Bionic research of pit vipers on infrared imaging

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Abstract: The members of viperidae crotalinae (pit viper) family have special pit organs to detect infrared radiation in normal room conditions, whereas most artificial uncooled infrared focal plane arrays (FPAs) operate only in a vacuum chamber. Dissection shows that the pit membrane is a unique substrate-free structure. The temperature rise advantage of this pit organ was verified in comparison with an assumed substrate pit organ (as an artificial FPA structure). Inspired by the pit viper, we introduced this structure to infrared FPA, replacing the conventional substrate FPA. The substrate-free FPA was fabricated by micro-electromechanical systems (MEMS) process and placed into an infrared imaging system to obtain thermal images of the human body in atmosphere and vacuum working conditions. We show that the infrared capability of the substrate-free pit organ was achieved.

OCIS codes: (110.3080) Infrared imaging; (040.6808) Thermal (uncooled) IR detectors, arrays and imaging; (230.4685) Optical microelectromechanical devices.

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1. Introduction

In the survival of the fittest evolutionary process, organisms optimize a variety of shapes, configurations, structures, and materials over millions of years, and show a wide range of functional characteristics. To avoid predators and capture prey, the viperidae crotalinae snakes (pit vipers) evolved a unique pit organ to detect infrared radiation. This special organ has been widely studied. Noble and Schmidt [1] discussed the ability of the pit organ to sense infrared radiation via behavioral experiments. Bullock verified the relationship between the pit organ and heat by potential changes in nerves. Whether in a dark or bright environment, if a hot object was placed in front of the pit organ, the nerve impulse frequency of the trigeminal nerve connected to the pit organ would increase rapidly [2]. He found that the pit organ was capable of detecting a 0.003 °C change in the temperature of water flowing across the pit membrane [3]. The nerve fibers in the pit membrane convey infrared signals from the pit organ to the optic tectum of the brain, where they merge with input from other sensory modalities [4, 5]. Gracheva et al. [6] demonstrated that the pit membrane serves as a passive antenna for radiant heat, transducing thermal energy to heat-sensitive channels on embedded nerve fibers. Chen et al. [7] found that visual and infrared information are both effective in prey targeting for this species. Kohl et al. [8, 9] found significant differences in the strength of the membrane's neural response to a constant stimulus presented at different orientations and over different distances, and demonstrated the topographic organizational principle of the pit viper’s infrared system. Bakken et al. [10] developed methods for relating anatomy to the optical performance of pit vipers. Cadena et al. [11] showed that pit vipers increase their ability to detect endothermic prey by cooling their pit organs.

After millions of years of evolution, the structure and function of survival organisms are nearly perfect. Learning from organisms and applying their function and structure to devices
are productive areas of research. A large body of work has achieved infrared bionic function for such devices as sidewinder missiles, conventional infrared cameras, and fabricated infrared focal plane arrays (FPAs). The pit vipers transduce thermal energy to the heat-sensitive channels on embedded nerve fibers, whereas uncooled FPAs transduce the thermal energy to the change of conductivity [12], or change of output light intensity [13–15]. Since the gap between the substrate and the thermal element of the FPA is only a few microns, the air layer transfers the heat from the thermal units to the substrate rapidly. To eliminate heat loss from air conduction and improve the temperature rise of the thermal units, FPAs are generally placed in a vacuum chamber, and the vacuum equipment greatly increases the fabrication cost and miniaturization difficulty. However, pit vipers do not have any vacuum equipment, and the pit organ works in a normal atmosphere environment. The pit organ is composed of three parts: an inner chamber, an outer chamber, and a pit membrane [16]. Most biological receptors grow directly on biological tissue substrates, but the pit viper’s membrane is separated from other biological tissue by an air layer of approximately one millimeter thickness.

In this paper, the temperature rise advantage of the substrate-free structure of the pit organ was numerically simulated by finite element analysis (FEA), and the structure is introduced to the design of an infrared FPA. In Section 2, behavioral and dissection experiments were conducted to verify the infrared detection ability and observe the pit organ structure. From the dissection, an FEA model of the substrate-free pit membrane was built, and compared to an assumed substrate pit membrane. Temperature distribution was derived for centric thermal radiation loads and periodic thermal radiation loads applied to the membrane. The thermal conductance and response time of the pit unit were calculated and thermal imaging was numerically simulated. In Section 3, the substrate-free structure was introduced to the design of an infrared FPA, and the substrate-free FPA was fabricated by the micro-electromechanical systems (MEMS). Temperature distribution was obtained when centric and periodic thermal radiation loads were applied to substrate-free and substrate FPAs, and the thermal conductance and thermal response time of the FPA units were calculated, showing the substrate-free FPA achieved optical infrared imaging.

2. Thermal properties of the pit organ numerically simulated by finite element analysis

2.1 Modeling
To study pit vipers, morphology and behavioral experiments were conducted on three members of the crotalinae viperidae family living in the southern mountain area of Anhui province in China: deinagkistrodon acutus (Fig. 1 (a)), trimeresurus gramineus (Fig. 1 (b)), and gloydius brevicaudus (Fig. 1 (c)). The pit organs grow between the eyes and nostrils in these vipers. To observe the pit membrane clearly, the surrounding tissue was cut off, see Fig. 1(d). The membrane is separated from the biological tissue by an air layer exceeding one millimeter thick, and this air layer connects with the ambient atmosphere by an ostiole in front of the eye, see Fig. 1(e). The pit organ itself is a very thin and almost transparent membrane, and the pit membrane sizes of the different species were not the same. Thickness was approximately 15 μm, but diameter ranged from 1.5 to 4 mm. Figure 1(f) shows a dissected pit membrane of deinagkistrodon acutus, which is surrounded by biological tissue. The pit membrane is hemispheric, and so pit vipers have a large infrared detection perspective. Figure 1(g) shows a transverse section micrograph of the pit membrane, and Fig. 1(h) is a schematic diagram of the pit organ showing the inner chamber, outer chamber, and pit membrane.

To confirm the pit viper’s infrared detection ability, behavioral experiments were performed while the eyes were shaded by opaque tape. When a container filled with room temperature water was close to the pit vipers, they had no reaction (see Visualization 1). However, when a container filled with hot water was placed at less than 0.2 m from the pit vipers, they quickly changed to defensive posture, and rapidly adjusted their position and defense angle when the container moved (see Visualization 2). When both the eyes and pit organs were shaded by opaque tape, the vipers did not react to either temperature container. These experiments verified that the pit organ specifically can sense thermal source in real-time when the source is near the pit vipers. Pit vipers have two symmetrical pit organs to form three-dimensional infrared vision, and they can accurately detect the spatial position of the thermal target. They also respond quickly to movement of the thermal object, implying a very short thermal response time of the pit organ.

The temperature advantage of the substrate-free structure of pit organ was numerically simulated by FEA, and the model of the pit organ was built, see Fig. 2. The pit membrane is surrounded by the biological tissue, see Fig. 2(a). The pit membrane units are in the middle layer, sandwiched by two layers of air units in the substrate-free model, see Fig. 2(b). The material parameters of pit membrane and air are shown in Table 1. The thickness, unit number, and thermal conductivity of pit membrane were set to 15 μm, 81 × 81, and 0.11 W/(m·K) [17], respectively. The unit size was chosen to be 20μm × 20μm, corresponding to the size of nerve cells [18]. The specific heat and density of pit membrane are $4.2 \times 10^3$...
J/(kg·K) and 1.0 × 10³ kg/m³, respectively, and were simulated by those parameters of water [17]. The thermal emissivity was chosen to be 0.95, and the thickness of the air layers was 1000 μm. To compare this substrate-free structure with a substrate structure, a substrate pit organ model was also designed, using biological tissue rather than an inner air layer, see Fig. 2(c).

Table 1. Material parameters of pit membrane and air

| Material     | Thermal conductivity k (Wm⁻¹K⁻¹) | Density ρ (kgm⁻³) | Specific heat c (Jkg⁻¹K⁻¹) | Emissivity ε |
|--------------|----------------------------------|-------------------|-----------------------------|--------------|
| Pit membrane | 0.11                             | 1.0 × 10³         | 4.2 × 10³                   | 0.95         |
| Air          | 0.0244                           | 1.2               | 1.0 × 10³                   | -            |

After the models have been built, the thermal loads would be applied in the models. Six aspects should be considered as follows:

a. The thermal radiation of thermal source must be taken into account. To simplify the calculation, the thermal radiation is equivalent to heat flux [19]. \((\frac{dP}{dT_s})\) is defined as the fraction of the radiation energy emitted by the source at temperature \(T_s\) (~300K). Within the band of 8~14μm, \(dP/dT_s = 0.63\text{Wm}^{-2}\text{K}^{-1}\text{sr}^{-1}\) [19], thus the change of radiation intensity \(P\) can be approximated as follows:

\[
\Delta P = \frac{dP}{dT_s} \cdot \Delta T_s = 0.63 \cdot \Delta T_s
\]

As the distance from the pit organ ostiole to the pit membrane is only about 1 millimeter, which is far less than the distance from the thermal source to the pit organ, the thermal receiving area of the pit membrane is approximately equal to the area of the ostiole, and then the heat flux \(h\) can be approximately expressed as follows:

\[
h = \frac{A_o \cdot \theta \cdot \epsilon \cdot \Delta P}{A_o} = \frac{A_o \cdot \frac{A_o}{l_o^2} \cdot \epsilon \cdot \Delta P}{l_o^2} = \frac{A_o \cdot \epsilon \cdot \Delta P}{l_o^2} = 0.63 \cdot \frac{A_o \cdot \epsilon}{l_o^2} \cdot \Delta T_s
\]

Where \(A_o\) is the area of the radiation source set as 0.04 m², \(\theta\) is the space angle from the radiation source to the pit organ ostiole, \(\epsilon\) is the absorption factor of the pit organ set as 0.95, \(A_o\) is the area of the pit organ ostiole, \(l_o\) is the distance from the radiation source to the pit organ ostiole set as 0.3m. When the heat flux is set as 5pW/μm², the temperature change is about 18.8K which is close to the difference between the mammal temperature and the ambient temperature, thus the heat flux is set as 5pW/μm² in the FEA process;

b. The heat loss by thermal radiation from the pit membrane to the surrounding environment should be involved in the numerical calculation process;

c. The air thermal conduction should be involved in the simulation;

d. As the pit organ is recessed, the air circulation is weak, besides the temperature rise of the pit organ is very low, thus the air thermal convection is neglected;

e. The pit membrane is surrounded by biological tissue which has large heat capacity and can be seen as heat sink, thus the constant temperature load of 25 °C is applied around the pit membrane;

f. For the substrate model, the inner biological tissue layer has large heat capacity and can be seen as heat sink, thus the constant temperature load of 25 °C is applied on the inner surface of the pit membrane.
2.2 Centric loading on the pit membrane

Heat flux loads ($5 \text{ pW}/\mu \text{m}^2$) were applied on the outside surface of centric units of the two models. When the loaded area was one unit, the maximum temperature rise of the substrate model was approximately 62.5% ($2.5 \times 10^{-4} \text{ K}/4 \times 10^{-4} \text{ K}$) of the substrate-free model (Fig. 3(a) and (b)). Thus, the thermal isolation of the substrate-free structure is significantly superior to the substrate structure. When the loading area was increased to $3 \times 3$ units the maximum temperature rises are approximately 2.2 times ($5.5 \times 10^{-4} \text{ K}/2.5 \times 10^{-4} \text{ K}$) that of the substrate model (Fig. 3(a) and (c)) and 4.6 times ($1.85 \times 10^{-4} \text{ K}/4 \times 10^{-4} \text{ K}$) that of the substrate-free model (Fig. 3(b) and (d)), because the linear superposition of the temperature pre-rise by the adjacent units greatly increases the overall temperature rise. The maximum temperature rise of the substrate-free model was approximately 3.36 times ($1.85 \times 10^{-4} \text{ K}/5.5 \times 10^{-4} \text{ K}$) that of substrate model (Fig. 3(c) and (d)).

Fig. 3. Temperature distribution of $9 \times 9$ units when applying centric heat flux loads. (a) load applied to the centric $1 \times 1$ unit of the substrate model, maximum temperature rise = $2.5 \times 10^{-4} \text{ K}$, (b) load applied on the centric $1 \times 1$ unit of the substrate-free model, maximum temperature rise = $4 \times 10^{-4} \text{ K}$, (c) load applied to the centric $3 \times 3$ unit of the substrate model, maximum temperature rise = $5.5 \times 10^{-4} \text{ K}$, (d) load applied to the centric $3 \times 3$ unit of the substrate-free model, maximum temperature rise = $1.85 \times 10^{-3} \text{ K}$.
When heat flux loads are applied on the centric units of the pit organ, the maximum temperature rise increases with the number of loaded units due to the temperature pre-rise effect of the adjacent units. Numerical simulations are shown in Fig. 4. For the substrate model, the maximum temperature rise of the centric units is saturated (approximately 0.0007 K) soon after a slight increase, whereas the thermal isolation of the substrate-free structure allows maximum temperature rise to increase with the number of loaded units and reach approximately 40 times (0.03 K /0.0007 K) that of the substrate model.

2.3 Periodic loading on the pit membrane

Fig. 5. Temperature distribution calculated by FEA when periodic heat flux loads are applied. (a)-(c) For substrate pit organ, loaded spatial periods 40, 10, and 2 units and MTF 0.99, 0.93, and 0.28, respectively. (d)-(f) For substrate-free pit organ, loaded spatial periods 40, 10, and 2 units and MTF 0.33, 0.06, and 0.005, respectively.
To analyze the infrared imaging contrast reconstruction ability (or contrast transfer function) of the pit organ, the modulation transfer function (MTF) was calculated. MTF is the ratio of the output signal modulation to the input signal modulation at different spatial frequency, and is a reliable method to evaluate the imaging quality of a device [20],

\[ MTF = \frac{M(\text{Image})}{M(\text{Source})}, \]  \hspace{1cm} (3)

where modulation, \( M \), is obtained from \( T \), the temperature rise of the pit organ models,

\[ MTF = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{max}} + T_{\text{min}}}. \]  \hspace{1cm} (4)

MTF ranges from 0 to 1, and larger MTF implies better contrast reconstruction ability. Different periodic heat flux loads (5 pW/µm²) were applied on the outer surface of the pit membrane model, which has 80 × 80 units, and the temperature distribution results were obtained by FEA, as shown in Figs. 5(a)–5(f).

Different periodic heat flux loads were applied numerically to obtain the MTF curves along with the loaded spatial frequency, see Fig. 6. As the spatial frequency increases, MTF reduces for both models. However, MTF of the substrate-free model is always significantly smaller than that of the substrate model. As the substrate has large heat capacity and is seen as heat sink, most heat flow to the substrate, and the temperature pre-rise by adjacent units are weak. But for the substrate-free model, the air layer has good thermal isolation effect, heat flow to the adjacent units and the temperature pre-rise by adjacent units are strong. Thus, the contrast reconstruction ability of the substrate-free model is weaker than that of the substrate model.

2.4 Thermal performance of the pit organ: total thermal conductance and thermal response time

From the FEA, two parameters of the pit organ, commonly used to indicate the thermal properties of the infrared detectors, were calculated: total thermal conductance of one unit and thermal response time.

The total thermal conductance of one unit is [21]

\[ G_{\text{total}} = \frac{Ah}{\Delta T}, \]  \hspace{1cm} (5)
where $A$ is the loaded area of one pit membrane unit, $h$ is the heat flux, and $\Delta T$ is the maximum temperature rise of the unit. To eliminate the temperature pre-rise effect caused by adjacent units, the temperature rise of loading only one centric unit was used when calculating $G_{\text{total}}$. The thermal conductance was 5 $\mu$W/K for the substrate-free model, and 8 $\mu$W/K for substrate model.

The thermal response time is

$$\tau = \frac{C}{G_{\text{total}}},$$

where $C$ is the heat capacity of the pit membrane unit. The calculated thermal response time was 5.04 ms for substrate-free model, and 3.15 ms for the substrate model. Thus pit vipers can respond quickly to movement of the target, which is consistent with the behavioral experiments.

2.5 Numerical simulation of the infrared imaging process of the substrate-free pit organ

Numerical simulations of the infrared imaging process of the pit organ were conducted by FEA. Rat and hand shaped heat flux loads were applied to substrate-free pit membranes of 80 $\times$ 80 and 160 $\times$ 160 units. Figure 7(a) shows the rat shaped heat flux distribution load applied on the outer surface of the pit membrane model, and the temperature distributions of the 80 $\times$ 80 units pit membrane and 160 $\times$ 160 units pit membrane are shown in Figs. 7(b) and 7(c), respectively. Figure 7(d) shows the hand shaped heat flux distribution load, and the temperature distributions of the 80 $\times$ 80 units pit membrane and 160 $\times$ 160 units pit membrane are shown in Figs. 7(e) and 7(f), respectively. The numerical simulations indicate that pit vipers can discern the broad outline of the infrared object rather than distinguish details. The outlines become clearer with increased pit membrane size and unit number.

![Fig. 7. FEA simulations of the infrared imaging process of the substrate-free pit organ. (a) Rat shaped heat flux load distribution. (b) Temperature distribution of the 80 $\times$ 80 unit membrane. (c) Temperature distribution of the 160 $\times$ 160 unit membrane. (d) Hand shaped heat flux load distribution. (e) Temperature distribution of the 80 $\times$ 80 unit membrane. (f) Temperature distribution of the 160 $\times$ 160 unit membrane.](image-url)
3. Bionic infrared imaging

3.1 Advantage of substrate-free FPA in vacuum condition

3.1.1 Substrate-free FPA

Infrared FPAs are fabricated by micro-electro mechanical system (MEMS) technology to achieve infrared imaging [22, 23]. Figures 8(a) and 8(b) show schematics of electronic readout [12] and optical readout substrate FPA units [13–15], respectively. In an electronic readout FPA, the infrared signal is converted into an electronic signal; whereas in optical readout FPAs, the infrared signal is converted into a light intensity signal. Since the gap between the FPA unit and the integrated circuit or substrate is only a few micrometers, infrared FPAs are usually packaged in a vacuum chamber to reduce energy loss via air thermal conduction. Inspired by the substrate-free structure of the pit organ, we introduced this substrate-free structure to the infrared detector chip, and designed a substrate-free FPA based on bi-material micro-cantilever without an integrated circuit [24, 25], and propose the optical readout method based on the knife-edge filter to achieve infrared imaging [26, 27].

The schematic of the proposed optical readout substrate-free FPA unit design is shown in Fig. 8(c), which is directly grown on the #-shaped silicon nitride (SiN_x) braced frame. Each unit includes a reflector plate (or an absorber plate), consisting of Au and SiN_x, thermal isolation beams (SiN_x) and thermal deformation beams (Au and SiN_x). SiN_x has good absorbability of 8-14 μm infrared radiation, and the stress control of bi-material beam of Au and SiN_x is relatively mature, thus SiN_x is widely used in the fabrication of optical readout infrared FPA [19, 24]. The unit pitch is 50 μm. Substrate-free FPA is fabricated by MEMS technology, see Fig. 8(d):

- c1: A double side polished Si wafer of 500 μm thickness.
- c2: A low stress SiN_x film of 0.5 μm in thickness is deposited on both sides by low pressure chemical vapor deposition (LPCVD).
c3: Inductively coupled plasma (ICP) etching is used to pattern a wet-etching window on the back side of the Si wafer.

c4: The ICP etching is used again to pattern the SiNx geometry on the front side.

c5: Lift-off technology is followed to form the two-fold interval gold-plating beams and the reflector. The thickness of the Au in the beams is 0.2\textmu{}m, and the thickness of the Au in the reflector is 25nm.

c6: The final step is the removal of the Si substrate using wet etching.

| Table 2. Material parameters of SiN\textsubscript{x} and Au |
|------------------|----------------|----------------|----------------|
| Material        | Young’s modulus\ (GPa) | Thermal Expansion coefficient \ (10\textsuperscript{-6}K\textsuperscript{-1}) | Thermal conductivity \ (Wm\textsuperscript{-1}K\textsuperscript{-1}) | Density \ (\times 10\textsuperscript{3}kgm\textsuperscript{-3}) | Specific Heat \ (Jkg\textsuperscript{-1}K\textsuperscript{-1}) | Emissivity |
| SiN\textsubscript{x} | 180            | 0.8            | 5.5             | 2.4             | 691            | 0.8 |
| Au              | 73             | 14.2           | 296             | 19.3            | 129            | 0.01 |

| Table 3. Dimensions of the FPA |
|------------------|----------------|----------------|----------------|
| Pixel size   | Absorber size | Au thickness (in the beams) | Au thickness (in the reflector) | SiN\textsubscript{x} thickness | Frame width | Leg size |
| \(50 \times 50\) | \(45 \times 21\) | 0.2            | 25             | 0.5             | 2            | 45 \times 1.5 |

In comparison with conventional optical readout FPA, the substrate-free FPA shows the several advantages: (1) without the Si substrate, nearly 100% of the incident IR energy reaches the micro-cantilever beam, whereas up to 50% of the incident IR energy is lost as the IR radiation transits the substrate for the conventional design [19]; (2) substrate-free FPA avoids sacrificial layer during release processes, which greatly decreases fabrication difficulty and provides easy adhesion between the micro-cantilever and substrate. The temperature rises of the FPA models were compared by FEA. The partial schematic of the FEA model is shown in Fig. 8(e). The parameters of Au and SiN\textsubscript{x} are listed in Table 2, and the dimensions of the FPA are shown in Table 3. The unit number of the FPA is \(81 \times 81\). The loads should be considered in numerical simulation as follows:

a. The thermal radiation of target object must be taken into account. To simplify the calculation, the thermal radiation is equivalent to heat flux \(h\). The heat flux \(h\) can be expressed as follows [19]:

\[
h = 0.63 \cdot \tau \cdot \varepsilon \cdot \frac{\pi}{4F^2} \cdot \Delta T
\]

Where \(\tau\) is the transmissivity of the infrared acquisition system set as 0.9, \(\varepsilon\) is the absorption factor of the absorber set as 0.8, and \(F\) is the F number of the infrared lens set as 0.7. When the heat flux is set as 10pW/\textmu{}m\textsuperscript{2}, the temperature change is about 13.8K which is close to the difference between the human body temperature and the ambient temperature, thus the heat flux is set as 10pW/\textmu{}m\textsuperscript{2} in the FEA process; b. The heat loss by thermal radiation from the FPA to the surrounding environment should be involved in the numerical calculation process;

c. To analysis the temperature advantage of the substrate-free FPA in vacuum condition, the model has no air units, thus the air thermal conduction and air thermal convection are neglected;

d. For the substrate-free FPA, the surrounding Si layer is about 500\textmu{}m thick and can be seen as a heat sink, thus the constant temperature load of 25 °C is applied on the border of the substrate-free FPA;
e. For the substrate FPA, the substrate is very thick and can be seen as a heat sink, thus the FPA unit is independent to each other [28, 29], and the constant temperature load of 25 °C is applied on the frame of each unit to approximate the substrate FPA which can greatly simplify the calculation.

3.1.2 Centric loading on the FPA

Heat flux loads (10 pW/μm², a typical value of heat flux received by FPAs) were applied on the absorbing surface of centric units of the two models. When the loaded area was a single unit, the maximum temperature rise of the substrate model was approximately 1.45 times (0.1718 K /0.1181 K) that of the substrate-free model (Figs. 9(a) and 9(b)). Thus the thermal isolation of the substrate-free structure is significantly superior to the substrate structure. When the loading area was increased to 3 × 3 units, the maximum temperature rise was equal to when applying loads on 1 × 1 unit for the substrate model (Figs. 9(a) and 9(c)), because the constant temperature load was applied on the frame of each unit, which makes them independent of each other. However, for the substrate-free model, the maximum temperature rise was approximately 2.25 times (0.3874 K /0.1718 K) that calculated by applying loads on 1 × 1 unit, due to the temperature pre-rise effect (Figs. 9(b) and 9(d)). Thus, the maximum temperature rise of the substrate-free model is approximately 3.28 times (0.3874 K /0.1181 K) that of the substrate model.

Numerical simulations are shown in Fig. 10. For the substrate FPA, the maximum temperature rise does not change, due to the units being independent of each other. For the substrate-free FPA, the maximum temperature rise increases with the number of loaded units.
due to the temperature pre-rise effect of the adjacent units. It reaches saturation approximately 13 times (1.6 K / 0.1181 K) that of the substrate model.

3.1.3 Periodic loading on the FPA

As the units of the substrate FPA are independent of each other, the contrast reconstruction ability of the substrate FPA is very good and MTF is 1. To analyze the infrared imaging contrast reconstruction ability of the substrate-free FPA, different periodic heat flux loads (10 pW/μm²) were applied on the absorbing surface (80 × 80 units), and the temperature distribution obtained by FEA, as shown in Figs. 11(a)–11(d).

Fig. 11. Temperature distribution calculated by FEA when periodic heat flux load was applied for the substrate-free FPA model. (a)–(d) Loaded spatial periods 40, 20, 10, and 2 units, MTF = 0.90, 0.55, 0.26, and 0.07, respectively.
Different periodic heat flux loads were applied to the substrate-free model to obtain the MTF for the loaded spatial frequency, see Fig. 12. As the spatial frequency increases, MTF for the substrate-free FPA decreases.

![Fig. 12. MTF changes with the loaded spatial frequency.](image)

### 3.1.4 Thermal performance parameters of the FPA: total thermal conductance and thermal response time

The total thermal conductance of one unit, $G_{total}$, and thermal response time, $\tau$, of the FPA were calculated using FEA. To eliminate the temperature pre-rise effect caused by adjacent units, the temperature rise of loading only centric one unit was used when calculating $G_{total}$: $G_{total} = 8.64 \times 10^{-8}$ W/K, and $1.26 \times 10^{-7}$ W/K, while $\tau = 22.7$ ms and $15.6$ ms for the substrate-free and substrate FPA models respectively.

### 3.2 Advantages of substrate-free structure in anti-vacuum condition

To analyse the advantage of substrate-free structure in anti-vacuum condition, the total thermal conductance $G_{total}$ of a FPA unit is firstly discussed. The total thermal conductance $G_{total}$ of a FPA unit is conveniently divided into three independent parts: radiation, supporting legs and air

$$G_{total} = G_{rad} + G_{leg} + G_{air}$$  \hspace{1cm} (8)

$G_{rad}$ is the radiation conductance of the unit, which is expressed as follows:

$$G_{rad} = 4\sigma(\varepsilon_{ab} + \varepsilon_{SiNx})A_{ab}T^3$$  \hspace{1cm} (9)

where $\sigma$ is Stephen Boltzmann constant ($5.67 \times 10^{-8}$Wm$^{-2}$K$^{-4}$), $\varepsilon$ is the emissivity of the material, $A_{ab}$ is the area of the absorber, and $T$ is the unit temperature (about 300 K in this paper), and the calculated $G_{rad}$ is $4.6 \times 10^{-9}$W K$^{-1}$.

The supporting legs’ thermal conductance can be expressed as [30]

$$G_{leg} = \frac{2L}{n} \left( \frac{1}{k_{SiNx}A_{SiNx} + k_{ab}A_{ab}} + \frac{1}{k_{SiNx}A_{SiNx}} \right)^{-1}$$  \hspace{1cm} (10)
where \( n \) is the multifold number (\( n = 2 \) in this paper), \( A \) is the cross-sectional area of the leg, \( k \) is the thermal conductivity of the leg material, and \( L \) is the leg length. The calculated \( G_{\text{leg}} \) is \( 8.78 \times 10^{-8} \text{W K}^{-1} \).

\( G_{\text{air}} \) is the sum of the thermal loss due to heat conduction \( G_{\text{cond}} \) and heat transfer due to heat convection \( G_{\text{conv}} \) through the surrounding air. To estimate the effect of air convection, the Rayleigh number of the air gap between the reflector and the wall of the vacuum chamber is calculated

\[
R_a = g \beta (T_c - T_{\text{sub}}) D^3 / \alpha 
\]

(11)

where \( g \) is the acceleration due to gravity, \( T_c \) is the cantilever temperature, \( T_{\text{sub}} \) is the temperature of the wall of the vacuum chamber, \( \beta = 1/T_c \), \( D \) is set as 2 mm which is the gap distance between the reflector and the wall of vacuum chamber, \( \alpha \) is the thermal diffusivity of the air, set as \( 22.5 \times 10^{-6} \text{m}^2\text{s}^{-1} \), and \( \nu \) is the viscosity of the air, set as \( 15.89 \times 10^{-6} \text{m}^2\text{s}^{-1} \). Assuming the temperature difference between the cantilever and the wall of vacuum chamber \( T_c - T_{\text{sub}} = 1 \text{K} \), the calculated \( R_a \) is 0.73, which is much smaller than the critical value \( R_{ac} = 1708 \) for natural convection to occur. Thus, the influence of \( G_{\text{conv}} \) can be neglected and \( G_{\text{air}} \) can be expressed as

\[
G_{\text{air}} = G_{\text{cond}} = k_{\text{air}} A_{\text{sub}} / d 
\]

(12)

where \( k_{\text{air}} \) is the thermal conductivity of the air. For the substrate FPA, \( d \) is the distance (about 2 \( \mu \text{m} \)) of the air gap between the biomaterial cantilever membrane and the substrate, but for the substrate-free FPA, \( d \) is the distance (about 2 mm) between the membrane and the wall of vacuum chamber in which the substrate-free FPA is located. As the temperatures of the frames, legs and absorbers (reflectors) tend to equilibrium, the effect of the temperature gradient of the air gaps between the frames and the absorbers or the legs and the absorbers can be ignored compared with the influence of the \( G_{\text{cond}} \) (\( d = 2 \text{ mm} \)). Thus, the heat exchange by air gaps between them can be ignored.

Normally \( k_{\text{air}} \) can be expressed as [31]

\[
k_{\text{air}} = n_0 v_0 c_{\text{air}} l / 3
\]

(13)

where \( n_0 \) is the number of air molecules per unit volume, \( v_0 \) is the average speed of the air molecules, \( c_{\text{air}} \) is the heat capacity of the air molecule, and \( l \) is the mean free path of the molecules, which is defined as the average path length traveled before collisions occur between either the molecules themselves or between the molecules and the container walls. In the Kinetics theory [31], \( n_0 \propto P, l \propto P^{-1} \) (\( P \) is the air pressure in vacuum chamber), and \( v_0 = v_0 (T) \), so \( k_{\text{air}} \) exhibits no pressure dependence. However, for the case of molecules moving in the narrow space \( d \), \( l \) is influenced by the pressure and the \( d \) both. A model describing the pressure dependence of \( k_{\text{air}} \) can be expressed as [32]

\[
1 / k_{\text{air}} = 1 / k_{\text{hp}} + 1 / \gamma_{\text{lp}} P d
\]

(14)

where \( k_{\text{hp}} \) is a pressure-independent thermal conductivity (0.0263 W K\(^{-1}\) m\(^{-1}\)), and \( \gamma_{\text{lp}} \) is the thermal conductivity per unit pressure and length which acts as a correcting part for the case of the mean-free path larger than \( d \). The value of \( \gamma_{\text{lp}} \) is 1.799 m s\(^{-1}\) K\(^{-1}\). With this expression used in Eq. (12), \( G_{\text{air}} \) can be expressed as two thermal conductances in series according to
\[
\frac{1}{G_{\text{air}}} = \frac{d}{k_{\text{hp}a}A_{\text{hp}}} + \frac{1}{\gamma_{\text{lp}}PA_{\text{lp}}}
\]  
(15)

Since the heat transmission depends on the collisions, when \(l \ll d\) in the high-pressure regime, the collisions mostly occur between the molecules themselves, the heat transmission is mainly accomplished by the molecule-molecule collisions, so the second part on the right of Eq. (15) can be neglected, and \(1/G_{\text{air}} = d/k_{\text{hp}a}A_{\text{hp}}\). \(G_{\text{air}}\) remains almost constant. As the pressure \(P\) gets lower, the \(l\) is larger, and when the \(l \geq d\), the second part on the right of Eq. (15) can’t be neglected, and \(G_{\text{air}}\) changes with the pressure \(P\). At high vacuum, \(l\) is much longer than \(d\), so the first part can be neglected, \(G_{\text{air}} = \gamma_{\text{lp}}PA_{\text{lp}}\).

Thus, when the FPA is located in the vacuum condition, the \(G_{\text{total}}\) is the sum of the \(G_{\text{rad}}\) and \(G_{\text{leg}}\), and the value is \(9.24 \times 10^{-8}\) W K\(^{-1}\), which is closely to the value calculated by the FEA method. The curves of the \(G_{\text{total}}\) with pressure \(P\) are shown in Fig. 13.

![Fig. 13. Total thermal conductance, \(G_{\text{total}}\), response to air pressure. (a) Black line = substrate-free FPA (\(d = 2\) mm), red line = substrate FPA (\(d = 2\) \(\mu\)m). (b) Amplification of the black line in (a).](image)

The curves for total thermal conductance, see Fig. 13, have similar shape, but substrate-free FPA is quite low (~\(10^{-7}\) W K\(^{-1}\)). Substrate FPA increases quickly when the pressure is above 1 Pa, and reaches approximately \(10^{-5}\) W K\(^{-1}\) at ordinary pressure. As temperature rise is inversely proportional to \(G_{\text{total}}\), the temperature rise of the substrate FPA unit in atmosphere is only one percent of that in the vacuum. Thus, infrared imaging is hard to achieve using substrate FPA in atmosphere.
3.3 Infrared imaging based on the substrate-free FPAs

Substrate-free FPA was fabricated by MEMS, and the experimental light path is shown in Fig. 14. The inserted figures in the top right of Fig. 14 are substrate-free FPA images of different amplification factors recorded by Keyence microscope. The FPA was placed in a vacuum chamber to eliminate air thermal conduction. A schematic of the vacuum chamber is shown as the insert in the lower left of Fig. 14. One side of the vacuum chamber is a germanium glass plate which transmits infrared rays, and the other side is a transparent glass observation window which transmits visible light. The infrared radiation of the object transmits the infrared lens and irradiates the FPA, which causes temperature rise of the thermal deformation beams. As the thermal expansion coefficients of the two materials (Au and SiNx) are different, the bi-material deformation beams bend. Simultaneously, LED light irradiates the FPA gold reflector plate on the side opposite the incident IR radiation, see Fig. 14, and the reflected light is received by a CCD camera after knife-edge filtering. When the infrared light irradiates the FPA, the FPA gold reflector plate deflects. The deflection reduces the LED light intensity received by the CCD, thus optical readout infrared imaging is achieved.

A 160 × 160 substrate-free FPA of 120 μm pitch was fabricated [33], and the hand infrared image was obtained with the FPA under atmosphere conditions, see Fig. 15(a). Following that, a 240 × 240 substrate-free FPA of 50 μm unit pitch was fabricated, and infrared images were obtained under vacuum conditions. Figure 15(b)-15(d) are the hand, watch on the wrist, and face infrared images obtained by the substrate-free FPA under vacuum conditions, respectively. The spectrum range of recorded objects is about 8-14 μm.
4. Discussions

Pit vipers can achieve infrared detection in atmosphere conditions. The pit membrane is hemispheric, and so the pit membrane has a wide infrared detection perspective. The thermal image position in the pit membrane helps the pit vipers to locate the thermal source position. If the thermal source is large enough, hot enough, or near enough, the temperature rise of the pit membrane is sufficient (0.003 °C) for the pit vipers to detect. In the conditions from Section 2, if the pit membrane is directly grown on the biological tissue (substrate structure), the maximum temperature rise would be only 0.0007 °C, significantly less than the detection limit, thus the pit vipers could not detect the thermal image of predators or prey. Thermal isolation and temperature pre-rise effects help the substrate-free structure to have larger temperature rise. Pit vipers can detect the thermal source if the loaded area is larger than twenty units when the heat flux is 5 pW/μm² (temperature rise exceeds 0.003 °C). The substrate-free structure has higher temperature rise, and the response time is in millisecond level, thus the pit vipers can sensitively detect predators and prey, which is beneficial for the vipers to survive in the fierce competition.

When the FPAs were placed in vacuum conditions, both of substrate-free and substrate FPA can achieve infrared imaging, but the temperature rise of the substrate-free FPA reaches approximately 13 times of that of substrate FPA. When the FPAs are placed in atmosphere conditions, the total thermal conductance of the substrate FPA is approximately 100 times that of the vacuum condition, and the temperature rise is hard to detect. However, the total thermal conductance of the substrate-free FPA is low at all air pressures, so the thermal response is large enough for detection. Thus infrared imaging is realized by the substrate-free FPA in atmosphere conditions. The designed substrate-free FPA can be used in practical applications, and the fabrication difficulty, cost and scrap rate will be greatly decreased.

5. Conclusion

Conventional artificial uncooled FPAs are usually placed in vacuum conditions to eliminate heat losses due to air conduction. This greatly increases fabrication cost and miniaturization difficulty. However, pit vipers can achieve infrared detection in atmosphere conditions. To
learn from the pit vipers, the pit organ was dissected and a substrate-free structure observed. The temperature rise advantage of such a substrate-free structure was verified by FEA, and the significance of the substrate-free structure revealed. Sensitive detection of predators and prey by this unique substrate-free structure helps pit vipers survive in the fierce competition.

Inspired by the pit vipers, we designed and fabricated substrate-free optical readout FPAs in contrast to conventional substrate FPA. The temperature rise advantages of substrate-free FPA in the vacuum and atmosphere conditions were verified by FEA and numerical calculation. High quality infrared images were successfully obtained using the substrate-free FPA in vacuum and atmosphere conditions. The dependence on vacuum equipment was decreased, and substrate-free FPAs will be of great significance in promoting the development of infrared cameras.

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