

Supporting Information

An Ultracompact GRIN-Lens-Based Spot Size Converter using Subwavelength Grating Metamaterials

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Abstract

We provide supporting information on the behavior of the proposed GRIN metamaterial when it is fed by TM polarized input light, a theoretical discussion about the normalized expansion ratio and alternative designs for silicon thicknesses of 250 nm and 300 nm.

1. Behavior of the GRIN metamaterial SWG structure for the TM polarization

In the main manuscript we show that the GRIN metamaterial works as a spot size converter for TE polarization with anisotropy playing a key role in reducing the device length. Here we discuss, by using 3D-FDTD simulations, the behavior of the GRIN metamaterial for TM polarization. In Figure S1(a) we show the real part of the simulated TM electric field. Then, we propagate the same TM input field along an isotropic GRIN material [see Fig. S1(b)]. By comparing these two propagations it is apparent that the structure is behaving as an isotropic GRIN metamaterial. This result is expected since in a z-periodic SWG structure the anisotropy affecting the TM modes is negligible compared with the TE modes^[S1]. In this device, for the TE polarization we require about 11 μm to achieve the desired expansion, while for TM

polarization about 24 μm are required. Thus, the main consequence of the isotropic nature of the metamaterial for TM modes is the longer collimation distance.

2. Normalized expansion ratio in anisotropic media

We use the normalized expansion ratio (NER) to compare different state-of-the-art spot size converters. The NER is defined as^[S2]:

$$NER(\lambda) = \frac{w_{out}/w_{in}}{L/\lambda} \cdot IL(\lambda) = \overline{ER} \cdot IL(\lambda), \quad (\text{S.1})$$

where w_{out} and w_{in} are the widths of the output and input waveguides, L is the length of the spot size converter, λ is the vacuum wavelength of the propagating light and IL are the insertion losses (in linear scale). This parameter can be interpreted as an expansion ratio ($ER = w_{out}/w_{in}$), normalized by the electrical length of the device (L/λ), and by the insertion losses of the device $IL(\lambda) = P_{out}(\lambda)/P_{in}(\lambda)$. While insertion losses are highly implementation specific and thus difficult to treat analytically, the expansion ratio is more amenable to such a treatment. In the following we present an analytic estimation of the maximum value of $\overline{ER} = \frac{ER}{L/\lambda}$ by using the well-known gaussian beam propagation formulas for isotropic and anisotropic media.

The width expansion of a gaussian beam propagating through a homogeneous isotropic material can be calculated as^[S3]

$$W(z) \approx \theta_0 \cdot z, \quad (\text{S.2})$$

$$\theta_0 = \frac{\lambda/n}{\pi \cdot W(0)}, \quad (\text{S.3})$$

where $W(z)$ is the beam radius at a distance z , θ_0 is the divergence cone half-angle, λ is the free-space operating wavelength, n is the refractive index of the material and $W(0)$ is the beam radius at $z=0$.

The above expressions can be used to evaluate the (\overline{ER}) of a gaussian beam propagating through an isotropic medium, thus obtaining:

$$\overline{ER} = \frac{w_{out}/w_{in}}{L/\lambda} = \frac{4 \cdot \lambda^2}{\pi \cdot w_{in}^2 \cdot n}, \quad (\text{S.4})$$

where the beam spot-sizes have been approximated as $w_{in} \approx 2W(0)$ and, $w_{out} \approx 2W(L)$.

The beam spread can be even larger if the medium is anisotropic. In this case, the divergence half-angle can be calculated as^[S4] $\theta_0 = \frac{\lambda}{\pi \cdot W(0)} \frac{n_{xx}}{n_{zz}^2}$. The \overline{ER} of the gaussian beam propagating

through an anisotropic material is then

$$\overline{ER} = \frac{w_{out}/w_{in}}{L/\lambda} = \frac{4 \cdot \lambda^2}{\pi \cdot w_{in}^2} \frac{n_{xx}}{n_{zz}^2} \quad (S.5)$$

It should be noticed that, for an isotropic medium, $n_{xx} = n_{zz} = n$, thus obtaining (S.4).

Although a gaussian beam diffracting in a homogeneous medium does not exhibit a plane phase front, it provides a reference to compare with the expansion ratios of integrated beam expanders.

We propose to use (S.5) as an estimation of the upper limit for the maximum normalized expansion ratio that can be obtained with a beam expander of length L .

Considering an initial beam width $w_{in} = 0.5 \mu\text{m}$, an operating wavelength $\lambda = 1.55 \mu\text{m}$, and an isotropic material with refractive index $n = 2.85$ (equivalent index for a silicon thickness $h_{core} = 220 \text{ nm}$ and TE polarization), we obtain $\overline{ER} < \sim 4.3$. All the designs included in Table 1 of the main manuscript exhibit NER values below this limit. Note that we assume no insertion losses in this upper limit. For the same silicon thickness, an anisotropic SWG metamaterial with a duty cycle $DC = 50\%$, gives $n_{xx} \sim 2.26$ and $n_{zz} \sim 1.82$. Substituting these values in eq. (S.5) we obtain $\overline{ER} < \sim 8.4$. Note that this value should be normalized by the insertion losses of the spot size converter to calculate the NER.

3. SWG GRIN metamaterial for other silicon thickness

The proposed methodology to implement an anisotropic gradual index metamaterial is demonstrated in the main manuscript for a silicon thickness of 220 nm. In this section we reinforce the generality of this methodology by performing two additional GRIN lens spot size converter designs for the 250 nm and the 300 nm silicon thickness platforms. The design process of these lenses follows the one's described in the manuscript: i) We calculate the look-up table with the duty-cycles that synthesize the desired GRIN metamaterial. ii) We simulate

this metamaterial using a GRIN anisotropic homogenized structure in order to find the optimum value for the period and the minimum feature size. iii) We slightly refine the length of the device by using 3D-FDTD simulation arriving at the final dimensions shown in table S1 for the 250nm and 300nm silicon thicknesses. The field profile expansion for both GRIN lenses is shown in Figure 2S. In both cases (250 nm and 300 nm silicon thickness) the insertion losses of the device are below 1 dB and the NER is 2.71 and 3.1 respectively. Note that for the 300 nm silicon thickness the minimum feature size has been slightly decreased to 60 nm in order to achieve a good design.

References

- [S1] J. M. Luque-González, A. Herrero-Bermello, A. Ortega-Moñux, Í. Molina-Fernández, A. V. Velasco, P. Cheben, J. H. Schmid, S. Wang, and R. Halir, *Opt. Lett.* **43**, 4691 (2018).
- [S2] S. Abbaslou, R. Gatlula, M. Lu, A. Stein, and W. Jiang, *Opt. Lett.* **42**, 4383–4386 (2017).
- [S3] B. E. A. Saleh, and M. C. Teich, *Fundamentals of Photonics* (John Wiley & Sons, Inc., New York, USA, 1991).
- [S4] D. D. Bhawalkar, A. M. Goncharenko, and R. C. Smith, *Br. J. Appl. Phys.* **18**, 1431–1441 (1967).

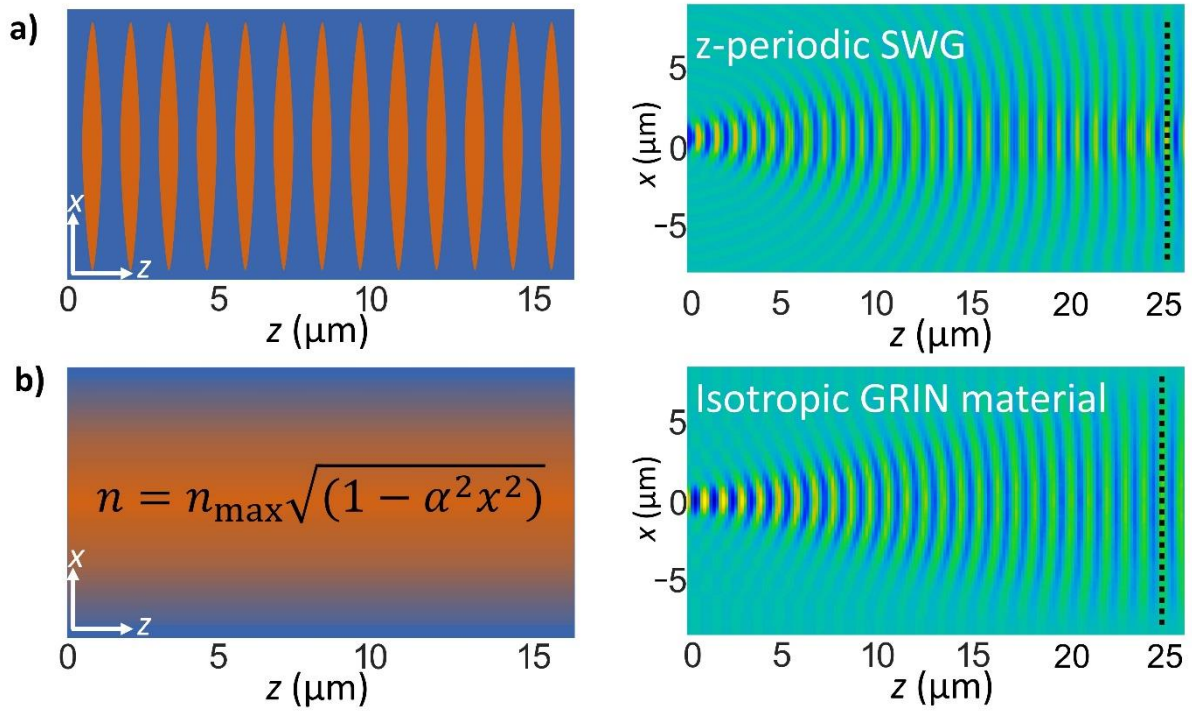


Figure S1. Schematic of the structure (left) and real part of the 3D-FDTD simulated main component of the electric field propagation for a TM polarized input field, $\mathcal{R}e\{E_y(x, z)\}$, along the proposed GRIN lens (right) implemented with a) a z-periodic SWG structure, b) a gradual isotropic material.

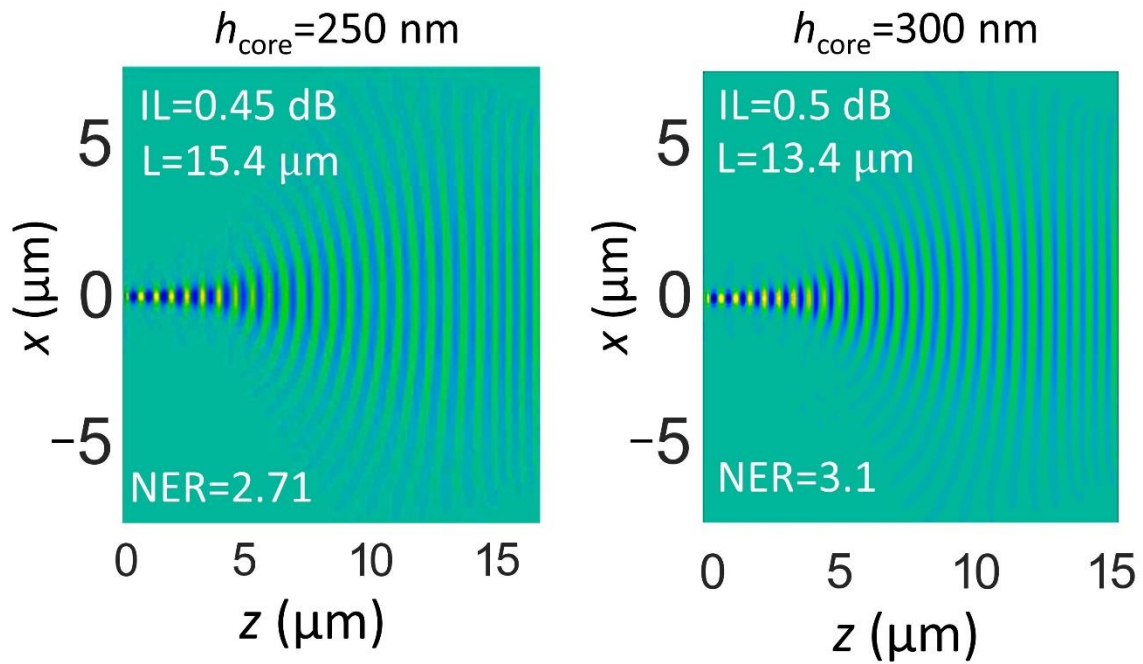


Figure S2. Real part of the 3D-FDTD simulated main component of the TE electric field propagation, $\mathcal{R}e\{E_x(x, z)\}$, along the proposed GRIN lens for a silicon thickness of a) $h_{\text{core}} = 250$ nm and b) $h_{\text{core}} = 300$ nm.

	$h_{\text{core}}=250 \text{ nm}$	$h_{\text{core}}=300 \text{ nm}$
Input taper	$w_{\text{InTaper}} = 0.5 \mu\text{m}$	
	$w_{\text{OutTaper}} = 2.5 \mu\text{m}$	
	15 periods	
	$DC = 0.60$	$DC = 0.7$
	$\Lambda = 220 \text{ nm}$	$\Lambda = 200 \text{ nm}$
GRIN lens	$w_{\text{GRIN}} = 16 \mu\text{m}$	
	$L_{\text{Tip}} = 50 \text{ nm}$	
	$a(x)$: Figure 2 algorithm.	
	$\Lambda = 220 \text{ nm}$	$\Lambda = 200 \text{ nm}$
	55 periods	52 periods
	$MFS_C = 80 \text{ nm}$	$MFS_C = 60 \text{ nm}$

Table S1. Geometrical parameters of the proposed spot size converters for the 250 nm and 300 nm silicon platforms.