Mode Engineering via Waveguide Structuring

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Abstract: *We analyze the lateral modes of dielectric waveguides that include refractive index corrugations parallel to the direction of light propagation. We show that we can engineer the resulting far-field profile arising from structured waveguide modes, leading to improved modal discrimination and brightness.*
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Control of the optical modes of a semiconductor laser, be it determination of the quantity of lasing modes or the qualities of these modes, is critical in semiconductor laser diode design and can be used to optimize the laser properties for specific applications. Mode control in semiconductor laser diodes has been introduced via longitudinal index gratings [1], 2-dimensional photonic crystals [2], waveguide phase structures [3], and gain structuring [4]. Recently it has been shown that structured modes can have higher proportion of diffraction-limited power in the far-field [5]. Here we explore introduction of refractive index perturbations parallel to the waveguide and more generally show that the resultant structured modes may allow control of the number of lateral modes as well as provide a means to engineer a desired mode with certain characteristics.

Fig. 1 shows the lateral profile of a simple dielectric waveguide and the calculated intensity profiles of the three lowest order lateral modes, while Fig. 2 and Fig. 3 show the lateral index profiles for two cases where the index corrugations are parallel to the waveguide. The waveguide cores are 20λ in width and have index n=3.01 surrounded by cladding with index n=3.0. The structured waveguides depicted in Figs. 2 and 3 have lower index (n=3.009) corrugations across the waveguide within the core region.

The calculated effective indices of the eigenmodes for the three cases are compared in Fig. 4. We note that while the structured waveguides both have uniformly lower modal effective indices for all lateral modes as compared to the simple waveguide, the difference in effective indices between the fundamental mode and the first higher order lateral mode is increased 78% for the structured waveguide WG1 shown in Fig. 2 ($\Delta n_{eff} = 4.9\text{x}10^{-4}$). Fig. 5 plots the mode confinement Γ defined as the fraction of the modal intensity located within the waveguide core. We see that the modal discrimination between the two lowest order modes is increased by more than 300% for the structured waveguide WG1 shown in Fig. 2 ($\Delta\Gamma=7.2\text{x}10^{-3}$) compared to the unstructured waveguide WG0 shown in Fig. 1. As evident in Fig. 5, the waveguide WG2 depicted in Fig. 3 is designed with a first higher order mode that has a mode confinement factor greater than that of the fundamental mode ($\Delta\Gamma=5.4\text{x}10^{-4}$). Hence by appropriate design of the refractive index corrugation, single lateral mode operation in structured higher order modes may be possible.

Waveguide index structuring may also enable mode engineering. For example the far-field brightness, e.g. the fraction of the far-field modal intensity within a specified half-angle, can be similarly improved. Fig. 6 shows a waveguide whose index profile was designed for increased far-field brightness for its fundamental mode. Notice the near-field of the fundamental mode is widened and flattened as compared to the Gaussian fundamental mode in Fig. 1. In Fig. 6 we show the far-field power fraction as a function of divergence half-angle extracted from the waveguides in Figs. 1 and 5. Note that up to approximately ±2° in Fig. 7, the fundamental mode of the structured waveguide has *higher* brightness than the Gaussian fundamental mode of the simple waveguide, and that more than 78% of the total power falls within ± 1.5°. We compare in Fig. 8 the far-field power fraction within ±1.5° for the waveguides shown in Figs. 1 and 6. Fig. 8 indicates the structured waveguide in Fig. 6 has a modest 6% greater intensity in its fundamental mode, and improved optimization is underway which would benefit applications such as optical fiber pumping.

In summary, we show that structured waveguides with appropriate and modest refractive index corrugations enables lateral mode engineering. As examples, we show that structured waveguides may increase modal discrimination in favor of the fundamental mode, or for a higher order mode, and can produce modes that have greater far-field intensity on a target than the Gaussian mode of an equal sized waveguide. This research is supported by the Joint Transition Office Multidisciplinary Research Initiative under Award No. 17-MRI-0619.

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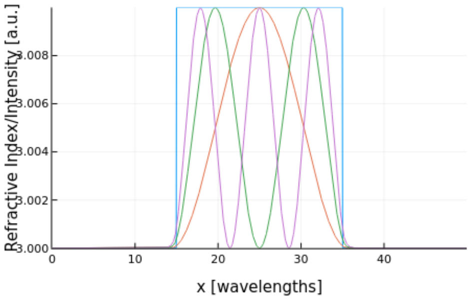

Fig. 1: Index profile and lateral mode intensities for unstructured waveguide, WG0.

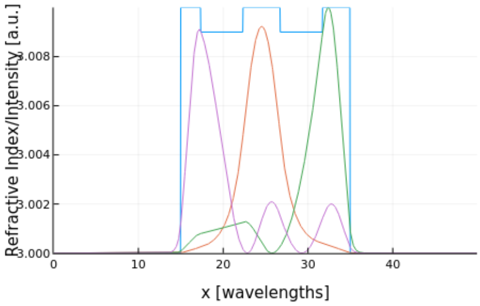

Fig. 2: Index profile and lateral mode intensities for structured waveguide, WG1, designed for fundamental mode confinement factor.

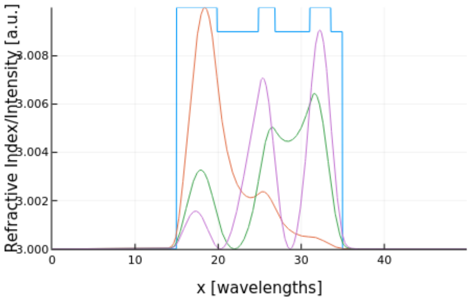

Fig. 3: Index profile and lateral mode intensities for structured waveguide, WG2, designed for 1st higher order mode confinement factor.

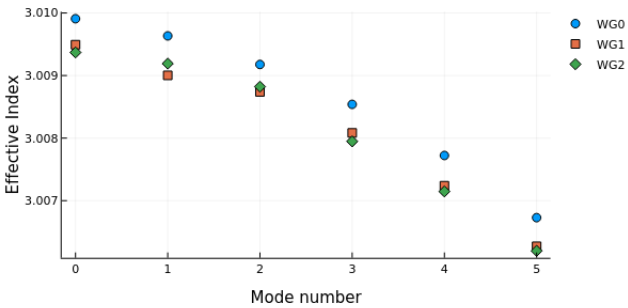

Fig. 4: Modal effective indices for the 6 lowest order modes of WG0 (Fig. 1), WG1 (Fig. 2), and WG2 (Fig. 3) waveguides.

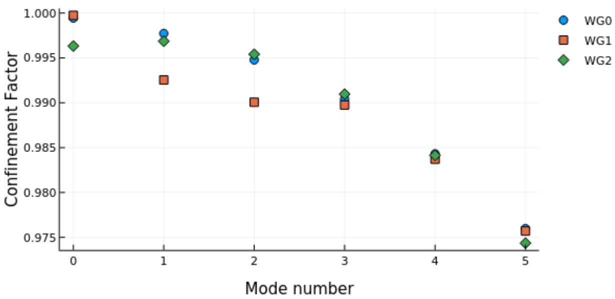

Fig. 5: Modal confinement factors for the 6 lowest order modes of WG0 (Fig. 1), WG1 (Fig. 2), and WG2 (Fig. 3) waveguides.

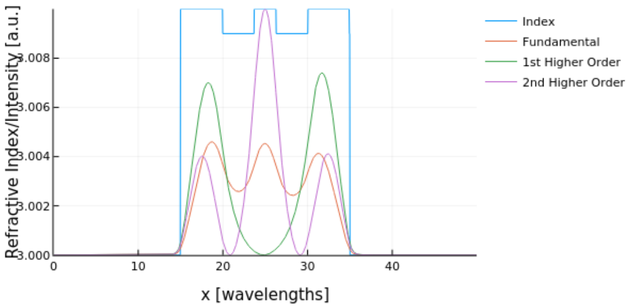

Fig. 6: Index profile and lateral mode intensities for structured waveguide, WG3, designed for improved far-field.

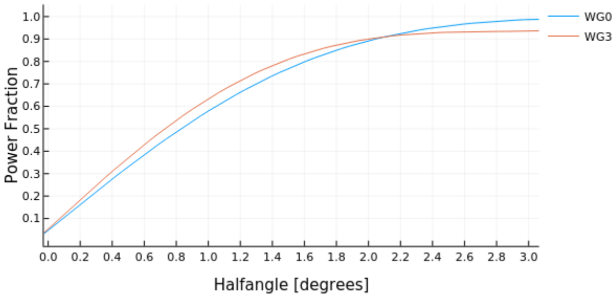

Fig. 7: Far-field power fraction within the half-angle from normal for the fundamental modes of unstructured WG0 (Fig. 1) and structured WG3 (Fig. 6) waveguides.

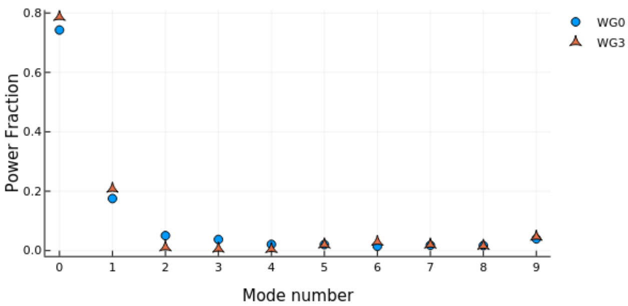

Fig. 8: Far-field power fraction within ±1.5° for the modes of unstructured WG0 (Fig. 1) and structured WG3 (Fig. 6) waveguides.