# Rules of Filamentation in Tapered Diode Amplifiers

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***Abstract*-Software for calculation of gain-current relation, gain saturation and light-induced refractive index change in diode amplifiers and lasers is developed. Three distinct types of filamentation in tapered (flared) amplifiers are found and their dependence on the amplifier geometry is investigated. Practical guidelines for filamentation suppression are suggested.**

## I. INTRODUCTION

High-brightness diode lasers and amplifiers are desirable for many applications, such as molecular spectroscopy, fiber-optic and free-space telecommunications, laser display technology, nonlinear frequency conversion, medical treatments, material processing and fiber-laser pumping. The main obstacle for achievement of high-brightness in this type of devices is filamentation. A significant effort has been made (see, for instance, [1-4]), to find structures and geometries where filamentation is less pronounced. It was found that tapered geometries favor filamentation suppression. In this work, we identify some basic features of filamentation in tapered diode lasers and amplifiers, investigate their dependence on the geometrical parameters and give practical recommendations on how to avoid filamentation.

## II. NUMERICAL METHODS

In this work, a common separate confinement heterostructure is considered. Electronic states and optical modes are calculated using the transfer matrices approach, which allows us to treat arbitrary layer structures. The gain is determined using standard formulas [5] as a function of quasi-Fermi-levels separation, while the carrier-induced refractive index change is found through Kramers-Kronig relations. Spontaneous emission, leakage and Auger contributions to the current are taken into account. Using the parametric approach (with quasi-Fermi-levels separation as a parameter) to the gain-current relation allows us to account for stimulated emission in a very simple manner:

$$J_{\mathrm{st}} = e g_{\mathrm{modal}} \frac{P_{\hat{x}}}{\hbar\omega},$$

where $g_{\mathrm{modal}}$ is modal gain, while $P_{\hat{x}}$ is the optical power per unit width of the structure.

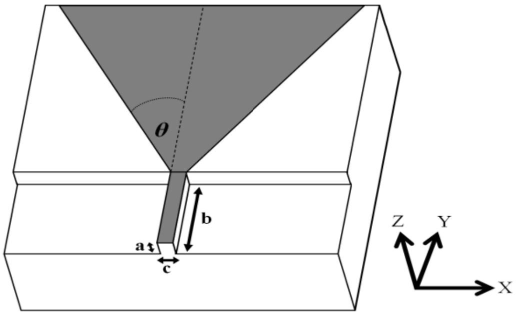

Fig. 1. Schematic diagram of the device. $\theta$ is the half taper angle. *a, b* and *c* are the ridge height, length and width (respectively).

Specification of the total current density yields the quasi-Fermi-levels separation as an implicit function of the light intensity. This allows calculating the gain saturation and the refractive index change induced by light. We then employ a standard Crank-Nicolson finite-difference Beam Propagation Method to determine the light propagation through an amplifier. A laser is simulated by sequential back and forth propagations until a convergence is achieved.

## III. FILAMENTATION

### A. Three Types of Filamentation

Three distinct types of filamentation have been identified in this work: First Order, Second Order and Bat Ears. Each type has unique characteristics. These include the location of filament onset, the propagation of filaments within the taper and the filamentation dependence on amplifier geometry. Under certain conditions, all three types of filamentation can be seen together, as in Fig. 2. Generally, one of them becomes dominant (see Fig. 3).

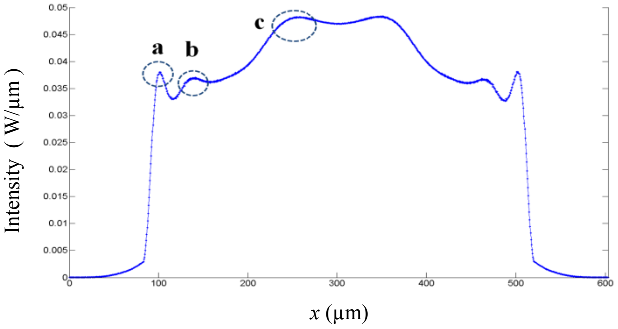

Fig. 2. Three types of filamentation are evident. *a, b* and *c* are 1st order, 2nd order and bat ears filaments (respectively).

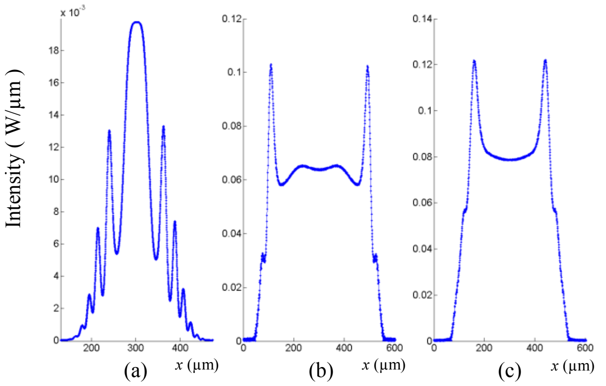

Fig. 3. Final beam shape when: (a) 1st order filaments have developed, (b) 2nd order filaments have developed, (c) bat-ears have developed.

### B. *First Order Filamentation*

First order filaments originate near the beginning of the taper region, though not necessarily within the taper itself. As seen from Fig. 4, which shows their trajectories in the xy-plane, they propagate in straight lines at certain angles. There exists a minimal filament angle; therefore, 1st order filamentation is suppressed when the taper angle is below this angle.

### C. *Second Order Filamentation*

Second order filaments propagate at smaller angles than first order filaments, and rarely form when first order filaments are present. As can be seen from the series of images shown in Fig. 5 (a), they start to form in the middle of the propagation through the taper. We noticed that they originate near the taper edge and that their angles of propagation are dependent on the taper angle. By "smoothing" the taper edge, i.e. gradually reducing the current density at the edge of the taper in a linear fashion from maximum current density to zero current density, second order filamentation can be significantly reduced or entirely eliminated. In contrast, 1st order filaments are not suppressed by taper edge smoothing because their origin is unrelated to the taper edge.

### D. *Bat Ears*

As can be seen from the series of images shown in Fig. 5 (b), bat ears, similar to 2nd order filaments, start to form in the middle of the propagation through the taper. They originate from the "top hat" intensity distribution, which typically, though not necessarily, emerges later than 2nd order filaments. The angles of bat-ears propagation are smaller than those of 2nd order filaments. At very small taper angles 2nd order filamentation is suppressed and bat ears become dominant.

## IV. CONCLUSIONS

There are three distinct types of filamentation. First order filaments originate at the beginning of the taper and are not caused by the taper edge. They can be eliminated by choosing a small enough taper angle. Second order filaments originate during the propagation. They are caused by the taper edge and consequently depend on the taper angle. They can be reduced or sometimes even eliminated by "smoothing" the taper edge. Bat ears become dominant at smaller taper angles. They originate from the "top hat" intensity distribution.

To achieve the highest brightness, the taper angle should be small enough to eliminate first order filamentation and large enough to avoid the appearance of bat ears. Further, taper edge "smoothing" should be employed to prevent second order filamentation.

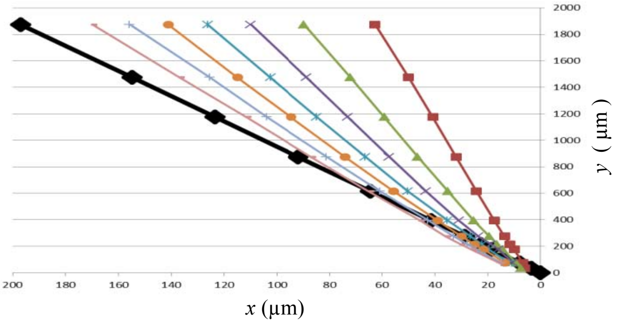

Fig. 4. Propagation of 1st order filaments in the left half of the taper. The thick black line shows the taper boundary. Each of the other lines represents the position of a filament. The filaments originate outside the taper and propagate linearly.

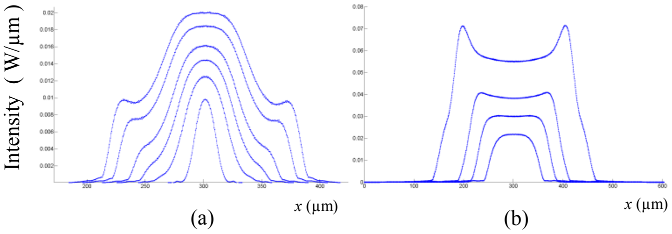

Fig. 5. (a) 2nd order filaments at the beginning of their development. The images are taken at the distances 500,1000,1275,1500,1800 and 2000 μm from the beginning of the taper. The filaments emerge as "shoulders" in the intensity distribution around its middle value. (b) Top-hat intensity distribution (two lower curves: $y = 3000$ and 4000 μm) leads to the formation of bat ears (two higher curves: $y = 5000$ and 7000 μm).

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