Diffraction Grating Based Optical Readout for Thermal Imaging

Ulas Adiyana^a, R.Burak Erarslan^a, Onur Ferhanoglu^b, Hamdi Torun^c, Hakan Urey^a
^aKoç University, Dept. of Electrical Engineering, Istanbul, Turkey; ^bUniversity of Texas at Austin, Dept. of Mechanical Engineering, Texas, USA ; ^cBogazici University, Dept. of Electrical Engineering, Istanbul, Turkey

Email: hurey@ku.edu.tr

ABSTRACT

The thermal sensor system presented in this paper is based on the mechanical bending due to the incident IR radiation. A diffraction grating is embedded under each pixel to facilitate optical readout. Typically the first diffraction order is used to monitor the sub-micron mechanical displacement with sub-nanometer precision. In this work; two different optical readout systems based on diffraction gratings are analyzed.

First setup employs a conventional 4f optical system. In this one-to-one imaging system, collimated light is propagated through a lens, filtered with an aperture and then imaged onto a CCD by a second lens.

Second system is more compact to improve image quality and to reduce noise. This is achieved by using an off-axis converging laser beam illumination that forms the Fourier plane near the imaging lens. This approach has important advantages such as reducing number of optical components and minimizing the optical path. The system was optimized considering parameters such as laser converging angle, laser beam size at MEMS chip, and magnification of the imaging system.

Keywords: Thermo-mechanical detectors, diffraction grating, 4f optical system, converging beam optical system

1. INTRODUCTION

Thermal detectors are used for thermal mapping of the environment for numerous defense, security, medical and industrial applications. The thermo-mechanical detector presented in this paper measures the temperature change of the device by measuring the mechanical bending.

Figure 1. (a) Side-view of an IR pixel illustrating grating readout (b) Intensity of light going to diffraction orders as a function of the distance from the membranes to the diffraction gratings (Assuming an initial gap (g_0), $\pm\lambda/8$ movements to achieve maximum and minimum target temperatures)

The incident IR radiation emitted from a target leads to a mechanical bending that changes the position of the reflector on a micromachined device which is read using a laser-based optical interferometer. Detector readout is performed from the backside of a transparent substrate with a light source illumination. In Figure 1.a side view of an IR pixel with grating readout is illustrated where a diffraction-grating interferometer is formed under each detector pixel to facilitate optical readout by illuminating with a coherent light source. Since diffraction grating is an interferometric method for optical readout, the sinusoidal behavior of the diffracted orders can be seen in the plot given in Figure 1.b related to normalized intensities of 0th and 1st diffraction orders as a function of normalized gap. Typically the first diffraction order is used to monitor the sub-micron mechanical displacement with sub-nanometer precision. Since the diffracted order intensities has a period of $\lambda/2$, the displacement can be detected within half the period, or when the sensor bends $\pm\lambda/8$ to each side, as illustrated in Figure 1.b. Uncooled thermo-mechanical detectors incorporating optical readout into MEMS structures promise high performance at low cost [1, 2]. We present converging beam illumination method for the optical readout and compare the method with a conventional 4-f imaging setup with a special emphasis on size and compactness of the optical readout systems.

2. MEMS THERMO-MECHANICAL IR SENSOR

The thermal detector array comprises micromachined membranes anchored to a substrate via bimaterial and isolation legs. Each membrane is identical and forms a pixel in the array. Bimaterial legs are made of materials with large mismatch in coefficients of thermal expansion (CTE) to induce mechanical deflection when exposed to temperature difference. We design the devices using standard IC materials. Silicon nitride is a good absorber in far infrared band [3] and is used as the structural material. In combination with nitride, aluminum forms a good thermal mismatch pair. Free-standing structures can be fabricated using nitride and aluminum with thicknesses of a few tens of nanometers that result in large displacements [3]. Figure 2.a shows a FEM model for one of our designs. This design has both two end fixed and it makes a piston motion parallel to the substrate.

(a)

(b)

Figure 2. (a) FEM result of thermo-mechanical deflection for the selected geometry (b) Fabricated MEMS Array for the selected geometry

The design shown in Figure 2.a has 35 μm total pixel size, with thicknesses of 150 nm aluminum and 150 nm silicon nitride as bimaterial layer with a length of 15 μm . According to the FEM result of thermo-mechanical model of the selected geometry, for 1 $^{\circ}\text{C}$ temperature change in the absorber results in 55 nm deflection in the body of the sensor. Fabrication of Si_3N_4 / Al thermal imaging sensor array at 35 μm pixel size was carried out at Middle East Technical University, MEMS Research and Application Center (METU-MEMS). The array format for the selected geometry is 320x240 and a part of a 320x240 array's SEM image is shown in Figure 2.b. There are diffraction gratings embedded under each uniformly fabricated IR pixel.

3. OPTICAL READOUT SYSTEMS FOR THERMAL IMAGING

Diffraction grating interferometer based readout method has been used with thermal detectors [4]. Theoretical findings reveal that there is further room for improving the performance of these detectors [4, 5]. We focus on two different optical setups to improve the performance of the detectors: a 4-f imaging setup and a converging beam optical setup. We evaluate the setups based on performance and system complexity.

3.1 4f Optical System

In the optical system as shown in Figure 3.a, light source beam is collimated to illuminate the FPA by using a tilted mirror. The angle of the tilted mirror in this configuration might be arranged such that 1st diffraction order of the light beam propagate on axis to the image plane. After meeting this condition, the 1st order diffraction order reflected from FPA goes through a 4f optical system into the CCD. The conventional 4f optical system includes 2 identical spherical lenses, and a pinhole as a spatial filter. The distances between FPA & 1st lens, 1st lens & pinhole, pinhole & 2nd lens, are set as the focal length of the identical spherical lenses (f). Furthermore, image plane is focal length f away from the 2nd lens. Therefore, the transmission function of FPA is Fourier transformed by the 1st lens, the wave function at the pinhole is the Fourier transformation of this transmission function. The pinhole is used at the Fourier plane to filter out the 1st order diffracted light and to block the 0th and other diffraction orders. Likewise, the wave function at the image plane is the inverse Fourier transformation of the wave passed through the pinhole [6].

Figure 3. 4f Optical System: (a) Schematic (b) Experimental setup

We perform the experiments in ambient to evaluate the performance of the FPA using a thermoelectric cooler (TEC). MEMS device is mounted on the TEC using thermal glue. Figure 3.b illustrates the experimental setup. A light source with a beam expander passes through the system in Figure 3.a and captured by a CCD camera at the image plane. In a typical experiment, we capture data at 15 fps using the CCD camera. We initialize the TEC is at the room temperature and keep the temperature constant for the first 100 – 150 frames. Then we increase the temperature of the MEMS device controllably by 5-30°C and capture a video.

3.2 Converging Beam Optical System

In contrast to plane wave illumination described in 4-f setup, we employ convergent beam illumination in this configuration. As shown in Figure 4.a, a lens is used after the light source in order to send a converging beam to the FPA. The source is tilted such that -1st diffraction order can propagate on the same axis. Only one lens is used to form the image after FPA and again a pinhole is used as a spatial filter at the Fourier Plane to get the best image.

Figure 4. Converging Beam Optical System: (a) Schematic (b) Experimental setup

Converging beam setup is realized by using an off-axis converging laser beam illumination that forms the Fourier plane near the imaging lens. 1st order diffracted light remains on-axis due to off-axis illumination. It is filtered out and it forms the image of the detector pixels on the CCD. This approach has important advantages such as reducing the number of optical components and minimizing the optical path and offers better image quality due to compact, on-axis imaging optics. The experimental setup is illustrated in Figure 4.b and the experimental procedure is same with the one discussed in the previous section.

Table 1. Converging Beam Optical System Parameters

System Parameters	Value	System Parameters	Value
Wavelength (λ)	633 nm	Imaging lens – CCD distance (d_3)	24 mm
Grating pitch (Λ)	3 μ m	Imaging lens focal length (f)	13.3 mm
Pixel size (P)	35 μ m	Incident beam - -1 st order separation at the Lens Plane (l_1)	6.65 mm
FPA length in horizontal axis	5.6 mm	0 th - 1 st order separation at the Lens Plane (l_2)	6.48 mm
Magnification of the system (M)	0.8	Incident readout beam width (w_1)	11.2 mm
Converging lens - FPA distance (d_1)	30 mm	Filtered 1 st order beam size at the Lens Plane (w_2)	2.1 mm
Imaging lens - FPA distance (d_2)	30 mm	Lens aperture size	6.48 mm

The system parameters in Table 1 are optimized considering parameters such as converging lens location, laser beam size at the MEMS sensor chip, magnification of the imaging system, the distances from chip to light source, lens and CCD. We adjust the magnification based on the MEMS chip size, and the CCD's sensor size to capture the entire detector array on the CCD. Laser convergence angle can be arranged by changing the location or the focal length of the converging lens such that the laser beam size is equal to the 160x120 formatted FPA at the TEC. Meanwhile the location of the Fourier plane can be adjusted near the imaging lens or even on the imaging lens without using any spatial filter. Imaging lens – CCD distance (d_3) is calculated by multiplying the magnification of the system with the imaging lens - FPA distance (d_2). The focal length of the imaging lens is chosen according to d_2 and d_3 related to imaging condition.

Figure 5. Beam width analyses for the converging beam optical system at the Lens Plane

Figure 5 shows incident beam – -1^{st} order separation (l_1) and -1^{st} - 0^{th} - 1^{st} order separations at the lens plane (l_2). The incident readout beam width w_1 in one axis is twice the FPA length related to the equally chosen d_1 and d_2 parameters given in Table 1. Similarly w_2 is chosen according to the filtered -1^{st} order at the Fourier Plane where three peaks are chosen experimentally in our configuration depending on taking the sharpest image on the CCD. The input parameters are arranged such that the size of the optical system in Figure 5 is minimized while diffraction orders are well separated. Equation 1 and 2 show how to calculate these system parameters w_2 , l_1 , l_2 at the lens plane.

$$w_2 \cong 3 \frac{\lambda}{P} d_2 \quad (1)$$

$$l_1 \geq \frac{w_1}{2} + \frac{w_2}{2}, \quad l_2 \cong \frac{\lambda}{\Delta} d_2 \quad (2)$$

Ray tracing simulations using the system parameters in Table 1 are performed using Zemax optical design software as illustrated in Figure 6.a. A slowly converging beam is achieved using the converging lens, which provides illumination beam on the FPA and defines the position of the Fourier plane. The rectangular aperture on the grating structure is used for image analysis. The absorber plate is used to block $m=0^{\text{th}}$ order (shown in green) and $m=+1^{\text{st}}$ order (shown in red) while $m=-1^{\text{st}}$ diffraction order (shown in blue) is used for imaging. The image of the rectangular aperture can be seen in Figure 6.b as a detector image.

Figure 6.(a) Ray tracing of converging beam optical system with a rectangular aperture on grating structure using Zemax Optical Software (b) Detector Image

The size of the system in Figure 6.a is almost 60 mm in horizontal and 30 mm in vertical excluding the size of the laser. It is possible to further decrease the size of the optical system using a fold mirror as illustrated in Figure 7 to 40mm x 30mm. The size of the setup scales linearly with the dimensions of the illumination beam and the FPA.

As a conclusion, the converging beam optical system provides good imaging, requires fewer components, requires a smaller imaging lens (less aberrations), and can be made more compact compared to the 4f system.

Figure 7. More compact form of the converging beam optical system

3.3 Experiment Results

We set the same experimental conditions for both setups for a fair comparison. While heating the FPA, $\Delta T = 15^\circ\text{C}$ is adjusted as the temperature difference in the TEC for both cases. Same MEMS device is used in the experiments. The same post processing procedure is applied while processing the image. Figure 8 illustrates the 1st order diffracted intensity

of an arbitrarily chosen part including 3x3 IR pixels with respect to 1st video frame. It is possible to add all relevant CCD pixels to achieve the total signal that diffracts from a sensor. An image processing algorithm is developed in order to analyze the captured CCD video and suppress the noise using some binning strategies. The working principle of algorithm can be reduced to 4 steps.

- i. Finding the maximum values by searching the CCD output image by using NxN blocks
- ii. According to the address of the maximum values, shaping the IR pixel and specifying the number of CCD pixels for binning.
- iii. Summing the addressed image pixel intensity values (binning) for the specific IR pixel and remapping image according to the total intensity values
- iv. Repeating it for the rest of the frames in the CCD output video.

Figure 8. CCD image of 3x3 IR Pixels

For the output that is shown in Figure 8, block size $N=15$ and for binning 9x9 pixels are used where the maximum of each block is in the center. Choosing the pixels to be used in binning is so important in the defined block, because the coupling between two adjacent IR pixels can become a significant noise source for each pixel. Red dashed marked pixel in Figure 8 is an arbitrary selected pixel according to a reference point in the FPA. It is analyzed for both optical systems. The total intensity value is stable at a certain intensity value with a noise when the TEC is off for the first 120 frames. 120 frames correspond to 8 seconds with a frame rate 15 fps. For the rest of the time TEC is on, which applies a heat that creates a temperature difference $\Delta T = 15$ °C. The intensity starts to change once heating starts, and settles down to certain intensity value, once thermal equilibrium is reached. As shown in the Figure 9, for the same IR pixel, signal to noise ratio is about 3 times better in the converging beam optical system. The standard deviation for the first 120 frames is $\sigma_{4f} \approx 25$ which corresponds to noise of the experimental setup with 4f optical system. Similarly the noise for the convergent beam is extracted as $\sigma_{CBOS} \approx 10$. The SNR of the optical systems are 60.5 and 169.2, which is calculated from the signal and noise levels. Convergent beam optical system provided better noise suppression in our initial experiments but this needs to be studied further.

Figure 9. Direct heating experiment (15°C heating) results for the marked pixel in Figure 8: (a) using the conventional 4f optical system (b) using converging beam optical system

4. CONCLUSION

In this work, two different optical systems for a MEMS based thermal detector arrays are analyzed. High sensitivity and immunity against saturation can be obtained with the embedded diffraction grating readout in thermal detectors. Two different schemes are compared for the typical optical readout by using commercial CCD cameras and imaging optics: (i) 4f Optical System (ii) Converging Beam Optical System. The size of the convergent optical system can be reduced to 30mm x 40mm while also reducing the number of components. This is the most important benefit of the converging optical system over the conventional 4f system. The convergent optical system is preferable for our thermal detector system due to compactness, potential SNR advantage, and smaller imaging lens compared to the standard 4f optical system.

REFERENCES

- [1] Yang Zhao, "Optomechanical Uncooled Infrared Imaging System", Dissertation for the Degree of Doctor of Philosophy, University of California, Berkeley, Fall 2002.
- [2] O. Ferhanoğlu, "Design, Fabrication and Characterization of a MOEMS based Thermal Imaging System," Dissertation for the Degree of Doctor of Philosophy, Koç University, Istanbul, Fall 2010.
- [3] H. Torun and H. Urey, "Uncooled thermo-mechanical detector array with optical readout," *Opto-Electronics Review*, 14, 54-58 (2006).
- [4] M. F. Toy, O. Ferhanoglu, H. Torun, and H. Urey, "Uncooled infrared thermo-mechanical detector array: Design, fabrication and testing," *Sensors and Actuators A: Physical*, 156, 88-94 (2009).
- [5] O. Ferhanoglu and H. Urey, "Sensitivity enhancement of grating interferometer based two-dimensional sensor arrays using two-wavelength readout," *Appl. Opt.*, 50, 3289-3295 (2011).
- [6] Yang Zhao, Minyao Mao, R. Horowitz, A. Majumdar, J. Varesi, P. Norton and J. Kitching, "Optomechanical uncooled infrared imaging system: design, microfabrication, and performance," *J. Microelectromech. Syst.*, 11(2), 136-46 (2002).