Uncooled infrared imaging device based on optimized optomechanical micro-cantilever array

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Abstract

It is a major issue to improve the thermo-mechanical sensitivity of uncooled optomechanical focal plane arrays (FPAs) for infrared imaging. This work presents an optimized multi-fold interval metallized leg (IML) configuration to increase the thermo-mechanical sensitivity of an uncooled optomechanical bi-material micro-cantilever array. The inclination angle changes of the cantilever elements are measured in the IR imaging system using an optical readout with a knife-edge filtering operation in the spectrum plane. The multi-fold IML configuration consists of alternately connected unmetallized and metallized legs. With the optimized fold number, the thermo-mechanical sensitivity of a micro-cantilever array can be amplified to two times of one-fold IML for a $120 \mu m \times 120 \mu m$ element with $1 \mu m$ thick SiN$_x/0.2 \mu m$ thick Au films. Room temperature objects are imaged with the fabricated FPA containing $160 \times 160$ elements and a 12-bit CCD. Further modeling analysis shows that the experimental results are well accordant with the theoretical calculation. An important practical feature of the implemented approach is its straightforward fabrication for a large FPA, without growing complexity and cost.

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1. Introduction

Infrared (IR) imaging in the 8–14 $\mu m$ spectral range is of great importance to a wide range of applications, such as night vision, remote sensing and driving aids etc. These applications not only demand low noise-equivalent temperature difference (NETD), but also require low cost and economical power consumption. IR detectors can be broadly divided into cooled (photonic) detectors and uncooled (thermal) detectors [1,2]. Although commercialized photonic detectors have a low NETD ($\sim 5–10$ mK [1]), they require auxiliary devices cooling the detectors to about 77 K for eliminating the thermal noise of electrons, which results in high cost and excessive power consumption. A conventional thermal IR imaging device (typical NETD $\sim 50–100$ mK [1]), in which the temperature rise of each element is measured electrically by changes in either resistance or capacitance, is already commercialized due to its compatibility with electric signal processing. However, electrical interconnect to each element leads to fabrication complexity as well as scanning electronics and a display system.

In recent years, there has been an increasing interest in uncooled bi-material micro-cantilever arrays for thermal imaging with optical methods [3–6]. Optical readout systems do not require highly sensitive readout integrated circuits and scanning electronics, thus reducing fabrication complexity. The groups of Majumdar [7,8] and Datskos [9] have succeeded in thermal imaging with optomechanical...
focal plane arrays (FPAs). To improve the thermo-mechanical sensitivity of cantilever elements, Majumdar’s group [10] proposed a bimorph micro-optomechanical sensor using a flip-over bi-material beam design, in which the out-of-plane displacements of cantilever elements were measured with an interferometry method. Within an area of 100 μm × 100 μm, the flip-over bi-material beam has about 53% higher thermo-mechanical sensitivity than a conventional one. The demerit of interferometry optical readout system is its high susceptibility to vibration noise. Furthermore, the FPA architectures [7–10] are fabricated employing sacrificial layer technique, which increases the fabrication complexity due to the sacrificial layer release difficulty and causes the structure disabled easily because of the adherence of cantilevers to the substrate.

From 2003, the author’s group has developed substrate-free bi-material FPAs for IR imaging using an optical readout with a knife-edge filtering operation in the spectrum plane [11]. In the optical readout method, inclination angle changes of micro-cantilever elements are measured. IR images of a 120 °C thermal object have been obtained, even though an FPA is placed in air environment [12]. Lately the author’s group has fabricated an FPA containing 100 × 100 elements (element size: 200 μm × 200 μm) and obtained thermal images of room temperature objects with NETD of 650 mK [13,14]. To make progress toward an applicable IR imager, the sensitivity and spatial resolution of an FPA need to be improved, which means an FPA with a smaller sensor element should have a higher sensitivity. Based on the previous works, this paper presents an optimized FPA with multi-fold interval metallized legs (IMLs) used for IR imaging. A bi-material (1 μm thick SiNₓ/0.2 μm thick Au) cantilever array has been fabricated with improved microfabrication techniques. Also, the array’s performance is optimized by the fold number of IML within a sensor area of 120 μm × 120 μm. Using the fabricated 160 × 160 FPA, thermal images of room temperature objects are improved. And NETD of the FPA has been improved to 400 mK.

2. Principles of deformation amplification and optical readout system

2.1. Principle of deformation amplification

To increase the thermo-mechanical deflection of a bi-material sensing structure in a finite element size, we propose a multi-fold IML design, in which unmetallized legs alternately connect with bi-material legs. Fig. 1 shows the thermal deformation principle of bi-material legs, which are made of two different materials (SiNₓ and Au) having evidently different coefficients of thermal expansion, and the deformation of a single bi-material cantilever (a), double connected bi-material legs (b), two-fold IMLs (c) and one-fold flip-over legs (d) for a same temperature change on free ends. Since the thermal conductivity of Au is much larger than that of SiNₓ, bi-material legs are good conductors compared with SiNₓ legs. Thus it is reasonable to suppose the temperature distribution is uniform on bi-material legs, linear on thermal isolation legs. It is noted that there is no deformation generated on SiNₓ legs. And the inclination angle of a single bi-material cantilever in Fig. 1(a) is θ_a. In Fig. 1(b), since a same inclination is generated on two connected bi-material legs, the end point has almost zero deflection, or θ_t~0. Therefore, nothing is gained from using double connections of bi-material legs. Fig. 1(c) gives serially connected two-fold IMLs, in which bi-material legs are alternately connected with thermal isolation legs. Considering the temperature linear distributions of thermal isolation legs 1 and 3, the temperature change of bi-material leg 2 is half that of leg 4, so does the thermo-mechanical deformation. Thus the end point has an accumulated deflection, θ_x = θ_a+0.5θ_a = 1.5θ_a. Therefore, a higher end point deflection can be achieved by increasing the fold number of IML. Fig. 1(d) shows one-fold flip-over bi-material legs connected with a thermal isolation leg. One of bi-material legs has Au on top of SiNₓ, and the other Au on bottom of SiNₓ. Since the temperature changes on both bi-material legs 2 and 3 are approximately equivalent, the almost same thermo-mechanical deformation generates on both legs, thus the end point has an inclination angle less θ_t<~20°. That is, the thermo-mechanical deflection with the design of flip-over legs is larger than that with multi-fold IML design within a same sensor area. However, we have not realized flip-over leg structure currently due to the limitation of fabrication techniques.

Fig. 2 illustrates a substrate-free micro-cantilever element design of 120 μm × 120 μm. It consists of a reflector, two sets of symmetric multi-fold IMLs and a 10 μm wide supporting frame, whose dimensions are shown in Table 1. The reflector is made of SiNₓ and Au films. The SiNₓ film serves as the incident IR absorber and the Au film as the reflector of visible readout light. Such cantilever elements are arranged to compose an FPA.

2.2. Principle of optical readout system

Fig. 3 demonstrates a schematic diagram of the optomechanical IR imaging system. Visible readout light from an LED through a pin hole, which is located on the focus of collimating lens L₁, becomes a parallel beam illuminating on an FPA. The reflected diffracting fluxes through BS synthesize the spectra of reflectors on the rear focal plane of transform lens L₁. (Lens L₁ performs the functions of both collimating readout light and Fourier transforming in the system.) By filtering with a knife-edge filter placed on the rear focal plane, a visible image of reflectors is collectively projected onto a 12-bit CCD (S/N: 70 dB) by an imaging lens. An IR source is imaged onto the FPA by an IR lens and the absorbed IR radiation causes the cantilevers bending, inducing a change of the direction of reflected readout light, then the spectra of reflectors shift. As a result, the light fluxes passing through the
knife-edge filter changes, so does the image intensity of reflectors. To obtain an IR image of the source, an image with IR stimulus is captured and the pre-captured background image without IR stimulus is subtracted from it, thus a visible grey image is obtained. In order to optimize the optical detecting sensitivity, the knife-edge filter should be placed at the centre position of the zeroth order spectra of reflectors to let half fluxes pass through, and the readout illumination should make the CCD approach its full measuring range. The FPA is sealed in a vacuum chamber (~0.1 Pa) to reduce the effects of convection and conduction of air, as well as to eliminate the random vibration noise of cantilever elements caused by air molecules’ collision.

The detecting sensitivity of the optical readout system can be denoted with the minimum detectable angle \( \theta_{\text{min}} \) corresponding to one grey level of CCD. For a rectangular reflector, the half-width of the zeroth order spectrum along the direction of cantilever legs can be expressed as \( \frac{l_f}{L_y} \) [15], where \( l \) is the wavelength of readout light, \( f \) the focus of a Fourier transform lens and \( L_y \) the reflector length along the leg direction. The quantization level of CCD is \( N \), then the half-width of the zeroth order spectrum is quantized to \( N \) shares. If the cantilever inclines with \( \Delta \theta \), so does the reflector, the reflector’s spectrum will shift with \( 2\Delta \theta f \). Therefore, the grey change \( \Delta I \) of the reflector image can be expressed as the function of \( \Delta \theta \):

\[
\Delta I = \frac{2\Delta \theta f}{\lambda f / (L_y N)} = \frac{2L_y N}{\lambda} \Delta \theta.
\]

Thus \( \theta_{\text{min}} \) can be given as

\[
\theta_{\text{min}} = \frac{\Delta \theta}{\Delta I} = \frac{\lambda}{2L_y N}.
\]
Table 1
Typical dimensions of proposed FPA (μm)

<table>
<thead>
<tr>
<th>Element size</th>
<th>$A_{\text{pixel}}$</th>
<th>$A_{\text{ab}}$</th>
<th>Reflector length</th>
<th>Leg length$^a$</th>
<th>Leg width</th>
<th>Au film thickness</th>
<th>SiN$_x$ film thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 × 120</td>
<td>106 × 106</td>
<td>106 × 46</td>
<td>106</td>
<td>106</td>
<td>3</td>
<td>0.2</td>
<td>1</td>
</tr>
</tbody>
</table>

*The length of SiN$_x$ or bi-material leg in one-fold IML.

Fig. 3. Schematic diagram of the uncooled opto-mechanical infrared imaging system.

$\theta_{\text{min}}$ is inversely proportional to $L_x$. Thus, in a predetermined element size, the reflector length along the leg direction is required to be as long as possible to minimize $\theta_{\text{min}}$. If the reflector has an initial bend caused by residual stress, the spectrum will be dispersed and widened, then the optical detecting sensitivity $\theta_{\text{min}}$ will degrade [16]. In fact, this case is inevitable in the FPA fabrication process.

3. Design and optimization

For a given incident IR flux, under the constraints of predetermined element size, it is of paramount importance not only to maximize the temperature rise but to optimize the thermo-mechanical sensitivity in an FPA design.

3.1. Thermal response $H$ of cantilever element

The temperature rise $\Delta T_C$ in a reflector due to the temperature rise $\Delta T_S$ of an IR source can be expressed as [1,8,12]:

$$H = \frac{\Delta T_C}{\Delta T_S} = \frac{A_{\text{ab}} \varepsilon \tau_0 \pi (dP/dT_I)}{4F_{\text{no}} (G_{\text{leg}} + G_{\text{rad}})},$$

(3)

where $A_{\text{ab}}$ is the element absorption area, $\varepsilon$ the absorber emissivity, $\tau_0$ ($=0.9$) and $F_{\text{no}}$ ($=0.8$) are the transmissivity and $f/#$ of the IR lens, respectively, and $(dP/dT_I)$ is the fraction of the radiative energy emitted by the source at temperature $T_I$ ($\sim 300$ K). Within the 8–14μm spectral band, $dP/dT_I = 0.63$ W/(m$^2$K sr). According to $G_{\text{leg}} = A_{\text{leg}} k/l_{\text{leg}}$, the legs’ conductance $G_{\text{leg}}$ of a cantilever element with $n$-fold IMLs can be expressed as [12–14]:

$$G_{\text{leg}} = \frac{n l}{k_{\text{Au}} A_{\text{Au}} + k_{\text{SiN}_x} A_{\text{SiN}_x}} + \frac{n l}{k_{\text{SiN}_x} A_{\text{SiN}_x}},$$

(4)

where $l$ is the length of a SiN$_x$ or bi-material leg in one-fold IML, $k$ the thermal conductivity of the selected materials and $A$ is the cross-section area. Factor 2 comes from the fact that the reflector is connected to the frame via two sets of IMLs, and $n$ from the fact that each set of IMLs is composed of $n$ folds. The first term in the bracket is the attribution of the bi-material legs and the second comes from the SiN$_x$ legs. $G_{\text{rad}}$ is the radiative conductance of the element, which follows:

$$G_{\text{rad}} = 4 A_{\text{pixel}} \sigma (\varepsilon_{\text{Au}} + \varepsilon_{\text{SiN}_x}) T_a^3,$$

(5)

where $\sigma = 5.67 \times 10^{-8}$ W/(m$^2$K$^4$) is the Stefan–Boltzmann constant, $A_{\text{pixel}}$ the active area of element, $T_a$ the element temperature ($\sim 300$ K). It should be noted that the air conductance in vacuum can be neglected [17], compared with $G_{\text{leg}}$ and $G_{\text{rad}}$ (Table 2). Thus, the total thermal conductance in Eq. (3) is expressed as ($G_{\text{leg}} + G_{\text{rad}}$).

3.2. Thermo-mechanical sensitivity $s_T$ of cantilever element

Table 3 lists the physical properties of SiN$_x$ and Au. It can be easily seen from Eq. (4) that the thermal conductance of bi-material legs is much larger than that of SiN$_x$ legs (over 10 times). Therefore, it is reasonable to suppose that the temperature distribution is uniform on bi-material legs, linear on SiN$_x$ legs. Fig. 4 shows a finite element simulation result of the temperature distribution on multi-fold IMLs for the reflector temperature increasing by 1 K. In Fig. 4, a three-fold cantilever element is simulated. The element is made of Au/SiN$_x$ films, whose dimensions are listed in Table 1. When the temperature of the reflector rises 1 K, the temperature distribution is linear on the SiN$_x$ legs, while the Au/SiN$_x$ legs are isothermal, which justifies the above assumption; the temperature rises of the Au/SiN$_x$ legs from the reflector to the frame are 1 K, 2/3 K, 1/3 K, respectively. Then, for a cantilever element with $n$-fold IMLs, when a temperature change $\Delta T_C$ is generated on the reflector, the temperature changes on the bi-material legs from the reflector to the frame are $\Delta T_C$, $\Delta T_C/n$, $\Delta T_C/n$ ($i = n, \ldots, 1$), respectively. The deflection $\theta_i$ of the $i$th bi-material leg due to the reflector
temperature rise $\Delta T_C$ can be given as [8,12,18]:

$$\frac{dz}{dx} = 6(z_{Au} - z_{SiN_x}) \left( \frac{t_{Au} + t_{SiN_x}}{t_{SiN_x}K} \right) \frac{i}{n} \Delta T_C,$$

$$z = 0; \quad \theta = 0 \quad \text{at} \ x = 0,$$

where $z$ is the thermal expansion coefficient, $t$ the cantilever thickness, $\theta$ the cantilever deflection at a distance of $x$, $K$ is a structure parameter given as

$$K = 4 + 6n_t + 4n_t^2 + \Phi n_t^3 + \frac{1}{\Phi n_t},$$

$$n_t = \frac{t_{Au}}{t_{SiN_x}}; \quad \Phi = \frac{E_{Au}}{E_{SiN_x}},$$

in which $E$ is the elastic modulus. The inclination angle $\theta_i$ of a reflector is the sum of $\sum \theta_i (i = 1, \ldots, n)$. Thus, the thermo-mechanical sensitivity $S_T$ of the cantilever element can be given as:

$$S_T = \frac{\theta_i}{\Delta T_C} = 6(z_{Au} - z_{SiN_x}) \cdot \frac{(n_r + 1)i}{Kt_{SiN_x}} \left( \frac{n + 1}{2} \right).$$

It is clear from Eq. (8) that $S_T$ is proportional to the fold number $n$. That is, a large value of $n$ is expected to increase the element sensitivity. On the other hand, $H$ is proportional to the element absorption area $A_{ab}$ and inversely to the legs' conductance $G_{leg}$. Since both $A_{ab}$ and $G_{leg}$ reduce with $n$, $H$ reaches a peak value for a proper $n$, and then falls with $n$. It is the ultimate design goal to get the maximum of

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Design parameters of FPA ($t_{SiN_x} = 1\mu m, t_{Au} = 0.2\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element size ($\mu m^2$)</td>
<td>$G_{leg}$ (W/K)</td>
</tr>
<tr>
<td>120 $\times$ 120</td>
<td>$9.6 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Properties of optional materials for FPA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emissivity $\varepsilon$</td>
</tr>
<tr>
<td>SiN$_x$</td>
<td>0.8</td>
</tr>
<tr>
<td>Au</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Fig. 4. Finite element simulation result of temperature distribution on multi-fold IMLs using ANSYS when the temperature of reflector increases by 1 K. The temperature distribution is linear on the SiN$_x$ legs, while the Au/SiN$_x$ legs are isothermal.
the thermo-mechanical response \( S_T \times H \) of cantilever elements. Fig. 5 demonstrates \( S_T, H \) and their product as the functions of \( n \) for the cantilever element whose dimensions are listed in Table 1. For the optimized \( n (= 3) \), the product \( S_T \times H \) reaches its maximum (Table 2). For \( n = 1 \) and 2, the products are \( 4.8 \times 10^{-4} \) and \( 9.6 \times 10^{-4} \) deg/K, respectively. The former is only about 40% of the maximized value and the latter 80%.

As mentioned in the previous work [12], it is necessary to reduce SiNx film thickness \( t_{SiNx} \), optimize the thickness ratio \( n_r \) (optimized \( n_r \approx 0.75 \) [12]) and reduce the cross-section area of legs to improve \( S_T \) or \( H \). Fig. 6 gives \( S_T, H \) and their product as the functions of the SiNx film thickness under the conditions that a 120 \( \mu \)m \( \times 120 \mu \)m element with three-fold IMLs absorbs incident IR fluxes sufficiently and the Au film thickness of the bi-material legs remains 0.2 \( \mu \)m. It can be found that the thinner the legs, the higher the performance. When \( t_{SiNx} \) is reduced to 0.3 \( \mu \)m, the thickness ratio approaches to the optimum and the product \( S_T \times H \) reaches \( 1.3 \times 10^{-2} \) deg/K, about 10 times of the current value. It should be noted that the absorbance of IR fluxes depends on the SiNx film thickness by \( 1 - \exp(-4t_{SiNx}/\pi \kappa \lambda_1) \) [16], where \( \kappa \) is the absorption coefficient of SiNx and \( \lambda_1 \) the wavelength of IR radiation. In the 8–14 \( \mu \)m spectral range, the absorbance is only about 32% when \( t_{SiNx} \) reduces to 0.3 \( \mu \)m (for \( \lambda_1 \approx 10 \mu \)m, \( \kappa \approx 1 \) [17]). Thus, in order to absorb effectively IR fluxes, an absorber with a resonant cavity [17] is required. Nevertheless, it is a key issue to control the residual stress when the thickness of SiNx film reduces. In this paper we just realized the fabrication of an FPA with 1 \( \mu \)m-thick SiNx because of the limitation of techniques. Furthermore, reducing the leg width will save space to increase the fold number \( n \) or the element absorption area \( A_{ab} \) and result in the improvement of \( S_T \times H \). Therefore, a higher performance can be expected with the improvement of fabrication techniques.

### 3.3. Thermal response time

The thermal response time \( \tau \) of the element is determined by the element’s heat capacitance \( C_{th} \), and thermal conductance \( G \):

\[
\tau = \frac{C_{th}}{G},
\]

in which \( C_{th} = \sum (\rho A_{ab})(c) \), \( \rho \) is the material density, \( t \) the thickness, \( c \) the material heat capacity and \( i \) indicates each material used in the cantilever element. The thermal response time \( \tau \) for the presented FPA is calculated to be 70 ms (see Table 2). To be compatible with a 30 frame/s real-time video IR imaging, \( \tau \) can be improved by reducing the reflector thickness. Another important factor is the cantilever element size. The thermal response time of an element with a 60 \( \mu \)m \( \times 60 \mu \)m pitch can be below 10 ms.

### 4. Fabrication

An FPA containing 160 \( \times \) 160 elements was fabricated with silicon bulk based surface micro-machining technologies. The process consisted typically of four steps, as shown schematically in Fig. 7. It started with a silicon wafer washed using de-ionized water. The first step was the deposition of double-side low stress LPCVD SiNx films 1 \( \mu \)m thick. The second step was to lithograph photore sist mask and then to remove the unwanted SiNx films employing reactive ion etching (RIE), thus the SiNx layer on topside and a wet-etch releasing window on backside were patterned. The third was thermal isolation leg masking and Au layer (0.2 \( \mu \)m thick) deposition after depositing a 10 nm adhesion layer, followed by the removal of Au layer on thermal isolation legs, and then the cantilever patterns were defined. Finally, the Si substrate beneath the FPA elements was removed through the wet-etch
window in KOH solution. Fig. 8 gives a micrograph of a portion of the fabricated FPA with a 120 μm × 120 μm pitch. Every cantilever element has a three-fold IML thermal deformation structure.

The FPA includes several key characteristics. First, Si substrate beneath the cantilever elements is removed. This can improve the transmissivity of IR radiation, simplify the fabrication process and avoid the cantilever adherence to substrate caused by heat or mechanical impact. Second, the thermo-mechanical sensitivity can be greatly enhanced by multi-fold IMLs. Third, the design with the multi-fold IMLs being put symmetrically on both sides of a reflector makes both the reflector and the IMLs as long as possible, improving the optical detecting and thermo-mechanical sensitivities, respectively. Moreover, a valuable implication of the present FPA is that higher resolution arrays can be easily fabricated, such as 1000 × 1000 or above, without progressively growing complexity and cost.

5. Experiment

Fig. 9 shows thermal images with an f/0.8 IR lens and a 12-bit CCD at the background temperature around 25 °C. Fig. 9(a) is an IR image of a man wearing glasses at the distance of about 2 m away and (b) is that of the man waving his right hand. It is easy from Fig. 9 to distinguish the glasses, clothes wrinkles, hair and the collar. There appear to be some hollows without elements, which failed in the fabrication process.

To obtain the grey response ΔI/ΔT of the fabricated FPA to the temperature rise of an IR source, an experiment was performed using a temperature controllable IR source with the control precision of 0.01 K. Thirty frames of thermal images were captured at each temperature from 26 to 50 °C by step of 3 °C. The grey response of each cantilever element can be calculated by the grey level response to the temperature change. Fig. 10 shows the IR source and its thermal image. The thermal image (b) of the source (a) contains images of 33 × 33 cantilever elements, and (c) and (d) are enlarged sections of (b). Every bright spot in (b) and (c) is an image of a reflector, and bright CCD pixels in Fig. 10(d) correspond to images of reflectors. To give an overview of the FPA’s response, the grey responses of stochastic five different cantilever elements are measured. For each element, the average response of the CCD pixels corresponding to its reflector is taken as the element’s grey response. Fig. 11 shows the experimental grey responses of the five elements to temperature changes by averaging the values of each element in the 30 captured images. The grey responses of different elements are some what different due to
nonuniformities in elements. The sensitivity ($\Delta I/\Delta T_S$) is estimated by averaging the responses of the five elements, which is calculated to be about 20 grey level/K.

6. Discussion

6.1. Sensitivity of the optical readout system

Substituting $\lambda = 0.5 \mu m$, $L_y = 106 \mu m$, $N = 4096$ (for a 12-bit CCD) into Eq. (2), the minimum detectable angle $\theta_{\text{min}}$ can be calculated to be $3.3 \times 10^{-5}$ deg/grey level. It can be seen in Table 2 that the product $S_T \times H$ is $1.2 \times 10^{-3}$ deg/K, and then the theoretical grey response $\Delta I/\Delta T_S$ to temperature change can be given as:

$$\frac{\Delta I}{\Delta T_S} = \frac{\Delta I}{\Delta \theta} \cdot S \cdot H = \frac{1}{3.3 \times 10^{-5}} \times 1.2 \times 10^{-3}$$

$$\approx 36 \text{ (grey level/K).}$$

(10)

The experimental grey response $\Delta I/\Delta T_S$ is about 20 grey level/K, which is smaller than the theoretical value (36 grey level/K). It can be explained as following: the reflectors have initial curvatures (the measured radius ~3 mm) due to residual stresses generated in the fabrication process, which makes the reflectors' spectra disperse, thus the sensitivity of the optical readout system degrades.

6.2. NETD of the fabricated FPA

NETD is typically used to define the sensitivity performance of an IR imaging system. It is the equivalent temperature rise in an IR source that can be detected with a signal-to-noise ratio of unit.

In an optical readout system, NETD can be calculated by

$$\text{NETD} = \frac{I_{\text{noise}}}{\Delta I/\Delta T_S} = \frac{I_{\text{noise}}}{\Delta I} \frac{\Delta I}{\Delta T_S},$$

(11)

where $I_{\text{noise}}$ is the grey level of system noise, the grey response $\Delta I/\Delta T_S = S_T H/\theta_{\text{min}}$, $\Delta I$ the grey level of IR source and $\Delta T_S$ is the source temperature rise compared with a background temperature.

To measure the system noise, an experiment was performed using the fabricated FPA at the background temperature of 25 °C. In the experiment, 300 background images were serially captured and the grey fluctuations for the CCD pixels that correspond to the reflector images, whose grey levels are greater than 3000, are statistically calculated. The measured system noise distribution is shown in Fig. 12. The mean noise fluctuation, eight grey levels, is taken as the system noise.
levels, can be regarded as the system noises reasonably. According to Eq. (11) and the experimental $\Delta I/\Delta T_S$ ($\sim$20 grey level/K), NETD can be approximately calculated to be 400 mK. When the grey response of the FPA approaches to the theoretical value with the improvement of microfabrication, NETD could be below 200 mK. Further, NETD of the FPA would improve much more if the optical readout with less noise was used.

6.3. Performance limitation

In order to gain an insight into the fundamental limits of the micro-cantilever FPA, the NETD for the background fluctuations, NETD$_{BF}$, temperature fluctuations, NETD$_{TF}$, thermo-mechanical fluctuations, NETD$_{TM}$ and optical readout noise, NETD$_{OR}$, have been discussed.

When the radiation exchange is the dominant mode of heat exchange, the noise associated with heat radiation between the surroundings and micro-cantilever elements is termed background fluctuation noise. The NETD for this noise is given by Kruse [19]:

$$\text{NETD}_{BF} = \frac{2 \sqrt{2k_B B(T_D^3 + T_B^3)} A_{ab}}{G H},$$

(12)

where $k_B$ is the Boltzmann constant (1.38 $\times$ 10$^{-23}$ J/K), $B$ the measurement bandwidth (30 Hz), $T_B$ and $T_D$ are the background temperature and the micro-cantilever element temperature ($T_B \approx T_D = 300$ K), respectively.

If the heat radiation between the detector and its surroundings is negligible compared to the conduction exchange, only the temperature fluctuation noise should be taken into account. The temperature fluctuation noise limit, NETD$_{TF}$, can be written as [8]:

$$\text{NETD}_{TF} = \frac{2 T_D \sqrt{k_B B/G}}{H}.$$

(13)

Unlike other types of uncooled IR detectors, the micro-cantilever detectors are mechanical devices (oscillators) which can accumulate and store mechanical energy. There is a continuous exchange of the mechanical energy accumulated in the device and thermal energy of the environment, which results in thermo-mechanical vibration of the micro-cantilever. NETD$_{TM}$ can be expressed as [8]

$$\text{NETD}_{TM} = \frac{\sqrt{4k_B T_D B/Q k_0}}{l S_T H},$$

(14)

where $Q$ the quality factor ($Q \approx 1000$ for our calculation), $k$ is the micro-cantilever’s spring constant and $\omega_0$ the resonant angular frequency:

$$k = \frac{E_{SNx} w_{SNx}}{4 l_T^3}, \quad \omega_0 = \sqrt{\frac{k}{m}} = \sqrt{\frac{k}{A_{ab}(\rho_{SNx} l_{SNx} + \rho_{Au} l_{Au})}}.$$

(15)

Here $L_T$ is the total length of legs, $w$ double width of legs.

The optical readout noise ($\Delta I/OR$ originates in both the CCD and the LED which are coupled together. The ideal optical readout noise is 1 grey level. It is then converted to an equivalent temperature difference through the theoretical grey response $\Delta I/\Delta T_S$:

$$\text{NETD}_{OR} = \frac{(\Delta I)_{OR}}{\Delta I/\Delta T_S}.$$

(16)

The total NETD of the system, NETD$_s$, can be given as

$$\text{NETD}_s = \sqrt{\text{NETD}^2_{BF} + \text{NETD}^2_{TF} + \text{NETD}^2_{TM} + \text{NETD}^2_{OR}}.$$

(17)

For a 120 $\mu$m $\times$ 120 $\mu$m element, the calculated noise limits are listed in Table 4. The measured NETD$_s$ is much larger than the theoretical value (28.1 mK) for the optical readout noise affects dominantly the system NETD in the present device. Therefore, an uncooled IR imaging with NETD on the order of 10 mK could be expected with the improvement of fabrication techniques and using less noise optical readout.

Another issue is the spatial resolution of IR images. As shown in Fig. 9, the spatial resolution of the system still needs to be improved. That is, the array element size must be reduced, yet the system performance degrades inevitably with the element size reduction. To retain or improve the FPA performance, it is necessary to present a new FPA design (such as Fig. 1(d)) and reduce the SiN$_x$ film thickness.

7. Conclusion

In this paper, an optimized multi-fold IML configuration is presented for an optomechanical substrate-free FPA to improve the thermo-mechanical sensitivity, in which SiN$_x$ legs alternately connect with bi-material legs. The substrate-free structure can improve the transmissivity of IR radiation and simplify the fabrication process. The thermo-mechanical sensitivity $S_T$ increases with the fold number $n$, while a corresponding peak value of $H$ exists. Accordingly, the product $S_T \times H$ has a maximum for a proper $n$. For a 120 $\mu$m $\times$ 120 $\mu$m element, the optimized $n$ is 3, $S_T$ reaches 6.6 $\times$ 10$^{-2}$ deg/K, and the optimized thermo-mechanical response to the source temperature rise
is $1.2 \times 10^{-3}$ deg/K with the bi-material legs made of 1\,\mu m thick SiN$_x$/0.2\,\mu m thick Au films. A thinner FPA containing 160 $\times$ 160 elements has been fabricated using improved micro-machining technologies. The improved thermal images of room temperature objects are obtained using the optical readout with a knife-edge filtering operation in the spectrum plane. NETD of the fabricated FPA is about 400\,mK. Further modeling analysis shows good agreement between the experimental results and the theoretical calculation. It should be noted that a valuable practical implication of the present FPA is its easy fabrication for much larger (>1000 $\times$ 1000) arrays.

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References