Semiconductor Laser Beam Quality Metrics for Free-Space Optical Communications

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Abstract: The beam propagation factor, M^2, exists as one of very few measures of a laser's performance, when really a more detailed analysis of the application and laser are necessary for judgement in most cases. In free-space optical communications, a crucial figure of merit is the proportion of diffraction-limited power in the far-field. A calculated structure has been made with a higher proportion of diffraction-limited power in the far-field than another calculated structure with a much better M^2. This calculated structure has an M^2 of 19, with 89% of its power within the diffraction limit in the far-field, compared to another calculated structure with M^2 of 1.7 that has 86% of its power within the diffraction limit in the far-field.

1 INTRODUCTION

The beam propagation factor M^2, often erroneously called the "beam quality," is a comparison of the near- and far-field second moment widths of a given beam to a fundamental Gaussian beam of the same wavelength. A fundamental Gaussian beam is ideal, meaning it can be focused down to a waist of minimal size—subject to a certain numerical aperture—or collimated such that its divergence angle is minimal, and its M^2 is 1 (Saleh and Teich, 2007). Another way of stating this is by calling the beam diffraction-limited. M^2 is given as:

$$M^2 = \omega_0 \theta_0 \frac{\pi}{\lambda} \quad (1)$$

Where ω_0 is the beam waist radius, θ_0 is the divergence half-angle, and λ is the operating wavelength (Saleh and Teich, 2007).

Since the operating wavelength is usually known or easily measured, the beam waist and divergence angle are the only two remaining beam metrics needed to know M^2. They are not as easy to measure and calculate though, and as such, ISO has created standard 11146 to specify procedures to do so. Specifically, ISO mandates usage of the second moment width of the near- and far-field intensity distributions to determine beam waist and divergence angle, respectively (1995).

Given the nature of the second moment, it is possible, in theory, to use this definition of beam waist/divergence angle in a way that brings light to the faults of using M^2 as beam quality. For example, begin with an intensity distribution of a fundamental Gaussian beam. By placing a small amount of energy very far from the central lobe of the distribution, the second moment width could be made infinitely large, even though a great proportion of the energy still lies within the diffraction limit. This would, in turn, cause M^2 to be large, even though the beam behaves very similarly to a fundamental Gaussian beam.

This paper demonstrates that a structure with an M^2 much greater than 1 can be engineered such that most of the power in the far-field lies within the diffraction limit—as desired for free-space optical communications. The significance of such a finding is that larger semiconductor laser structures capable of greater efficiency and higher power could be used for free-space optical communications without concerns about multimode activity. Additionally, M^2

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is an insufficient measure of beam quality for free-space optical communications, and a different metric, such as power in the bucket, would serve better.

2 CALCULATING A MODE PROFILE AND A REFERENCE GAUSSIAN PROFILE

The process of engineering a structure to meet the design intents begins with a basic refractive index profile: a centered region of higher refractive index, as illustrated in figure 1.

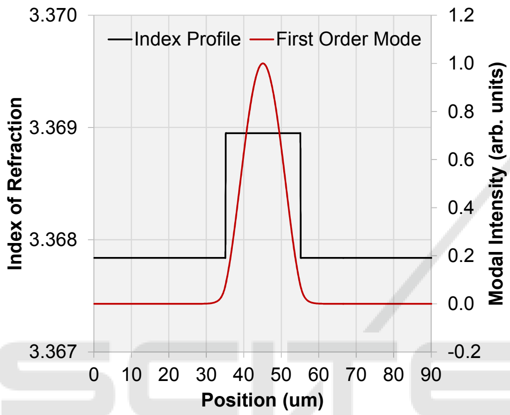


Figure 1: A basic refractive index structure and its first order mode profile. Note that many higher order modes are also supported by this structure.

This profile results in a simple, somewhat Gaussian, first order mode profile. The desired mode profile contains some of its energy far from the center, however, so this basic design is not sufficient on its own. For high power applications, it is desirable to have heat spread over a large physical area. Scaling the first order mode size is not useful because the index contrast required to do so is far too small for real-world use—both due to manufacturing limitations and sensitivity to thermal effects.

From the basic structure, one can observe that the mode profile has a peak centered about the region of higher refractive index. The desired profile features additional peaks in the mode before and after the central lobe, therefore the next evolution in the index profile should be adding high index material before and after the central lobe. Some additional factors to consider are the thickness of each high-index material layer and the magnitude of the index contrast between the base material and the lobes of higher index. As a demonstration of these effects, the structure observed in figure 2 is first used as a reference.

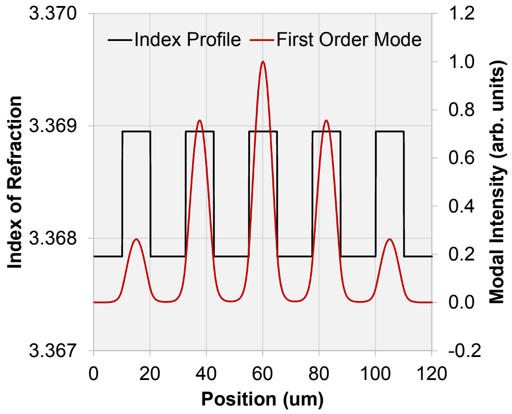


Figure 2: A structure useful for demonstrating the effects of changes to the index profile.

The central lobe of high-index material is then made twice as wide, and the effects are observed in figure 3.

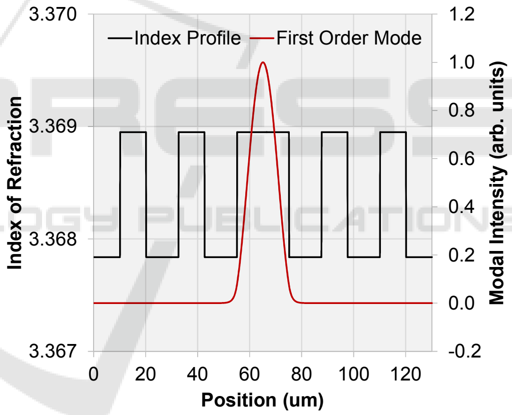


Figure 3: The same structure from Fig. 2, but with a wider central region.

As demonstrated in figure 3, a thicker high-index material pulls the first order mode into the lobe.

Again using the structure in figure 2 as a reference, the refractive index contrast between the central lobe and the base material is increased, and the effects are observed in figure 4.

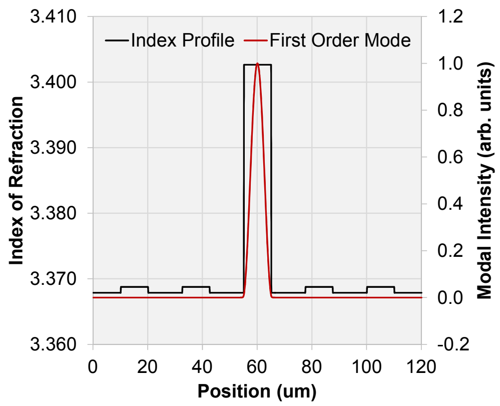


Figure 4: The same structure from Fig. 2, but with a greater index contrast between the central region and the base material.

A greater index contrast also pulls the first order mode into the lobe. These two relations are a consequence of solving the Helmholtz wave equation:

$$\nabla^2 U + k^2 U = 0 \qquad (2)$$

Where U is the complex field and k is the wave number (Goodman, 2005). The wave number k depends on the refractive index. As such, the normalized first order solution to the wave equation is guided to the region of highest average refractive index. The two methods demonstrated both direct that region towards the center of the structure.

The first order mode is generally a good indication of the behavior of the structure, however, one must still take into account higher order modes, if any are present in the laser, which adds additional levels of complexity. As such, the process of engineering the desired structure is an iterative one, requiring analysis after each iteration.

Once an index profile is created, analysis can begin. The modes—and therefore the near-field intensity distribution—are calculated using a Ritz iterative eigenmode solve of the Helmholtz wave equation given in equation 2. The near-field intensity is given by the absolute square of the complex field.

The far-field intensity distribution as a function of angle is found via the absolute square of the Fourier transform of the field near the aperture (Goodman, 2005). From this point forward, the profiles referred to in the near- and far-field are the intensity distributions.

It is worth note that even structures with exotic near-field distributions have far-field distributions that look mostly Gaussian in nature. For example, the near- and far-field profiles for the structure from figure 2 are displayed in figure 5. This is promising evidence in support of the hypothesis that a structure with poor M^2 can still have a large proportion of its power within the diffraction limit in the far-field.

After engineering a structure to test, it is necessary to create a reference Gaussian beam for that structure. This is done using software to find the optimal Gaussian for the near-field profile, based on the overlap. Begin with the basic form of a Gaussian function. Match the peak and mean to the peak and centroid of the near-field profile, then iteratively vary the width to find the best profile using the overlap with the near-field profile as a figure of merit. The result with the most overlap is the reference Gaussian profile.

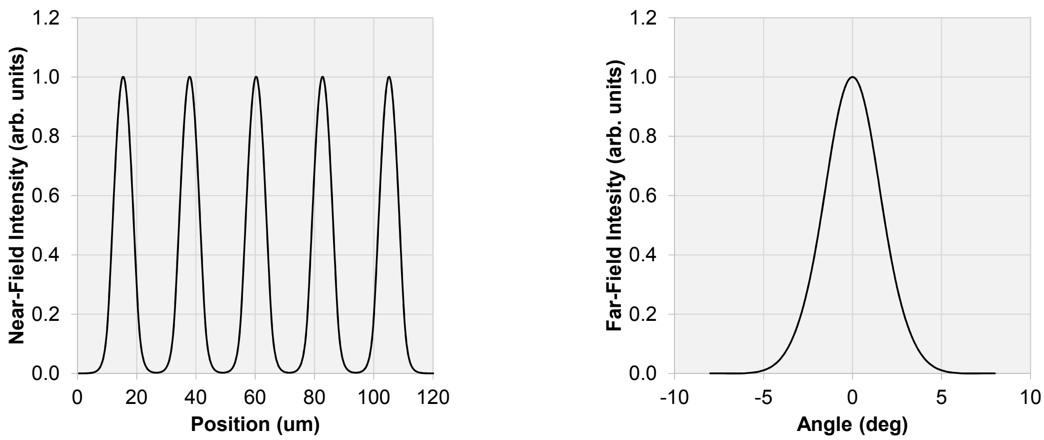


Figure 5: The near-field (left) and far-field (right) intensity profiles for the structure in Fig. 2.

In order to obtain a reference for the diffraction limit in the far-field, the Fourier Transform is used to propagate the reference Gaussian profile to the far-field. Important to note is the inverse nature of the Fourier Transform, which means that a broad near-field intensity profile will result in a narrow far-field intensity profile, and vice-versa. Figure 5 is an excellent example of this. The near-field profile is relatively wide, and the far-field profile is in turn quite narrow.

Provided a structure and its corresponding reference Gaussian profile, calculations can be performed to solve for M^2 and the proportion of diffraction-limited power in the far-field. Firstly, the beam parameter product (BPP) must be found for the reference Gaussian profiles, and the engineered structure. The BPP is simply defined as:

$$BPP = \omega_0 \theta_0 \quad (3)$$

Where ω_0 is the beam waist in the near-field, and θ_0 is the divergence angle in the far-field. Beam waist and divergence angle are found from the second moment width of the near- and far-field profiles, respectively, as per ISO standard 11146 (1995).

Since the M^2 of a fundamental Gaussian beam is known to be 1, the M^2 of the engineered structure can be found by dividing the BPP of the structure by the BPP of the reference Gaussian profile, as their operating wavelengths are assumed to be equal. The diffraction-limited power in the far-field (or near-field, if needed) may be calculated now using the engineered profiles and the reference profiles. A range for the diffraction-limited region must be specified. One way of doing so is using the far-field divergence angle (which was obtained earlier using the second moment method) as follows:

$$P = \frac{\int_{-\theta_0}^{\theta_0} F(\theta)\, d\theta}{\int_{-\infty}^{\infty} F(\theta)\, d\theta} \quad (4)$$

Where θ_0 is the far-field divergence angle of the reference Gaussian, and $F(\theta)$ is the far-field intensity profile of the engineered structure, as a function of angle.

3 RESULTS

There are four possible outcomes for a given structure: M^2 can be relatively high or relatively low (close to 1), and each of those cases can have a high or low proportion of diffraction-limited power in the far-field. The expected outcomes are those in line with the current assumptions about M^2. A small M^2 will have most of its power within the diffraction limit because it is similar to a fundamental Gaussian beam, and a large M^2 will have most of its power outside the diffraction limit because it is dissimilar to a fundamental Gaussian beam.

The significant outcome, the focus of this paper, is that a structure with large M^2 can be engineered to contain most of its power within the diffraction limit. The other possible outcome—in which a structure with small M^2 would have most of its power outside the diffraction limit—falls outside the scope of this paper.

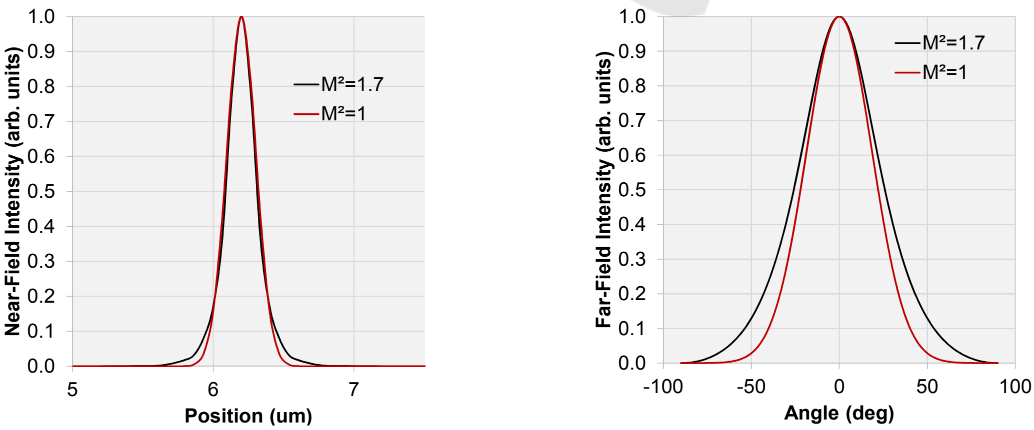


Figure 6: Near-field (left) and far-field (right) intensity distributions for an engineered structure with M^2 of 1.7 and 86 percent of its power in the far-field within the diffraction limit.

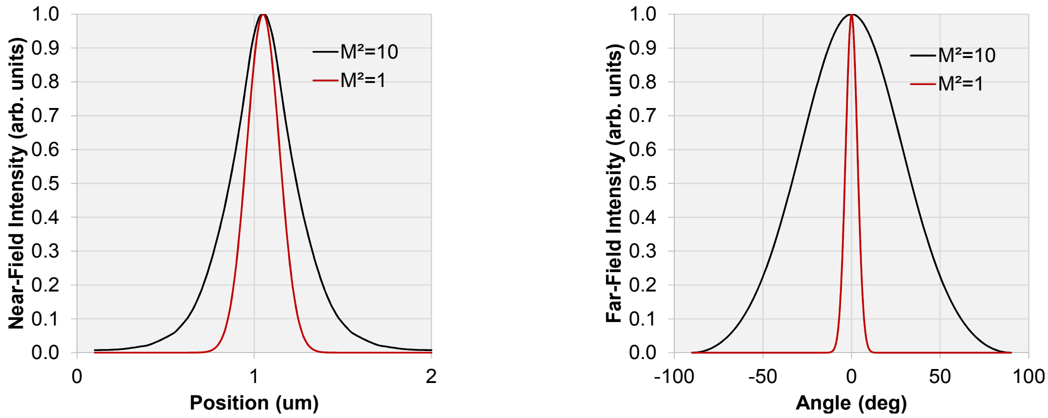


Figure 7: Near-field (left) and far-field (right) intensity distributions of an engineered structure operating with M^2 of 10 and only 20% of its power in the far-field within the diffraction limit.

Figure 6 illustrates the first expected outcome; a small M^2 resulting in most of its power within the diffraction limit in the far-field—in this case 86 percent of the power within the diffraction limit for an M^2 of 1.7. The reference Gaussian is also included for visual comparison. As expected, the shape of the near- and far-field profiles are quite similar to the reference Gaussian hence the small M^2. M^2 can be visualized in these plots as the product of the deviation of the black curve from the red curve in the near- and far-field, as this is the visual manifestation of the beam parameter product.

Figure 7 illustrates the second expected outcome; a large M^2 resulting in most of the power outside the diffraction limit—in this case only 20 percent of the power in the far-field is within the diffraction limit, and M^2 is 10. Although the shape of the near-field profile looks very similar to the reference Gaussian, the inverse nature of the Fourier transform exhibits itself very strongly as the far-field profile for the engineered structure is extremely broad compared to the rather narrow reference Gaussian profile. Using the beam parameter product definition from equation (3), fixing wavelength to be the same, and assuming that the beam waist are roughly the same, one can conclude that the far-field divergence angle is about 10 times that of the reference Gaussian, hence the vast difference in the size of the curves in the far-field (Siegman, 1998).

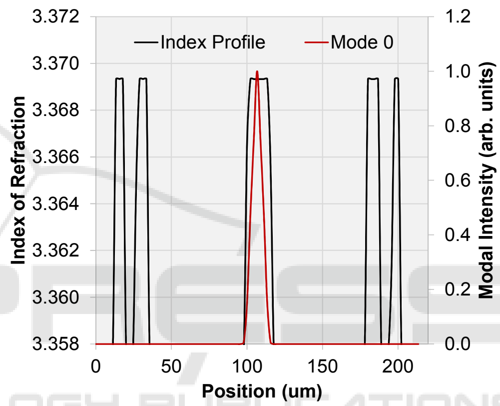
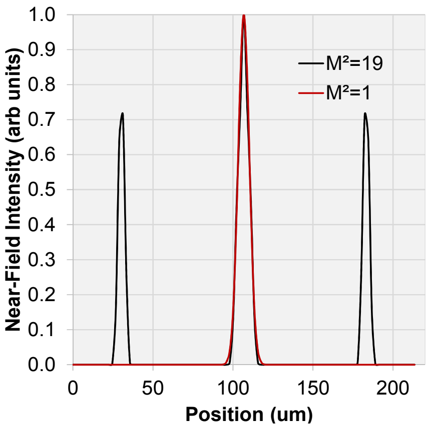


Figure 8: The index profile and first order mode of the engineered structure that supports the original hypothesis.

Figure 8 is the engineered structure that validates the original hypothesis. Its near- and far-field intensity distributions are shown in figure 9. It has an M^2 of 19 and contains 89 percent of its power in the far-field within the diffraction limit—more than even the M^2-1.7 structure in figure 6. The structure was created by cleverly manipulating the two lobes visible in the near-field such that they are very far from the central lobe relative to the width of the lobes. This makes the beam waist, as defined by the ISO standard second moment method, very large. This accomplishes two things. Firstly, the far-field profile is narrow—much narrower than that of an M^2-19 beam would normally be—thanks to the inverse nature of the Fourier transform. Secondly, M^2 is large as a result of the beam parameter product comparison with the reference Gaussian.



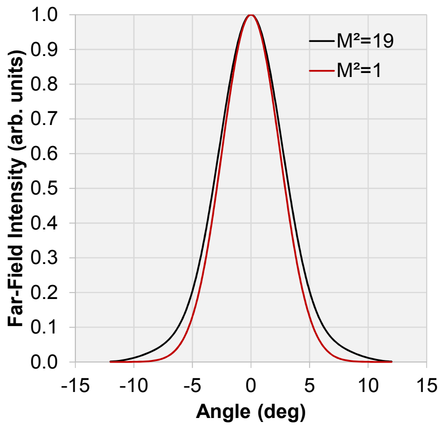


Figure 9: Near-field (left) and far-field (right) intensity distributions of an engineered structure operating with M^2 of 19 and 89% of its power in the far-field within the diffraction limit.

4 CONCLUSIONS

In conclusion, this paper demonstrates that a structure with large M^2 can be engineered such that most of its power lie within the diffraction limit is true. As a result, M^2 is not an appropriate measure of beam quality within the scope of free-space optical communications. The significance of such a structure is that a larger stripe width could be used in semiconductor lasers without fear of multimode activity, since diffraction-limited power is still large relative to the total power available. This could allow greater efficiency at higher power, as the trend observed by Crump et al verifies (2009). The engineered structure exhibited a greater proportion of diffraction-limited power than another structure with an M^2 ten times smaller. Perhaps the metric of beam quality for semiconductor lasers needs rethinking, especially in applications such as free-space optical communications.

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