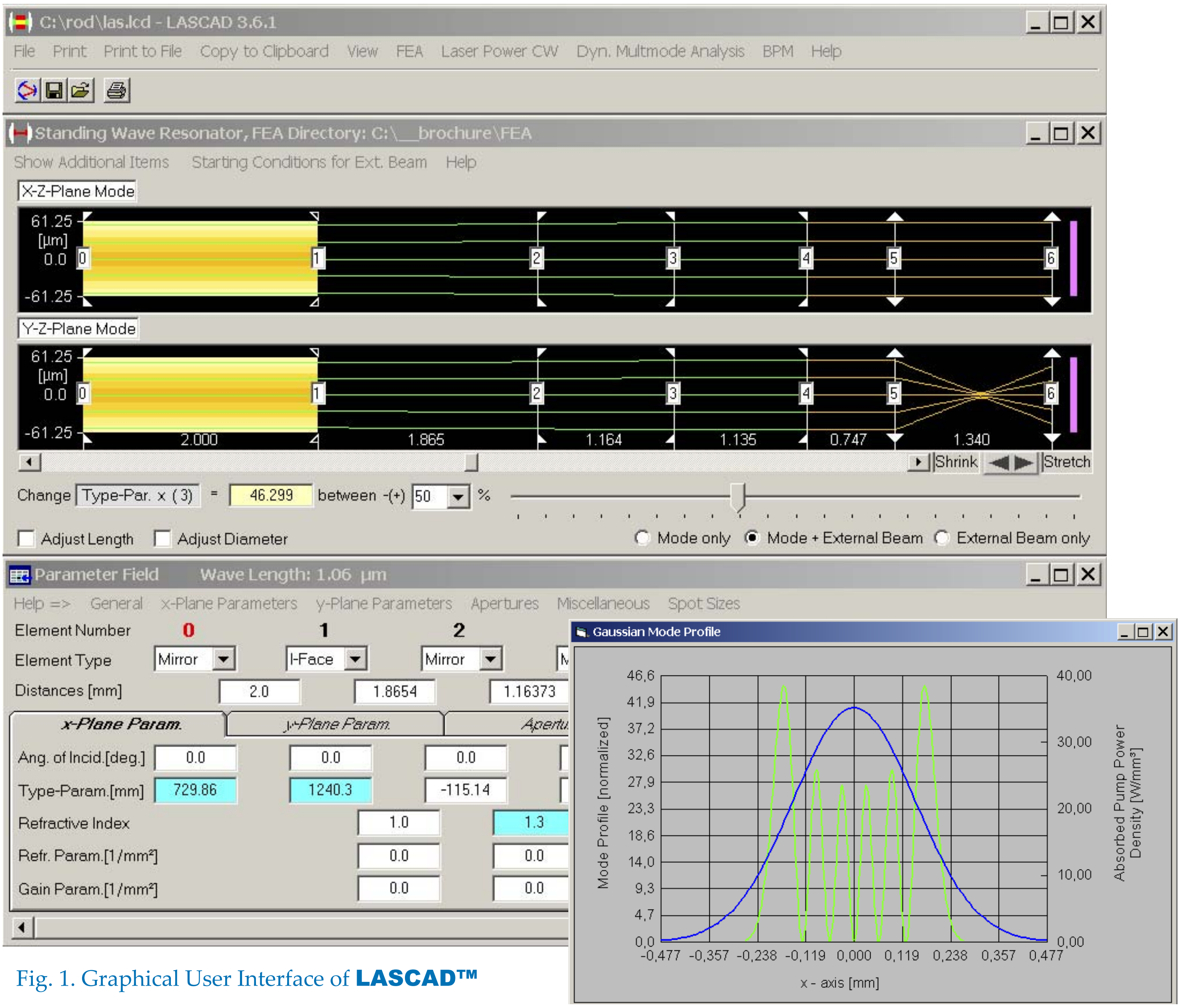
The unique combination of simulation tools for LASer Cavity Analysis and Design

During the last 15 years **LASCAD™** has become industry-leading software for **LAS**er **C**avity **An**alysis and **D**esign. The feedback from a large community of users has helped us gather experience for improving laser resonator design.

To optimize laser resonator design, **LASCAD™** provides a unique combination of simulation tools:

- **Thermal and Structural Finite Element Analysis (FEA)**
  of thermal effects in laser crystals
- **ABCD Gaussian Beam Propagation Code**
  taking into account thermal lensing, gain guiding, etc.
- **Dynamic Analysis of Multimode and Q-switched operation (DMA)**
  analyzing the dynamic, 3D behavior of laser beams
- **3D Physical Optics Beam Propagation Code (BPM)**
  including diffraction, gain dynamics, etc.



Change Type-Par. x (3) = 46.299 between -(+) 50 %

☐ Adjust Length ☐ Adjust Diameter

○ Mode only ● Mode + External Beam ○ External Beam only

Element Number	0		1		2	
Element Type	Mirror		I-Face		Mirror	
Distances [mm]		2.0		1.8654		1.16373
Ang. of Incid.[deg.]	0.0		0.0		0.0	
Type-Param.[mm]	729.86		1240.3		-115.14	
Refractive Index				1.0		1.3
Refr. Param.[1/mm²]				0.0		0.0
Gain Param.[1/mm²]				0.0		0.0

Fig. 1. Graphical User Interface of **LASCAD™**

LASCAD™
The Optical Workbench on the PC

LASCAD™ provides complex engineering tools developed for ease of operation. The user interface of the program, shown in Fig. 1, can be used like an optical workbench on the PC, allowing intuitive design of laser resonators. In this way **LASCAD™** helps users process experimental results without wasting valuable time studying complicated manuals.

- Optical elements, such as mirrors, lenses, or crystals can be added, combined, adjusted, or removed by mouse clicks.
- Astigmatism in the resonator and crystal is automatically taken into account.
- The program menu makes available thermal finite element analysis, Gaussian ABCD matrix code, physical optics code, analysis of Q-switched operation, computation of laser stability and power output.

LASCAD™
The Laser Engineering Tool

To develop a powerful resonator design, the laser engineer is confronted with many interacting technical and physical problems. Thermal lensing is of growing importance, due to the tendency to miniaturize laser systems, while simultaneously increasing power output. The effect strongly depends on system characteristics, such as: material parameters, resonator geometry, pump beam distribution, and cooling layout. It interferes with gain dynamics, mode competition, Q-switching, and other effects, which control beam quality and laser efficiency in a complicated manner. Based on numerical simulation of these effects, **LASCAD™** provides the laser engineer with a quantitative understanding of the characteristics of a cavity design.

Finite Element Analysis (FEA) of Thermal Effects

FEA is used to compute temperature distribution, deformation, stress and fracture mechanics in laser crystals. This takes into account material parameters, pump configuration and cooling geometry. FEA is a well known numerical method for solving partial differential equations of technical physics, such as the equation of heat conduction. Though indispensable and applied with great success in other engineering disciplines, the benefits of FEA have not been available so far in commercial laser design software.

To enable the straightforward use of FEA for laser cavity design, **LASCAD™** offers pre-designed FEA models for important configurations, such as: end and side pumped rods, slabs, and thin disk lasers. Models are also available for crystals composed of various materials, or of doped and undoped regions, such as undoped end caps. The user can customize dimensions, FEA mesh, boundary conditions, and other parameters within the models. Temperature dependence of material parameters can be taken into account by the use of analytical expressions provided by the user.

Analytical approximations, based on super-Gaussian functions, are used to model the absorbed pump power density. To enable numerical modeling of the absorbed pump light distribution, **LASCAD™** has interfaces to **ZEMAX** and **TracePro** raytracing programs. These programs generate 3D data sets of the absorbed pump power density that can be used as input for **LASCAD™**. Numerical modeling of the absorbed pump light with **ZEMAX** or **TracePro** is particularly useful for flash lamp pumped lasers or unusual pump configurations.

Figures 2a, 2b, and 2c show plots of temperature distribution, deformation, and stress intensity, respectively, in an end pumped cylindrical rod. Figures 3a, 3b, and 3c show absorbed pump power, temperature, and the zz-component of the stress tensor, respectively, in a side pumped rod.

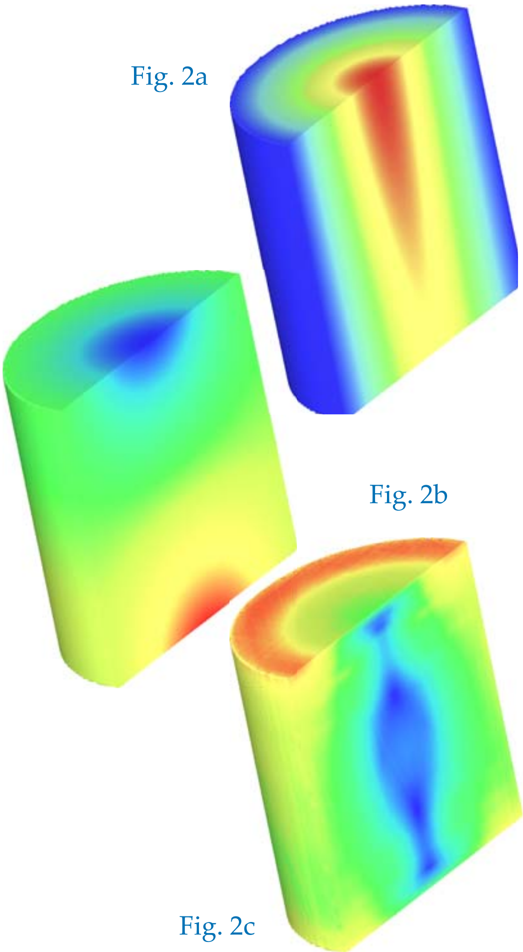


Fig. 2a

Fig. 2b

Fig. 2c

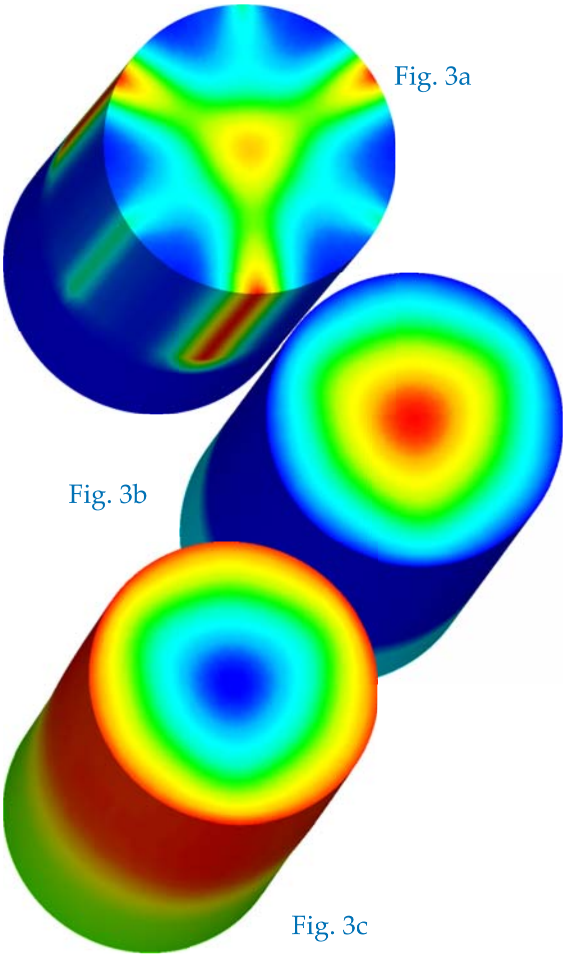


Fig. 3a

Fig. 3b

Fig. 3c

Gaussian ABCD Matrix Approach

When using the FEA results with the ABCD matrix code, the temperature distribution, multiplied by the temperature dependence of the refractive index, is fitted parabolically at right angles to the optical axis, as shown in Fig. 4. For this fit, the finite element mesh subdivisions along and perpendicular to the crystal axis are used. In the same way, a fit of the deformed end faces of the crystal is accomplished. For many configurations - end pumped rods for example - this approximation delivers reliable results for the laser mode.

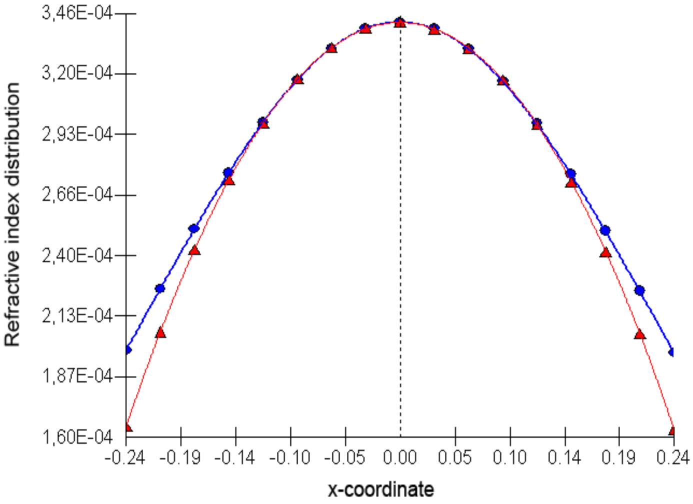


Fig. 4. ╱ FEA Result ╱ Parabolic Fit

To visualize the results of the ABCD matrix approach, fundamental mode spot size, as well as higher order Hermite-Gaussian polynomials, are displayed along the resonator axis. Inside the crystal overlap between pump beam and transverse laser modes can be visualized, as shown in Fig. 1. To account for astigmatism, the computations are carried through simultaneously in two planes perpendicular to the resonator axis.

In case of standing-wave resonators, a stability diagram, based on generalized g-parameters, can be computed, as shown in Fig. 5.

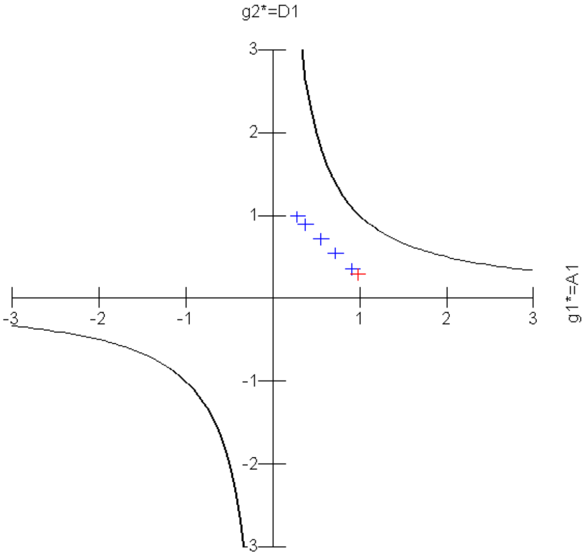


Fig. 5. Stability Diagram

The obtained Gaussian modes and the distribution of the absorbed pump power density are used to analyze CW, as well as transient laser behavior.

CW Laser Behavior

A straightforward tool is provided for CW operation. It computes the power output for fundamental mode and approximately also for multimode operation. Solution of the time independent 3D laser rate equations is obtained by iterative integration over the crystal volume. Fig. 6 shows an example with results for an end pumped Nd:YAG rod. The circles represent simulation results; the green triangles are measurements. See paragraph *Verification of Results*.

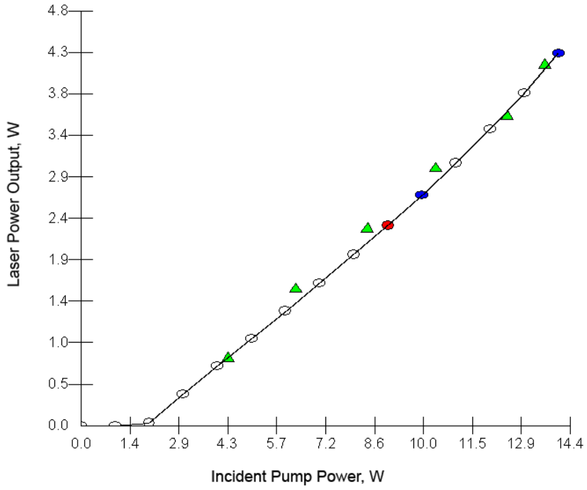


Fig. 6. Laser Power Output

Transient Laser Behavior

To analyze the transient laser behavior, **LASCAD™** provides a tool for the dynamic analysis of multimode and Q-switched operation (**DMA**). For this purpose, time dependent rate equations, describing the individual numbers of photons in a predefined set of Gaussian transverse eigenmodes, are solved by the use of a finite element solver. This approach provides a detailed description of mode competition, power output, beam quality, and pulse shape. Results turned out to be in good agreement with experimental measurements; see paragraph *Verification of Results*.

The **Dynamic Multimode Analysis (DMA)** offers important features:

- Computation of pulse shape and time-dependent power output for Q-switched lasers with high repetition rates, as well as for single pulse operation
- Computation of individual power output of transverse modes for CW and Q-switched operation
- Computation of beam quality M^2 for CW and Q-switched operation
- Effect of hard-edged and Gaussian apertures on beam quality
- Output mirrors with Gaussian and super-Gaussian reflectivity profile

Fig. 7 shows an example of the power output over time, as obtained by **DMA**. Since the computation starts with population inversion density, N(x,y,z,t=0) = 0, a spiking behavior can be seen at the beginning, that is attenuating with increasing time and finally approaching a constant value. Fig. 8 shows a typical **DMA** pulse shape result.

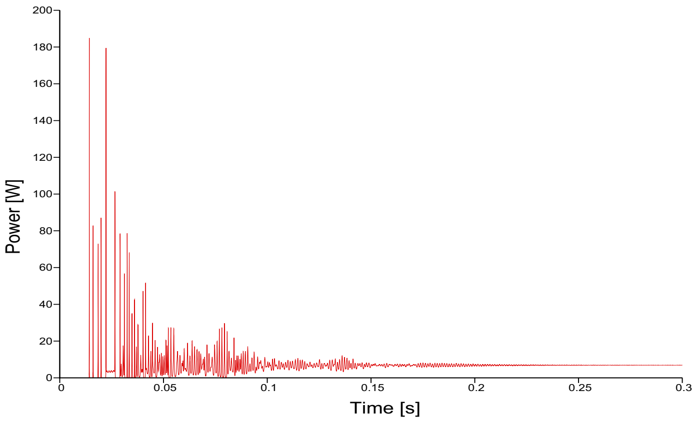


Fig. 7. **DMA** Power Output over Time

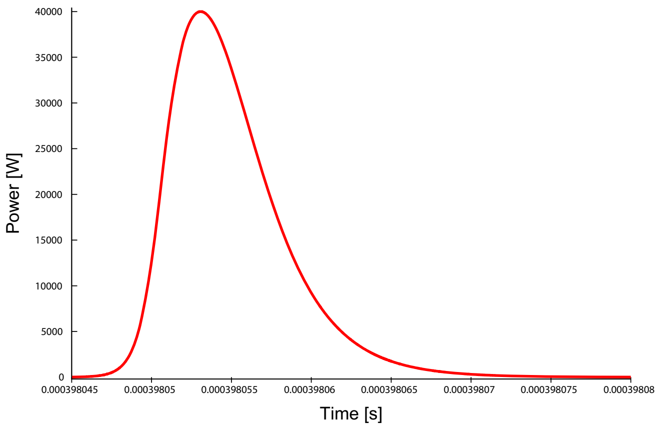


Fig. 8. **DMA** Pulse Shape Result

Physical Optics Approach

In cases where parabolic approximation and ABCD matrix code are not sufficient, FEA results can be used as input for a physical optics code. This code provides full 3D simulation of the interaction of a wavefront propagating through the crystal **without using parabolic approximation**. For this purpose, the code uses a split-step **Beam Propagation Method (BPM)** to propagate the wavefront in small steps through the hot, thermally deformed crystal. It takes into account the distribution of the local refractive index, as well as the deformed end faces of the crystal, as obtained by FEA. Based on the principle of Fox and Li, a series of round-trips through the resonator is computed, which finally converges to the fundamental mode or to a superposition of higher order transverse modes.

Two graphic windows are opened while this computation is running. One of them shows the intensity profile at the output mirror, as it develops with increasing number of iterations. An example is shown in Fig. 9. The other window displays the convergence of the spot size with cavity iteration and the simultaneously computed power output, as shown in Fig. 10. Additionally, a third window showing the beam quality can be opened.

The BPM tool is also capable of numerically computing the spectrum of resonator eigenvalues and the shape of the transverse eigenmodes.

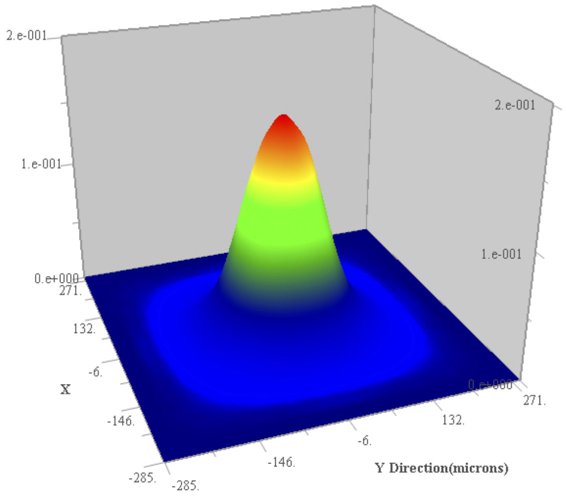


Fig. 9. BPM Beam Profile

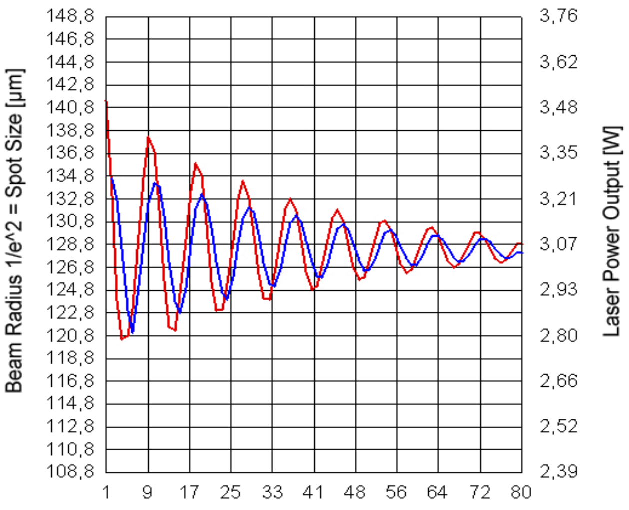


Fig. 10. / Beam Radius and / Power Output over Cavity Iteration

The BPM tool takes into account gain dynamics and diffraction effects, due to the finite extension of apertures and mirrors, more physically than the **DMA** code. Another important feature of the BPM physical optics code is the simulation of misalignment effects.

LASCAD™
The Educational Tool

Though primarily designed for laser engineering, the easy-to-use GUI makes **LASCAD™** ideally suited for educational purposes for students, as well as for practicing scientists and engineers. The principles of Gaussian beam optics can be studied interactively, and the behavior of complicated heterogeneous resonator configurations, including thermal lensing effects, apertures and Q-switches can be clearly demonstrated.

Verification of Results and Outlook

The laser group of Prof. R. Wallenstein at the University of Kaiserslautern, Germany has been using the program for several years for analysis and optimization of the behavior of composite crystals in diode-pumped, high-power lasers. A series of detailed measurements have verified the results of simulation to a high degree; see Fig. 6.

Currently, LAS-CAD GmbH is partner in the government supported research project *Simulation and Optimization of Innovative Laser Systems*. In this project LAS-CAD GmbH is cooperating with seven German laser manufacturers, the University Erlangen, and the Laser Laboratory Göttingen Germany, to develop new tools for the numerical simulation of laser cavities. An important result of this cooperation is the new tool, **DMA**, as described above. Numerical results obtained with **DMA** have been verified experimentally in cooperation with InnoLas GmbH Germany, as described in the paper *Dynamic multimode analysis of Q-switched solid state laser cavities* in Optics Express, Vol. 17, 17303-17316 (2009). Another objective of the research project is the development of an FEA approach to provide a dynamic 3D solution of the electromagnetic field equations in a laser cavity. First results were presented at Photonics West 2009; see *Finite element simulation of solid state laser resonators* in Proceedings of SPIE Vol. 7194-16 (2009).

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