Direct Semiconductor Diode Laser Mode Engineering and Waveguide Design

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Abstract—Starting from the desired modal field we solve for the supporting waveguide refractive index structure within a semiconductor diode laser. Specifically we analyze the problem of maximizing far-field on-axis intensity and discuss the practical aspects of waveguide design.

Index Terms—Laser modes, Semiconductor waveguides, Optical waveguides, Brightness

I. Introduction

Engineering the longitudinal and transverse refractive index structure of waveguides provides a path to engineering the laser modes of a semiconductor diode laser. Index structuring not only provides increased modal discrimination and permits modal selection [1], but also enables engineering the field profile and properties of the laser mode itself [2]. Analytically solving the Helmholtz waveguide equation has been used both for determining the index structure that produced a mode profile [3] (that is for waveguide characterization) and as a way of determining the optical fiber index structure that supports a desired mode profile [4] (for waveguide design). We believe a similar approach is applicable to the problem of engineering a semiconductor laser with a desired modal field profile. Combined with a Fourier optics analysis of the problem of far-field on-axis intensity, we can define engineered mode profiles with enhanced on-axis intensity and create semiconductor waveguide index structure that would support laser modes that approximate those profiles. We analyze the challenge of maximizing far-field on-axis intensity for higher-order laser modes.

II. Waveguide Solutions to Modal Fields

The Helmholtz waveguide equation can be solved analytically for a given modal field $U(\vec{r})$ with free-space wavevector k_0 for the supporting refractive index structure $n(\vec{r})$:

$$\nabla^2 U(\vec{r}) + (n(\vec{r})^2 - \overline{n}^2)k_0^2 U(\vec{r}) = 0$$
$$\implies n(\vec{r}) = \sqrt{\overline{n}^2 - \frac{\nabla^2 U(\vec{r})}{k_0^2 U(\vec{r})}} \tag{1}$$

Note that we have a set solution waveguide structures for varied values of modal effective index $\overline{n}$.

Not all functional forms of $U(\vec{r})$ will produce practical or even physical index structures. Indeed, the quantity $\frac{\nabla^2 U(\vec{r})}{U(\vec{r})}$ must be strictly finite for there to be a finite solution for (1). However, if said quantity is finite and bound, then by properly choosing $\overline{n}$ and by transversely scaling $U(\vec{r})$ we can obtain an waveguide index profile that is bounded to a desired range of index values. It can be shown that the transversely scaled modal field $U(\alpha\vec{r})$ will be supported by a waveguide index structure such that $n_{\min} \leq n(\vec{r}) \leq n_{\max}$ if we take

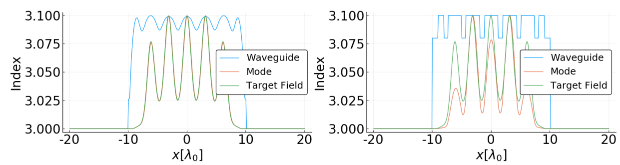
$$\overline{n} = \sqrt{\frac{n_{\max}^2 \chi_{\max} - n_{\min}^2 \chi_{\min}}{\chi_{\max} - \chi_{\min}}} \tag{2}$$

$$\alpha = \sqrt{\frac{n_{\max}^2 - n_{\min}^2}{\chi_{\max} - \chi_{\min}}} \tag{3}$$

where we define

$$\chi_{\min} = \min \frac{\nabla^2 U(\vec{r})}{k_0^2 U(\vec{r})} \tag{4}$$

$$\chi_{\max} = \max \frac{\nabla^2 U(\vec{r})}{k_0^2 U(\vec{r})} \tag{5}$$



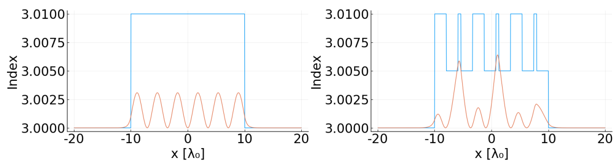
(a) (b)

Fig. 1: Waveguide and supported modal intensity (a) analytical solution with cladding perturbation, and (b) with additional binary index approximation.

In order to obtain a practically implementable waveguide structure one may (and likely will) need to apply approximations to the form of $U(\vec{r})$, as well as the $n(\vec{r})$ resulting from (1). A well-formed approximation of $U(\vec{r})$ will avoid infinities in $\frac{\nabla^2 U(\vec{r})}{U(\vec{r})}$, as in [4]. Generally, one can apply a lower index cladding once the modal field is sufficiently decayed, as shown in Figure 1(a). Further approximations of the calculated index structure, such as clipping to a select set of index values as shown in Figure 1(b), can yield structures that are simpler to implement, albeit at the cost of deviating from the target field form.

III. Far-Field On-Axis Intensity

Some applications call for maximizing the on-axis intensity of a laser beam. A Fourier optics analysis of near-field to far-field propagation problem relates the zero-frequency component of the near-field to the on-axis amplitude of the far-field, meaning that a more uniform



(a) (b)

Fig. 2: Index structures and the 6^{th} mode intensity for (a) unstructured and (b) engineered waveguides.

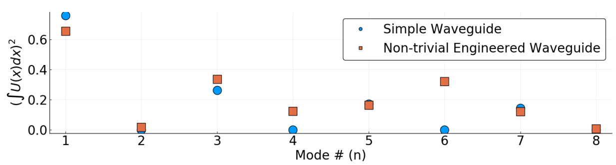


Fig. 3: Equation (7) for evaluated for the first 8 modes of the waveguides shown in Figure 2

mode profile (such as a top-hat or super-Gaussian profile) will tend to produce higher on-axis intensity [5]. We approximate the relative on-axis intensity of a standard semiconductor waveguide laser, assuming that the modes are approximately sinusoidal in field profile, an assumption appropriate for significant index confinement in a slab waveguide of width w while the modes (of mode index $n = 1, 2, 3, \dots$) are far from cut-off. So we have the approximate (normalized) modal field, $U_n(x)$:

$$U_n(x) = \sqrt{\frac{2}{w}} \sin(\frac{nx\pi}{w}) \text{ for } 0 \leq x \leq w \tag{6}$$

The square of the integral of the near-field (6) is proportional to the on-axis far-field intensity:

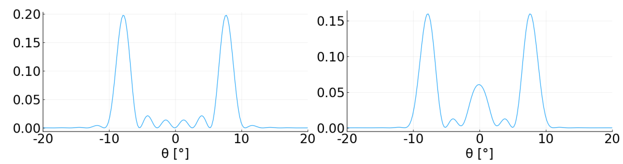
$$I_n(\theta = 0) \propto (\int_0^w U_n(x)dx)^2 \tag{7}$$

For the simple waveguide modal field approximation, this yields:

$$I_n(\theta = 0) \propto \frac{2w(1 - \cos(n\pi))^2}{n^2\pi^2} \tag{8}$$

Equation (8) shows two (intuitive) trends with regard to the mode index n; first, the even n modes have no on-axis intensity (their anti-symmetric near-fields destructively interfere on-axis), and second, higher order modes have decreasing on-axis intensity.

This Fourier optics perspective implies that the fundamental mode (especially one with a top-hat mode profile) is optimal. However, we can find other, higher-order, mode profiles that have enhanced on-axis intensity relative to the simple slab waveguide modes. Higher order mode on-axis intensity can be enhanced by inducing an asymmetry in the power distribution between adjacent (π-phase difference) lobes, and the on-axis intensity null of even n modes can be avoided by avoiding anti-symmetric mode profiles. Consider the waveguides and their $n = 6$ modes shown in Figure 2. By introducing an asymmetric grating perturbation into the waveguide, we are able to create a mode with such a asymmetric power distribution in the lobes. When we evaluate (7) for the modes of those two waveguides (plotted in Figure 3) we can see that the simple waveguide has modes for which (7) follows the trend of the approximation (8). Furthermore, we see that the asymmetric index structure shown in 2(b) yields to non-zero (7) for even n modes.



(a) (b)

Fig. 4: Far-field intensity of the 6^{th} modes for (a) unstructured and (b) engineered waveguides.

To verify the assumption that (7) correlates to on-axis power, we propagate the near-fields into the far-field (shown in Figure 4). Although the engineered 6^{th} mode does not have most of it's power on-axis, it does have a distinct on-axis lobe instead of a null as for the 6^{th} mode of a simple waveguide, an improvement for higher-order mode on-axis power, relative to an unstructured waveguide.

IV. Summary

By solving the Helmholtz waveguide equation for a given modal field we can obtain a support waveguide index structure. Although the analytical solution for the index structure may be non-practical, or even non-physical, appropriately approximating the field can yield a physical solution that can provide a starting place for deriving a practical approximate solution. A Fourier optics analysis of on-axis intensity provides guidance towards engineering modes with increased on-axis intensity. This material is based on work supported by Joint Transition Office Multidisciplinary Research Initiative, Award No. 17-MRI-0619

References

[1] Pawel Strzebonski, Bradley Thompson, Katherine Lakomy, Paul Leisher, and Kent D. Choquette. Mode engineering via waveguide structuring. In 2018 IEEE International Semiconductor Laser Conference (ISLC). IEEE, sep 2018. doi: 10.1109/islc.2018.8516196. URL https://doi.org/10.1109%2Fislc.2018.8516196.

[2] Pawel Strzebonski. Semiconductor laser mode engineering via waveguide index structuring. Master's thesis, University of Illinois at Urbana-Champaign, 12 2018. URL http://hdl.handle.net/2142/102511.

[3] L. McCaughan and E. Bergmann. Index distribution of optical waveguides from their mode profile. Journal of Lightwave Technology, 1(1):241–244, 1983. doi: 10.1109/jlt.1983.1072065. URL https://doi.org/10.1109/jlt.1983.1072065.

[4] I. Gris-Sánchez, D. Van Ras, and T. A. Birks. The airy fiber: an optical fiber that guides light diffracted

by a circular aperture. Optica, 3(3):270, March 2016. doi: 10.1364/optica.3.000270. URL https://doi.org/10.1364/optica.3.000270.

[5] David G. Voelz. Computational Fourier Optics: A MATLAB® Tutorial. SPIE, Jan 2011. doi: 10.1117/3.858456. URL https://doi.org/10.1117/3.858456.