Fast CAD Software For The Optical Design Of Long Wavelength Systems

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Abstract

We report on efficient CAD software (MODAL) that we are developing to specifically model long wavelength systems. Beam mode analysis which includes both aberration and truncation scattering using fast SVD methods allows sufficiently accurate and computationally highly efficient representations of a propagating beam for real time design feedback purposes.

Introduction

There is currently growing interest in the modelling and design of long wavelength optical systems, driven by the needs of the astronomy community working on THz/submillimetre systems such as ALMA and ESA's PLANCK and Herschel Space Observatory, as well as by the emerging applications of submillimetre/millimetre technology in security, defence and medical applications. At these frequencies radiation is often propagated and analysed as free-space beams. Unlike traditional optics however, these beams are only a few wavelengths in diameter and diffraction effects can become important. Therefore such optical systems are unique, requiring a different approach to those commonly used at visible wavelengths. Despite this, there is still a lack of dedicated software tools for modelling the range of conditions typically encountered and many such systems are still designed using optical ray-tracing techniques.

The ability of a range of commercial optical design software packages (GLAD, ASAP, CODE V, Zemax) to analyse the behaviour of submillimetre optical systems was reported on previously [1,2]. Although these packages are not specifically intended for use at (sub)millimetre wavelengths, they represent the only classes of commercial optical design tools available with some diffraction capability. Their results were compared with benchmark results generated using a Physical Optics (PO) package, GRASP, a software tool for reflector antenna design and analysis, as our benchmark software against which the results of the other optical packages could be compared. In that research, the conditions under which approximate methods (ray tracing, paraxial modes) can provide extremely efficient and accurate solutions, as well as situations where a more rigorous is required, were investigated. On the other hand GRASP, because of its computational intensity, is more suited to the verification phase rather than the instrument design phase.

One of the conclusions of that research was that there was a lack of dedicated tools for modelling and, in particular, designing of optical systems at (sub-)millimetre wavelengths. Existing tools frequently fail to accurately reproduce the physical reality because of the limitations of the underlying models and/or prohibitive computational load. Most of the available tools have a very steep learning curve and are generally difficult to use. The methods used to describe optical systems are dictated by the requirements of the analysis component, and are frequently not intuitive for the users. That makes it particularly difficult to use such software packages at the design stage.

MODAL

MODAL (Maynooth Optical Design and Analysis Laboratory) [3] was started as part of the ongoing theoretical research into development of an alternative approach to Gaussian Beam Mode (GBM) analysis, that could be effectively applied to off-axis and irregular elements, frequently used in real quasi-optical systems. One of the primary aims was to allow the user to define and analyse a quasi-optical system through an easy-to-use graphical user interface (GUI). The project has evolved substantially since then. The inclusion of other methods of analysis, including Physical Optics, implementation of a powerful approach to system definition and the ability to parallelize the most computationally intensive analysis tasks, mean that MODAL is advancing on its way to become a general purpose design and analysis package in the millimetre/submillimetre region of the spectrum (Fig. 1).

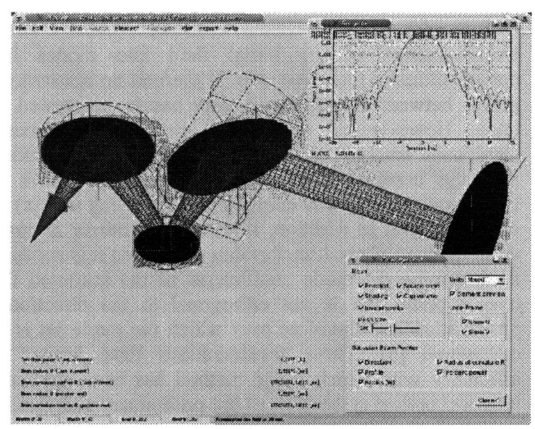

Fig. 1: MODAL in action (Hershel Space Observatory HIFI Ch#1 Mixer SubAssembly).

Targeted key features of MODAL are:

- Ease of use. The program offers CAD-like approach to system design and analysis, through intuitive graphical interface. Most frequently used features are emphasised, and wizards/solvers will be provided for standard design tasks.
- Easy system definition. MODAL allows the user to define the quasi-optical systems accurately, but at the same time without unnecessary effort. It uses Constructive Solid Geometry to describe the shape of optical elements. Space Spatial constraints, apertures and irregular shapes can in most cases be very easily defined using this approach.

- Beam visualisation. A unique approach to modal analysis implemented in MODAL will also allow a good approximation of the propagation of the beam to be visualised at design stage. This provides valuable feedback for the designer.
- Powerful analysis engine. A variety of analysis methods can be used to analyse the same system. They include Physical Optics and several modal approaches (including GBM and plane wave decomposition). This selection of methods offers the user a unique ability to trade accuracy for speed, and cross-check the results.
- Parallel processing. MODAL allows the user to speed-up some of the most computationally intensive tasks, such as PO analysis of large systems at high frequencies, by distributing the load over multiple machines or CPUs.
- Portability. MODAL is developed using cross-platform technologies such as OpenGL, FLTK and XML. It is currently tested under Linux (i386 and x64), Windows and Solaris.

SVD GBM analysis

In GBM theory a monochromatic coherent beam can be represented by a scalar field E_0, which can be written as a linear sum of independently propagating Gaussian modes Ψ_m. Generally the source field can be represented to a high accuracy by the sum of only a few modes. Once the mode coefficients are known, it is straightforward to model the propagation of the beam by employing analytically known propagation characteristics of individual modes [4].

However, two aspects of the modal approach to beam propagation have to addressed, for the GBM technique to be used effectively:

1. Decomposition of the initial field into modes is a computationally intensive step. If there is no scattering of power between the modes it only has to be carried out once. However, if an optical element introduces a significant amount of power scattering between modes, then the number of integrations needed to derive the transformation of mode coefficients (scattering matrix) can be prohibitive. In addition, if an off-axis mirror is treated as an inclined phase-transforming plane then it is necessary to determine the mode coefficients of the scattered field over a plane that is not orthogonal to the direction of propagation and therefore over which the mode set is not orthogonal [5]. These considerations have limited the efficiency with which GBM method has been applied to practical optical systems in all but preliminary analyses.

   We have addressed this deficiency of the GBM technique by using a novel fitting approach, based on Singular Value Decomposition (SVD). Basic use of the SVD technique is equivalent to generalized linear fitting, and gives approximated mode coeffcients for a predetermined mode set (Fig. 2a,d). In addition to this, the singular values of the mode matrix can be taken into account to compensate for non-optimal choice of mode set (Fig. 2b).
2. The choice of the optimum beam mode set is crucial to the efficiency of the GBM approach. High order modes extending far beyond the field region can cause problems in fitting approach (Fig. 2a), if not suppressed by adding explicit zero field points in that region (Fig. 2c). We have addressed this problem by using a mode extent matching technique to select the optimum mode set (Fig. 2d).

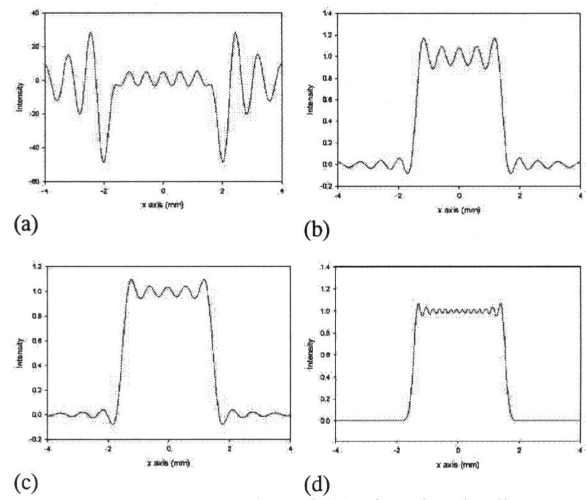

Fig. 2: Reconstruction of the field of uniformly illuminated aperture (D=3 mm) using SVD technique (N=30 modes, λ=1 mm). (a) poor choice of mode set (W=1 mm), (b) truncation based on analysis of singular values, (c) suppression of higher order modes by zero-padding, (d) optimal choice of mode set (no padding)

Beam visualisation

Early versions of MODAL used rudimentary beam visualisation based on tracking of the evolution of the fundamental mode (see Fig. 1). Unfortunately the beam profile derived using this simplified approach can be misleading for more complex systems, especially if they include off-axis components. We are working now on more advanced beam visualisation algorithms, based on SVD GBM propagation. This new approach provides much better balance between accuracy and speed.

Future work

MODAL is undergoing continuous development, which has now shifted from the Technical Demonstration stage to development of fully-featured Proof Of Concept version, with load and save functionality and much improved interface.

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