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Achromatic nanostructured gradient index microlenses

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Abstract: We present a development of microlenses achromatically corrected in near-infrared spectral windows. We show that the standard fiber drawing technology can be successfully applied to the development achromatic gradient index microlenses by means of internal nanostructurization. These gradient index microlenses can achieve similar performance to standard aspheric doublets, while utilizing a simpler, singlet element geometry with flat surfaces. A nanostructured lens with a parabolic profile was designed using a combination of the simulated annealing method and the effective medium approximation theory. Measurements on the fabricated lenses show that the microlenses have a nearly wavelength-independent focal plane at a distance of about 35 μm from the lens facet over the wavelength range of 600–1550 nm. The successful design and fabrication of achromatic flat-parallel rod microlenses opens new perspectives for micro-imaging systems and wavelength-independent coupling into optical fibers.

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1. Introduction

Achromatic lenses are highly desirable for both imaging systems and beam manipulation tasks. It is well known that singlet refractive lenses cannot be achromatic (Fig. 1(a)) due to the dispersive nature of all known glass materials the chromatic aberrations cannot be compensated by any shape of lens. A standard approach for achromatic behavior is the development of the doublet (Fig. 1(b)) composed of elements with different dispersion characteristics [1,2]. This configuration allows the optical parameters to be adjusted such that the axial chromatic aberrations exactly vanish for two wavelengths. By using a larger number of lenses e.g. triplet lenses, and combining three or more different materials it is possible to make a so-called apochromatic (apochromat) and superachromatic lens, where the chromatic aberrations vanish for three and four different wavelengths respectively [3] (Fig. 2).

Fig. 1. Examples of lenses: a) simple lens, b) achromatic lens doublet, c) hybrid diffractive-refractive achromatic, d, e) achromatic refractive GRIN singlet.
Fig. 2. Scheme of chromatic aberration for four types of lens. The focal lengths vary in different ranges for the different types of lenses. Typically, the variation of the focal length of a simple lens will be much larger than the variation of the focal length for various achromatic lenses.

All the solutions, described above, to eliminate chromatic aberrations are based on multi-element lens systems. However, a few works have discussed methods to create singlet-type achromatic lenses. Flynn et al. proposed to fabricate a hybrid diffractive-refractive achromatic lens, where a refractive lens made of homogenous material, is combined with an additional diffractive Fresnel lens [4] (Fig. 1(c)). In the several theoretical works the methods for development of achromatic gradient index (GRIN) lenses were also discussed [5–12]. There are considered GRIN lenses with non-homogenous material distribution either continuously along the axis of propagation – the axial gradient refractive index (GRIN) [5–7] (Fig. 1(d)) or continuously as a function of distance from the optical axis in a perpendicular plane – the radial GRIN [7–9] (Fig. 1(e)). Some of the proposed solution show a feasibility of development lenses made of 2 materials with spherical surfaces [10] or lenses made of 3 components with spherical or flat surfaces [11,12]. The GRIN lenses with at least one non-flat surface are difficult to integrate these elements e.g. in fiber optic systems. Moreover, the proposed solutions related to the distribution of refractive index required to obtain achromaticity are difficult to apply in micro-scale systems as microlenses. Therefore, up to now there are no reliable methods to develop achromatic microlenses.

The GRIN micro optical components are attractive due to their potential applications in imaging systems, fiber optics, laser collimation, and optical couplers. For those applications, there is a need for small-diameter, easily integrated microlenses. GRIN components are among the best solutions to achieve this since they exhibit inhomogeneous surface refraction and continuous bulk focusing [5]. They exhibit significantly more complex optical behavior than standard lenses, and are known to offer the potential for superior performance over traditional homogeneous optics [13]. However, the currently available GRIN lenses with flat front and back surfaces cannot been considered as achromatic components due to the lack of precise control over the dispersions of their constituent materials.

In previous years, infrared homogeneous achromatic doublets have been reported [14], and the possibility of designing achromatic GRIN singlet macro-lenses and rod GRIN singlets was explored theoretically [15,16]. Until now, due to technological limitations, no achromatic macro-lenses have been reported. In this work we discuss new possibilities for shaping microlens chromatic properties using the nanostructurization approach proposed in 2009 [17]. This approach uses a free-form optical design, enabled by the stack-and-draw fabrication technique coupled with the effective refractive medium approximation (EMA). We focus on the near-infrared (NIR) applications [18] of such small systems. Our proposed approach offers a fully flat-parallel rod GRIN lens, which can be easily integrated as part of the optical fiber line. This is a design step forward in comparison to most of the current designs of
achromatic GRIN singlet macro lenses, which are not flat-parallel and cannot be used as microlenses [5,9,19]. Our proposed achromatic GRIN microlenses can be easily integrated with fiber optics and can be used in Dense Wavelength Division Multiplexing (DWDM) systems, in beam shaping, endoscopy imaging systems as well as in 3D imaging microsystems.

The concept of nanostructured optics is based on the Effective Medium Approximation (EMA), in which a nanostructured optical element is constructed of discrete sub-wavelength sized glass rods made of two, or more, different glasses. The boundary condition for the use of the EMA is defined as the diameter of the individual rods being below \( \lambda/(2\pi) \) of the wavelength of the propagating light [20]. When this boundary condition is fulfilled the whole structure acts like a continuous medium with an effective refractive index distribution equal to the spatially averaged index of the rods [17]. The effective optical properties of the optical elements depend on the precise pattern of the rods in the structure as well as the refractive indices of the rods. The process of the design of a nanostructured optical element begins with the determination of the desired refractive index distribution, which will be the target function for the design of the glass nanostructure distribution. We have already demonstrated the practical use of this method by fabricating parabolic GRIN microlenses [21], elliptical GRIN microlenses [22], axicon GRIN microlenses [23], diffractive optical elements (DOE) [24], birefringent artificial glass materials [25] as well as fibers with nanostructured parabolic refractive index profile cores [26].

Here, we report for the first time the chromatic properties of nanostructured GRIN (nGRIN) microlenses. A proof-of-concept microlens development and characterization results are also presented.

2. Analysis of chromatic properties of nanostructured GRIN microlenses

We study an innovative approach that allows the fabrication of an achromatic GRIN type microlens with flat surfaces on both sides (Fig. 3). In this approach we utilize a discrete array of rods made of two types of glasses with refractive indexes \( n_0 \) and \( n_1 \) (Fig. 4(a)), and apply the standard stack-and-draw fiber drawing technology [21,23]. As a result, we obtain a microlens with an effectively continuous refractive index profile with maximum and minimum refractive indices determine by the \( n_0 \) and \( n_1 \) glasses (Fig. 4(b)).
In this case, the chromatic properties of the fabricated element will be determined by the refractive indices of the individual glasses for a given wavelength (Fig. 4(c)). The refractive index on the optical axis is equal to the refractive index of the high index glass \((n_0)\), while the refractive index at the edge of lens is equal to the low index of the glass \((n_1)\). In the intermediate region, the effective permittivity is the weighted average of the permittivities of both glasses [20]. However, to simplify an algorithm for calculations of effective refractive index distribution in the nanostructured elements, we use an approximated formula where the effective refractive index is the weighted average of both refractive indices:

\[
 n_{\text{eff}} = \varphi n_0 + (1 - \varphi) n_1,
\]

where \(\varphi\) is the fill factor of \(n_0\) in a local neighbourhood.

![Fig. 4. Chromatic properties of nanostructured GRIN microlens: a) internal structure GRIN microlens with the radius \(r_{\text{max}}\) composed of low and high refractive index glass rods \(n_1\) and \(n_0\), respectively, b) effective refraction index distribution in nGRIN microlens with the radius \(r_{\text{max}}\), c) effective refractive index profile of nanostructured GRIN microlens for several wavelengths of light, \(n_0(\lambda)\) and \(n_1(\lambda)\) denote refractive indices in the center and at the edge of the nanostructured GRIN microlens for wavelength \(\lambda\).]

The standard GRIN lens has a parabolic refractive index cross-section with the radial dependence of the refractive index being given by the equation [27]:

\[
 n = n_0 \left(1 - \frac{A}{2} r^2 \right)
\]

where \(A\) is a gradient constant determined by the difference between maximum and minimum in refractive index, \(r\) is the distance from the optical axis (radial distance, units: mm), and \(n_0\) is the index of refraction at the centre of the element. The gradient constant \(A\) is defined as:

\[
 A = \frac{2 (n_0 - n_1)}{n_0 r_{\text{max}}^2} = \frac{2\Delta n}{n_0 r_{\text{max}}^2}
\]

where \(r_{\text{max}}\) is a maximum radius of the lens structure (Figs. 4(a) and 4(b)).
The focal length $f$ of GRIN lens depends on its length $L$ and can be expressed as [27]

$$f = \frac{1}{n_0 \sqrt{A} \sin \left( L \sqrt{A} \right)}$$

(4)

For practical reasons, in addition, a working distance (WD) parameter, also called the back focal length, is usually introduced [27]:

$$WD = f \cos \left( L \sqrt{A} \right)$$

(5)

By considering several pairs of hypothetical glasses with various material dispersion relations it is possible to obtain GRIN lenses with different focal lengths depending on the wavelength. The ideal lens devoid of axial chromatic aberration can be obtained when the difference in material dispersion for both basic glasses is constant across the considered wavelength range (Fig. 5(a)). In cases where the material dispersion difference for both glasses is a linear function it is not possible to obtain an achromatic GRIN lens (Figs. 5(b) and 5(c)). If, however, the difference between dispersions is given by a quadratic (Fig. 5(d)) or other higher-order function (Fig. 5(e)) it is possible to obtain an achromatic or apochromatic lens, respectively.

![Fig. 5. Analysis of chromatic properties for a nanostructured GRIN lens made of pairs of hypothetical glasses: a) $\Delta n = c$, ideal case for a lens with compensated axial chromatic aberration, b) $\Delta n = -c \lambda$, axial chromatic aberration is not compensated c) $\Delta n = -c + c \lambda$, axial chromatic aberration is not compensated d) $\Delta n$ has the form of a square function, case of achromatic lens, where axial chromatic aberration is compensated for two wavelengths e) $\Delta n$ achieves two extremes (the axes in an arbitrary units), case of apochromatic lens, where axial chromatic aberration is compensated for three wavelengths](image)

The red dots in the fourth column show the sample wavelengths for which the focal lengths are the same.

Next we consider a GRIN lens made of real glasses. In this case we consider the material dispersions of the selected commercially available glasses and GRIN lenses with a length of 100 $\mu$m. In this study, we ignore whether a given pair of glasses are thermally matched and therefore can be processed in an optical fiber drawing tower, which is necessary for the fabrication of a real nanostructured GRIN lens. Examples of the chromatic properties for lenses composed of selected pairs of glasses are presented in Fig. 6. In the first case we consider a GRIN lens is made of BASF51 and N-SF2 glasses from Schott [28] (Fig. 6(a)).
The lens is an achromatic, its focal length has a single maximum length at the wavelength 1.03 µm. In the second case we assume that the lens is made of LASF36A and N-SF64 glasses from Schott [28] (Fig. 6(b)). This lens is also an achromatic but its focal length reaches a single minimum. For the N-LAF2 and N-F2 glasses of Schott catalogue [28], the GRIN lens is an apochromatic since its focal length is the same for three different wavelengths (Fig. 6(c)). In the next case (Fig. 6(d)) we consider a lens made of H-K9L glass from CDGM [29] and S-BSL7M glass from Ohara [30]. For this lens, the axial chromatic aberration is compensated for 4 wavelengths. For some pairs of glasses it is also possible to compensate the chromatic dispersion for five wavelengths, as in the case of a microlens made of H-BAK6 glass from CDGM [29] and S-BAL41M glass from Ohara [30] (Fig. 6(e)).

In these cases, variations of the focal length in the broadband wavelength range 0.5-2 µm is below 0.1%. In practice the proposed microlenses are wavelength independent. On contrary, the superachromatic lens presented in Fig. 6(e) has a variation of nearly 2.3% for the focal length in the wavelength range 0.4-1.2 µm. However, it is important to note that the presented results are not a general conclusion. For microlenses with another set of geometrical parameters or glass systems we can obtain another results. The presented examples show that a combination of various glasses can lead to various chromatic properties of microlenses. In practical applications more important is minimum variation of the focal length with wavelength than superachromatic performance.

![Fig. 6. Theoretical analysis of chromatic properties of GRIN microlenses made of pairs of glasses: a) BASF51 and N-SF2, b) LASF36A and N-SF64, c) N-LAF2 and N-F2, d) H-K9L and S-BSL7M, e) H-BAK6 and S-BAL41M. The red dots denote sample wavelengths for which the focal lengths are equal. Calculations are performed for parabolic GRIN lens with diameter of 20 µm and length of 100 µm.](image-url)
3. Design and development of achromatic nanostructured GRIN microlenses

In order to design and fabricate a nanostructured GRIN lenses, it is necessary to use pair of glasses with good rheological properties and similar expansion coefficients as well as thermal properties, which allow joint thermal processing in a fiber drawing tower. To ensure achromatic properties of lenses, the first derivative of the difference between the material dispersion of the glasses has to cross a zero as shown in Fig. 5(d). Recently we have developed in-house a pair of borosilicate glasses labelled as NC34 and NC21A which fulfils these requirements for the development of achromatic nGRIN microlenses. NC21A glass consists of 56.83% SiO₂, 23.19% B₂O₃, 9.52% Na₂O, 6.23% Li₂O, 3.63% K₂O and 0.61% Al₂O₃. NC34 glass consists of 54% SiO₂, 21% B₂O₃, 9% BaO, 8% Na₂O, 5% Li₂O, 2.5% K₂O and 0.5% Al₂O₃. The thermo-physical properties of both glasses are given in Table 1. The NC21A/NC34 pair of glasses has an expansion coefficient difference of \( \Delta \alpha = 0.4 \times 10^{-7} \text{K}^{-1} \), which is sufficiently small for joint thermal processing. During the drawing in the fiber drawing tower the glasses are kept at a temperature between the curvature and sphere points. For NC21A/NC34 the difference in the curvature temperature is \( \Delta T_c = 50^\circ \text{C} \) and difference in sphere temperature is \( \Delta T_{sp} = 35^\circ \text{C} \). The material dispersion for both glasses and the calculated focal length for 100 \( \mu \)m thick microlenses are presented in Fig. 7.

Table 1. Thermo-physical properties of NC21A and NC34 glasses.

| Glass label | NC21A | NC34 |
|-------------|-------|------|
| Refractive index \( n_d \) | 1.5273 | 1.5581 |
| Thermal expansion coefficient for the range 20-300°C \( a \ [10^{-7} \text{K}^{-1}] \) | 86.6 | 87.0 |
| Transition temperature \( T_g \ [^\circ \text{C}] \) for log\( \eta \) = 13.4 [logP] | 504.7 | 529.8 |
| Dilatometric softening point \( SP \ [^\circ \text{C}] \) for log\( \eta \) = 11.0 [logP] | 540 | 562 |
| Characteristic temperatures in Leitz heating microscope T [^\circ \text{C}] temperature of: | | |
| curvature \( T_c \) for log\( \eta \) = 9.0 [logP] | 620 | 670 |
| sphere \( T_{sp} \) for log\( \eta \) = 6.0 [logP] | 725 | 760 |
| hemisphere \( T_{sp} \) for log\( \eta \) = 4.0 [logP] | 775 | 810 |
| spreading \( T_{sp} \) for log\( \eta \) = 2.0 [logP] | 860 | 910 |

Fig. 7. Refractive indices of NC21A and NC34 glasses (a) and their difference (b) for the wavelength range 500 - 1700 nm. (c) Calculated effective focal length for parabolic GRIN lens with diameter of 20 \( \mu \)m and length of 100 \( \mu \)m.

The nanostructure of the proposed GRIN lens has been designed so the effective refractive index would change parabolically between these two refractive indices, from the maximum at the optical axis to the minimum on the edge of the aperture. The desired effective focal length (EFL) of the microlens can be achieved by modification of the microlens length, according to Eq. (4).

The internal structure of the nGRIN microlens is determined by the distribution of low and high index nanorods in the structure. It is calculated using the simulated annealing (SA) method, which is commonly used for optimization of the e.g. computer generated hologram (CGH) [31,32]. In this method, the effective refractive index distribution for the lens is calculated, using EMA, for a given rod distribution in the structure. The cost function is defined as the difference between the effective refractive index distribution and the target refractive index distribution of the lens with a continuous refractive index distribution. The
SA method is employed in order to minimise this cost function and provides results close to the global minimum of that cost function. In both the simulations and fabrication process, we assume that the nanorods are distributed on a hexagonal lattice. This ensures that the circular rods remain in the same positions with respect to each other during preform assembly and further fiber drawing (Fig. 8). A more detailed description of design method for nanostructured microlenses was presented in work of Hudelist et al [17]. The designed structure of achromatic nGRIN microlens composed of NC21A and NC34 glass nanorods is shown in Fig. 8(a).

We have used a standard stack and draw method commonly used for photonic crystal fiber fabrication to develop achromatic nGRIN microlenses. The preform was formed with 0.6 mm diameter NC21A and NC34 glass rods. A hexagonal structural preform was then stacked layer by layer, according to the calculated pattern from Fig. 8(a). A total of 7651 glass rods were used and the final element had 101 rods on the diagonal. The preform was drawn into sub-preforms of diameters ranging from 1 to 5 mm. The draw temperature was 680°C, the feed speed was 0.5 mm/min and the pulling speed ranged from 1.8 to 0.07 m/min respectively. Sub-preforms were then clad with additional NC21A glass tubes and filled with small-diameter NC21A glass rods to draw final fibers with the diameter of the nanostructured central area. A 30 mm outer diameter NC21A glass tube was used with 5 mm sub-preform to achieve a 125 µm diameter fiber with a 20 µm nanostructured core. The drawing temperature for the final draw was 720°C, the feeding speed was 0.1 mm/min and the pulling speed 6 m/min. All drawing processes were conducted using a drawing tower typically used for soft glass fiber manufacture.

As a result, we obtain over 100 m of the fiber with an external diameter of 125 µm and with the 20.0 µm diagonal nGRIN lens positioned at the centre (Fig. 8(c)). A diamond saw was used to cut the fiber into a series of 2 mm long samples. Next the samples were glued on a glass plate, ground and polished by means of a standard glass polishing machine. This sequence was repeated to polish the second surface of the nGRIN microlenses. The thickness of the nGRIN rods are controlled during the final polishing phase to an accuracy of 3 µm due to the available polishing tools.

The quality of the fabricated structure has been verified using Scanning Electron Microscopy (SEM). The obtained results allow the agreement between the designed and fabricated nanostructured patterns to be confirmed (Figs. 8(c) and 8(d)). The pitch parameter for the fabricated lenses is equal to 309 µm for 1550 nm wavelength. In the third step the fibre is cut with a diamond saw and polished into the final lens samples had a thickness of 36 µm. The presented method of fiber cut and lens polishing is not optimized since over 95% of the glass material is removed by polishing. However, there is no any fundamental limits to cut nanostructured fiber into submillimeter slices, increase a yield and reduce waste of glass.

The aperture size of the lens is limited to a diameter of below 20 µm, due to two main factors. The first is the limit on the number of elements in the nanostructure, which results from the manual assembly process of the nanostructure preform and is imposed by the size of the furnaces used in the fabrication process. The second factor is the maximum diameter of a single nanorod in the lens structure related to the boundary condition of the EMA [33]. According to this theory, the size of a single element should not be greater than $\lambda/(2\pi)$ [20]. In our case the size of a single glass rod is smaller than 180 nm (Fig. 8(d)). This means that the EMA boundary condition $\lambda/(2\pi)$ is strictly fulfilled for $\lambda > 1150$ nm. However, the fiber drawing process introduces diffusion between glass nanorods and smooths the boundary between the glasses. Due to this process the change of refractive index between individual nanorods is a continuous one. This phenomenon results in a modification of the EMA boundary condition and a reduction in the wavelength for which the microlens is still effectively a continuous medium.
4. Characterization of nanostructured GRIN microlenses

The light propagation through the lens has been characterized using the imaging setup shown in Fig. 9. The nGRIN lens was clamped to a high precision translation stage controlled by a computer. It was illuminated by a collimated beam from continuous-wave laser sources at wavelengths of $\lambda = 532, 658, 850, 980, 1310$ and $1550$ nm. The beam formed by the nanostructured lens was imaged by a $40 \times$ microscope lens onto a camera. For each laser source, CCD, CMOS, and phosphate enhanced CCD cameras with appropriate sensitivities were used. The images of the beam cross-sections could be focused on the CCD continuously by the translation of the structured lens, as shown in Fig. 9. The spatial resolution of each transversal image was determined by imaging the microscope calibration target with the same system at the same magnification. A series of images were taken at different distances from the lens facet with the distance changing with a step of $1 \mu m$ and an accuracy of $0.1 \mu m$. The images were then combined to give the plot of the beam FWHM (Fig. 10) and the longitudinal profile of the beam formed by the measured lens (Fig. 10). In order to calculate the working distance, a two-dimensional Gaussian distribution was fitted to each recorded image, which allows the determination of FWHM at different distances from the lens and ultimately finding the distance at which FWHM reaches the minimum value.

The evolution of the beam FWHM with propagation behind the microlens is shown in Fig. 10. The focal spot was observed at a distance of $34.1 – 35.6 \mu m$ over a wavelength range of an octave. It is nearly wavelength independent, however axial achromatic behavior is clearly observed (Fig. 11). A maximum working distance, defined as the distance from the final lens facet to the focal plane, of $35.6 \mu m$ was observed for $980$ nm illumination. For the remaining
longer and shorter wavelengths, the working distance is shorter. The measured beam diameter at the focal plane with FWHM criterion is equal to $2.1 \, \mu m - 4.1 \, \mu m$ in the considered wavelength range.

It is important to note that the microlens works properly for as short a wavelength as 532 nm where the beam diameter in the focal spot was 2.1 \( \mu m \). This is a much shorter wavelength than that predicted by the $\lambda (2\pi)$ EMA boundary condition which for the microlens considered is 1130 nm. The better-than-predicted performance is related to the diffusion process between nanorods, which results in a smooth transition between glasses. A second reason is the use of a nanostructure that is invariant along the optical axis. The original EMA approach considered the use of a random medium [34] whereas the axial invariant nanostructure approach works for much shorter wavelengths and we can therefore modify the boundary condition for nGRIN microlenses to $\lambda/2.5$.

![Image of laser beam profiles](image)

**Fig. 10.** The profiles of laser beams that propagate behind the tested nGRIN microlens measured along the propagation axis for the various wavelengths of $\lambda = 532, 634, 850, 980, 1310$ and 1550 nm.

The properties of the fabricated lens have been verified numerically, using the Beam Propagation Method (BPM). The propagation of a Gaussian beam at various wavelengths starting from 500 nm to 1550 nm through the 36 \( \mu m \) thick 0.12 pitch microlens with a diameter of 20 \( \mu m \) has been simulated. In all the simulations the lenses were positioned in free space and illuminated by a planar wave. The calculations were performed for an ideal refractive index distribution described by the parabolic equation. In addition, we calculated the working distance for the considered microlens based on Eq. (5). Values for the working distance obtained based on the analytical equation (Eq. (5)) and PBM modelling differ
although they are calculated for the same ideal parabolic profile GRIN microlens (Fig. 11). The reason for this discrepancy is that on the one hand the analytical equation is derived from ray optics and uses the paraxial approximation [35] and, on the other hand for the simulation we used a BPM which does not take into account diffusion between nanorods, neither a use of high order Padé approximation [36] in the transverse direction, which is important for high refractive index contrast structures. The considered microlens do not fulfil the conditions of the paraxial approximation since their gradient parameter is large ($A = 412 \text{ mm}^{-2}$ for 1000 nm wavelength). Therefore, the analytical equation can provide information about working distance with limited accuracy.

The BPM numerical simulations predict that the designed nGRIN lens has a focal plane with a working distance ranging from 33.7 $\mu$m for 500 nm to 35.5 $\mu$m for 1600 nm. The maximum predicted working distance is 36.3 $\mu$m for 1100 nm wavelength (Fig. 11). Experimentally measured working distance has a similar variation, however it is usually shorter by 0.8 $\mu$m. The difference between the measured and simulated working distance is a result of errors related to determining the position of the nGRIN surface during the beam profile measurements (Fig. 8). An additional source of error is the limited accuracy of the measurement of the refractive indices of the component glasses NL21A and NL34. Their material dispersion is determined using a Michelson interferometer setup with a precision of $\Delta n = 2 \times 10^{-5}$ RIU (RIU – Reference Index Unit). Therefore, the material parameters of the modelled GRIN microlenses are slightly different than the measured ones.

As a result, the measured values fits better to the analytical curve than to BPM simulations. It shows that diffusion between glasses in developed nGRIN lenses plays important role. nGRIN lens has effectively a continuous-like profile as assumed in the analytical equation (Eq. (5)). A diffusion between glasses should be taken into account in BPM simulation as well as high order Padé approximation to improve accuracy of this modelling.

![Fig. 11. Working distance of the nGRIN lens as a function of incident light wavelength – a comparison of experimental and modelling results with BPM method and using GRIN lens analytical equation (Eq. (5)). Error bars denote accuracy of working distance determination as shown in Fig. 10.](image)

5. Conclusions

We have demonstrated the design and fabrication of an achromatic nanostructured GRIN lens with flat-parallel faces. Distribution of nanorods in the structure allows the arbitrary control of a 2D effective refractive index distribution in the microlens. Selection of two glasses with appropriate material dispersions allows control of the chromatic properties of the microlenses.
We have demonstrated a proof-of-concept microlens with axial achromatic properties. For lens development we used two thermally matched borosilicate glasses. The variance of the refractive index difference between maximum and minimum for the lens changes by less than \(\Delta \text{RIU} = 5 \times 10^{-4}\) over 532–1550 nm wavelength range. The lens is therefore a singlet achromatic lens for those wavelengths. Measurements performed with the fabricated test structure revealed a focal plane at a distance of 35 \(\mu\text{m}\) from the 0.12 pitch lens output facet.

Such robust and compact, integrated fiber-collimating lens system should potentially find application in e.g. laser heating in very confined devices, or in the interconnects between fiber links and photonic integrated circuits.

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