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Ryszard Buczyński, Adam Filipkowski, Hue Thi Nguyen, Dariusz Pysz, Ryszard Stepien, Andrew Waddie, Mohammad R. Taghizadeh, Rafal Kasztelanic, "Development of achromatic flat-surface gradient index micro lenses," Proc. SPIE 11522, Optical Manipulation and Structured Materials Conference 2020, 115220Y (15 June 2020); doi: 10.1117/12.2573777

SPIE.

Event: SPIE Technologies and Applications of Structured Light, 2020, Yokohama, Japan

Development of achromatic flat-surface gradient index microlenses

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Abstract

A development of microlenses achromatically corrected for near infrared range is reported. Internal nanostructurization of microlens allows to obtain an effective parabolic gradient index profile. A standard stack-and-draw method was used to fabricate the microlens. They have a nearly wavelength-independent working distance of 35 µm over the wavelength range of 600-1550 nm. The proposed achromatic microlens can be applied in micro imaging systems and for wavelength independent coupling into optical fibers.

Keywords: microoptics, nanostructured optics, effective medium theory, soft glass.

I 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. The standard solutions 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[1]. Other solutions show a feasibility of development lenses made of 2 materials with spherical surfaces[2] or lenses made of 3 components with spherical or flat surfaces[3].

In this work we discuss new possibilities for shaping microlens chromatic properties using the nanostructurization approach[4]. 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 of such small systems.

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Our proposed approach offers a fully flat-parallel rod gradient index (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.

II 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. 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% SiO_2, 23.19% B_2O_3, 9.52% Na_2O, 6.23% Li_2O, 3.63% K_2O and 0.61% Al_2O^3. NC34 glass consists of 54% SiO_2, 21% B_2O_3, 9% BaO, 8% Na_2O, 5% Li_2O, 2.5% K_2O and 0.5% Al_2O_3. The NC21A/NC34 pair of glasses has an expansion coefficient difference of $\Delta\alpha=0.4\times10^{-7}\cdot K^{-1}$, which is sufficiently small for joint thermal processing. During the drawing in the fiber drawing tower the glasses

Optical Manipulation and Structured Materials Conference 2020, edited by T. Omatsu, K. Dholakia, H. Ishihara, K. Sasaki,
Proc. of SPIE Vol. 11522, 115220Y · © 2020 SPIE · CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2573777

are kept at a temperature between the curvature and sphere points. For NC21A/NC34 the difference in the curvature temperature is ΔT_c=50˚C and difference in sphere temperature is ΔT_{sph}=35˚C.

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. 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.

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 (Fig. 1). 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 5 mm. A 30 mm outer diameter NC21A glass tube was used to create sub-preform and finally achieve a 125 μm diameter fiber with a 20 μm nanostructured lens structure in the middle.

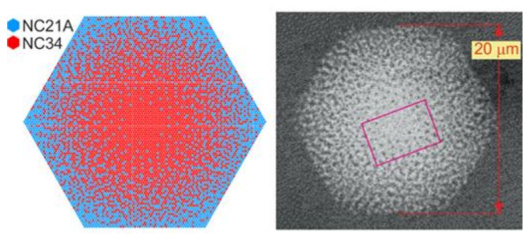

Figure 1. Internal structure of the achromatic nanostructured GRIN microlens composed of NC21A and NC34 glass nanorods: a cross-section of design and fabricated component.

III Results and Discussion

The light propagation through the lens has been characterized using the imaging setup, where 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 in the range 532 nm - 1550 nm. The beam formed by the nanostructured lens was imaged by a 40× 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. A series of images were taken at different distances from the lens facet with the distance changing with a step of 1 μm and then combined to give the plot of the beam FWHM and the longitudinal profile of the beam formed by the measured lens (Fig.2).

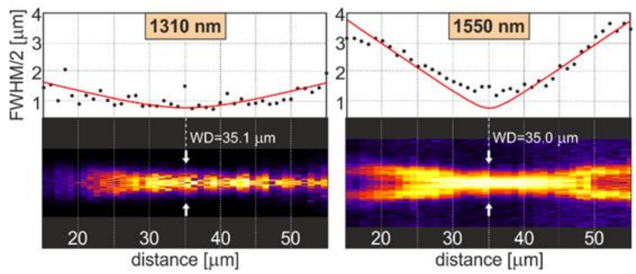

Figure 2. The profiles of laser beams that propagates behind the tested nGRIN microlens measured for the 1310 nm and 1550 nm wavelengths.

The focal spot was observed at a distance of 34.1 – 35.6 μm over a wavelength range of an octave between 600 nm and 1550 nm. It is nearly wavelength independent, however axial achromatic behavior is clearly observed. A maximum working distance, defined as the distance from the final lens facet to the focal plane, of 35.6 μm 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 μm – 4.1 μm in the considered wavelength range.

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