Inverse dispersion engineering in integrated waveguides

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Abstract— We present a differential tool to find the cross-section geometry of integrated waveguides that matches a target dispersion profile. Our approach is more efficient than usual trial-and-error procedures, particularly for geometries with several degrees of freedom. By applying our strategy, we find several ultraflattened dispersion curves over 350 nm bandwidth in a silicon-on-insulator waveguide in less than 10 iterations.

On-chip integration of optical functionalities traditionally developed in fiber is a very active research field nowadays. Integrated waveguides are key components to carry out such functions. Typically, their material constituents possess very different refractive indices. This high index contrast makes their geometries significantly affect the physical properties of these waveguides. It allows engineering waveguide's features like effective refractive index, dispersion or nonlinear coefficient by means of suitable designs of the cross section. Nevertheless, it is not straighforward to evaluate the impact of geometrical changes on these properties. Indeed, these tasks are often based on the systematic numerical calculation of the property of interest, *e.g.*, the dispersion, for a huge number of configurations [1]. Consequently, this strategy becomes time-consuming when the cross section have two or more degrees of freedom. Therefore, alternative approaches that improve the efficiency of the design are highly desirable.

Gradient-based algorithms is one of the preferred optimization methods if the derivatives of the property to be optimized are available [2]. Firstly, a suitable merit function that quantify the similarity between the target feature and that shown by a particular configuration is defined. Secondly, a local approximation of the merit function in the parameter space must be calculated somehow. Finally, the point in the parameter space (close to the initial point to keep the local approximation valid) where the merit function becomes minimum is selected as a new starting point. This procedure can be iterated until achieving the target (provided it can be reached). Our approach belongs to this class of optimization methods. Particularly, the points in the parameter space, p, represent different configurations in our case. Furthermore, we present a proposal to evaluate the above derivatives in high-index-contrast waveguides that removes numerical inaccuracies related to their tight light confinement.

Here we are interested in the waveguide's dispersion, $\beta_2 = \partial_\omega^2 \beta$, where β is the propagation constant of a waveguide mode. We define the local approximation of our merit function as

$$\chi^2(p;p_{(\mathrm{m})}) = \frac{1}{N_\omega} \sum_{k=1}^{N_\omega} \Big(\big[\beta_2(p_{(m)};\omega) + \partial_p \beta_2(p_{(m)};\omega)\cdot(p-p_{(m)})\big] - \beta_2^{\mathrm{target}}(\omega_k)\Big)^2. \qquad (1)$$

Note that a linear approximation of β_2 in the parameter space is explicitly included inside the squared brackets. If χ^2 becomes minimum at $p_{(\mathrm{m}+1)}$, then $p_{(\mathrm{m}+1)}$ represents a new configuration closer to the target and the procedure can be repeated. Of course, Eq. (1) assumes $\partial_p\beta_2$ is known. We propose to evaluate $\partial_p\beta_2 = \partial_\omega^2(\partial_p\beta)$ based on

$$\partial_p \beta = \frac{\varepsilon_0 \omega}{2} \frac{\displaystyle\int_S \left((\partial_p \varepsilon_{nn}^{-1}) d_n^2 - (\partial_p \varepsilon_{TT}) e_T^2 + (\partial_p \varepsilon_{zz}) e_z^2\right) \mathrm{d}S}{\displaystyle -\int_S (\mathbf{e}_\mathrm{t} \times \mathbf{h}_\mathrm{t}) \cdot \hat{\mathbf{z}}\, \mathrm{d}S}, \qquad (2)$$

where d_n is the component of the electric displacement field normal to the interface, e_T is the component of the electric field tangent to the interface in the transverse plane, $\mathbf{e}_\mathrm{t}$ and $\mathbf{h}_\mathrm{t}$ indicate

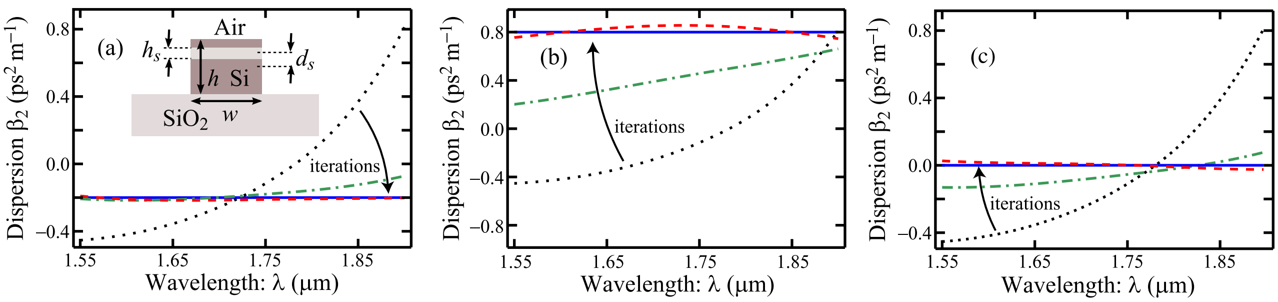

Figure 1: Three examples of optimization starting from the same geometry (dotted black curve) and with three different flattened dispersion profiles as a goal (solid blue line): (a) $\beta_2 = -0.2\,\mathrm{ps^2m^{-1}}$, (b) $\beta_2 = 0.8\,\mathrm{ps^2m^{-1}}$, and (c) $\beta_2 = 0$. The inset in (a) represents the cross-section of the waveguide.

the transverse components of the electric and magnetic fied, respectively, and ε represents the permitivity tensor. It must be evaluated at several frequencies ω to compute numerically its second derivative with respect to ω. It is worth noticing that $\partial_p\beta$ does not depend on $\partial_p e$, where e is the electric field. This result corresponds to a generalization of the Hellmann-Feynman theorem for nonself-adjoint operators [3]. From a practical point of view, it allows us to calculate $\partial_p\beta$ by means of the mode fields at p (no additional calculations at $p + \delta p$ are required). Furthermore, Eq. (2) takes explicitly into account the vectorial nature of the mode fields through the axial term $(\partial_p\epsilon_{zz})e_z^2$, that is imperative in high-index-contrast waveguides. Moreover, it deals with d_n instead of e_n to avoid numerical inaccuracies related to the abrupt transition of e_n around interfaces in high-index-contrast waveguides [4].

To illustrate our inverse dispersion engineering approach, we consider in Fig. 1 several target dispersion profiles in a cross section with four degrees of freedom [see inset in Fig. 1(a)]. It corresponds to a strip silicon waveguide with a silica slot [1]. Starting from a dispersion profile far from the targets, our algorithm finds in less than 10 iterations dispersions in very close agreement to the targets. Note that these targets ranges from low negative dispersion, see Fig. 1(a), to high normal dispersion, see Fig. 1(b), also including zero dispersion, see Fig. 1(c). It demonstrates the efficiency of our approach to design cross sections with predefined properties, even for high-index-contrast waveguides.

ACKNOWLEDGMENT

This work has been financially supported by the Spanish Government (research project TEC2013-46643-C2-1-R) and by the Generalitat Valenciana (grant PROMETEO II/2014/072). D. C.-L. gratefully acknowledges funding from the ERC-FP7/2007-2013 grant 336940.

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