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Thermo-mechanical responses of cracked quasi-transparent film to laser irradiation

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ABSTRACT

Thermal and mechanical responses of a cracked transparent conducting film to laser irradiation were investigated. A representative coin-shaped crack was modeled in the transparent conducting film and the case of vertical incidence of laser beam considered. Firstly, the multiple reflections, transmissions as well as absorptions are formulated in the quasi-multilayer media due to the effect of inner crack. Then, the temperature characteristics generated by the dissipated light energy are computed for the film of typical thermal boundary conditions. Finally, the thermal stress and stress intensity factors around the crack tip are particularly analyzed. The effects of the coin-shaped crack are discussed on the multi-physical responses of the film to laser irradiation.

1. Introduction

The transparent conducting film of Al-doped ZnO (AZO film) have been largely used as in the photovoltaic cells, waveguides and many other important photoelectric devices because of its excellent performance and relatively low price [3,13,10,33,6,23,7,31,9]. Of course, the AZO film is actually not absolute transparent as there is necessarily absorption of light transmitting through it. The electrical conductivity as well as surface morphology of Al-doped ZnO film could be enhanced obviously by increasing its thickness [1]. Although the rough surface of AZO layer could lead to inner discontinuity, which could act as defects especially when the bi-layer structure of AZO/ZnO is taken into concept [17]. These defects are always strictly unacceptable in optical materials as the discontinuity would increase the reflection and scattering of the incident light and dissipate much light energy into heat, which means that unexpected temperature elevation and thermal stress would arise in the structure. Such thermo-mechanical responses would slightly change with the absorption of guided waves if the wave-guide structures are taken into account. Therefore, the correct mathematical descriptions are required on the characteristics of temperature, thermal stress as well as its possible singularity to estimate the reliability of a device involving such AZO film, in particular when tiny flaws appear.

The thermo-mechanical properties of the intact AZO film has been modeled based on the public data distributed in the large literatures [18,8,11 and 21]. However, subsurface or interface discontinuity could be developed in the optical glasses as well as various surface functional films by many processing wherein the contact pressure is involved, or as aforementioned [5,20,22,34]. At the same time, the responses, such as scattering and intensification of the flaws to the incident light have also been utilized to detect them [27,40]. In these detection methods, the mechanical stress effect has also attracting much attention [28]. Although, the full physical mechanism on the interaction between a subsurface crack and light irradiation has not been revealed thoroughly except for some simplified model that approximating the incident light energy as simple thermal loadings without considering the reflection,

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Nomenclature

A_0	amplitude of the plane harmonic wave
A_k	amplitude of the reflected beams
A_k^t	amplitude of the transmitted beams
a	model coefficients
b	model coefficients
C_i	model coefficients
c	specific capacity
D	thermal diffusivity
D_i	computing domains
d	thickness of the sample
d_1	crack location, distance from the irradiated surface to the crack location
d_2	distance from the bottom surface to the crack
d_m	center value of d_1 for the averaged calculations
E	elastic modulus
E_i	energy flow
E_I	effective energy density of the incident laser
h	convective heat transfer coefficient, 10 W/m^2/K
K_c	characteristic Stress intensity factor
K_I	stress intensity factor of type I
$[K_I]$	dimensionless Stress intensity factor of type I
K_{II}	stress intensity factor of type II
$[K_{II}]$	dimensionless Stress intensity factor of type II
k_c	thermal conductivity
n	outward normal unit vector of the surface
n_i	complex refraction index of the medium i
Q	heat generation rate
Q_c	characteristic heat generation rate
Q_i	heat generation rate per unit volume for domain
$[Q_i]$	dimensionless heat generation rate per unit volume for domain
R	radius of the sample
R_c	radius of the coin-shape crack
R_b	radius of the laser beam
r_f	upper bound for the nodes selected for curve-fitting
t	time
T	temperature
T_c	characteristic temperature
$[T_{\max}]$	dimensionless maximum temperature
$T_{\max}$	maximum temperature
T_{amb}	ambient temperature, 20 °C
$\boldsymbol{u}$	displacement vector
α	thermal expansion coefficient
β_i	model coefficients
θ_i	angle in medium i
λ	laser wavelength
ρ	density
ν	Poisson's ratio
ϵ	surface emissivity, 0.85
σ	Stefan–Boltzmann constant
σ_{xy}	xy -component of the stress tensor
σ_{yy}	yy -component of the stress tensor
σ_c	characteristic stress
$[\sigma_{ij}]$	dimensionless ij -component of the stress tensor

Definitions of the dimensionless parameters

Q_c	$\frac{E_I}{d}$
$[Q_i]$	$\frac{Q_i}{Q_c}$
$[T]$	$\frac{T-T_{amb}}{T_c-T_{amb}}$
$[T_{\max}]$	$\frac{T_{\max}-T_{amb}}{T_c-T_{amb}}$
σ_c	$\alpha E(T_c - T_{amb})$
$[\sigma_{ij}]$	$\frac{\sigma_{ij}}{\sigma_c}$
K_c	$\sigma_c\sqrt{R_b\alpha(T_c - T_{amb})}$
$[K_I]$	$\frac{K_I}{K_c}$
$[K_{II}]$	$\frac{K_{II}}{K_c}$

transmission of the light at the cracks [37].

Laser induced damage in such quasi-transparent optical materials, or commonly known as glass materials as well as the interaction between laser and the flaws in these materials play significant role in optical engineering, especially when the multi-disciplinary design optimization is considered wherein light, thermal and mechanical reliability are targeted simultaneously [24,25,32,35].

Actually, the interaction between monochromatic light and opaque material is largely discussed in the field of laser manufacturing [19,12], wherein the temperature, phase change and stress are particularly focused on [29,26]. For materials with a

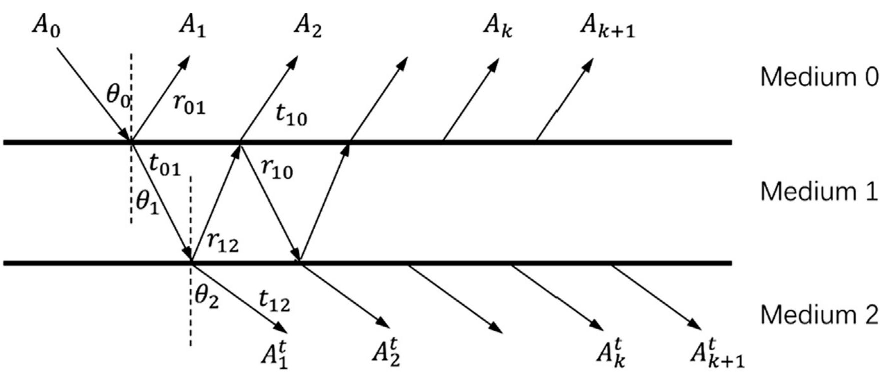

Fig. 1. Sketch of monochromatic light propagation through homogeneous medium.