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Thermo-pneumatic micro-optics

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Abstract: We discuss the development of thermo-pneumatic micro-optics and illustrate this progress using examples from our own research as well as recent literature. Pneumatic actuation is used for tuning micro-fluidics based optics, including micromirrors and membrane microlenses, which rely on pressure applied to liquids or liquid/gas interfaces for operation. Thermo-pneumatic actuation uses on-chip temperature changes to generate the requisite pressure differences. We discuss the variety of devices, structures, liquids and membrane materials used for these micro-optical structures and provide typical operating characteristics.

Key words: tunable micro-lens; thermo-pneumatic actuator; micro-optics

热驱动微光学

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摘要:通过实例研究和近期报道的文献,论述了热驱动微光学的研究进展。驱动器主要通过应用在液体和液气界面的压力来调控光学微流体,包括微镜片和薄膜微透镜,热驱动器利用芯片上的温度变化产生所需要的压力差,从而对微透镜进行调控。同时还讨论了用于微光学结构的各种设备、结构、液体和膜材料,并提供了典型操作特性。

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1 Introduction

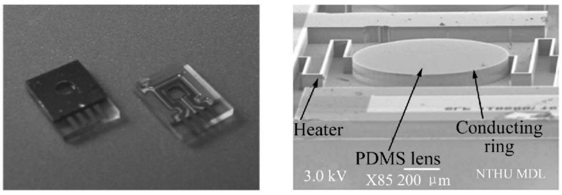
Tunable membrane-based liquid microlenses are employed in a wide range of applications, including optical communications, consumer electronics, and medical engineering. These lenses have been the subject of research in both micro-fluidics and micro-optics. Compared with glass lenses made of solid glass or plastic with a fixed shape, liquid micro-lenses are easily tuned to vary the focusing power without requiring mechanically moving parts[1-2].

Pneumatic actuation is the most frequently used actuation mechanism for membrane microlenses[3-5]. The pressure is often generated by bulky and expensive external pressure controllers which make lens system integration impracticable. Therefore, to realize more compact and more flexible systems, various novel on-chip actuation mechanisms, such as piezoelectric[6], electrostatic[7], and magnetic[8] have been considered. These devices usually have a complex structure and fabrication technology, such that they are frequently expensive, with limited performance and large size, as well as requiring complex manufacturing techniques.

In this review, we consider micromirrors and microlenses that use thermo-pneumatic means for actuation. The advantages of thermo-pneumatic actuation include a simplified micro-lens design, the generation of high forces through thermo-pneumatic pressure, the reduction in driving voltage, and easy fabrication using soft lithography micromachining processes. This review will begin with an overview of the various thermo-pneumatically actuated devices demonstrated to date, and we subsequently discuss the liquids and membrane materials employed in these systems and conclude with a look at typical operating characteristics of tunable micro-lenses.

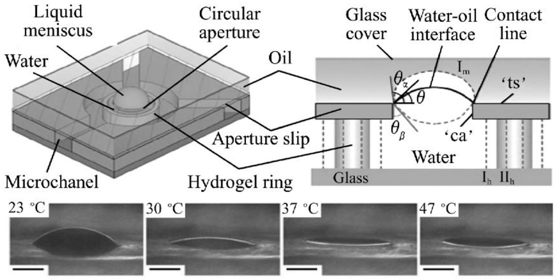
2 Thermal tuning of micro-lenses

A variety of micro-lenses which can be tuned using thermal means has been presented in the literature. The curvature change of a tunable membrane lens surface results from a change in the pressure applied to it, which can in turn be induced by thermal expansion of the medium (gas or liquid) inside the lens cavity. A thermally tunable micro-lens based on optical liquid expansion has been reported[9]. Fig. 1 (a) shows this device: a Pyrex glass plate with heater and sensor structures is bonded onto a silicon chip, and the silicon chip has a fluid chamber on its back side. A polydimethylsiloxane (PDMS) membrane is suspended on the silicon chip, forming the lens surface and a liquid (3M PF 5080) with high thermal expansion coefficient is filled into the lens



(a) Microlens based on themal expansion of the optical liquid; the chip size in the picture is 8.5×6.5×1.5 mm^3[9](Images reprinted with permission from IOP science)

(b) Microlens based on expansion of PDMS; shown are typical fabricated devices after PDMS dispensing[12]



(c) Tunable liquid lens based on hydrogel swelling[11]

Fig. 1 A selection of thermally tunable micro-lenses chamber. After applying a voltage to the micro-heater, the liquid expands and deforms the lens membrane. This micro-lens can easily be embedded into a microsystem or a conventional optical system with the benefits of low cost, a small package, and a relatively low driving voltage (maximum 14 V). The major disadvantage of this design is that the heater is located in the lens cavity itself and thus heats the optical liquid directly. Thus, the lens optical performance is degraded due to a thermally-induced inhomogeneous refractive index distribution and the resulting thermal gradient in the optical liquid.

Alternatively, a tunable solid PDMS lens, based on the mismatch of coefficients of thermal expansion and stiffness of PDMS and silicon, has also been demonstrated[10,12]. Fig. 1 (b) shows SEM photos of this lens, which consists of a silicon heater, a conduction ring, and a solid PDMS lens. The heat is conducted to the micro-lens by the conduction ring, and the PDMS lens expands due to the high temperature. The shape of the PDMS is confined by the conducting silicone ring on the edge, such that expansion results in a change in the radius of curvature and thus the focal length. Compared with liquid microlenses, the solid polymer lens offers a more robust approach and can more readily withstand fluctuations of temperature, pressure, and motion[13]. Nevertheless, to achieve sufficient change of lens curvature, due to the small volume expansion of the solid material, a high temperature (up to 350 ℃) and a large power consumption are required. The tuning range of focal length is thus limited.

A temperature-sensitive hydrogel also has potential for fabrication of a thermal actuator for microlenses[11]. Fig. 1 (c) shows the lens structure shaped by an interface between water and oil. Before exposing the lens to a temperature stimulus, the oil/water contact line is stably pinned on a circular aperture. When a temperature stimulus is applied to the lens, the hydrogel ring underneath the aperture expands at a lower temperature or shrinks at a higher temperature. The expansion or shrinkage of the hydrogel absorbs or releases the water through the hydrogel's network interstices. This effect results in a volume change of the water in the aperture and thus tunes the focal length. The hydrogel lens has a slow response time (20 – 30 s), due to low thermal diffusion and water penetration into the hydrogel material. When a fast tuning system is needed, it is possible to make a thinner and smaller hydrogel actuator. However, the system will likely be too fragile for practical use.

3 Thermo-pneumatic actuation for micro-optics

Thermo-pneumatic actuation is based on deflection of a flexible diaphragm resulting from heating a gas inside a sealed cavity. This actuation approach is widely employed in a large range of applications, including micro-fluidics[14], micro-mirrors, and micro-lenses. The thermodynamic relation among the absolute temperature T, the pressure p and the volume V of the lens system is given by the well-known ideal gas equation:

$$pV = nRT , \qquad (1)$$

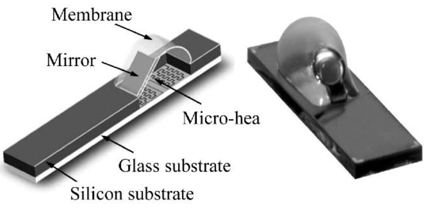
where R is the gas constant, and n is the number of gas molecules in moles enclosed in the thermal cavities. Therefore, in the sealed cavity,

$$\frac{p_0 V_0}{T_0} = \frac{p_1 V_1}{T_1} , \qquad (2)$$

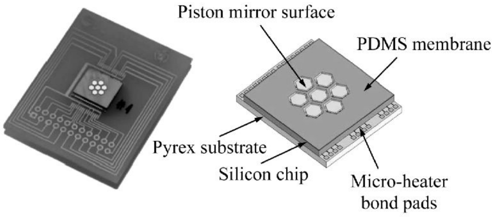
where V_1 is the volume and p_1 is the pressure at a set temperature T_1, whereas V_0 and p_0 are the volume and pressure at a starting temperature T_0. As the temperature of the enclosed gas increases, the air volume expands, and the pressure in the sealed chamber increases to deform the flexible lens membrane.

3.1 Thermo-pneumatic micro-mirrors

Thermo-pneumatic actuators were first employed to fabricate tunable micro-mirrors in 2008[15]. Typical examples are depicted in Fig. 2. The mirror devices are based on a PDMS membrane, which is spanned over a silicon cavity. A silicon cantilever, which forms the movable mirror, remains on top of this cavity. A glass substrate is bonded to the back side of the silicon substrate and a micro-heater, which is evaporated on the glass substrate, heats the enclosed air in the cavity. The corresponding temperature is monitored by a thermistor made from the same material. In addition, a piston mirror array was fabricated using the same technology. The structure, shown in Fig. 2(b), consists of seven hexagonally-shaped single mirror elements, which may move vertically. The micro-heaters heat each mirror cavity individually allowing separate temperature and thus mirror control.



(a) A tilting mirror



(b) A piston mirror array, showing an assembled chip[15]

Fig. 2 Thermo-pneumatically tunable micromirrors (Images reprinted with permission from IOP science)

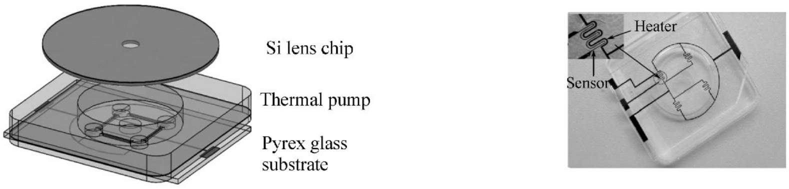
Since the membrane material used (PDMS) is gas permeable, the pressure in the cavities due to high temperature decreases with time, even for constant actuation. To reduce gas permeability, 0.7 μm parylene as a gas diffusion barrier layer was deposited on the surface of the PDMS membrane using a CVD coating process, since Parylene exhibits a low gas permeability with a good adhesion to PDMS.

3.2 Thermo-pneumatic micro-lenses

Compared to the thermally tunable microlens concepts discussed in Section 2, thermopneumatic actuation can overcome many of the concomitant disadvantages, such as the heating of the optical, the high liquid evaporation rate, and the inhomogeneous temperature distribution. Thermo-pneumatic actuation can provide uniform heating to the optical liquid while also allowing maintenance of a stable focal point during the heating or cooling process due to the low thermal conductivity coefficient of air ($0.025\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$).

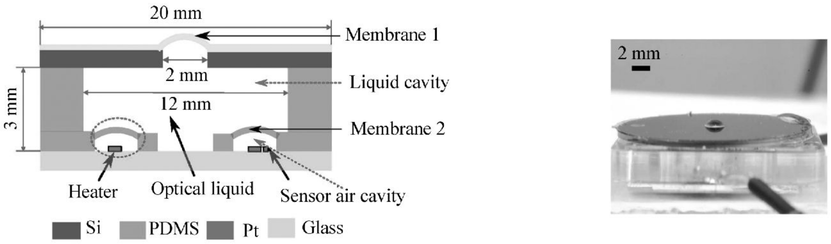
The first design of a thermo-pneumatically actuated micro-lens appeared in 2011, and employed a "thermal micro-pump"[16]. As shown in Fig. 3(a), the micro-lens is composed of three layers: a silicon lens chip, a PDMS structure with thermal micro-pumps, and a glass substrate which carries heater and sensor structures. Oxygen plasma treatments were applied to bond the different parts together, to yield a sealed optical liquid cavity and an air-filled thermal micro-pump. A highly elastic PDMS membrane, which is spanned over a silicon lens cavity, forms a refractive lens surface.

When a voltage is applied to the Pt heaters in the air-filled cavities (the thermal micropumps), Joule heating causes the temperature of the air inside these chambers to increase, and consequently the air volume increases. As sketched schematically in Fig. 3(b), the air pump membranes (membrane 2) are thus deformed and increase the pressure on the fluid in the optical chamber. The pressure change causes a deformation of the lens PDMS membrane (membrane 1), thus changing the refractive power of the lens. Fig. 3(c) shows the heater chip, showing the meander shaped heater (thick line) and sensor (slim line) structures. Fig. 3(d) shows the completed integrated lens structure. The curve of the distended PDMS membrane, forming the refractive surface, can be seen on the top of the silicon chip.



(a) 3D schematic view

(b) Cross-sectional view of the device with dimensions



(c) Photograph of a glass heater chip with evaported Pt heater and sensor structures

(d) Photograph showing the silicon chip, the PDMS layer, and the glass heater chip, assembled to form a complete device by O_2 plasma bonding[16]

Fig. 3 A micro-lens actuated using a thermal micro-pump (Images reprinted with permission from the Optical Society of American (OSA))

A second design for a thermo-pneumatic micro-lens was developed in 2012[17]. It features operation requiring neither a micro-pump nor any other mechanically moving parts. Instead, as shown in Fig. 4, the tunability of this so-called "channel lens" is achieved by increasing the pressure in a separated air chamber where the heater is located, such that the expanding air advances an air/liquid meniscus towards the lens chamber, thereby increasing the pressure in the lens chamber and thus deforming the lens membrane.

Fig. 5 (a) presents the such a fully integrated

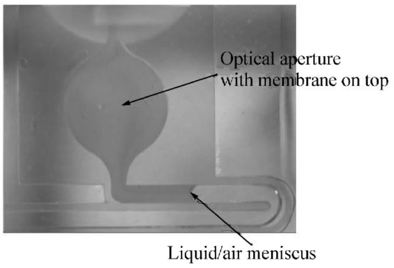


Fig. 4 Operating principle of the channel micro-lens: a thermo-pneumatically-induced pressure increase in a separate actuation chamber (not visible, below the bottom of the photo) moves a liquid/air meniscus toward the lens chamber, increasing the pressure and thus tuning the lens

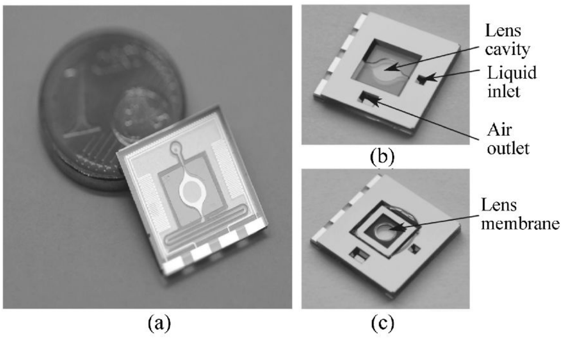


Fig. 5 Channel micro-lens: (a) back side of the lens, showing the micro-fluidic structures including the meandering channel in which the air/liquid meniscus propagates (12 mm × 12 mm × 1.22 mm); (b) diced lens frame; in the large openings of the lens frames, the blue dry film resist marge are later attached with the polyacrylate membrane in-between; (c) fully integrated lens device; the membrane is sandwiched between the rectangular silicon frame and the silicon lens chip

micro-lens with chip size of 12 mm × 12 mm × 1.2 mm, consisting of a silicon lens frame, a silicon lens chip with 2 mm aperture, a polyacrylate lens membrane, a microfluidic network, and a glass substrate with heater and sensor structures.

As shown in Fig. 5(b), three square cavities are used for introducing the optical liquid into the lens chamber, removing the displaced air, and clamping the silicon lens chip, respectively. A dry film resist(DFR) frame is used to attach the polyacrylate lens membrane. In Fig. 5(c), a thin polyacrylate membrane, which is sandwiched between the silicon lens chip and the DFR frame, forms the refractive lens surface.

In comparison to the optical micro-pump design, the channel micro-lens structure offers several advantages: the devices are fabricated by standard batch processes on wafer-lever; the micro-lens can be controlled very accurately due to the microfluidic channels; the trapped air and micro-channel structures greatly improve the thermal isolation and minimize the thermal cross-talk; the delamination of the lens membrane from the silicon substrate is prevented due to the novel sandwich structure; and a stable and long-term operation is realized using silicone oil with low vapor pressure.

4 Materials for micro-lenses

Two essential materials, not conventionally used in classical optics, are required for the realization of thermo-pneumatically tunable microlenses: distensible membranes and optical liquids. We discuss these in details, as the characteristics of these materials have a strong influence on the performance of the lenses.

4.1 Optical liquids

The design of thermo-pneumatic tunable micro-lenses is restricted by available optical liquids with which the microfluidic optical chamber is filled. In addition to suitable optical properties, primarily dispersion and refractive index, other characteristics also have to be considered for successful application to micro-lenses, including chemical compatibility(with the membrane), low vapor pressure, low temperature coefficient of refractive index, low kinematic viscosity, and low surface tension.

Water is widely used as an optical liquid for PDMS membrane lenses, primarily because of the chemical compatibility with the PDMS membrane material. However, the high vapor pressure of water results in air bubbles being produced in the lens cavities. In addition, the PDMS membranes are water permeable. For a completely integrated system, the liquid loss through the membrane can not be compensated for by injecting fresh liquid, so that this effect makes long-term applications impractical. We list some common optical liquids and thier properties in Tab. 1.

Tab. 1 Properties of optical liquids compatible with PDMS membrane lens at 25 ℃, 100 kPa

Liquid	n	μ	ρ	σ	P	Membrane
DI-water	1.33	0.89	997	73	24	PDMS
Isopropanol	1.33	1.96	786	23	40	PDMS
Glycerol	1.47	1 069	1 261	63.4	1	PDMS
Immersol W2010	1.33	1 600	1 678	NA	NA	PDMS
Immersol oil type DF	1.55	150	0.923	NA	<5	PDMS
FC 72	1.25	0.8	1 680	NA	232	PDMS
Silicone oil	1.38 - 1.41	0.494 - 976	760 - 976	16 - 22	<5	SiO_2

n: refractive index, μ: dynamic viscosity(mPa · S), ρ: density(kg/m^3), σ: surfacetension(mN/m), P: vapor pressure (mmHg, 25 ℃)[18-19].

4.2 PDMS membrane

PDMS is a very popular material for the distensible micro-lens membrane, which is made of two-part liquid component kits incorporating silicone oil and cross linked elastomers. The two kits are mixed with a ratio of 10∶1 and cured afterwards at a typical temperature of 60 – 120 ℃. Starting in about 2003, PDMS has been the most popular material for tunable lenses, primarily because PDMS has a high optical transmittance (≥92%), and a high elasticity. Its Young's modulus is between 1 and 10 MPa, only 1/250 times of SiO_2. PDMS is compatible with MEMS technology, and is easily bonded onto silicon or glass substrates using oxygen plasma treatment. Therefore, miniaturized lens systems with high numerical aperture have been obtained by combining PDMS and MEMS technologies.

However, PDMS has numerous shortcomings which have become clear as micro-lens structures advance. It is well-known that water, oxygen, and carbon dioxide molecules can freely diffuse through the PDMS membrane, and gas diffusion behavior was investigated by Merkel *et al.*[20]. The highest permeability is for CO_2 with 3 800 Barrer at 35 ℃, followed by H_2(890 Barrer), O_2(800 Barrer), and N_2(400 Barrer).

The permeability of PDMS is an advantage for some applications in microfluidics, such as gas separation[21], and drug delivery[22]. However, this effect degrades the stability of PDMS based fluidic micro-lenses and will hinder most commercial applications of membrane lenses using this material. In addition, PDMS does not have good solvent resistance such that its use is limited to water-based chemistries. Finally, the hydrophobicity of PDMS also makes fluidic lens systems difficult to fill with the optical fluids, especially for high surface tension liquids such as water.

4.3 Polyacrylate membranes

As we can see in Tab. 1, silicone oil offers some advantages as an optical liquid, including high refractive index, low vapor pressure and low viscosity. However, due to its low vapor pressure, it is not compatible with PDMS since it causes that material to swell. An alternative membrane material, compatible with silicone oil, is polyacrylate[23].

The commercially available polyacrylate 3M™ VHB™ 4905 is sold as a solid polymer with a removable Polyethylene(PE) liner backing. These polyacrylate elastomers have been widely used in electroactive polymer actuators, where large deformations are required[24] but we have shown that it is very attractive as a tunable lens membrane material. Polyacrylate has some useful properties, including high transparency in the visible range(≥90%), high elasticity and reversible elongation, strong adhesion on Si or glass substrates, good chemical compatibility with optical liquids, and low permeability for gases and liquids.

Most importantly for fluidic microlenses, polyacrylate does not swell in silicone oil. Fig. 6 compares the swelling behavior of polyacrylate and PDMS after being in contact with silicone oil for 1 h. The polyacrylate membrane exhibits no visible swelling whereas the PDMS membrane clearly swells in silicone oil since the small molecules are absorbed in the porous structure of the PDMS polymer. As a result, PDMS membrane lenses using silicone oil as

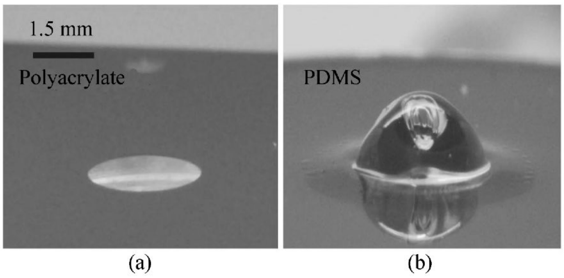
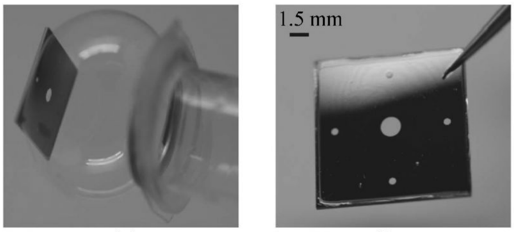


Fig. 6 (a) Polyacrylate membrane showing no visible swelling after immersion in silicone oil for 1 h. (b) PDMS membrane exhibiting strong swelling under the same conditions[23] the optical liquid quickly become non-functional. The swelling also leads to delamination of the membrane from the substrate, typically glass or silicon.

To generate a thin polyacrylate membrane with a radially symmetric prestress distribution, the commercial membrane tape is stretched by essentially generating a bubble. As shown in Fig. 7, a piece of polyacrylate tape is first fixed to the end of a tube. A pressure is applied to the tube which inflates a bubble, and this bubble is pressed onto a silicon substrate, on which it sticks due to the naturally tacky nature of the polymer. After a few seconds, the bubble may be cut away around the edge of the silicon chip, leaving the stretched membrane on the silicon surface.



(a) (b)

Fig. 7 (a) Photo of the inflated polyacrylate membrane attached to a Si substrate. (b) The cut polyacrylate membrane suspended on the silicon substrate; an optical aperture is seen at the center[23]

5 Characterization

The optical characterization of thermo-pneumatically actuated tunable micro-lenses is much the same as for fixed-focus micro-lenses. Fig. 3 shows the structure of tested thermo-pneumatic micro-lenses, with a clear aperture diameter of 2 mm, of the type which has been characterized in this paper[16]. This micro-lens consists of a transparent substrate (BK7 glass) integrated heater and sensor structures, a PDMS thermo-pumps and lens cavity, a structured silicon chip and a PDMS membrane which forms an aspherical convex lens surface. Applying different voltages, the curvature of the PDMS membrane will change due to the air expansion of thermo-pumps, resulting in different focal lengths.

To demonstrate the level of performance achievable, we briefly consider two optical characteristics, back focal length (BFL) and modulation transfer functions (MTF), for these tunable devices. The MTF is calculated from measurement of the two-dimensional intensity distribution of the PSF image generated by the lens[25].

Fig. 8 shows the focal length tuning over a wide range, from 3 to 15 mm, with a total power consumption(≤200 mW), using low drive voltages(≤

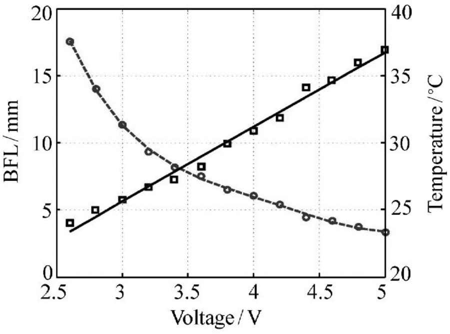


Fig. 8 Measured BFL and corresponding temperatures as a function of the applied voltage using the optical liquid FC40[16] (Images reprinted with permission from OSA)

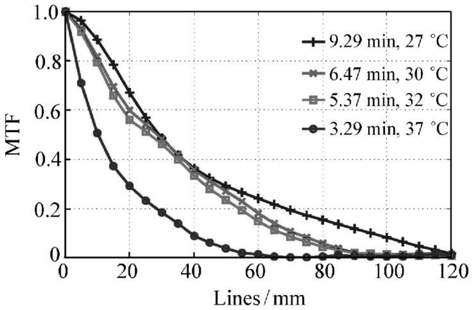


Fig. 9 Measured MTF curves of the thermo-pneumatically actuated lens at different temperature values and hence back focal lengths. The back focal lengths for a given temperature are determined from Fig. 8 [16] (Images reprinted with permission from OSA)

5 V). The required temperature change for actuation thus ranged from 27 ℃ to 37 ℃ (at a room temperature of approximately 20 ℃). In the MTF measurement, shown in Fig. 9, it is seen that the measured cut-off frequency varied from 30 to 65 lines/mm over the complete tuning range, corresponding to a change in numerical aperture from 0.067 to 0.333.

6 Conclusion and outlook

We have reviewed the state of research into thermo-pneumatically actuated micro-lenses. Major advantages of thermo-pneumatic actuation are that on-chip regulation of the pressure is possible and that all components (lens, actuator, temperature sensor) may be integrated in a single microsystem. Such a compact integrated system is particularly relevant for endoscopy or for adaptive optical systems used for wavefront correction.

The technology described here would also allow the fabrication of integrated micro-lens arrays. Thermo-pneumatic actuation with low drive voltages has not been reported for micro-lens arrays, since the actuation requires an optical liquid with stable properties at high temperatures. We have shown here how the use of silicone oil and polyacrylate membranes is a promising route for the fabrication of tunable thermo-pneumatically actuated micro-lens arrays.

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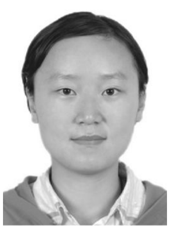

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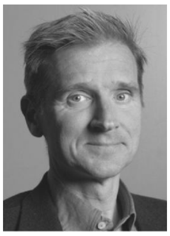

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