Recent advances and results in waveguide shape optimisation techniques

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Abstract: We show how judicious usage of optimisation techniques combined with a rigorous Maxwell solver can be used to create novel designs such as ultra-short injection devices capable of efficiently channeling light in much shorter lengths than conventional tapers.

Introduction

In this paper we show how judicious usage of optimisation techniques combined with accurate EM solvers can be successfully used to design novel ultra-compact structures with excellent transmission properties. Via an example we show how we were able to arrive at designs for ultra-short injectors capable of efficiently transmitting light from large input devices to small output devices. The currently prevailing technique for injecting light into smaller devices is to use tapered waveguides, where the cross-section varies monotonically and continuously along the propagation direction. It is well known that the power lost through the taper side-walls decreases for increasing taper lengths, becoming effectively loss-less or "adiabatic" for large lengths [1]. However in many practical situations it is often desirable to have far shorter injectors. The device we present here achieves the same transmission as quasi-adiabatic tapers, but in much shorter lengths. Such devices could open the way to fabrication of injectors directly on photonic chips - such as photonic crystal devices - by including the designs on the same fabrication mask. The methods used herein also have much wider applicability, including for example design of longitudinal profiles for gratings and tapers to obtain a large range of spectral filters [2], and optimized transverse index profiles to simultaneously achieve desired optical fiber dispersion, dispersion slope, cutoffs, effective areas, etc.

The example problem

We consider a glass uniform waveguide (refractive index 1.5) interfacing to air, with a width of 7 μm. The output waveguide is of the same material, but with a width of 0.5 μm. We choose the working wavelength to be 1.51 μm. Although in this presentation we consider a two-dimensional model of this structure, the same design approach will work for more general 3D structures. A linear tapered profile joining these waveguides would have an angle of 45°. The resulting losses would therefore very high (Fig. 1). For adiabaticity to be achieved such a linear taper would require lengths greater than 40 μm, i.e., at least 6 times this length.

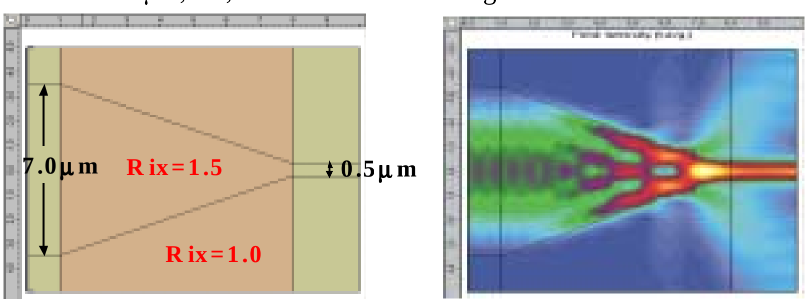

Fig. 1. Initial 2D model of an injector. The linear taper has merely 53% efficiency, most power being lost to radiation.

Solving the propagation problem: A necessary requirement is the availability of a robust field calculation engine capable of modeling such wide angle, high contrast structures. While classical Beam Propagation Methods (BPMs) can be used to determine propagation in low-index-contrast, small-angle tapers, clearly classical BPMs are inadequate here. Instead the commercial propagation tool FIMMPROP by Photon Design was used [3]. This uses the Mode Matching Method (MMM), which provides rigorous solutions to the full Maxwell equations, and is therefore capable of correctly modeling the strong diffraction phenomena likely to occur in such structures.

The optimization problem

We define the optimisation problem by replacing the linear taper profile with a piecewise linear function. The cross-sectional widths $w_1, w_2, \ldots, w_N$ at the N function nodes will be the parameters varied in the optimization process. We also impose the shape to remain laterally symmetric. The resulting transmission at the wavelength λ becomes a function of these parameters alone $P_\lambda\left(w_1, w_2, \ldots, w_N\right)$.

Choosing the appropriate objective function that minimises wavelength sensitivity: One useful characteristic of adiabatic tapers is that they are very wavelength insensitive – they transmit equally well over a large wavelength range. To ensure our injector remains as wavelength insensitive as possible over a desired range, we choose to maximise the sum of the transmission evaluated at several wavelengths:

$$P_{\lambda_1}(w_1, w_2, ..., w_N) + P_{\lambda_2}(w_1, w_2, ..., w_N) + ... + P_{\lambda_M}(w_1, w_2, ..., w_N)$$

instead of optimising the transmission at just the working wavelength. This directs the optimiser to finding a shape that is both highly transmitting and with low wavelength dispersion.

The results

Here we show the optimal design achieved using 9 nodes (N=9), and 3 sampling wavelengths in the objective function λ_1=1.49µm, λ_2=1.51µm, λ_3=1.55µm in an attempt to minimise wavelength dispersion in a window 0.4µm either side of the working wavelength. Fig. 2 shows the shape obtained after 20 iterations of the optimization process. This shape has a transmission of 92%! Moreover the transmission remains virtually unchanged in the specified wavelength window. Clearly it is not an increased adiabatic effect that is responsible for this improvement. Instead, the shape produces resonance effects between the local modes that re-inject the power initially coupled into higher order local modes back into the fundamental mode at the RHS exit. In fact, for the fastest profile changes are close to the "sudden approximation" regime where, although the local modes may change, the total field has a certain inertia remaining relatively unchanged in lengths much smaller than a wavelength. This has important and desirable consequences with regard to insensitivity for fabrication limitations.

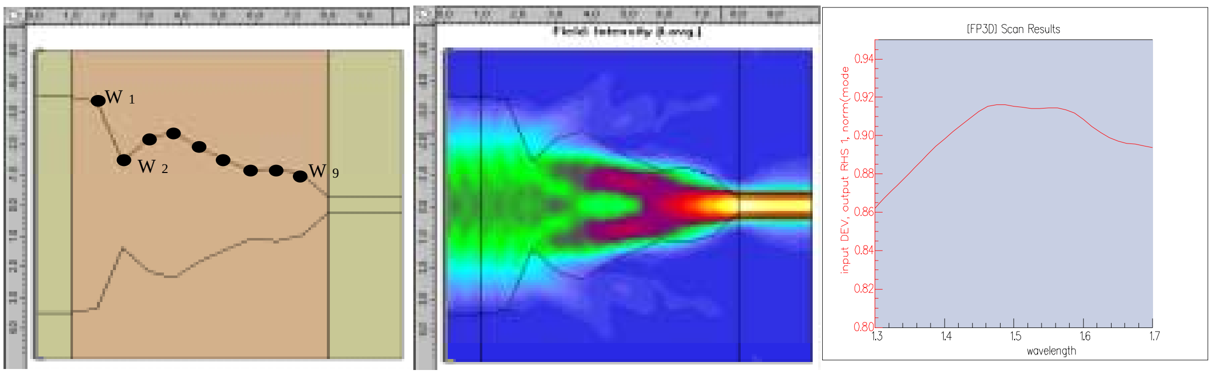

Fig.2. Result of optimizing over 3 wavelengths. Field plot is for wavelength = 1.51 µm. Not only is the power transmission is even better (92%), it also remains virtually unchanged in the wavelength window 1.47 µm to 1.55 µm.

Sensitivity wrt. shape and input perturbations: The sensitivity with respect to shape perturbations is quite low – perturbations of the node positions $w_1, w_2, ..., w_9$ by 50nm have negligible impact on the transmission, meaning that the design responds well to fabrication limitations such as the rounding of corners, etc. Note though that this shape gives optimal transmission for the fundamental mode of the input (multimode) waveguide; the transmission efficiency will vary with other input field profiles, but it will be at least as good as the power carried in the fundamental mode. Gaussian input profiles, whose shape is similar to the fundamental mode and are therefore predominately carried by it, will typically still give good transmission.

Higher discretisations: Increasing the number of nodes would be the natural choice in attempting to improve on these results, as it is assumed that the more degrees of freedom in the optimization, the better the optimal solution. This indeed is true but it should be noted that the more the number of variables, the more unstable the optimization process becomes. For a detailed discussion on these instability issues we refer the reader to [4].

Conclusions: The full Maxwell solver optimisation techniques used herein have wide applicability generating results rich in physics and application ranging from novel fiber designs to efficient high-contrast integrated-optic waveguides (even 3.5:1 for semiconductors:air).

References

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