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Matlab Laser Toolbox

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Abstract

MATLAB® is a program for numeric computation, simulation and visualization, developed by The Mathworks, Inc. It is used heavily in education, research, and industry, for solving general, as well as application area-specific problems, that arise in various disciplines. For this purpose MATLAB has numerous sets of application-specific scripts, called "toolboxes".

A Laser Toolbox is introduced providing several scripts for analysis and visualisation of laser beam properties, as well as, simulation of laser material interaction & processes. The toolbox, examples and documentation can all be found at the author's website. The Laser Toolbox was developed for MATLAB version 7.5, and will run on any operating system supported by MATLAB. © 2010 Published by Elsevier B.V. Open access under CC BY-NC-ND license.

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1. Introduction

MATLAB® is high-level interpreted language and interactive environment for algorithm development, data visualization, data analysis, and numeric computation [1]. It is used heavily in education, research, and industry, in a wide range of applications, including signal and image processing, communications, control design, test and measurement, financial modeling & analysis, and computational biology. Add-on toolboxes, which are collections of special-purpose MATLAB functions and scripts, extend the MATLAB environment to solve particular classes of problems.

Here a new toolbox, referred to as the Laser Toolbox, is presented, providing several functions and scripts for analysis and visualization of laser beam properties, as well as, functions to calculate the temperature induced by absorbed laser energy in a solid. The first and current version of the toolbox includes scripts:

- for reading, analyzing and visualizing of measured power density distributions, and their propagation, as well as calculation and visualization of theoretical power density profiles, such as Transverse Electro-magnetic Modes, etc.,

- to calculate 3D temperature profiles in a solid induced by absorbed laser energy.

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The Laser Toolbox, examples and documentation can all be found at the author's website:
    http://www.wa.ctw.utwente.nl/software/laser/

The Laser Toolbox was developed for MATLAB version 7.5, and will run on any operating system supported by MATLAB. Critical evaluation of the Laser Toolbox is welcomed.

2. Data structures

The development of nearly every program or software system starts with the design of data structures to hold and organize related data to be handled and processed by the software. In the case of the Laser Toolbox, these data structures are structures holding data related to laser beams (e.g. power density distribution at one or several planes along the optical axis, beam dimensions (diameter, width, length), beam propagation ratios, etc.) and the results of laser material interaction (e.g. temperature profile induced by absorbed laser energy in a solid).

In version 7.6 of MATLAB, classes and standard Object-Oriented (OO) design patterns were introduced [2]. Object-oriented programming (OOP) is a programming paradigm that uses "objects" as data structures consisting of datafields, as well as methods (or operations) on these datafields. The typical MATLAB user, however, is not (yet) accustomed to, nor familiar with OOP. That is why the majority of the current toolboxes (still) consist of separate MATLAB functions (scripts) operating on independent variables. Moreover, OOP was only introduced as part of release 2008a of MATLAB. Therefore, to ensure backward compatibility of the Laser Toolbox to older versions of MATLAB, as well as to ensure conformity with the coding style of the average MATLAB user, it was decided not to apply OOP as a paradigm for the Laser Toolbox. In stead, four structures–i.e. four sets of data records– were defined to hold and logically organize the data. That is a structure to hold data including and related to:

1. one or more *power density distributions* $I(x, y)$ [W/m^2] (measured or calculated) at one or more "planes" along the axis z of propagation of the laser beam, see figure 1,
2. *propagation properties of a laser beam*, including beam dimensions (diameter, width, length), far-field divergence angles, (a)stigmatism, beam waist (or focus) dimensions and location, etc. These parameters can be calculated from the power density distribution(s) mentioned above, see figure 2,
3. *transient or quasi-stationary 3D temperature profile* (or temperature rise) $T(x, y, z, t)$ [K] in a material, induced by absorbed laser energy. These parameters, can be calculated (or estimated) from the the power density distribution(s) and/or the propagation properties of a laser beam mentioned above,
4. material properties, including absorption coefficient, density, heat capacity, heat conductivity, melt temperature, etc.
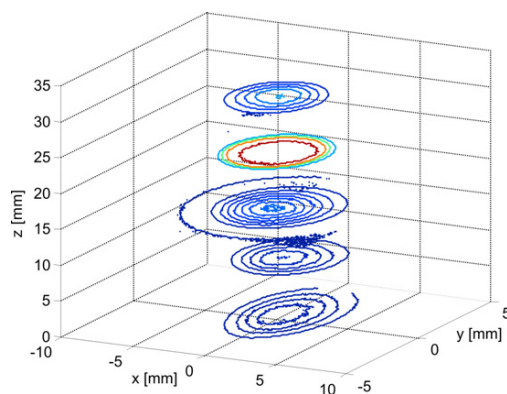

Figure 1: Three dimensional representation of contours (iso plots) of laser power density distributions measured at five locations (*xy* planes) along the axis of propagation *z* of a laser beam. The waist/focus of the laser beam is located at $z \approx 25$mm. See also figure 4.
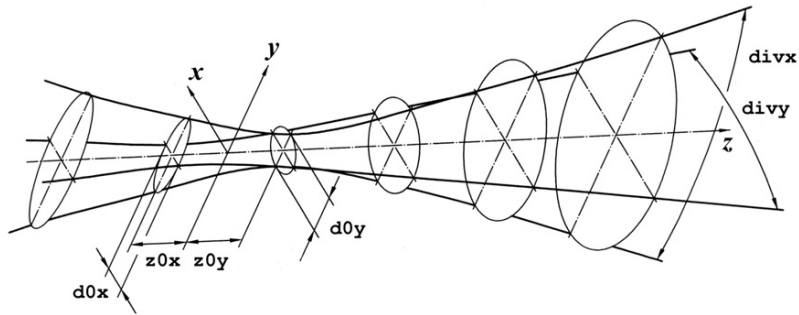
Figure 2: Some propagation parameters of a simple astigmatic laser beam, such as far-field divergences and beam dimensions and foci locations [3]. Not shown are Rayleigh lengths, nor are waist diameter and its location in polar coordinates.

It is tempting to collectively store power density distributions, as well as propagation properties of a laser beam into a single data structure, because the propagation properties can be calculated from a set of at least three power density distributions. However, as power density distributions may have been determined experimentally, it is good programming practice to store measurement data (power density distributions) and the results of operations on this data (propagation properties) in separate variables of appropriate data structures.

In the remainder of this section the four structures are briefly discussed. Note that these data structures are easy to analyze and easily extended by a user to meet his/her own needs.

2.1. Power density distribution(s)

A data structure, referred to as pdd (an abbreviation of 'power density distribution'), holds data related to a power density distribution $I(x, y)$ [W/m^2] (measured or calculated) at a specified plane along the axis z of propagation of the laser beam, see also figure 1. It includes datafields like laser wavelength, total power of the density profile, and of course the power density $I(x, y)$ at each location (x, y) in the plane specified. In the case several power density distributions are defined (or measured) at specified locations z along the optical axis, an array of these structure is constructed. Then, each entry of the array holds a pdd structure; one for each specified location z. Although arrays of structures in MATLAB are less computationally efficient, than structures of arrays, the readability and usability of the code of the Laser Toolbox requires the use of arrays of structures.

Section 3.1 discusses some functions which create a pdd structure, or create it from measured data.

2.2. Propagation properties of a laser beam

The data structure, referred to as beam, holds propagation properties of a laser beam as defined in the ISO11146 standard dealing with *Lasers and laser-related equipment - Test methods for laser beam widths, divergence angles and beam propagation ratios* [3]. It includes datafields such as the diameter of the waist/focus of the beam, the location of the waist/focus of beam along propagation axis, the Rayleigh length, the far-field divergence angle and the beam propagation ratio M^2. This data structure also allows the characterization of simple astigmatic laser beams, see figure 2. As the propagation of the beam diameter along the axis of propagation is described by a second order polynomial, the beam structure also contains the coefficients of this polynomial.

The function iso11146 (see section 3.1) of the Laser Toolbox can be used to calculate the data fields of the beam structure from the data fields of the pdd structure of section 2.1.

2.3. Temperature distribution

The data structure, referred to as temp (short for 'temperature profile'), holds data related to a 3D temperature profile–i.e temperature rise–$T(x, y, z)$ [K], e.g. induced by absorbed laser energy. In the case a transient temperature distribution is defined, at specified time instances t [s], an array of this data structure is constructed. Then, each entry of the array holds a temp structure; one for each every instant t specified.

2.4. Material

The data structure, referred to as `material`, holds material properties, such as absorption coefficient at the laser wavelength, complex index of refraction, density, heat conductivity heat capacity, melt and vaporization temperature, etc. In the case the material properties are temperature dependent, an array of this data structure is constructed. Then, each entry of the array holds a `material` structure; one for each temperature.

3. Laser Toolbox functions

Sequences of MATLAB commands can be saved in a text file as a script or encapsulated into a function. These functions extend the standard commands available in MATLAB. The functions of the Laser Toolbox are easy to analyze and easily modified, in the case the user needs to extend or adapt the functionality of the scripts. In the remainder of this section, some of these functions are illustrated by examples.

3.1. Functions related to power density distributions and laser beams

The functions related to power density distributions are scripts to create variables (of the structure `pdd`) holding power density distributions, or read these from a file containing measured data. Additional scripts return variables (of structure `beam`) to allow analysis and graphical presentation of these variables.

The function `templ(p,l,P,dr,N)` returns a variable of structure `pdd`, containing a Gauß-Laguerre Transverse Electro-Magnetic mode (usually denoted as TEM_{pl}) of a passive laser resonator [4], which is characterized by power P [W], waist/focus diameter `dr` [m], and with radial and angular mode orders `p` and `l` respectively. Finally, N the number of grid points in *x* and *y* direction, see figure 3.
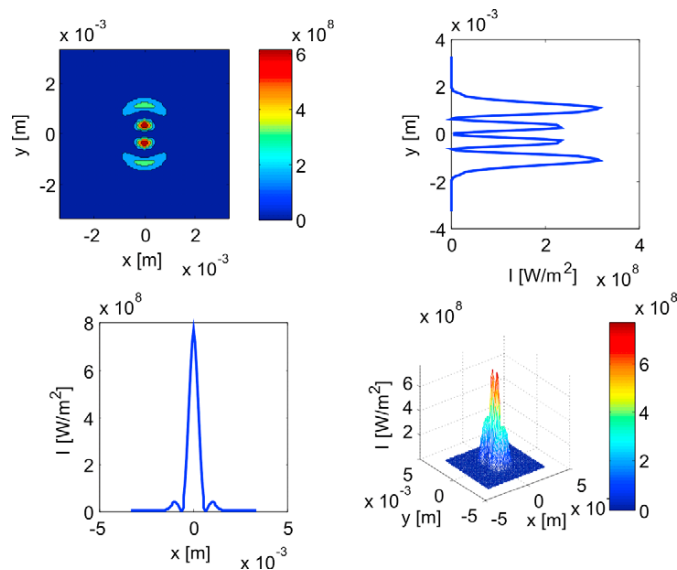

Figure 3: Graphical representation of a TEM_{11} power density distribution, obtained by invoking the Laser Toolbox commands `m=templ(1,1,1000,3e-3,100); plotpdd(m);`

The TEM_{00} mode corresponds to a Gaussian power density distribution. Similarly, the function `temmn(m,n,P,[dx dy],N)` returns a variable of structure `pdd`, containing a Gauß-Hermite Transverse Electro-Magnetic mode, usually denoted as TEM_{mn} [4].

Invoking the functions `m=gauss(P,dr,N)`, `m=tophat(P,dr,N)` and `m=rectunif(P,[dx dy]),N`, return a Gaussian, top hat and rectangular uniform power density distribution, respectively. The top hat power density distribution
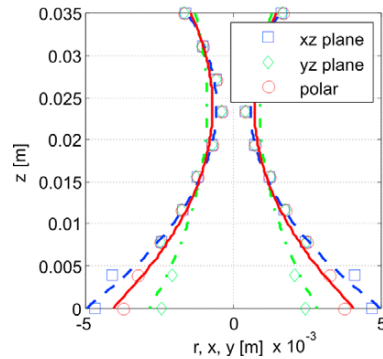
Figure 4: Graphical representation of laser beam properties, obtained by invoking the Laser Toolbox commands `m=mdfread('example2.mdf');` `b=iso11146(m); caustic(b);`

is the typical (theoretical) density distribution in focus of a laser beam transported by an optical fiber. The rectangular uniform power density distribution is the typical (ideal) density distribution generated by a diode laser source.

These power density distributions, in fact any variable of the structure `pdd`, can be plotted graphically by the function `plotpdd(m)`, taking a variable, in this case `m` as an input. Figure 3 shows an example. In the case the input `m` to `plotpdd` is an array of structures, `plotpdd` is automatically invoked to generate a plot for each entry of the array `m(i)`.

The function `mdfread(filename)` takes the filename of a text file, generated by the measurement device FocusMonitor [5] of Primes GmbH, Germany, as an input and returns a variable of the `pdd` structure. Likewise, `ufffread(filename)` takes the filename of a text file, generated by the measurement device UFF100 LaserScope [6] of Prometec GmbH, Germany.

Invoking the function `b=iso11146(m)` takes a variable, here `m`, with a power density distribution and returns a variable, here `b`, of the `beam` structure, with the dimensions (width, length, diameter) of the density distribution, as well as the ellipticity–i.e. the ratio of the width and length of the density distribution–all according to the ISO 11146 standard [3]. In the case, the input variable is an array holding three or more density distributions (at defined locations z along the axis of propagation), laser beam parameters (focus dimension, location, Rayleigh length, far-field divergence, M^2, etc.) are calculated automatically by a 2nd order polynomial fit of the beam dimensions along the axis of propagation. The function `caustic(b)` takes a variable, here `b` of beam structure and plots the propagation parameters graphically, see figure 4 for an example.

Manufacturers and developers of laser beam diagnostic tools are invited to send an example data file of their device(s), including a description of the file format, to the authors, to allow the creation of scripts specific for these devices.

3.2. Functions related to the conduction of heat in solids

The Laser Toolbox functions discussed in this section calculate the temperature profile (`temp` structure) in a semi-infinite solid, induced by a moving heat source–i.e. induced by absorbed laser energy. That is, the temperature rise is calculated in a homogenous solid (so no melting, nor vaporization) of infinite thickness, with constant material properties. Solutions of classical heat conduction problems were presented by Carslaw and Jeager [7], but the implementation of most functions of the Laser Toolbox were based on the solutions derived in a more recent book on thermal modelling of laser material processing from Dowden [8], including, but not limited to a point heat source, a line heat source and a surface heat source. These functions can be used to simulate the laser surface treatments like laser-annealing and laser-transformation hardening [9]. The scripts can also be used to compute the induced temperature profile of other processes, like laser-welding and -cutting, but as the models are based on heat conduction in solids only, the scripts must be used with an understanding of their limitations.

The function `T1=tpntsrc(mat,P,v,x,y,z,t)` returns a variable, here `T1`, of the `temp` structure, with the transient temperature profile due to a heat point source with P [W] at the surface ($z = 0$) of a solid (with only the relevant
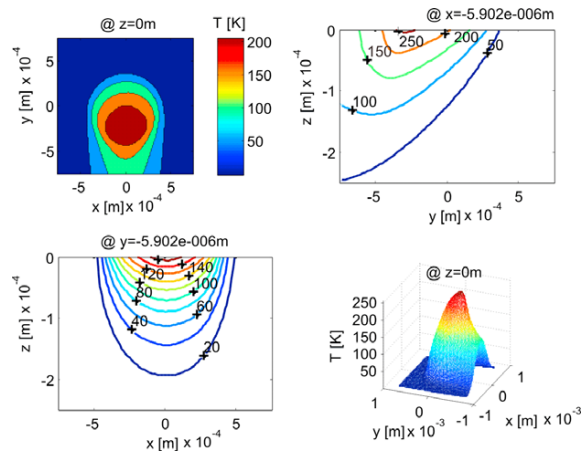
Figure 5: Graphical representation of 3D temperature profile–i.e temperature increase–obtained by invoking the following Laser Toolbox commands: m=mdfread('example2.mdf'); load C45; T3=tsurfsrc(C45, m(4),0.3,linspace(0,0.25e-3,10),Inf); plottemp(T3);
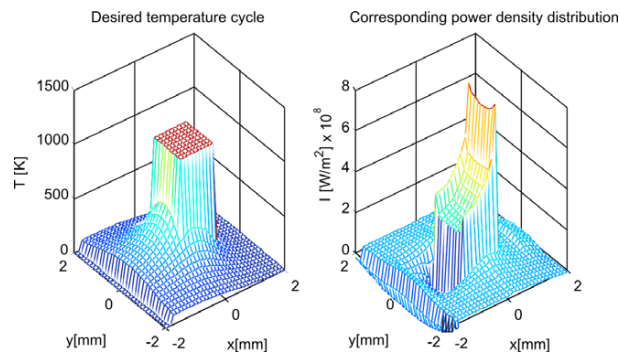

Figure 6: Graphical representation of the power density distribution (right), obtained by invoking Laser Toolbox commands including m=t2srfsrc(C45,T,10e-3), in which the desired temperature profile (left) is specified. This profile 'moves' over the surface in the positive *x*-direction.

material properties defined in mat, moving at velocity *v* [m/s] relative to the solid [7]. The input parameter t is a scalar or vector with time instances to be evaluated by tpntsrc. If t=Inf (infinity), the quasi-stationary solution is returned. The input parameters x, y and z are vectors defining the volume of interest for which the temperature profile is to be calculated. Likewise, invoking T2=tlinesrc(mat,Q,v,x,y,z) returns the temperature profile due to a moving line heat source of Q [W/m]. This model can be used to estimate the temperature profile a the solid during laser-cutting and -welding.

The function T3=tsurfsrc(mat,m,v,z,t) takes a single (measured or theoretical) power density distribution (of pdd structure), here m, as input, and returns the temperature profile in the solid, here T3, induced by this density distribution, moving at *v* [m/s]. It is assumed that all the laser energy of the density distribution is absorbed and converted into heat in a infinitely small surface layer of the solid. That is, it is assumed that the optical penetration depth of the laser light is (much) smaller than the heat penetration depth. The *xy* dimensions of the power density distribution and the vector z, define the volume of interest for which the temperature profile is calculated. Figure 5 shows an example. In this figure a measured power density distribution (at $z \approx 25$mm in figure 1) has been applied as

an input.

The above functions take laser power or a power density distribution as input and return the induced temperature profile. The last function discussed in this section takes the opposite route. The function `m=t2srfsrc(mat,T,v)` takes a desired temperature distribution `T` at the surface, moving at v [m/s] over the surface as an input. With the beam velocity v this, in fact, defines a desired temperature cycle in time. The function `t2srfsrc` returns the power density profile, here `m`, which, when absorbed at the surface, will induce the specified (desired) temperature profile [10]. Figure 6 shows an example.

4. Future work

Future work includes the development of more functions for laser material interactions, and functions containing simple models for simulating processes, like laser- cutting, (keyhole) welding, and surface treatments. In addition, several Graphical User Interfaces (GUI's), based on the scripts of the Laser Toolbox are under development.

Acknowledgements

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