Optics Communications 383 (2017) 566–570

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Dynamic modelling and experimental study of asymmetric optothermal microactuator

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ARTICLE INFO

Keywords:
Optothermal microactuator
Dynamic modelling
Deflection

ABSTRACT

This paper reports the dynamic modelling and experimental study of an asymmetric optothermal microactuator (OTMA). According to the principle of thermal flux, a theoretical model for instantaneous temperature distribution of an expansion arm is established and the expression of expansion increment is derived. Dynamic expansion properties of the arm under laser pulse irradiation are theoretically analyzed indicating that both of the maximum expansion and expansion amplitude decrease with the pulse frequency increasing. Experiments have been further carried out on an OTMA fabricated by using an excimer laser micromachining system. It is shown that the OTMA deflects periodically with the same frequency of laser pulse irradiation. Experimental results also prove that both OTMA's maximum deflection and deflection amplitude (related to maximum expansion and expansion amplitude of the arm) decrease as frequency increases, matching with the theoretical model quite well. Even though the OTMA's deflection decrease at higher frequency, it is still capable of generating 8.2 μm maximum deflection and 4.2 μm deflection amplitude under 17 Hz/2 mW laser pulse irradiation. This work improves the potential applications of optothermal microactuators in micro-opto-electro-mechanical system (MOEMS) and micro/nano-technology fields.

1. Introduction

With the development of micro-opto-electro-mechanical systems (MOEMS), high-performance microactuators have been increasingly required, which are considered as the key part for MOEMS devices to perform physical function. Many microactuators based on electrostatic [1], magnetic [2], piezoelectric [3,4], magnetostrictive [5], and thermal actuation [6,7] principles have been reported, among which, thermal actuation-based actuators [8,9] have been widely used in MOEMS where slow motions and large displacements are required. Electrothermal actuators [10] are capable of gaining bigger deflection angles and generating larger actuating forces, while photothermal micro-cantilevers and actuators are able to realize actuation directly by laser beam [11–13]. In our previous work [14], a kind of optothermal microactuator (OTMA) with hot/cold arms was proposed, and its static properties of expansion and deflection under continuous laser beams have been discussed. While in most of the practical applications, the MOEMS devices and OTMAs are required to work under dynamic conditions. Therefore, further efforts are needed to investigate dynamic properties of OTMA.

In this paper, dynamic modelling and experimental study of an asymmetric OTMA is presented. Instantaneous temperature distribution and dynamic expansion properties the OTMA's expansion arm are theoretically analyzed. Experiments are then conducted on such OTMA to check its dynamic properties, as well as to prove the validity of dynamic model.

2. Dynamic modelling of an OTMA

The scheme of an asymmetric OTMA is shown in Fig. 1. The OTMA consists of two asymmetric arms which are joined at the free end and connected to the base through two narrow bridges at the fixed end. Heating is generated when a focused laser beam irradiates the OTMA's expansion arm (length L, width W, thickness D), causing temperature rise and volume expansion. The arm then elongates for ΔL and acquires an enlarged lateral deflection of ΔD due to connected free end..

Set the left end of the expansion arm as the coordinate origin (x=0), and the center of spot as x=L_1, the free right end as x=L. A theoretical model describing the dynamic mechanism of optothermal temperature distribution and expansion is established.

As shown in Fig. 2, an arbitrary element with dx length at the position x is chosen to analyze the heat transmission of the expansion arm. Within the dt period, the element gains a heat flux Q_{Laser} (Q_{Laser} is zero when the element is out of the spot) from laser irradiation, and Q_x

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http://dx.doi.org/10.1016/j.optcom.2016.09.063
Received 29 April 2016; Received in revised form 29 August 2016; Accepted 29 September 2016
Available online 12 October 2016

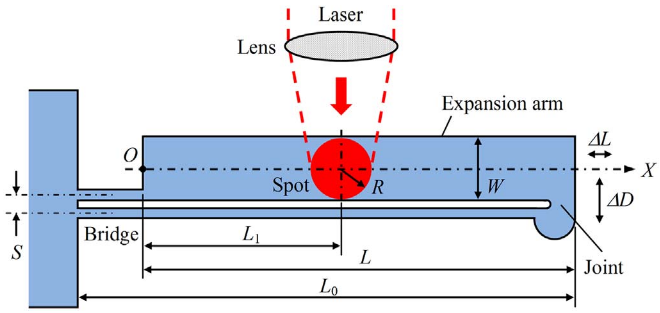

Fig. 1. Scheme of an asymmetric optothermal microactuator (OTMA) with its expansion arm irradiated by a laser spot.

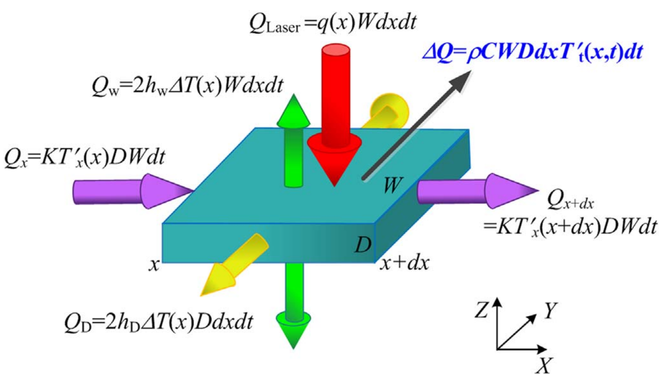

Fig. 2. Heat flux model of an arbitrary element of the expansion arm. Q_{Laser} is the heat flux from laser irradiation, Q_x and Q_{x+dx} are conduction heat along the arm, Q_W and Q_D are convection heat through up/down and side surfaces. The element gains Q_{Laser} and Q_x, loses Q_{x+dx}, Q_W and Q_D, and finally achieves an increased heat ΔQ.

from the former element. At the same time, it loses Q_{x+dx} flowing into the next element, and Q_W and Q_D due to convection through up/down and side surfaces. ΔQ is the increased heat of the element during the transmission process. The direction of heat flux is defined as positive in accordance with the arrows, conversely, the direction is negative..

In principle, the increased heat equals to the difference of obtained and lost heat fluxes. The equation can be expressed as:

$$\Delta Q = Q_{Laser} + Q_x - Q_{x+dx} - Q_D - Q_W \tag{1}$$

Replace the terms of Eq. (1) by the fluxes shown in Fig. 2, and simplify as:

$$\frac{\partial T}{\partial t} = \frac{K}{\rho C}\frac{\partial^2 T}{\partial x^2} - \frac{2(Wh_w + Dh_D)}{\rho WDC}\Delta T + \frac{q}{\rho DC} \tag{2}$$

Where K, C and ρ are the thermal conductivity, heat capacity and density of the expansion arm, q is the power-density distribution of laser spot, ΔT and T=T_0+ΔT are respectively the temperature rise and the real-time temperature of the element when the arm is irradiated (T_0, the initial temperature), h_D and h_W are the coefficients of the convective heat transfer with air on the side and up/down surfaces.

As the heat environment at the fixed end is different from the free end, the coefficients of the convective heat transfer are different, named h_1, h_2 respectively. h_2 is the same with h_D. The thermal boundary conditions can be expressed as:

$$K\cdot\frac{\partial T}{\partial x}\Big|_{x=0} - h_1\cdot\Delta T(0, t) = 0 \tag{3}$$

$$K\cdot\frac{\partial T}{\partial x}\Big|_{x=L} - h_2\cdot\Delta T(L, t) = 0 \tag{4}$$

Set the original temperature rise when t=0 is zero, that is

$$\Delta T(x, 0) = 0 \tag{5}$$

Therefore Eq. (2) with the boundary conditions can be regarded as partial differential equations with fixed solution:

$$\begin{cases} \frac{\partial T}{\partial t} = a^2\frac{\partial^2 T}{\partial x^2} - b\cdot\Delta T + f(x, t) \\ K\cdot\frac{\partial T}{\partial x}\big|_{x=0} - h_1\cdot\Delta T(0, t) = 0 \\ K\cdot\frac{\partial T}{\partial x}\big|_{x=L} - h_2\cdot\Delta T(L, t) = 0 \\ \Delta T(x, 0) = 0 \end{cases} \tag{6}$$

Where a,b and $f(x,t)$ are defined as:

$$a = \sqrt{\frac{K}{\rho C}},\quad b = \frac{2(Wh_w + Dh_D)}{\rho WDC},\quad f(x, t) = \frac{q(x, t)}{\rho DC} \tag{7}$$

Solving Eq. (6) using eigen function method [15], the distribution of temperature rise can be given as follows:

$$\Delta T(x, t) = \sum_{n=1}^{\infty}\frac{\exp(-bt - a^2\lambda_n t)V_n(x)}{\nu_n}\int_0^t U_n(\xi)\exp(b\xi + a^2\lambda_n\xi)d\xi \tag{8}$$

According to the relation between thermal expansion and temperature rise, the thermal expansion increment ΔL along the X direction can be expressed as:

$$\Delta L(t) = \alpha\int_0^L \Delta T(x, t)dx = \alpha\sum_{n=1}^{\infty}\left[\frac{\exp(-bt - a^2\lambda_n t)(K\sqrt{\lambda_n}\sin(\sqrt{\lambda_n}L) + h_1 - h_1\cos(\sqrt{\lambda_n}L))}{\sqrt{\lambda_n}\nu_n}\int_0^t U_n(\xi)\exp(b\xi + a^2\lambda_n\xi)d\xi\right] \tag{9}$$

Where α is the linear thermal expansion coefficient of the material, λ_n(n=1, 2,...) is a group of eigen values, $V_n(x)$ is a set of eigen functions,

$$\begin{cases} \sqrt{\lambda}L = n\pi + ctg^{-1}\left(\frac{K^2\lambda - h_1h_2}{K\sqrt{\lambda}(h_1 + h_2)}\right) \\ V_n(x) = K\sqrt{\lambda_n}\cos(\sqrt{\lambda_n}x) + h_1\sin(\sqrt{\lambda_n}x) \\ U_n(t) = \int_0^L V_n(x)f(x, t)dx \\ \nu_n = \int_0^L V_n(x)^2dx = \frac{1}{2}(K^2\lambda_n + h_1^2)\left(L + \frac{h_2K}{K^2\lambda_n + h_2^2}\right) + \frac{1}{2}h_1K \end{cases} \quad (n = 1,\ 2,\ \cdots) \tag{10}$$

Eqs. (8) and (9) are the general formulas of temperature rise and dynamic optothermal expansion. For an expansion arm made of certain material irradiated by a certain kind of laser, the distribution of temperature rise and the optothermal expansion can be obtained as long as all parameters are substituted into the equations.

Laser pulse with a duty cycle of 0.5 and alterable frequencies is employed to analyze the dynamic properties of the expansion arm. For simplicity, the power-density distribution of laser spot is approximately assumed to be uniform. Therefore, the power-density distribution $q(x,t)$ can be described as:

$$q(x, t) = \begin{cases} \rho_A q_0, & L_1 - R \le x \le L_1 + R \text{ and } 2mt_0 \le t < (2m + 1)t_0 \\ 0, & x < L_1 - R \text{ or } x > L_1 + R \text{ or } (2m + 1)t_0 \le t < 2(m + 1)t_0 \end{cases} \quad (m = 0, 1, 2, \ldots) \tag{11}$$

Where q_0 is the incident laser power density, ρ_A is the laser absorption ratio of the expansion arm, t_0 the single pulse duration and $2t_0$ the pulse period.

Within a certain laser pulse, $2mt_0 \le t < (2m+1)t_0$ stands for the "pulse-on" duration, and $(2m+1)t_0 \le t < 2(m+1)t_0$ the "pulse-off" duration, set t_r=t-$2mt_0$ and ε_n=b+$a^2\lambda_n$, Eq. (8) can be rewritten as: