Abstract We provide supporting information on the calculation of the effective index tensor, the derivation of the beat length, and details on the fabrication tolerance analysis.

Ultra-broadband nanophotonic beamsplitter using an anisotropic sub-wavelength metamaterial – Supporting information

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1. Calculating the effective indices n_{xx}, n_{zz}

To calculate the effective indices of the sub-wavelength structure we consider the geometry shown in Fig. 1, corresponding to the lateral cross-section of the sub-wavelength structure. Note that this structure extends periodically along the z-axis; this periodicity is included in the simulation tools by defining periodic boundary conditions as shown in Fig. 1.

For the calculation of n_{zz} we use a conventional mode solver [1], and obtain the effective index of the fundamental TE mode traveling along the x-direction and polarized along the z axis.

For the calculation of n_{xx} a Bloch-Floquet mode solver is required [2]. In this case we calculate the effective index of the fundamental TE mode travelling along the z-direction and polarized along the x axis.

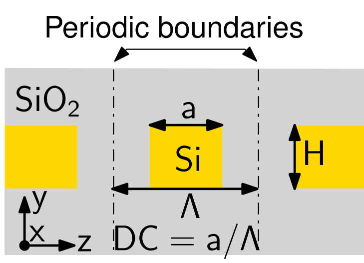

Figure 1 Cross-section of the sub-wavelength structure. The dimensions are given in table 1 of the main manuscript.

2. Derivation of the beat length in an anisotropic medium

In the main manuscript we state that the beat length of a multimode interference coupler in an anisotropic medium is given by:

$$L_\pi^{\text{aniso}} \approx \frac{4W_e^2}{3\lambda}\frac{n_{zz}^2}{n_{xx}}. \quad (1)$$

The derivation of (1) is analogous to the derivation for isotropic media presented in [3]. Consider the 2D effective index model of a multimode waveguide shown in Fig. 2, with z the direction of propagation. The dispersion equation in the anisotropic medium is given by [4]:

$$(k_x/n_{zz})^2 + (k_z/n_{xx})^2 = k_0^2, \quad (2)$$

where k_x is the wave-vector component in the x direction, $k_z = \beta$ is the propagation constant, and $k_0 = 2\pi/\lambda$ [4]. Assuming that the guided modes $\varphi_m(x)$ are well confined in the waveguide, i.e. $\varphi_m(x) = \sin(m\pi x/W_e)$, the x component of the wave-vector of the m-th mode is given by [3]:

$$k_{x,m} = \frac{m\pi}{W_e}. \quad (3)$$

Inserting (3) into (2), solving for $k_{z,m}$ and using a first order Taylor expansion of the resulting square root (i.e. assuming paraxiality), we arrive at the propagation constant of the

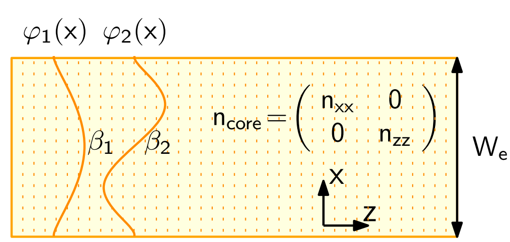

Figure 2 Multimode waveguide composed of an anisotropic medium. W_e indicates the effective width that takes into the account the Goos-Hänchen shift at the waveguide walls.

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m-th mode:

$$k_{z,m} = \beta_m \approx n_{xx} \left(\frac{2\pi}{\lambda} - m^2 \frac{\lambda \pi}{4 W_e^2 n_{zz}^2} \right). \tag{4}$$

From (4) we find

$$\beta_1 - \beta_2 = \pi \frac{3\lambda}{4W_e^2} \frac{n_{xx}}{n_{zz}^2}, \tag{5}$$

which upon application of the definition of beat length, $L_\pi = \pi/(\beta_1 - \beta_2)$, yields (1).

3. Fabrication tolerance analysis

We used full 3D-FDTD simulations to study the fabrication tolerances of the device. We independently varied the duty-cycle, width of the multimode section and length of the multimode section (number or periods), leaving the remaining parameters at their nominal values. For each variation the wavelength response in the 1250 nm - 1750 nm range was recorded. The worst value of excess loss, imbalance and phase error in that wavelength range was obtained for each geometry. Figure 3 summarizes the performance of the device for variations in duty-cycle, MMI width and number of periods. From figure 3 we observe that the nominal design (50 % duty-cycle, $W_{\mathrm{MMI}} = 3.25\,\mu$m and 74 periods of length) provides that best overall performance. In order to keep excess losses and imbalance below 1 dB, and the phase error below 5° in the complete 500 nm bandwidth around the 1500 nm central wavelength the duty-cycle should be controlled to ± 7 %, the width of the device should vary in less than ± 50 nm, and the optimum number of periods can vary in about ± 2. Careful calibration of lithography and etching are required to meet these duty-cycle and width specifications.

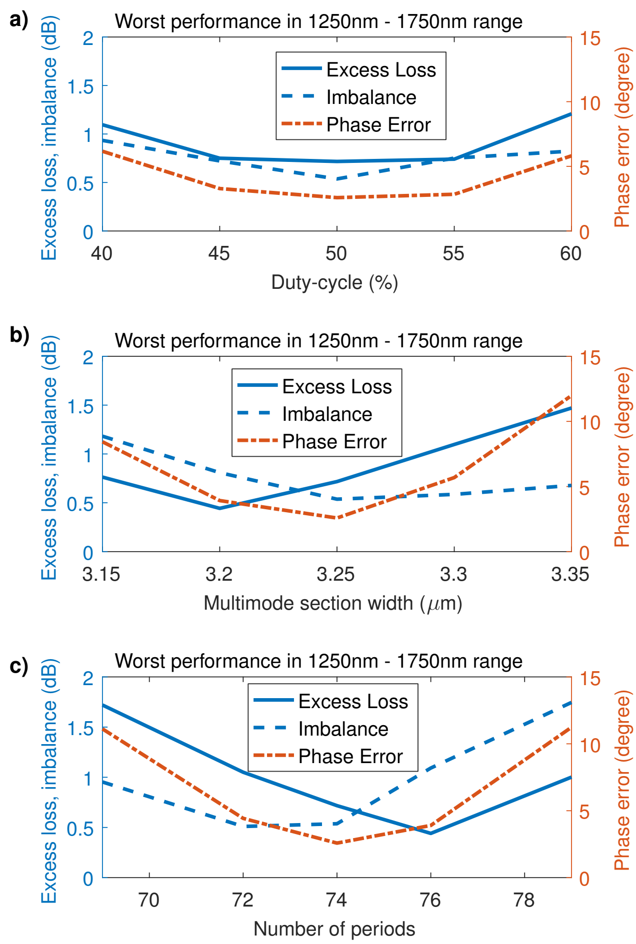

Figure 3 Simulated worst performance in the 1250 nm to 1750 nm wavelength range, for variations in a) the duty-cycle b) MMI width c) and number of periods, with all other parameters nominal.

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