Superhigh numerical aperture (NA > 1.5) micro gradient-index lens based on a dual-material approach

Yingyan Huang and Seng-Tiong Ho

Department of Electrical and Computer Engineering, Northwestern University, Evanston, Illinois 60208

Received December 23, 2004

We describe a novel scheme for obtaining a superhigh numerical aperture gradient-index (SHNA GRIN) lens from multiple thin layers of two or more materials with large refractive-index contrast. Design procedures for the lens are described, including variation of the layer thickness to achieve focusing and of the thickness limit to reduce scattering loss. We use an exact numerical solution by the finite-difference time-domain method to evaluate the lens's performance. Specific examples of a SHNA GRIN lens with a SiO_2-TiO_2 material system designed for fiber coupling to a nanowaveguide are shown to have focusing FWHM spot sizes of 0.53–0.7 μm at $\lambda=1.55$ μm (corresponding to a NA of approximately 1.6–1.1) with 2.7–2.4% more loss than an ideal continuous index profile GRIN lens. With this approach, a SHNA GRIN lens with a NA of >1.5 and a length of <20 μm can be achieved with currently available thin-film deposition techniques. © 2005 Optical Society of America

OCIS codes: 080.3630, 110.2760, 230.4170, 310.6860.

Microscopic lenses with numerical apertures (NAs) that exceed unity (NA > 1) are of great interest for nanophotonics or near-field optics. For example, nanophotonic integrated circuits are utilizing waveguides with increasingly smaller dimensions to increase integration density; the vertical dimensions of such waveguides can approach $\lambda/(2n)$ (λ is the free-space wavelength), or ~0.3 μm at $\lambda=1.55$ μm for $n=3.5$ III–V semiconductors.[1] Even conventional semiconductor lasers have vertical mode sizes as small as 1 μm.[2] The horizontal beam spot sizes are usually larger and can be more easily transformed with tapered waveguides. To achieve high coupling efficiency between optical fibers and on-chip devices requires the coupling optics to be able to focus a collimated beam to submicrometer mode size vertically. Small spot sizes require optics with large NAs, as the diffraction-limited FWHM focusing spot size d of an optical beam is given by $d=\lambda/(2\mathrm{NA})$,[3] where λ is the free-space wavelength.

One way to achieve strong vertical focusing is to use a gradient-index (GRIN) lens. However, the conventional GRIN lens's performance is limited by the small refractive-index difference Δn achievable with typical fabrication techniques such as chemical-vapor deposition, ion exchange, and crystal growing (maximum $\Delta n \sim 0.15$; NA ~ 0.5).[4–6] In this Letter we show that we can obtain a GRIN lens with a high Δn, giving NA > 1.5, by depositing thin films of two or more materials with large differences in refractive index alternately with variation in thickness ratio to achieve an effective variation in the refractive index. We refer to such a lens as a superhigh numerical aperture (SHNA) multilayer GRIN (MLGRIN) lens. We discuss the design procedures for a SHNA MLGRIN lens and the simulation results that show strong lens focusing. The numerical simulation is based on a finite-difference time-domain method that solves Maxwell's equations spatiotemporally without additional approximations.[7]

To construct a SHNA MLGRIN lens with an approximate parabolic refractive-index profile as shown by the dashed curve in Fig. 1(a), the design procedures are as follows: First, the parabolic profile is replaced by a step refractive-index profile as shown by the solid curve in Fig. 1(a). Next, each step refractive-index region n_{step} is broken down into a few periods of mixing one high-refractive-index (n_1) material with thickness L_1 and one low-refractive-index (n_2) material with thickness L_2, as shown by Fig. 1(b), according to the approximate formula

$$n_{\mathrm{step}}=(n_1L_1+n_2L_2)/(L_1+L_2). \tag{1}$$

By varying the ratio or thickness of these two materials, any n_{step} value between n_1 and n_2 can be achieved. For a one-quarter-pitch length GRIN lens with continuous parabolic index profile $n^2(x)=n_0^2[1-(n_0^2-n_R^2/n_0^2)(x^2/D^2)]$, the NA is given by $\mathrm{NA}_{\mathrm{con}}=dn\equiv(n_0^2-n_R^2)^{1/2}$,[8] where n_0 and n_R are the respective refractive indices at the center and the edge of the

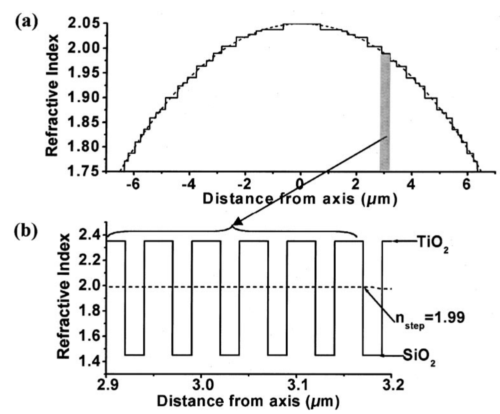

Fig. 1. (a) Parabolic refractive-index profile (dashed curve) of a 13-μm-thick GRIN lens and the approximate step refractive-index profile of a SHNA MLGRIN lens (solid curve). (b) TiO_2 and SiO_2 layers (solid curve) used to approximate a certain step refractive index (dashed line).

0146-9592/05/111291-3/$15.00

GRIN lens, x is the distance from the axis, and D is the half-width of the GRIN lens (note that $dn \neq \Delta n \equiv n_0 - n_R$). For submicrometer spot size we need to have a lens with Δn of at least 0.19 for $\lambda = 1.55\ \mu$m, assuming that $n_R = 1.5$. For illustrative purposes we take the refractive indices of the two materials to be $n_1 = 2.35$ and $n_2 = 1.45$ (achievable by TiO_2 and SiO_2). Ideally those values can give Δn as high as 0.9 (NA = 1.85), resulting in a potential focusing spot size of 0.42 μm at wavelength $\lambda = 1.55\ \mu$m.

From Eq. (1) we can see that, for the two given materials, the maximum Δn achievable is dependent on the maximum film thickness ratio. The minimum layer thickness is limited by the current thin-film deposition technology, whereas the maximum film thickness is limited by the scattering loss at layer interfaces. Material absorption is neglected owing to the small lens size. Current thin-film deposition methods have thickness control accuracies of 1 nm or better. To achieve a fabricated film thickness error within 5% of the targeted value, for example, requires that the minimum thickness L_{MIN} of each layer be 20 nm, which is the value used in our design described below.

The maximum film thickness L_{MAX} is restricted by the scattering loss at layer interfaces. Scattering loss in multilayer thin films arises mainly from refractive-index fluctuation in the structure. The scattering loss in the SHNA MLGRIN lens is dependent on the actual film structure, which is shown below for specific cases. For design purposes it is useful to obtain an upper bound estimation of the dependence on the scattering loss of L_{MAX}. We consider a worst-case situation in which the thickness of each thin-film layer L_i [Fig. 2(a)] is a random value uniformly distributed between L_{MIN} and L_{MAX}. The total scattering loss is calculated by a transfer matrix method.[9] The refractive indices at the incident and exit planes are matched to the effective refractive index n_{eff} in the center, so the Fabry–Perot resonance effect caused by the slab boundaries is eliminated. The total reflection will then all come from the scattering within the slab. Figure 2(b) shows the calculated scattering loss from 3-, 5-, and 7-μm structures with a normally incident plane wave at $\lambda = 1.55\ \mu$m. We obtain each data point by averaging the results

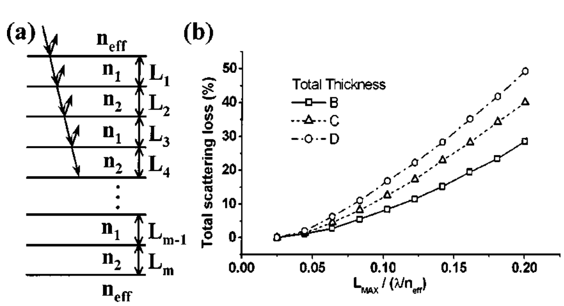

Fig. 2. (a) Layer structure used in estimation of scattering loss by the transfer matrix method. (b) Total scattering loss calculated by the transfer matrix method for three total structure thicknesses: 3 μm (B, solid curve), 5 μm (C, dashed curve), and 7 μm (D, dashed–dotted curve).

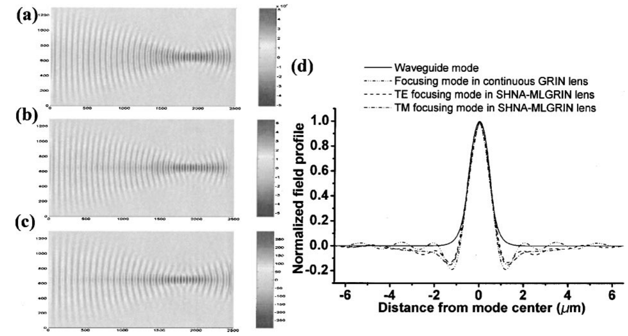

Fig. 3. FDTD simulated field pattern for a fiber mode propagating inside lenses [vertical size (V), 13 μm; horizontal size (H), 25 μm: (a) TE light (E field) in the continuous-index GRIN lens, (b) TE light (E field) in the SHNA MLGRIN lens with TiO_2–SiO_2, (c) TM light (H field) in the SHNA MLGRIN lens with TiO_2–SiO_2, (d) mode profile at the focusing point of the SHNA MLGRIN lens and the continuous GRIN lens compared with the mode profile of the matched III–V waveguide (core thickness, 1.1 μm; core–cladding refractive index, 3/2.8).

over 2000 random structures. To get a loss of less than 10% for a focusing fiber mode in a 10-μm-thick structure with 5-μm vertical propagation, one should have L_{MAX} of less than 10% of λ/n_{eff}, which means $L_{\mathrm{MAX}} = 80$ nm.

Below, we use the finite-difference time-domain method to study the characteristics of the propagation of light inside some specific SHNA MLGRIN lens design. Based on the analysis above, we first construct a SHNA MLGRIN lens structure, using ~300 layers of TiO_2 and SiO_2 with carefully designed thicknesses of 20–80 nm for an approximate parabolic index profile with $n_0 = 2.05$ and $n_R = 1.75$ (NA=1.1) as shown in Fig. 1. The total thickness of the lens is 13 μm, large enough for an 8 μm fiber mode.

The TE light propagating inside a continuous parabolic refractive-index profile GRIN lens [Fig. 3(a)] with the above n_0 and n_R values is compared with that of the SHNA MLGRIN lens [Fig. 3(b)], where a $\lambda = 1.55\ \mu$m optical mode from a single-mode fiber is launched into both structures. The snapshot is taken at a time when the light propagates slightly longer than the quarter-pitch length. We can see that the SHNA MLGRIN lens from the two-material system has behavior almost identical to that of a continuous-index GRIN lens. The quarter-pitch length is ~18 μm, making the lens highly compact. The corresponding TM light propagating inside the SHNA MLGRIN lens is shown in Fig. 3(c). The SHNA MLGRIN lens shows little difference in TE–TM focusing behavior. The focused spot size at the quarter-pitch point is compared in Fig. 3(d) to an optical waveguide mode. The SHNA MLGRIN lens's focusing spot size has a FWHM of ~0.7 μm, close to the estimation of $d = \lambda/(2\mathrm{NA}_{\mathrm{con}})$, with $\mathrm{NA} = \mathrm{NA}_{\mathrm{con}}$ given by the continuous GRIN-lens formula.

For the SHNA MLGRIN lens to act as a focusing lens from the optical fiber to a III–V semiconductor waveguide, its facet should not touch the waveguide; we shorten the length of the lens by ~1 μm to slightly less than the quarter pitch, so the focusing point will be outside the lens. Antireflection coating is added to both the lens facet and the waveguide facet to prevent Fresnel mismatch. The configuration and finite-difference time-domain simulated field pattern is illustrated in Fig. 4. Both the input energy from the fiber and the output energy from the waveguide were collected numerically. The result shows that 95.3% of the input energy was coupled into the waveguide. In comparison, a continuous-index GRIN lens with the identical configuration has 97.7% coupling efficiency. The two-material system introduces only 2.4% additional loss.

To reach an even smaller spot size we simulated a SHNA MLGRIN lens with $n_R = 1.45$ (all SiO_2) and $n_0 = 2.17$ (SiO_2, 20 nm; TiO_2, 80 nm), obtaining a NA of 1.6. The fiber mode is focused to a III–V waveguide with core thickness $0.5\ \mu m$ and core–cladding refractive-index difference $3.35-3.2$. The FWHM focused spot size is $0.53\ \mu m$. The simulation result is shown in Fig. 5, where 89.5% of the fiber mode energy is coupled into the mode-matched nanowaveguide. In comparison, a continuous-index GRIN lens with an identical configuration has 92.2% coupling efficiency. The two-material system introduces only 2.7% more loss than the continuous GRIN lens.

In conclusion, we have discussed the theory and design of a superhigh numerical aperture multilayer gradient-index lens. We showed that a focusing spot size as small as $0.53\ \mu m$ and a NA of 1.6 (at $\lambda = 1.55\ \mu m$) potentially can be achieved with a TiO_2-SiO_2 material system, which comprises materials that are widely used in dense wavelength-division multiplexing thin-film filters that have similar or more stringent thin-film deposition requirements. The employment of only two materials and a thin-film structure makes the scheme attractive for use in practical fabrication situations. Other material systems with even higher Δn are possible as long as the required deposition and fabrication methodology exists. The scheme is versatile in that the multilayer deposition will allow arbitrary refractive-index profiles to be employed, yielding lenses that are capable of other wave-front transformations. The examples discussed in this Letter are for vertical focusing with planar deposition of thin films; either a waveguide taper or an etched cylindrical lens can be used to achieve focusing for the horizontal dimension. If coaxial deposition is possible, the same principle can be readily extended to two-dimensional SHNA MLGRIN lenses.

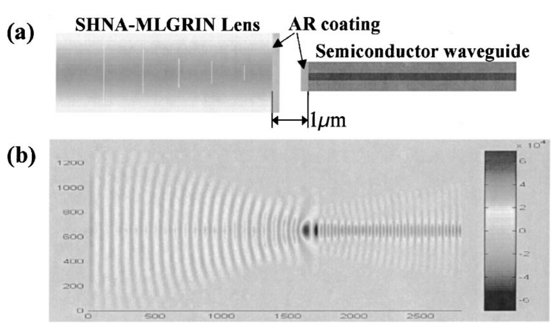

Fig. 4. Focusing in a SHNA MLGRIN lens from the optical fiber mode to a III–V waveguide with an air gap and an antireflection (AR) coating: (a) structure, (b) FDTD simulated TE-light E-field pattern ($V \times H = 13\ \mu m \times 28\ \mu m$).

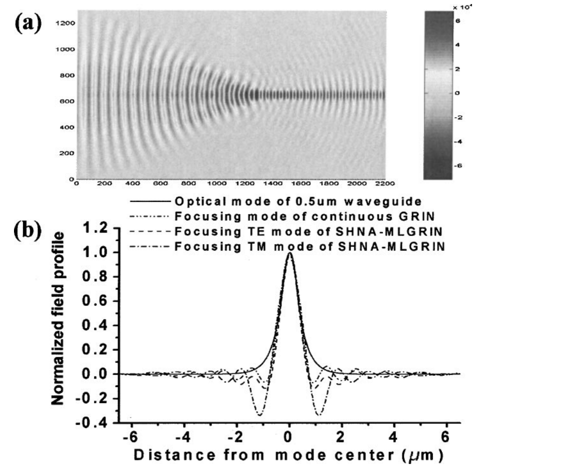

Fig. 5. FDTD simulation of a SHNA MLGRIN lens with $n_R = 1.45$ and $n_0 = 2.17$. (a) Simulated TE light E-field pattern ($V \times H = 13\ \mu m \times 22\ \mu m$), showing the optical fiber mode focused to a $0.5\text{-}\mu m$ III–V waveguide (core–cladding refractive index, 3.35/3.2; core thickness, $0.5\ \mu m$). (b) Mode profile at the focusing point of the SHNA MLGRIN lens and the continuous GRIN lens compared with the mode profile of the matched III–V waveguide.

The authors acknowledge valuable discussions with Yan Zhou. Y. Huang's e-mail address is yingyan@ece.northwestern.edu.

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