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Influence of the frame stiffness on the Second Harmonic Generation of the mounted optics with large aperture

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ABSTRACT

With the aim to decrease the distortion and the stress as well as to increase the Second Harmonic Generation (SHG) efficiency, a novel mounting configuration with plug function of the optics was proposed, a comprehensive model of the mechanics and the optics was built, and the influences of the frame stiffness on the distortion and the stress as well as on the SHG efficiency were investigated. The distortion and the stress were calculated by using a Finite Element Method (FEM) and their changing trends with the varying frame stiffness were pointed out. Furthermore, the phase mismatches induced by the distortion and the stress were calculated, and the SHG efficiency considering the phase mismatch was studied. The results revealed the availability of the mounting configuration and the feasibility of increasing the SHG efficiency by improving the frame stiffness.

1. Introduction

The SHG technique [1], since it was discovered, was applied in the Inertial Confinement Fusion (ICF) field and used in high power laser systems, such as the National Ignition Facility (NIF) in USA [2] and SG-III system in China [3]. KDP crystal, with excellent performance on the SHG [4], functions as the frequency conversion element in these systems to obtain the SHG. Most of these optics have the geometrical characteristics of large aperture and low thickness, which easily causes distortion and stress due to the combined effects of gravity and the mount. As a result, both the incident angle of the laser beam [5] and the refractive index [6] change from their ideal conditions, consequently introducing phase mismatch and finally decreasing the SHG efficiency [7].

A variety of mounting techniques were put forward in the ICF field to solve this problem. J.M. Auerbach [8] proposed three types of mounting configurations of simple support at corners, simple support at edges and clamp at edges, and concluded that the third one is the optimal one with the smallest distortion and the highest frequency conversion efficiency. R.L. Hibbard [9] designed a full edge mounting set, in which the external load was applied on the edges of the optics by the means of the elastic deformation of the compliant element. Oliver Lubin [10] employed the bonding scheme, where the optics was bonded to the supporting frame on its side edges. Besides the ICF field, optics applied in other fields also encounters this problem and their solutions are suggestive. According to the supporting and constraint types, generally there are three types of mounting configurations, which are the rigid, the flexible and the bonding types. In the rigid type, optics is supported on the rigid structures and squeezed by the external load. A.H. Li [11] supported the optics on the mechanical frame, A. Nordt [12] fixed the optics to the frame with bolts, G. Figueira [13] supported the optics with actuators on its back, J. Schwarz [14] supported the optics at its inner circumference and loaded at the outer one, and U.J. Greiner [15] supported the optics at the outer circumference and loaded at the inner one. In the flexible type, optics is supported by a certain flexible mechanism. E.T. Kvamme [16] axially and radially supported the optics with spring and flexible pads, respectively, G. Kroes [17] radially fixed the optics with the flexible pad, which was connected with the springs, B. Saggin [18] radially supported the optics with the thermal adapter, which was connected with the elastic blades, and A.H. Li [19] applied a flexible structure consisting of the nylon gasket and the elastic steel to support the optics; in addition, both A.H. Li [20] and L.J. Wang [21] supported the optics with a steel strap. In the bonding type, the optics is bonded to the supporting frame. Both D.M. Stubs [22] and C.L. Hom [23] bonded the optics at its periphery to the bond pad, which was fixed to the supporting frame.

In general, the optics rests on or is fixed to the supporting frame, the supporting frame deforms under both the optics and its own weight, and this frame distortion causes additional distortion and stress for the optics other than the gravitational ones, which further affects the SHG efficiency. Since the frame distortion is a

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function of its stiffness, it is clear that the frame stiffness plays an important role in the distortion and the stress of the optics, as well as on the SHG efficiency, which was not assessed in the previous work, which focused on the gravitational distortion and stress. In this paper, a mounting configuration with plug function of the optics was proposed, where the optics was radially restrained and axially supported by the frame, which was settled down in the housing. A comprehensive model of the mechanics and the optics was built, by employing which the influences of the frame stiffness were discussed. Three components of the frame stiffness, the constraint, the structure and the material stiffness, were proposed, the distortion and the stress considering these three kinds of stiffness were numerically calculated by using the FEM, and their changing trends with these varying stiffness were pointed out. Moreover, the variation of the incident angle caused by the distortion was calculated, and then the phase mismatch induced by it was deduced. On the other side, the variation of the refractive index caused by the stress was calculated according to the photo-elastic effects, and then the induced phase mismatch was deduced. By solving the coupling wave equations considering the phase mismatch, the SHG efficiency was studied.

2. Optical and mechanical configurations

2.1. Optical configuration

To gain the SHG, a frequency converter, mainly consisting of a type I KDP crystal in the optics, is constructed; the KDP crystal is named as a doubler, which is arranged in the type I angle phase matching configuration ($o+o\rightarrow e$). The inertial fundamental wave ($1.064\ \mu m$) is linearly polarized along the ordinary axis of the doubler, producing the residual fundamental and the second harmonic ($0.532\ \mu m$) waves polarizing along the ordinary and the extraordinary axes, respectively; the phase matching and the azimuth angles are 41.19° and 45°, respectively, as shown in Fig. 1. The frequency converter is installed into the mechanical set, which was fixed at certain location in the optical path, where the SHG is performed.

2.2. Mechanical mounting configuration

A mounting configuration, named as the full edge supporting configuration, is proposed. It has a plate structure with the geometry dimensions of 430 mm × 430 mm × 12 mm; it rests on the supporting frame at its full edges and axially (Z direction) constrained by the frame at its bottom surface. On the other side, it is squeezed by the stop block at the top surface, where the external load is generated. In addition, the plastic staples support the optics around the periphery, providing the radial (X and Y directions) constraints. The optics needs a plug function in the optical path, and the frame housing is designed to settle this requirement. By inserting the frame, together with the mounted optics, into or pulling from the housing, the optics accomplishes the plug action, since the housing is mechanically fixed at the assigned location of the optical path. When the frame settles down in the housing, it is axially and radial supported and constrained by the housing, as shown in Fig. 2. The system aslant lies in the optical path with gravity at 45° angle to the normal (Z direction) in YZ plane, as required by the optical demands.

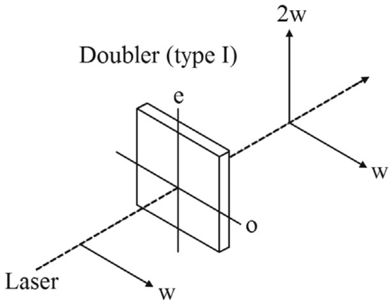

Fig. 1. Optical configuration of the frequency converter.

3. Theory

Influences of the frame stiffness on the distortion and the stress as well as on the SHG efficiency are studied by using the comprehensive model, which consists of both the mechanical and the optical models. By using the mechanical model, the influences of the frame stiffness on the distortion and the stress are studied. By using the optical model, the phase mismatch induced by the distortion and the stress are calculated; furthermore, the SHG efficiency is studied considering the phase mismatch.

3.1. Mechanical analysis

The optics is a plate structure; its distortion could be solved according to the elasticity law [24]:

$$[K]\ \{U\}=\{F\} \tag{1}$$

where $\{U\}=\{u\ v\ w\}^T$is the distortion matrix and $[K]$ is the stiffness matrix, determined by the conditions of constraint, structure and material. $\{F\}$ is the load matrix, including gravity and the external load.

The stress is solved following the distortion:

$$\begin{cases}\{\sigma\}=[D]\ \{\varepsilon\}\\ \{\varepsilon\}=[B]\ \{U\}\end{cases} \tag{2}$$

where $\{\sigma\}=\{\sigma_{xx}\ \sigma_{yy}\ \sigma_{zz}\ \sigma_{yz}\ \sigma_{xz}\ \sigma_{xy}\}^T$ is the stress matrix, $\{\varepsilon\}=\{\varepsilon_{xx}\ \varepsilon_{yy}\ \varepsilon_{zz}\ \varepsilon_{yz}\ \varepsilon_{xz}\ \varepsilon_{xy}\}^T$ is the strain matrix, and $[D]$ is the elastic matrix, representing the relationship between the stress and the strain; as for the KDP crystal, the relationship is anisotropic Ref. [10]:

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{xz}\\ \sigma_{xy}\end{Bmatrix}=\begin{bmatrix}D_{11} & D_{12} & D_{13} & 0 & 0 & 0\\ D_{12} & D_{11} & D_{13} & 0 & 0 & 0\\ D_{13} & D_{13} & D_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & D_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & D_{44} & 0\\ 0 & 0 & 0 & 0 & 0 & D_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ 2\varepsilon_{yz}\\ 2\varepsilon_{xz}\\ 2\varepsilon_{xy}\end{Bmatrix} \tag{3}$$

where $D_{11}=71.2$, $D_{12}=-5.0$, $D_{13}=14.1$, $D_{33}=56.8$, $D_{44}=12.6$, and $D_{66}=6.22$ (in units of GPa). $[B]$ is the geometry matrix:

$$[B]=\begin{bmatrix}\partial/\partial x & 0 & 0 & 0 & \partial/\partial z & \partial/\partial y\\ 0 & \partial/\partial y & 0 & \partial/\partial z & 0 & \partial/\partial x\\ 0 & 0 & \partial/\partial z & \partial/\partial y & \partial/\partial x & 0\end{bmatrix}^T \tag{4}$$

The distortion and the stress could be calculated by solving the combined equations (1)–(4); however, it is challenging to analytically solve these equations; the alternative is numerical solution by using the FEM. The principle of FEM is discretizing the integral structure into elements with nodes, solving the local distortion and stress for nodes as the fundamental solution, then calculating the element solution by interpolating the node results, and finally, obtaining the global solution for the structure by integrating the element solution.