High performance and small footprint spot size converters based on SWG metamaterial lenses

(Student Paper)

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ABSTRACT

Spot size converters with high expansion ratio are required in a variety of situations. This is the case of non-focusing Silicon on Insulator (SOI) fiber-to-chip grating couplers, which typically require long adiabatic tapers (L_{taper} >100µm) from the narrow single-mode waveguides ($W_{Si\text{-}wire}$ ~ 500nm) to the wide grating region ($W_{grating}$ ~ 15µm). Here, we explore the potential of subwavelength grating (SWG) dielectric metamaterials to implement integrated GRaded INdex (GRIN) lenses to expand the mode field. Our designs achieve the desired Beam Expansion (BE) with insertion losses below 1dB over a distance of only L_{BE} ~ 17µm.

Keywords: Subwavelength grating, Graded Index, Beam expander, Silicon-On-Insulator, Grating coupler.

1. INTRODUCTION

Silicon-on-insulator is emerging as a promising fabrication platform for integrated optical systems, as it enables high-volume fabrication, with existing CMOS infrastructure, and highly compact devices, owing to the high index contrast between the core and cladding materials ($n_{Si} = 3.476$ and $n_{SiO_2} = 1.444$). These materials set the dimensions of typical SOI single-mode waveguides to ~ $500 \times 220\text{nm}^2$ at telecom wavelengths. However, these small dimensions make direct coupling to standard optical fibers, with a mode field diameter of 10.4µm, very challenging, which is why grating couplers are widely used for low-loss coupling [1]. Since grating couplers are about 30 times wider than single mode waveguides ($W_{grating}$ ~ 15µm vs. $W_{Si\text{-}wire}$ ~ 500nm), some kind of beam expansion between them is required. Adiabatic linear tapers are conventionally used for this purpose but, to keep losses low, a length of 100-200 µm is required [2] which makes this a bulky solution. Other solutions such as adiabatic parabolic tapers [2] only achieve a slight reduction of the device length. Recently proposed non-adiabatic tapers [3] achieve a substantial length saving at the expense of reducing the bandwidth.

In this work we present two different realizations of GRaded INdex (GRIN) lens beam expanders, using SubWavelength Gratings (SWG) [4,5]. As illustrated in Fig. 1 the parabolic GRIN lens is implemented with a subwavelength structure in the transversal x-direction in Design I (Fig. 1.a) and in the longitudinal z-direction in Design II (Fig. 1.b). In both cases, we have kept the pitch Λ constant and we have designed the duty cycle (DC) to achieve the desired parabolic profile $n_{eq}(x)$ ~ $n_0(1\text{-}\alpha\, x^2)$. Design I was originally proposed in [4] for a different application, but it has been redesigned here to improve its performance. With respect to Design II, to the authors´ knowledge this is the first time that an integrated beam expander has been implemented using this approach (i.e. using a z-periodic SWG based GRIN lens). We have demonstrated by rigorous 3D full-vectorial FDTD simulations that both designs achieve less than 1dB coupling losses between a silicon wire and a conventional grating coupler, with lengths < 20µm, for the TE polarization. This is much shorter than the conventional solution based on linear adiabatic tapers, which requires lengths greater than 100µm to obtain the same performance.

2. DESIGN OF THE SWG BASED GRIN LENS

First, the lens width is set to the desired grating width, i.e. W_{GRIN} ~ $W_{grating}$ ~ 15µm. Then, as it was previously stated, we implement the parabolic refractive index profile of the lenses controlling the duty cycle of the periodic structure. This can be done by mapping the desired parabolic refractive index profile $n_{eq}(x)$ into a duty cycle profile DC(x), benefiting from the relation between the duty cycle and the equivalent refractive index n_{eq} (DC) of the SWG structure. This can be seen in Figure 2.a) which represents the duty cycle in Design I as a function of the transverse position x (x = 0 is the centre of the lens). The nearly parabolic shape of this curve is due to the almost linear dependence of the equivalent refractive index of the SWG structure with the duty cycle, as shown in the figure 2.a) inset. It must be noticed that, as the pitch has been fixed to Λ_x = 400nm and the duty cycles used to synthetize the parabolic refractive index range from $DC_{x,min}$ = 30% to $DC_{x,max}$ = 70%, the minimum feature size (MFS) for this design is ~ 120 nm.

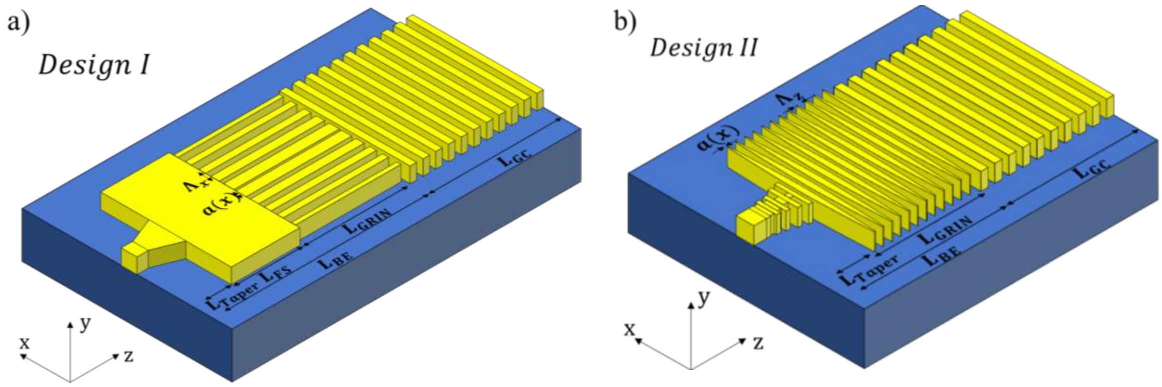

Figure 1: Schematic drawing of the beam expanders based on SWG GRIN lenses proposed in this work. For the sake of clarity, the figure includes not only the beam expander but also the input access waveguide and taper and the output chip to fiber grating coupler. The equivalent parabolic index of the lenses $n_{eq}(x)$ is implemented in both cases by maintaining the pitch constant and optimizing the duty cycle. a) Design I is composed of an input adaptation taper, a free-space propagation zone, a quasi-periodic in x SWG lens working as a collimator, and the grating coupler. The SWG is arranged along the x-direction, so the duty cycle is defined as $DC_x(x) = a(x) / \Lambda_x$ b) Design II comprises an adaptation taper, a z-periodic SWG lens and the grating coupler. The SWG is arranged along the z-direction, so the duty cycle is defined as $DC_z(x) = a(x) / \Lambda_z$.

As proposed in [4], the total length of the beam expander can be reduced if light first diffracts in a free-space propagation zone (i.e. a slab waveguide) before being collimated by the GRIN lens (see Fig, 1.a). Short adiabatic taper has been also included at the input to optimize the excitation of the free-space zone. Figure 3.a) shows the field propagation through the beam expander with Design I, which exhibits insertion losses below 1dB and a total length of L_{BE}~17µm.

The next design of the beam expander is based on a z-periodic SWG parabolic lens (Design II). The function $DC_z(x)$ that defines the lens has been drawn in Fig 2.b). We have chosen a period Λ_z = 220nm (much smaller than in the previous case) to avoid Bragg reflections within all the wavelength operation range of the device [5]. Once again, the relation between the synthetized effective index and the duty cycle is almost linear (see inset of Fig. 2.b)), so the function $DC_z(x)$ is roughly parabolic. The MFS of this design is ~100nm in the centre of the lens and larger than 80nm for |x| <5µm, where most of the optical intensity is confined. The total length of the beam expander (including a short adaptation taper at the input) is L_{BE} ~17µm, whereas the insertion losses are again below 1dB. Figure 3.b) represents the simulated field propagation through the designed device.

These designs are therefore much shorter than linear adiabatic tapers L_{taper} >100µm (see Fig. 3c) typically used in grating designs.

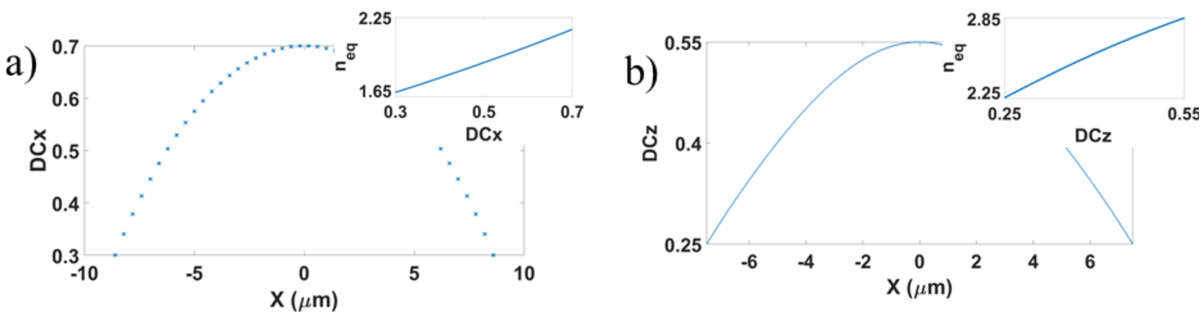

Figure 2: Duty cycle as a function of the transverse x-position within the lenses (x = 0 is the centre of the lens). a) Design I - $DC_x(x)$, b) Design II- $DC_z(x)$. Insets: Equivalent index of the SWG metamaterial as a function of the duty cycle ($n_{eq}(DC_x)$ and $n_{eq}(DC_z)$ respectively). It should be noticed that in both cases $n_{eq}(DC)$ are nearly linear, so the duty cycle shapes are parabolic.

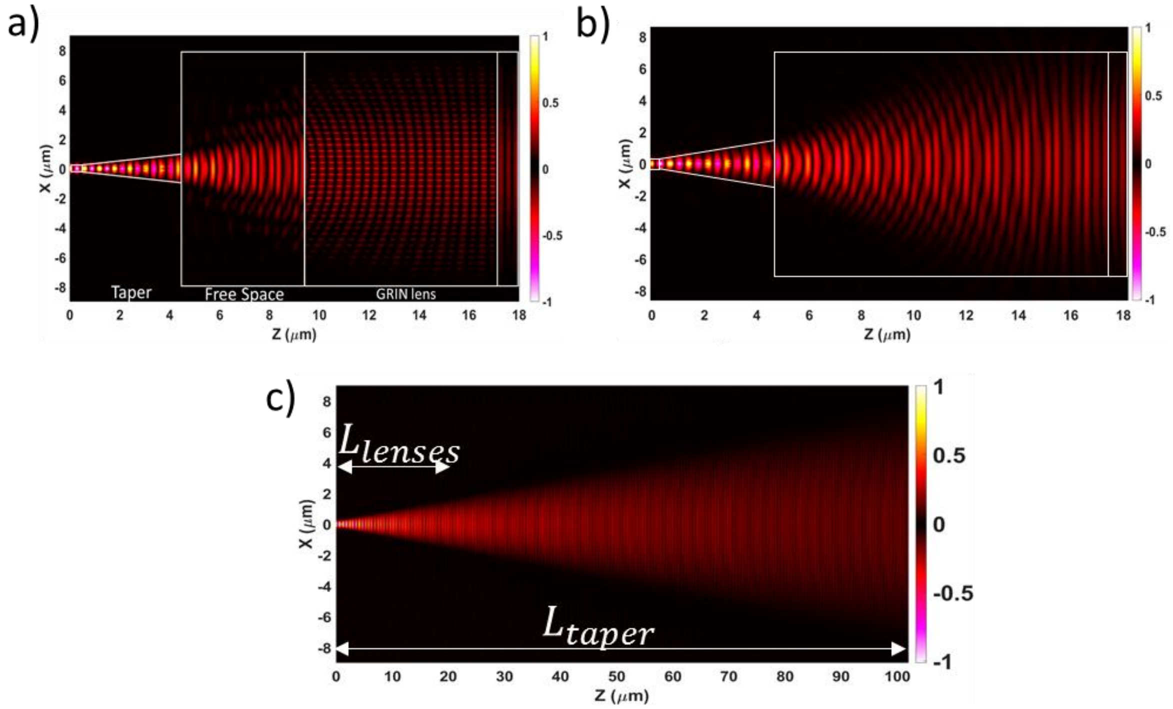

Figure 3: Electric field (real part) propagation through the two beam expanders proposed in this work. a) Design I, based on a quasi-x-periodic SWG GRIN lens working as a collimator. b) Design II, based on a z-periodic SWG GRIN lens. c) Electric field propagation through an adiabatic linear taper with the same beam expansion and similar losses.

3. CONCLUSIONS

In this work we have explored the potential of subwavelength grating dielectric metamaterials to implement GRIN integrated devices in a conventional SOI platform. We have presented two different SWG-based parabolic GRIN lenses working as beam expanders in the plane of the chip. Our designs achieve a huge spot-size lateral expansion (~30×) with a very reduced length (L_{BE} ~ 17µm) maintaining the insertions losses below 1dB. These results pave the way to the development of more involved integrated GRIN metamaterials based on SWG periodic structures.

ACKNOWLEDGEMENTS

We acknowledge funding from the Ministerio de Economía y Competitividad, Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad (cofinanciado FEDER), (TEC2016-80718-R); Universidad de Málaga. Ministerio de Educación, Cultura y Deporte (MECD) (FPU16/06121);

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