the nanostructured lenses with respect to ideal lenses. In practice, the properties of the fabricated nanostructured lens should be better than that observed in the simulations, due to the presence of sharp refractive index differences on the borders between various quantised levels in the simulations. In the fabricated structures diffusion processes between the glasses result in “fuzzy” border transitions.

![Fig. 9. Propagation of light within infinite quantised nanostructured lens with diameter of 100 µm: (a) the cross-section along optical axis, (b) cross-section at focus perpendicular to the optical axis. Simulations are performed for 850 nm.](image)
The measurements presented in section 5 were performed using a lens with a thickness of 140 µm and simulations to identify the working distance for this length of lens were necessary. In addition, the simulations allow a prediction of the diameter of beam at focus to be made. The working distance of nanostructured quantised microlens was determined to be 65 µm (Fig. 11(a)) with a FWHM beam diameter at the focus of 0.9 µm (Fig. 11(b)). As a reference, the ideal continuous (unquantized) lens with similar parameters of diameter and wavelength has a working distance equal of 68 µm (Fig. 12(a)) and a FWHM beam diameter at focus of 1.0 µm (Fig. 12(b)).

The FFT BPM method has permitted the calculation of the chromatic properties (at 633 nm) of the 140 µm long nanostructured lens with a diameter of 100 µm to be made. In the
case of the quantised nanostructured lens, the working distance is 60 \mu m (Fig. 13(a)) with a FWHM beam diameter at the focus of 0.6 \mu m (Fig. 13(b)). As a reference, an ideal continuous (unquantized) lens with similar parameters of diameter and wavelength has a working distance equal to 63\mu m (Fig. 14(a)) and a FWHM beam diameter at focus of 0.7\mu m (Fig. 14(b)).

In summary, the simulations show that the fabricated nanostructured lenses, with a diameter of 100 \mu m and a length of 140\mu m, will have optical performance similar to that of an unquantized ideal lens. The working distance will lie within 5% of that of the ideal lens and there will be a variation of around 9% over a wavelength range of 200nm (633nm – 850nm).

5. Experimental results

In order to characterise the focusing properties of the microlens, the apparatus presented in Fig. 15 was used. The set-up consists of an infrared diode laser, multimode fibre (core diameter 50\mu m) fitted with a collimation package optimised for 850nm, ND filters, mirrors and a linear CCD camera COHU (4910 Series) fitted with a tube and microscope objective (Fig. 16). The camera works with a fixed gain in the linear regime and is mounted on a computer controlled 2-axis translation stage. A x40 microscope objective with a numerical aperture of NA = 0.65 was used. The experiment was performed with 3 sources in the setup with wavelengths of 532 nm, 633 nm and 850 nm. The diameter of every laser beam behind collimation package is about 10mm.

We have determined the beam diameter at the focus based on the 2D image obtain with the CCD camera. The translation resolution of this measurement is \pm 1 \mu m. We used the criterion of the full width in half maximum (FWHM) to determine the diameter of a beam. The focal plane of the lens was determined by scanning with CCD along the optical axis. The
computer controlled translation stage has a submicron precision and the error for the measurement of the distance between subsequent steps is below 1 µm. The error in the position of the output facet of the microlens, which is used in the determination of the working distance, is larger and is estimated to be ± 10 µm.

![Image](image1.png)

Fig. 15. Measurement set-up (a). Typical output image of the measured lens imaged at the lens focus captured by linear CCD camera (b). Scattering at lens border can be observed.

The observed intensity distributions in the focal plane show that the focal spot has an approximately elliptical shape. This can be explained by the well known phenomenon of elliptical focusing of a linearly polarised beam \[15\]. For the 850 nm illumination we have obtained a working distance of 34 µm, with a beam diameter of 0.9 µm and 1.3 µm along X and Y axis respectively. The intensity profiles in the focal plane along the X and Y axes are shown in Fig. 16. The intensity distributions in the planes perpendicular to the optical axis just before and just after the focal plane are presented in Fig. 17. It can be seen that the shape of the central spot is irregular and some scattering around the central spot is present in each of the images.

![Image](image2.png)

Fig. 16. (a) The intensity distribution in the focal plane at working distance of 34 µm for linearly polarized laser beam at the wavelength of 850 nm. Intensity profiles along (b) X and (c) Y axis are also shown.

![Image](image3.png)

Fig. 17. Intensity distribution for wavelength of 850 nm in the plane perpendicular to the optical axis at a distance of (a) 30 µm, (b) 32 µm, (c) 34 µm, (d) 36 µm and (e) 38 µm from the output facet of the microlens.

A similar series of measurements were performed for a wavelength of 633 nm. The observed working distance was 40 µm with a beam diameter at the focus of 0.9 µm and 1.2 µm along the X and Y axes respectively. The intensity profiles in the focal plane along the X and
Y axes are shown in Fig. 18 and the intensity distributions in the planes perpendicular to the optical axis just before and just after the focal plane are presented in Fig. 19.

Fig. 18. (a) The intensity distribution in the focal plane at working distance of 40 µm (a) for linearly polarized laser beam at the wavelength of 633 nm. Intensity profiles along (b) X and (c) Y axis are also shown.

Fig. 19. Intensity distribution for wavelength of 633nm in the plane perpendicular to the optical axis at a distance of (a) 36µm, (b) 38µm, (c) 40µm, (d) 42µm and (e) 44µm from the output facet of the microlens.

Finally the same measurements were performed for a wavelength of 532 nm. In this case the exact position of the spot could not be determined. A central spot surrounded by a large number of relatively bright randomly distributed scattered spots was observed. This behaviour may be related to the nanostructured origin of the quantised lens. The minimum feature size of the fabricated lens is too large with respect to the illumination wavelength to ensure proper performance.

The experimental results confirm the expected optical performance of the fabricated lens. The focal spot diameter is similar to that predicted for 850nm illumination and of the same order for 633nm. However for 633nm illumination, this is larger than that predicted by the theory and simulation. This may be due to the resolution of our optical measurement system with the nanostructured origin of the quantised lens also playing a role. The slightly elliptical shape of observed focal spots is due to the linear polarization of the incident light [15]. The observed working distances are approximately 50% smaller that those predicated by theory. This is primarily due to the accuracy of our measurement system and the difficulties associated with determining precisely the surface and total diameter of the lens – a process which is more complicated for the infra-red wavelength measurements and accounts for the apparent discrepancy between the simulations and experimental results. By assuming we have a systematic error in the measurement of the working distance as well as in the measurement of the overall lens diameter, the difference in working distances obtained for both the 633nm and 850nm illumination are in good agreement with predicted values.

7. Conclusions

The design and fabrication of nanostructured microlenses, where a quasi-continuous refractive index gradient is produced by means of a nanometre scale composite of two mechanically and thermally compatible soft glasses, has been successfully demonstrated. The quantised approach, where a set of discrete refractive index structures are created and then combined to create a quantised refractive index profile, has been used to design a 7 level lens. The
practical limit of the proposed method for the development of nanostructured GRIN microlenses was calculated, through simulation, to be 140 µm for 7 refractive index levels.

The fabricated lens shows good focusing properties with focal spot diameters of 0.9 x 1.2 µm at the focus. This is in very good agreement with the simulated results for similar nanostructured lens designs. The working distance of the lens was observed to be 34 µm and is 50% shorter than the working distance predicted by simulation. This difference is due to both systematic errors in the measurement setup as well as difficulty in determining the position of the transition between the final lens ring and the surrounding bulk material. In the fabricated lenses, the transitions between all the zones will be more gradual than in the discrete simulations and the precise diameter of the lens is therefore more difficult to determine accurately. The chromatic properties of the lens have also been verified with the fabricated lens showing good performance at both 633 nm and 850 nm. The working distances for 633 nm and 850 nm were observed to be 40 µm and 34 µm, respectively, while the focal spot sizes remain unchanged.

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