Study on the structure of bridge surface of the micro Fabry-Perot cavity tunable filter

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Abstract. Micro Fabry-Perot cavity tunable filters are widely applied in the area of Pushbroom Hyperspectral imaging, DWDM optical communication system and self-adaptive optics. With small volume, lower consumption and cost, the Micro Fabry–Perot cavity tunable filter can realize superior response speed, large spectral range, high definition and high reliability. By deposition metal membrane on silicon chip by MEMS technology, the micro Fabry–Perot cavity has been achieved, which is actuated by electrostatic force and can realize the function of an optical filter. In this paper, the micro-bridge structure of the micro Fabry–Perot cavity tunable filter has been studied. Finite element analysis software COMSOL Multiphysics has been adopted to design the structure of the micro-bridge of the micro filter. In order to simulate the working mechanism of the micro Fabry–Perot cavity and study the electrical and mechanical characteristics of the micro tunable filter, the static and dynamic characteristics are analyzed, such as stress, displacement, transient response, etc. The corresponding parameters of the structure are considered as well by optimization the filter's sustain structure.

Keywords: MEMS, tunable filter arrays, FEA analysis, structure optimize

1. Introduction

In the field of satellite imaging with visible light, Pushbroom Hyperspectral Imager (PHI) is a new intensively researched subject in the spectral imaging field. It obtains hundreds of channels from the nearby wavelength and continuously sampling narrow bands [1]. It has wide application in commercial and military field.

Dispersive component is one of the important parts of Pushbroom Hyperspectral Imager. The traditional imaging spectrometers use prisms or gratings as dispersive components which are bulky and suffer low resolution. While the Fabry-Perot (F-P) cavity has high resolution and excellent frequency selectivity [2-4]. In this paper, MEMS F-P array filter is used as a dispersive component to replace the traditional one. It is compact, fast modulated, precise and easy to be integrated with other elements, such as photo-detectors.
The authors have studied the structure of tunable micro F-P cavity filter integrated with the infrared Focal Plane. The development of the key MEMS device will make the Hyperspectral imager devices light and compact. In this paper, the structure of microbridge of the integrated tunable micro F-P cavity filter have been studied, and some proposals for further development are provided.

2. Design of the micro F-P filter

The hyperspectral imager chooses the wavelength by changing the F-P cavity length. As shown in Figure 1, based on multi-beam interference, if \( \lambda = 2l/m \), \( m = 1, 2, 3 \) (\( \lambda \): incidence wavelength, \( l \): cavity length), the light (wavelength \( \lambda \)) can transmit at a vertical incidence angle. When the incident light is a broadband source, F-P cavity can be used for frequency selecting.

![Figure 1. The principle of F-P cavity](image)

The F–P cavity of MEMS hyperspectral imager is constituted by two dielectric mirrors, the top and the bottom mirrors, which are formed by alternately deposition high and low refractive index dielectric layers. The F–P cavity length can be tuned by applying electrostatic force to achieves the function of wavelength selectivity.

![Figure 2. Four typical micro-bridge Structure](image)

The four patterns of F-P filters’ bridge structure are shown in Fig. 2. They are H arm-square membrane, Cross arm-square membrane, Z-arm-square membrane and X arm-circular membrane.
structures, separately. The electrostatic force per unit area on the micro-bridge \( f_e \) is given by the formula

\[
f_e = \frac{F}{A} = \frac{\varepsilon_0 U^2}{2(L - \Delta L)^2}
\]  

(1)

where \( U \) is the voltage applied, \( L \) is the initial cavity length, \( \Delta L \) is the difference between the initial length and thickness of the air gap after the movement of top mirror, \( \varepsilon_0 \) is the vacuum dielectric constant.

3. **Modeling and simulation analysis**

The geometric parameter of the structures in Figure.2 is shown in the Table 1.

**Table 1.** Four typical micro-bridge structure, the set of their geometric parameter

| type | Cantilever | Microbridge surface | Diameter of circular area for Microbridg e surface |
|------|------------|---------------------|-----------------------------------------------|
|      | Length     | width               |厚度 |                              |                              |
| (1). | 50\(\mu\)m | 10\(\mu\)m           | 1\(\mu\)m | 200\(\mu\)m×150\(\mu\)m | 100\(\mu\)m |
| (2). | 50\(\mu\)m | 20\(\mu\)m           | 1\(\mu\)m | 200\(\mu\)m×200\(\mu\)m | 100\(\mu\)m |
| (3). | (20+200)\(\mu\)m | 20\(\mu\)m | 1\(\mu\)m | 200\(\mu\)m×200\(\mu\)m | 100\(\mu\)m |
| (4). | 50\(\mu\)m | 20\(\mu\)m           | 1\(\mu\)m | (Outside diameter) 100\(\mu\)m | 50\(\mu\)m |

The circular areas in the center of the four structures are reserved for the mirror. The size of these areas are decided by the size of the microbridge. In the simulation, the material was chosen to be aluminum. The relationship between the displacement and voltage is shown in Table 2 and Figure 3.

**Table 2.** Four typical structures’ simulation results

| Type | Applied voltage/V | Maximum displacement /\(\mu\)m | Maximum stress/MPa |
|------|-------------------|------------------------------|-------------------|
| (1)  | 4.5               | 0.5063                       | 9.22              |
| (2)  | 8.5               | 0.4757                       | 17.13             |
| (3)  | 1.9               | 0.4802                       | 4.615             |
| (4)  | 9                 | 0.5218                       | 16.31             |
Figure 3. Relationship between the maximum displacement and the applied voltage

From Figure 3, we can make a conclusion that the Z-arm structure has lowest actuation voltage at same displacement of the mirror. It is important to keep two parallel mirrors flat which affects the micro-fine constants and the F-P cavity wavelength sensitivity. Mirror parallelism analysis is shown in Figure 4.

Figure 4. The comparison of the mirror deformation of the four typical structure

The simulation result in Fig.4 shows that Z-arm structure has the best parallelling performance. This structure with folded cantilever can balance the stress well, and the leg of the microbridge has a good flexibility. The above simulation shows that the Z-arm structure has advantages on actuation voltages and parallelism over the others.

4. The detailed analysis and simulation of Z-arm structure

There different Z-arm structures are shown in Figure 5. The parameters are listed in the table 3. In our simulation, the material of microbridge is Ni, the mirror is supposed to be made of SiO$_2$, the cavity space is filled up with air. Voltage is applied to the surface of micro-bridge, with the bottom electrode grounded.
Figure 5. Three geometrical structures with Z-arm

Table 3. The parameters of three Z-arm structures

| Type                  | Cantilever | Bottom electrode | Diameter of circular area for top mirror | initial cavity length |
|-----------------------|------------|------------------|------------------------------------------|-----------------------|
|                       | Length     | width            | thickness                                |                       |
| (a)                   | (7+70) µm  | 7µm              | 1µm                                      | 70µm × 70µm           | 35µm                | 2µm                |
| (b) Arm widening      | (3+73) µm  | 12µm             | 1µm                                      | 70µm × 70µm           | 35µm                | 2µm                |
| (c) Arm extended      | (19+63) µm | 7µm              | 1µm                                      | 70µm × 70µm           | 35µm                | 2µm                |

4.1 The relationship of Voltage, displacement, stress and deformation angle is shown in the table 4.

Table 4. Comparison of the structure of the simulation parameters a.b.c

| type   | Applied voltage/V | Maximum displacement /µm | Maximum stress/MPa | Mirror deformation angle /° |
|--------|-------------------|--------------------------|--------------------|-----------------------------|
| (a)    | 29                | 542.9                    | 57.53              | 0.00235                     |
| (b)    | 35.5              | 626.2                    | 92.22              | 0.00504                     |
| (c)    | 29.1              | 645.9                    | 51.93              | 0.0416                      |
4.2. Deformation of the three structures, displacement distribution are shown in the Figure 6.

![Figure 6](image-url)  
(a) (b) (c)

**Figure 6.** a\b\c Displacement distribution of three structure

4.3. Stress distribution is shown in the Figure 7

![Figure 7](image-url)  
(a) (b) (c)

**Figure 7.** Stress distribution on three structures

Analysis of structure (a): When the driving voltage is 29V, we get a maximum travel distance of 542.9nm, which meets our initial criteria. The distribution of displacement at the maximum driving
voltage is shown in Fig.6(a). We can see from the figure that the larger deformation mainly lies in the cantilever. When the driving voltage \( V_{\text{in}} \) is 29V, the structure reaches the maximum moving distance, the stress at each point is shown in Fig7(a). We find out that the mirror part suffers the minimum force while the force on the sustain part and the middle part of the cantilever is medium, at cantilever’s fixed end, and the folding site of the folding beam suffers a relatively large force. The maximum stress is up to 57.53Mpa, less than metal Ni’s allowable stress. So theoretically, the phenomenon of bridge broken leg won’t happen.

Analysis of structure (b): Increasing the width of cantilever can make it withstand greater stress while at the same time reduce the flexibility of the bridge legs. At maximum driving voltage, the displacement distribution is shown in Figure 6 (b). cantilever. When \( V_{\text{in}} = 35.5V \), the structure reaches the maximum moving distance, the stress suffered on each point is shown in Figure 7 (b). Compared to structure (a), the maximum stress is relatively bigger. However, the remaining part’s stress, especially stress on the cantilever are much smaller than structure (a).

Analysis of structure (c): Increasing the length of cantilever bridge legs can optimize the flexibility of the cantilever. Figure 6 (c) shows the maximum displacement distribution. When reaching the maximum displacement, the bridge withstands a maximum stress of 51.93Mpa, within the allowance of Ni. The stress distribution on the microbridge is shown in Figure 7 (c).

5. Materials Influences
The relationship of voltage, displacement, stress, deformation angle of the same mechanical structure with 6 different materials is shown in table 5. Relationship between the maximum displacement and applied voltage of these 6 models is shown in the Figure 8.

|          | Applied voltage /V | Maximum displacement /µm | Maximum stress/MPa | Mirror deformation angle /° |
|----------|--------------------|---------------------------|--------------------|-----------------------------|
| Al       | 21                 | 577.4                     | 21.23              | 0.0057                      |
| Au       | 22.5               | 625.6                     | 24.78              | 0.0087                      |
| Ni       | 37                 | 645.4                     | 74.28              | 0.0077                      |
| Cr       | 41                 | 616.6                     | 90.83              | 0.0081                      |
| Ti       | 16                 | 593                       | 12.49              | 0.0046                      |
| Pt       | 28.5               | 662.8                     | 58.79              | 0.0115                      |
Through the comparison of the voltage-displacement curves we find that Ti is the most sensitive, followed by Al and Au. Datum in Table 5 shows that, Pt has the greatest maximum displacement, followed by Ni, and then Au, the displacement of Ti is relatively small. When displacement occurs, bridges with the materials of Ti, Al, Ni can keep mirror parallelism better. As to bridge stress, Al, Au, and Cr structures are relatively small. In general, Ti and Al have the best performance in many aspects, and have achieved all the parameters required.

6. Conclusion
In this paper, different micro bridges structures of the F-P tunable filter is analyzed and simulated. The Z-arm structure has advantages on actuation voltage and parallelism over the others. We also make further analysis on the relationship of voltage, displacement, stress, deformation angle of the same mechanical structure with 6 different materials. The simulation results show that Ti is the most sensitive, Pt has the greatest maximum displacement and bridges with the materials of Ti, Al, Ni can keep mirror parallelism better. The simulation result in this paper will guide the device fabrication process in the near future.

Acknowledgments
This work is supported by the Program New Century Excellent Talents in University in China (No.NCET-07-0319), and also by the Program for Teacher Early basic research fund of Guangxi Teachers Education University(2010-3).

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