Romanian Reports in Physics, Vol. 65, No. 3, P. 979–983, 2013

Dedicated to Professor Valentin I. Vlad's 70th Anniversary

MULTIPLE NANO-SECOND LASER ABLATION OF METALS BASED UPON A NEW TWO-TEMPERATURE APPROACH

N. SERBAN, M. OANE, I. N. MIHAILESCU*

National Institute for Laser, Plasma and Radiation Physics, Str. Atomistilor 409,
Magurele, 077125, Romania
*E-mail: ion.mihailescu@inflpr.ro

Received March 26, 2013

Abstract. We used a new approach to describe the laser-metals thermal interaction based upon the two-temperature (electron and phonon) model. Using only one Fourier equation, we got information about 3D thermal field, surface temperature, and steady state quantum effects during laser irradiation of metals. To this purpose, we applied the integral transform technique to the Anisimov and Nolte models. As an example, we computed the surface temperature in laser-Au thin film interaction during multi-pulse nanosecond laser ablation of the metal.

Key words: two-temperature model, laser-metal interaction, Anisimov and Nolte models.

1. INTRODUCTION

The two temperature model (TTM) was introduced by the Russian school of theoretical physics [1] almost 35 years ago. The model was used in the following years in many research papers the most of them published in *Physical Review*. The solutions to TTM can be obtained by solving two coupled differential equations. In 1997, Nolte [2] proposed a simplified TTM model.

We developed since 2001 [3–6] a powerful method to solve the Fourier heat transfer equation. We have combined now [7] the Nolte model with our approach, in order to develop a unique heat equation for TTM. We made several physical simplifications, but we could achieve information about 3D thermal field, surface temperature, and steady state quantum effects that usually take place during laser-metal interaction [8].

2. SOLUTIONS OF THE PROPOSED MODEL

We start from three differential equations [7], where K represents the eigen-functions and λ, μ, ξ the eigen-values:

$$\frac{\partial^2 K_x}{\partial x^2} + \lambda_i^2 K_x = 0 \ ; \frac{\partial^2 K_y}{\partial y^2} + \mu_j^2 K_y = 0,$$

$$\frac{\partial^2 K_z}{\partial z^2} + \xi_k^2 K_z = 0\,. \tag{1}$$

The solutions are:

$$K_x = \cos\left(x_i \cdot x\right) + \frac{h}{K\,\lambda_i}\sin\left(\lambda_i \cdot x\right), \tag{2.a}$$

$$K_y = \cos\left(\mu_j \cdot y\right) + \frac{h}{K\mu_j}\sin\left(\mu_j \cdot y\right), \tag{2.b}$$

$$K_z = \cos\left(\xi_k \cdot z\right) + \frac{h}{K\xi_k}\sin\left(\xi_k \cdot z\right). \tag{2.c}$$

Here *h* represents the heat transfer coefficient.

The electron (solid) temperature is:

$$T_e = \sum_{i=1}^{\infty}\sum_{j=1}^{\infty}\sum_{k=1}^{\infty} a\left(\lambda_i,\mu_j,\xi_k\right)\cdot b\left(\lambda_i,\mu_j,\xi_k,t\right)\cdot K_x\left(\lambda_i,x\right)\cdot K_y\left(\mu_j,y\right)\cdot K_z\left(\xi_k,z\right) \tag{3}$$

If we take into account in eq. (3) only the first 10 terms (for *i ,j,k*), we obtain the analytical solution:

$$T_e = \sum_{i=1}^{10}\sum_{j=1}^{10}\sum_{k=1}^{10} a\left(\lambda_i,\mu_j,\xi_k\right)\cdot b\left(\lambda_i,\mu_j,\xi_k,t\right)\cdot K_x\left(\lambda_i,x\right)\cdot K_y\left(\mu_j,y\right)\cdot K_z\left(\xi_k,z\right). \tag{4}$$

Here:

$$a\left(\lambda_i,\mu_j,\xi_k\right) = \frac{1}{KC_iC_jC_k}\int_0^a\int_0^b\int_0^c P_a\left(\vec{r},t\right)\cdot K_x\left(\lambda_i,x\right)\cdot K_y\left(\mu_j,y\right)\cdot K_z\left(\xi_k,z\right) \tag{5}$$

and

$$b\left(\lambda_i,\mu_j,\xi_k,t\right) = \frac{1}{\lambda_i^2+\mu_j^2+\xi_k^2}\left[1-e^{\gamma_{ijk}^2\cdot t}-\left(1-\mathrm{e}^{-\gamma_{ijk}^2(t-t_0)}\right)\cdot H\left(t-t_0\right)\right]. \tag{6}$$

Here:

$$\gamma_{ijk}^2 = \gamma\left(\lambda_i^2+\mu_j^2+\xi_k^2\right). \tag{7}$$

C_i, C_j, C_k are the normalizing constants [3–6].

$$P_a = \sum_{m,n} I_{mn}\left(y,z\right)\left(\alpha_{mn}\mathrm{e}^{-\alpha_{mn}x}\right)\left(1-r_{Smn}\right)+r_{Smn}\delta\left(x\right)+q.c.\right)\cdot\left(H(t)-H(t-t_0)\right), \quad (8)$$

where $I_{mn}(y,z)$ is the laser transverse mode $\{m, n\}$, α_{mn} is the linear absorption coefficient for the mode $\{m, n\}$, r_{Smn} is the surface absorption coefficient for the mode $\{m, n\}$, and *q.c.* are quantum steady state corrections. H is the step function and t_0 is the exposure time.

3. SIMULATIONS

We selected for simulation the case of thermal distribution generated by the interaction of a Gaussian Q switched Nd-YAG laser beam with Au thin films. The coupling factor is [8, 9]: $G = 2.6\times10^{6}$ W/m^{3}K. The Au foil was 1 mm thick.

We considered the heat source of the form:

$$I(t) = \begin{cases} I_0 \exp(t/\tau_L), t < 0 \\ 0, t \geq 0 \end{cases}. \quad (9)$$

Here: $\tau_L = 4.5\text{ns}$ is laser pulse duration, $\nu_p = 10\text{Hz}$, E_{pulse}=200 mJ, $\lambda = 532$ nm, w = 0.1mm (beam width) and I_{laser}=10^{9} W/cm^{2}. A similar experiment is described in reference [10].

We present in Fig. 1 the Au thin film surface temperature after the action of one laser pulse. On the other hand, in Fig. 2, it is presented the Au thin film surface temperature after interaction with 100 subsequent laser pulses.

Our simulations are in very good agreement with the experimental data, for metals like: Au, Al, Cu and Ag [11].

4. CONCLUSIONS

We have obtained a simple solution for the two model temperature. The solution can help for the evaluation of thermal effects in laser-metal interaction. The metals under consideration are [9, 10] Au, Cu, Ag and Al. The temperature should be lower than the melting point of the respective metals. In order to illustrate the “power” of the presented approach we determined the 3D thermal distribution field during irradiation of an Au thin film.

Numerical calculations based upon heat equation, will allow obtaining more precise information about 3D thermal field by taking into account the quantum effects in the solution of the modified heat equation. Our model is an analytical one, because we take into account only the first 10 values of the indices*: i, j* and *k*. This involves an absolute error of about 10^{-2} K [11]. Our solution is a simple approach giving the first information about the thermal field in laser-metal interaction and can be of great help for any future experiments.

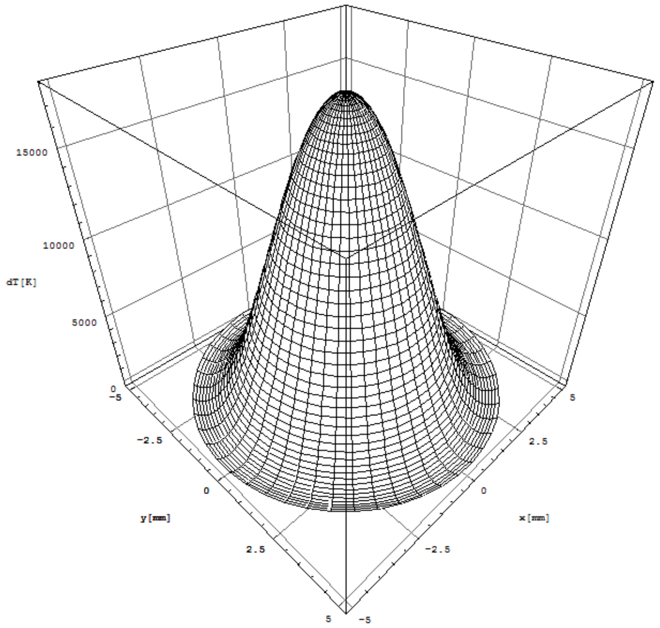

Fig. 1 – The thermal field of Au thin film surface after interaction with one laser pulse.

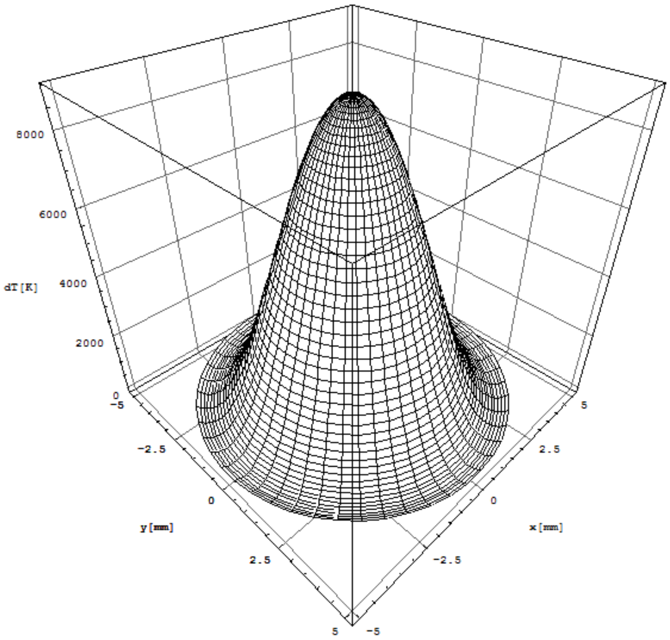

Fig. 2 – The thermal field of Au thin film surface after interaction with 100 laser pulses.

The present method could also be applied for very short time interactions, when quantum effects (for instance, multi-photons absorption or a high absorption coefficient at the sample surface) can become important. For different values of the surface absorption coefficient, one can construct a detailed model in order to obtain the temperature field for two pulses of irradiation with a delay time (10 – 100) ns. The model opens a theoretical basis for developing an analytical expression for the metal surface absorption coefficient with two heating laser pulses which are separated by very short time duration.

Acknowledgements. NS and INM acknowledge with thanks the financial support of this work by UEFISCDI under the contract ID 304/2011.

REFERENCES

1. S. I. Anisimov, B. L. Kapeliovich and T. L. Perelman, JETP Lett., **39**, *2* (1974).
2. S. Nolte, C. Momma, H. Jacobs, A. Tunnermann, B.N. Chichkov, B. Wellegehaussen, and H. Welling, Journal Optical Society of America B, **14**, *10*, 2716–2722 (1997).
3. M. Oane and D. Sporea, Infrared Physics & Technology, **42**, 31–40 (2001).
4. M Oane, A Peled, F. Scarlat, I.N. Mihailescu, A. Scarisoreanu and G. Georgescu, Infrared Physics & Technology, **51**, 242–245 (2008).
5. M. Oane, A. Peled, F. Scarlat, I.N. Mihailescu and G. Georgescu, Infrared Physics & Technology, **51**, 348–350 (2008).
6. M. Oane, F. Scarlat and I.N. Mihailescu , Infrared Physics & Technology, **51**, 344–347 (2008).
7. M. Oane, M. Taca, S. L. Tsao, Lasers in Engineering, **24**, *1–2*, 105–113 (2012).
8. *** American Institute of Physics Handbook, 3rd ed., McGraw-Hill, New York, 1972.
9. G. Du, F. Chen, Q. Yang, S. Jinha and X. Hou, **283**, 1869–1872 (2010).
10. M. Stafe, C. Negutu and I. M. Popescu, Journal of Optoelectronics and Advanced Materials, **8**, 1180–1186 (2006).
11. T. Visan, D. Sporea and G. Dumitru. Infrared Physics & Technology, **39**, 335–346 (1998).