Designing polarization management devices by tilting subwavelength grating structures

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ABSTRACT

Subwavelength gratings (SWG) are periodic structures which behave as controllable homogeneous metamaterials. SWGs are extremely interesting when they are used in platforms with a limited choice of material refractive indices, enabling the design of a myriad of high-performance devices. Here we present a novel technique to gain control over the intrinsic anisotropy of the synthesized metamaterial. We show that tilting the silicon segments in a SWG structure mainly affects the in-plane (TE) modes, with little impact on the out-of-plane (TM) modes. Moreover, we present a methodology to quickly but accurately calculate the modes of a tilted periodic structure modeling the structure as a rotated uniaxial crystal which can be solved with an anisotropic mode solver. Measurements on a set of fabricated tilted SWG waveguides validate our simulation results. By using the presented technique, we design a polarization beam splitter based on a 2x2 multimode interferometer. The design is based on the optimization of the tilting angle to tone the beat length of the TE modes to be a half of the beat length of the TM modes.

Keywords: Integrated optics, Subwavelength structures; Anisotropic optical materials; Metamaterials.

1. INTRODUCTION

Subwavelength gratings (SWG) are periodic structures with a period, Λ, much shorter than the wavelength of the propagating light[1], i.e. $\lambda \gg \Lambda$. Under this condition, SWGs behave as homogeneous metamaterials which are usually controlled by tuning the period of the structure and/or the duty cycle (DC). Since the SWGs was demonstrated in Silicon-On-Insulator (SOI) waveguides[2] a plethora of high-performance devices has been proposed[3–5]. In most of the SWG designs, the periodic structure is modeled as an isotropic metamaterial defined by its equivalent refractive index, n_{eq}, which is tuned to optimize the device performance. However, in recent publications the SWG structures are model as anisotropic metamaterial defined by its permittivity tensor $\boldsymbol{\varepsilon} = \text{diag}[n_{xx}^2, n_{yy}^2, n_{zz}^2]$. This point of view enable to fully exploit the potential of SWGs, achieving further capabilities such as control over the bandwidth of the device[6,7], polarization management[8] or evanescent field confinement control[9,10].

In this work we overview the potential of exploiting the anisotropic properties of SWG structures, reporting a novel methodology to gain control over the anisotropy tensor of the synthesized metamaterial. We show that tilting the segments of an SWG waveguide [see Fig. 1(a)], we mainly affect the in-plane (TE) modes, with a low impact on the out-of-plane (TM) modes. Here we explain this behavior by modeling the tilted SWG core of the waveguide as a tilted uniaxial metamaterial, defined by its permittivity tensor $\tilde{\boldsymbol{\varepsilon}}$ [see Fig. 1(b)], which

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can be calculated from the non-tilted permittivity tensor $\boldsymbol{\varepsilon}$ and the rotation matrix $\mathbf{T}$ in the x-z plane. The anisotropic homogenization strategy proposed here provides not only a valuable physical insight of the problem but also a quickly and precise methodology to work with this kind of structures. The proposed model and control over the anisotropy is validated by a set of fabricated tilted SWG waveguides [Fig. 1(c)]. Finally, we propose a Polarization Beam Splitter (PBS) based on a multimode interferometer (MMI) with tilted SWG segments which shows the control over the polarization that tilted SWGs provide [See Fig. 1(d)]. We foresee that the proposed strategy to gain control over the anisotropy will help to the SWG designers to improve their designs, mainly in polarization management applications, providing of a new degree of freedom to perform high-performance devices.

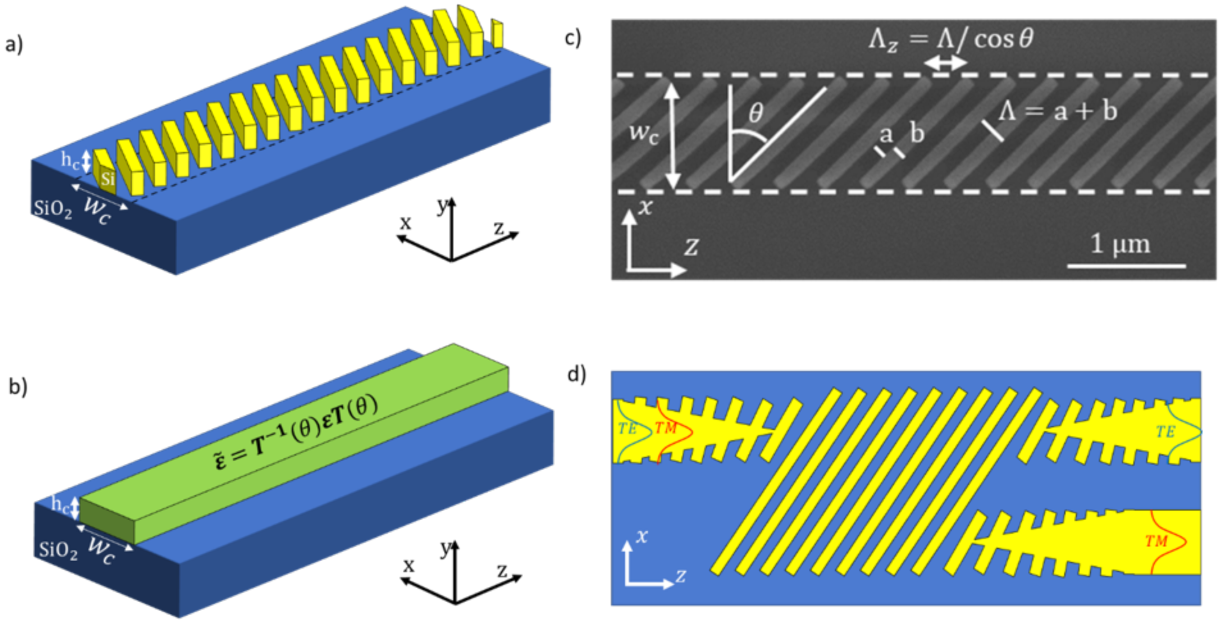

Figure 1. a) Schematic of the proposed tilted SWG waveguide. b) Homogenized anisotropic waveguide c) Scanning Electron Microscope (SEM) image of a fabricated tilted SWG waveguide. $w_c = 1\ \mu m$, $h_c = 0.22\ \mu m$, DC=0.5, $\Lambda = 0.25\ \mu m$, $\theta = 45°$. d) Schematic of the proposed polarization beam splitter. The single image condition is tuned by tilting the segments to achieve the polarization splitting.

2. ANISOTROPIC HOMOGENIZATION OF SWG WAVEGUIDES

An SWG waveguide is homogenized by finding an equivalent homogeneous anisotropic metamaterial that doesn't change the light propagation behavior when the original periodic structure is substituted by this metamaterial. Let assume a non-tilted SWG waveguide with a period Λ=a+b and duty cycle DC=a/Λ [See Fig. 2(a)]. To perform the homogenization of this structure, we have to study first the periodic core, isolated from the waveguide. We assume a laminar periodic structure composed of two materials with refractive indices n_1 and n_2 and thickness a and b respectively [See Fig. 2(b)]. A plane waveguide propagating along this structure with any angle θ is completely characterized by its wave-vector $\vec{k}_{\text{laminar}}(\theta) = k_x\hat{x} + k_z\hat{z}$, where $\theta = \text{atan}(k_x/k_z)$. The dispersion relation which allow us to semi-analytically calculate this wave-vector is[11]:

$$\cos(k_z\Lambda) = \cos(k_{1x}a)\cos(k_{2x}b) - \Delta\sin(k_{1x}a)\sin(k_{2x}b), \tag{1}$$

$$\Delta_{TE} = \frac{1}{2}\left(\frac{n_2^2}{n_1^2}\frac{k_{1x}}{k_{2x}} + \frac{n_1^2}{n_2^2}\frac{k_{2x}}{k_{1x}}\right) \text{ and } \Delta_{TM} = \frac{1}{2}\left(\frac{k_{1x}}{k_{2x}} + \frac{k_{2x}}{k_{1x}}\right). \tag{2}$$

where $k_{ix} = \sqrt{(k_0 n_i)^2 - k_x^2}$, $k_0 = 2\pi/\lambda_0$. TE and TM polarizations are defined in Fig. 2(b). Let assume a TE plane wave propagating along the described structure which satisfies the SWG condition, $\lambda \gg \Lambda$. Its wave-vector $\vec{k}_{\text{laminar}}$, given by the dispersion relation shown in Eq. (1), follows an ellipsoidal shape [See Fig. 2(c)]. Thus, we model the periodic structure as an anisotropic metamaterial, defined by its permittivity tensor, $\boldsymbol{\varepsilon} = \text{diag}[n_{xx}^2, n_{yy}^2, n_{zz}^2]$, with an elliptical dispersion equation [see Fig. 2(e)]:

$$\left(\frac{k_z}{n_{xx}}\right)^2 + \left(\frac{k_x}{n_{zz}}\right)^2 = k_0^2, \tag{3}$$

$$n_{xx} = n_{yy} = \frac{|\vec{k}_{\text{laminar}}(0°)|}{k_0}, \quad n_{zz} = \frac{|\vec{k}_{\text{laminar}}(90°)|}{k_0} \tag{4}$$

In the next section we will show that modeling the SWG core as an anisotropic metamaterial, calculated through this process, allow us to quick and accurately calculate the modes of the SWG waveguide, even when tilting the SWG segments.

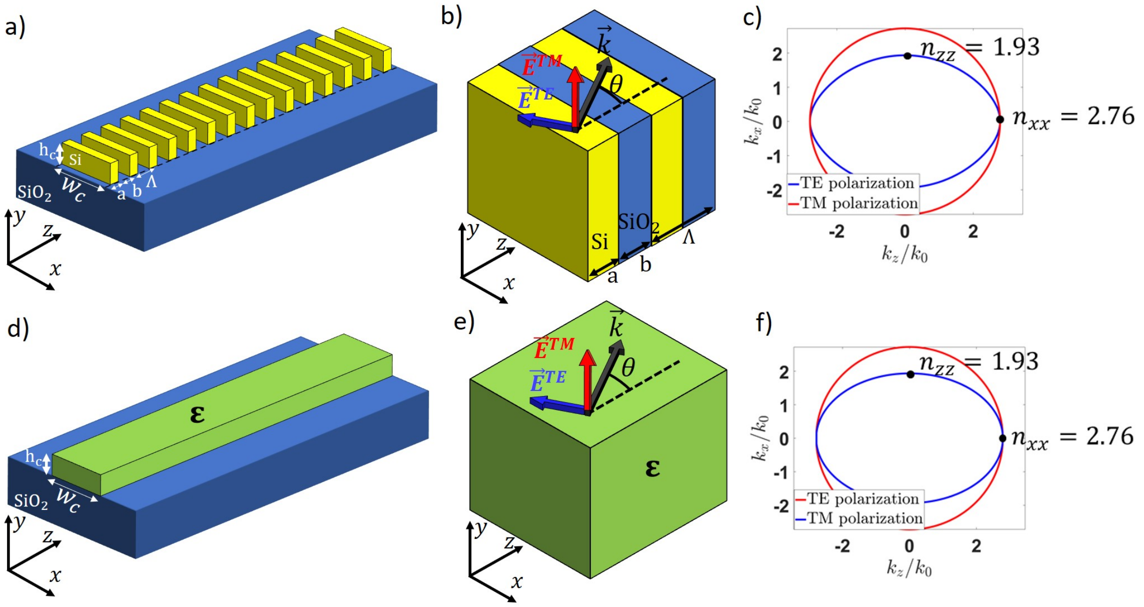

Figure 2. a) Standard Z-periodic SWG waveguide composed of two materials periodically arranged. For the sake of clarity, the SiO_2 cladding is not drawn. b) Laminar periodic structure which models the periodic core of the SWG waveguide shown in Fig. 2(a). c) Dispersion relation, for both polarizations, of the laminar periodic structure shown in Fig. 2(b). d) Corresponding anisotropic homogenization of the SWG waveguide shown in (a). The permittivity tensor is obtained from the relation dispersion shown in Fig 2(c). e) Anisotropic metamaterial which behaves similar to the laminar structure shown in Fig. 2(b). f) Dispersion relation of the anisotropic metamaterial for both polarizations.

3. SUBWAVELENGTH GRATING WAVEGUIDES: ANISTROPIC HOMOGENIZATION AND CONTROL TOOLS OVER THE ANISOTROPY

Now we explore how an SWG waveguide can be model as a homogeneous structure by replacing the periodic core by an anisotropic metamaterial defined just like we have explained in section 2. Moreover, we develop the foundations of the proposed technique to control the anisotropic properties of the synthesized metamaterial by tilting the SWG segments. This model is based on the aforementioned calculations of the permittivity tensor but rotating the crystal axis in which it is defined, yielding the new tilted permittivity tensor[12]:

$$\tilde{\boldsymbol{\varepsilon}}(\theta) = \mathbf{T^{-1}}(\theta)\boldsymbol{\varepsilon}\mathbf{T}(\theta) = \begin{bmatrix} \tilde{\varepsilon}_{xx}(\theta) & 0 & \tilde{\varepsilon}_{xz}(\theta) \\ 0 & \tilde{\varepsilon}_{yy} & 0 \\ \tilde{\varepsilon}_{xz}(\theta) & 0 & \tilde{\varepsilon}_{zz}(\theta) \end{bmatrix}, \tag{5}$$

where $\mathbf{T}$ is the rotation matrix in the x-z plane and the components of the tensor are:

$$\begin{aligned} \tilde{\varepsilon}_{xx} &= n_{xx}^2 \cos^2(\theta) + n_{zz}^2 \sin^2(\theta), \\ \tilde{\varepsilon}_{yy} &= n_{yy}^2, \\ \tilde{\varepsilon}_{zz} &= n_{xx}^2 \sin^2(\theta) + n_{zz}^2 \cos^2(\theta), \\ \tilde{\varepsilon}_{xz} &= (n_{zz}^2 - n_{xx}^2) \cos(\theta) \sin(\theta). \end{aligned} \tag{6}$$

Therefore, we assert that the tilted SWG core behaves as a tilted uniaxial crystal core described by the tensor $\tilde{\boldsymbol{\varepsilon}}$. To corroborate that, we now propose a wide SWG waveguide which supports multiple TE and TM modes with parameters: $w_c = 3.25\ \mu m$, $h_c = 3.25\ \mu m$, $\Lambda = 0.2\ \mu m$ and $DC = 0.5$. We will discuss the behavior of the propagating light along this structure when tilting the segment from 0 to 45 degrees. First, we calculate the Floquet modes of the periodic structure by using a 3D-FDTD simulator[13]. Then, we model the proposed periodic waveguide using the aforementioned anisotropic model, obtaining a homogeneous waveguide with the same width and height but described by its permittivity tensor $\boldsymbol{\varepsilon} = \mathrm{diag}[2.76^2, 2.76^2, 1.93^2]$ [See Fig. 2(c) and 2(f)]. We use a commercial anisotropic simulator to solve the modes of this waveguide, modeling the different tilt angles by applying Eq. (5) and Eq. (6) to adequately model the tilt of the segment. In Fig. 3(a) we compare the effective indices of the fundamental TE and TM modes of the periodic waveguide and its corresponding anisotropic homogenization. Figure 3(b) shows the dispersion behavior of the homogenized and periodic waveguide for the 30° tilt structure. Two important conclusions stand out from these figures: i) The tilt angle of the SWG segments affects only to the TE modes, enabling a new methodology to gain control over the polarizations. ii) The proposed model adequately models the behavior of the tilted SWG structures in a wide bandwidth. This is advantageous because the computation time is decreased more than ten times if the homogenization is performed. A deeper study of the anisotropic homogenization of tilted and non-tilted structures can be found in Ref.[14].

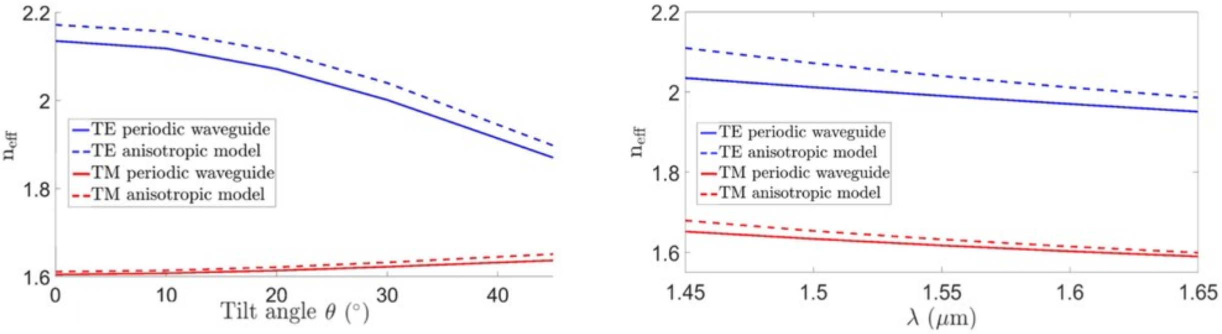

Figure 3. a) Effective indices of the fundamental TE and TM modes of the proposed tilted SWG with parameter: $w_c = 3.25\ \mu m$, $h_c = 3.25\ \mu m$, $\Lambda = 0.2\ \mu m$ and $DC = 0.5$ and its anisotropic homogeneous waveguide. b) Wavelength dispersion of the fundamental TE and TM mode of the $\theta = 30°$ tilted SWG waveguide.

4. POLARIZATION BEAM SPLITTER BASED ON TILTED SWG WAVEGUIDES

A potential application of tilted SWG waveguides are polarization management devices. For example, we can split the polarizations by using a 2x2 tilted SWG based multimode interferometer [See Fig.1(d)]. In a 2x2 MMI the input beam is replicated N times every $3L_\pi/N$, where L_π, known as beat length, can be calculated as $L_\pi = \lambda/2(n_{\mathrm{eff0}} - n_{\mathrm{eff1}})$ where λ is the wavelength at the vacuum and n_{eff0} and n_{eff1} are the effective indices of the fundamental and first order mode respectively[15]. By using the degree of freedom provided by tilted SWGs we can tune the L_π of TE and TM modes separately, achieving the splitting condition, $2L_\pi^{TE} = L_\pi^{TM}$, which allow us to separate both polarizations. In Fig. 4(a) we show how the beat lengths change when we tilt the segments for the same wide SWG waveguide studied in the section 3. A preliminary design can be obtained via the proposed anisotropic homogenization. In Fig. 4(b) we show the propagation of the TE and TM polarizations simulated with 3D-FDTD simulation. This figure shows how the polarization splitting is obtained for the aforemententioned wide waveguide for a 7 degrees tilt.

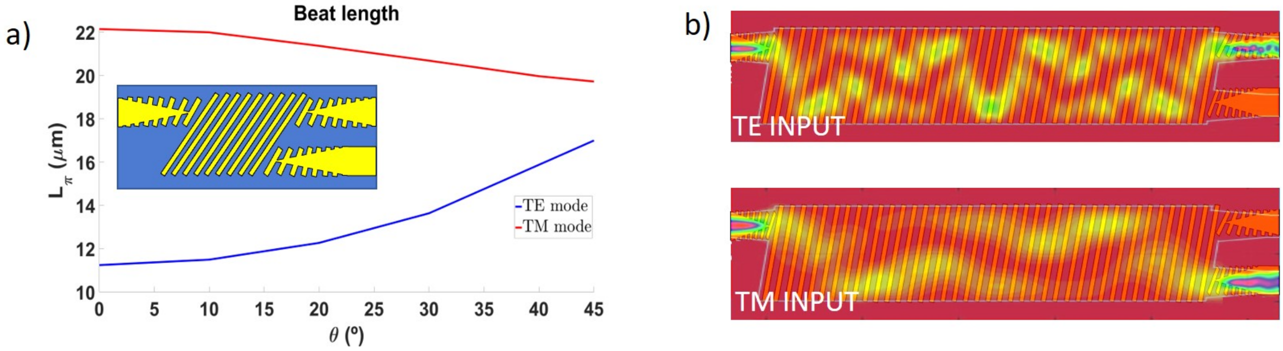

Figure 4. a) Beat lengths of the TE and TM modes when tilting the segments of the structure. b) Propagation of the TE and TM polarizations (E_x and E_y respectively) along the proposed structure for a tilt of 7 degrees.

5. CONCLUSIONS

In conclusion, in this work we have shown that tilted SWG structures enable the precise control of the effective metamaterial anisotropy in SWG waveguides. Tilting the SWG segments mainly affects TE modes, while TM modes are virtually unaffected. This provides a new degree of freedom to engineer the refractive index of silicon photonic devices, while avoiding small variable duty cycles that hinder fabrication. Furthermore, an accurate homogenization model has been developed. The proposed model significantly reduce the computation time when compared with FDTD simulations. Finally, we have shown a practical application of the tilted SWGs: a Polarization Beam Splitter based on a 2x2 MMI with tilted SWG segments. We foresee that tilted SWG waveguides will enable advanced polarization management devices and the implementation of metamaterials for transformation optics because of the novel degree of freedom that they provide.

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REFERENCES

[1] Rytov, S. M., "Electromagnetic properties of a finely stratified medium," *Soviet Physics JETP* **2**(3), 466 (1956).

[2] Cheben, P., Xu, D.-X., Janz, S., and Densmore, A., "Subwavelength waveguide grating for mode conversion and light coupling in integrated optics," *Opt. Express* **14**(11), 4695 (2006).

[3] Halir, R., Bock, P. J., Cheben, P., Ortega-Moñux, A., Alonso-Ramos, C., Schmid, J. H., Lapointe, J., Xu, D.-X., Wangüemert-Pérez, J. G., Molina-Fernández, Í., and Janz, S., "Waveguide sub-wavelength structures: a review of principles and applications," *Laser Photonics Rev.* **9**(1), 25 (2014).

[4] Halir, R., Ortega-Moñux, A., Benedikovic, D., Mashanovich, G. Z., Wangüemert-Pérez, J. G., Schmid, J. H., Molina-Fernández, Í., and Cheben, P., "Subwavelength-grating metamaterial structures for silicon photonic devices," *Proceedings of the IEEE* **PP**(99), 1 (2018).

[5] Cheben, P., Halir, R., Schmid, J. H., Atwater, H. A., and Smith, D. R., "Subwavelength integrated photonics," *Nature* **560**(7720), 565 (2018).

[6] Halir, R., Cheben, P., Luque-González, J. M., Sarmiento-Merenguel, J. D., Schmid, J. H., Wangüemert-Pérez, G., Xu, D.-X., Wang, S., Ortega-Moñux, A., and Molina-Fernández, Í., "Ultra-broadband nanophotonic beamsplitter using an anisotropic sub-wavelength metamaterial," *Laser Photonics Rev.* **10**(6), 1039 (2016).

[7] González-Andrade, D., Wangüemert-Prez, J. G., Velasco, A. V., Ortega-Moñux, A., Herrero-Bermello, A., Molina-Fernández, I., Halir, R., and Cheben, P., "Ultra-broadband mode converter and multiplexer based on sub-wavelength structures," *IEEE Photonics Journal* **10**(2), 1 (2018).

[8] Xu, L., Wang, Y., Kumar, A., Patel, D., El-Fiky, E., Xing, Z., Li, R., and Plant, D. V., "Polarization beam splitter based on MMI coupler with SWG birefringence engineering on SOI," *IEEE Photonics Technology Letters* **30**(4), 403 (2018).

[9] Jahani, S. and Jacob, Z., "Transparent subdiffraction optics: nanoscale light confinement without metal," *Optica* **1**(2), 96 (2014).

[10] Jahani, S., Kim, S., Atkinson, J., Wirth, J. C., Kalhor, F., Noman, A. A., Newman, W. D., Shekhar, P., Han, K., Van, V., DeCorby, R. G., Chrostowski, L., Qi, M., and Jacob, Z., "Controlling evanescent waves using silicon photonic all-dielectric metamaterials for dense integration," *Nat. Commun.* **9**(1), 1893 (2018).

[11] Yeh, P., Yariv, A., and Hong, C.-S., "Electromagnetic propagation in periodic stratified media. I. General theory," *J. Opt. Soc. Am.* **67**(4), 423 (1977).

[12] Marcuse, D., "Modes of a symmetric slab optical waveguide in birefringent media-part I: Optical axis not in plane of slab," *IEEE J. Quantum Electron.* **14**(10), 736 (1978).

[13] Wangüemert-Pérez, J. G., Cheben, P., Ortega-Moñux, A., Alonso-Ramos, C., Pérez-Galacho, D., Halir, R., Molina-Fernández, I., Xu, D.-X., and Schmid, J. H., "Evanescent field waveguide sensing with subwavelength grating structures in silicon-on-insulator," *Opt. Lett.* **39**(15), 4442 (2014).

[14] Luque-González, J. M., Herrero-Bermello, A., Ortega-Moñux, A., Molina-Fernández, Í., Velasco, A. V., Cheben, P., Schmid, J. H., Wang, S., and Halir, R., "Tilted subwavelength gratings: controlling anisotropy in metamaterial nanophotonic waveguides," *Opt. Lett.* **43**(19), 4691–4694 (2018).

[15] Soldano, L. B. and Pennings, E. C. M., "Optical multi-mode interference devices based on self-imaging: principles and applications," *Journal of Lightwave Technology* **13**(4), 615–627 (1995).