Micromechanical tunable optical filters: general design rules for wavelengths from near-IR up to 10 μm

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Abstract

General design rules and the scaling laws with wavelength for MEMS tunable optical filters are discussed for the first time. We describe how to determine dimensions and component materials from the system requirements such as tuning range, central wavelength, tuning voltage, tuning speed and resolution. The systematic design allows fair comparison among different topologies such as cantilever, bridge and trampoline. Design examples are shown for filters with center wavelengths at 850 nm and 4 μm.

Keywords: Tunable filter; Optoelectronic devices; Reconfigurable optical networks; MEMS filter; Reconfigurable focal plane arrays; Optical sensors

1. Introduction

Tunable optical filters are key components for various applications, such as dense wavelength division multiplexed (DWDM) optical networks, spectroscopy, IR imaging and optical sensing. Different structures have been reported [1]. Micromechanically actuated components are desirable because of their wide tuning range, process compatibility with other optoelectronic devices and low cost [2–9].

MEMS filters, Fig. 1, consist of layers forming a single Fabry-Perot cavity that has two distributed Bragg reflectors (DBRs) and an air gap in-between (formed by removal of a sacrificial layer). Grating mirrors have been recently proposed to replace DBRs, mainly for long wavelength applications [10]. However, this paper will consider only the DBR case as devices have not yet been fabricated using that technology. The top mirror moves when voltage is applied across the device, changing the cavity size and consequently the transmitted wavelength. The top DBR must be anchored somewhere and the difference among the different proposed topologies resides mainly on how to anchor this top DBR and on the used materials. Table 1 gives top view, cross section and spring constant for four different anchor types. The spring constants were derived by applying the elementary theory of beam bending together with the approximation for small deflections (deformations are all in the linear region). A concentrated load was considered and located at the filter optical path (circles in the figures of Table 1) for the first three cases and at the counterweight for the torsional topology (opposite to the optical path with respect to the anchors). This approximation gives analytical solutions for the spring constants.

Wide and continuous tuning range was demonstrated in a family of micro-electro-mechanical (MEM) photonic devices using the simple cantilever structure [2–6]. The devices included tunable filters, detectors and vertical cavity surface emitting lasers (VCSELs). Other tunable photonic devices include static deformable beam (bridge) structure [11] and deformable membrane (trampoline) structures [7,8]. We recently reported over 100 nm tuning using the torsional structure [9]. However, design rules were never discussed. Modeling has been presented only for specific designs [7,12]. The aim of this paper is to show how to systematically calculate the filter parameters and scaling laws with wavelength for the deflection beam structures in Table 1.
2. Design rules

The design flow chart for any type of deflection beam MEMS filter is shown on Fig. 2. The desired application gives the requirements: central wavelength ($\lambda_c$), tuning range ($\Delta \lambda_{tuning}$), maximum voltage ($V_{max}$) and tuning speed (resonant frequency, $f_0$). As $\Delta \lambda_{tuning}$ is ultimately limited by DBR reflectivity bandwidth, the designer can choose among the various material systems in order to have the necessary mirror stop band (step 1). The maximum available tuning range as function of central wavelength for different material systems is shown in Fig. 3. However, not all systems shown in the graph are proved to be MEMS compatible. The larger the difference in the index of refraction between the materials forming the DBR layers, the broader the maximum tuning range. Index of refraction for different materials is listed by Palik [13].

The next step (step 2) is to calculate the overall effect of the DBR mirrors. An efficient way of doing this is to use transmission matrix theory [14], which allows the designer to play with the number of DBR pairs by simply cascading their correspondent matrices. By performing this exercise, it is possible to determine how many pairs (step 3) are needed to achieve the required linewidth, which is function of mirror reflectivity and thus the number of DBR pairs. A different number of pairs may be required as the top mirror has two interfaces with air and the bottom mirror has only one interface with air and another interface with the semiconductor substrate. This gives a smaller reflectivity for the bottom mirror so that it needs a larger number of pairs than the top mirror to match its reflectivity. If the top and bottom reflectivities are not matched, transmission will decrease from its optimum value of 100%.

The filter beam thickness ($t$) can then be determined (step 4) based on the number of DBR pairs. The minimum value is the sum of all the layers above the gap. However, bulk material can be added or the DBRs can be etched out of the optical path if the beam needs to be stiffer or softer. This would make the processing much more complex and may not be worth the gain in design flexibility or device performance.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Top view</th>
<th>Cross section</th>
<th>Spring constant (rectangular beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cantilever</td>
<td>$l \times t$</td>
<td>$t \times t$</td>
<td>$k_c = \frac{1}{3} E t^3 / w^2$</td>
</tr>
<tr>
<td>Bridge</td>
<td>$l \times t$</td>
<td>$t \times t$</td>
<td>$k_b = \frac{1}{12} E t^3 / w^2$</td>
</tr>
<tr>
<td>Trampoline</td>
<td>$l \times t$</td>
<td>$t \times t$</td>
<td>$k_t = 32 \frac{E t^3}{w^4}$</td>
</tr>
<tr>
<td>Torsional</td>
<td>$t \times t$</td>
<td>$t \times t$</td>
<td>$k_t = \frac{1}{2} E t^4 / (l \cdot d_0)$</td>
</tr>
</tbody>
</table>

Parameters: $l$, supporting beam length; $t$, supprting beam thickness; $w$, supporting beam width; $E$, Young’s modulus; $G$, shear modulus.
The discussion that follows assumes the anchor beam with the same thickness as the filter in order to make processing easier.

The filter radius \( r \) is dependent on \( \lambda_c \) as different wavelengths have different spot sizes (step 5). At 1.55 \( \mu m \), the radius can be determined based on direct coupling from a diffracted beam coming from an optical fiber. If the filter is to be placed 50 \( \mu m \) away from the fiber and has a mode field diameter of 9 \( \mu m \), the spot at the filter would have a diameter of approximately 15 \( \mu m \) and thus a 20 \( \mu m \) diameter for the filter may be a suitable choice. Similar calculations can always be performed keeping in mind the desired spot size to be filtered and the optical system to be used. Scaling is always be performed keeping in mind the desired spot size. The ratio \( \frac{r}{w} \) is the beam spring constant, \( \frac{w}{l} \) is the material density. For the same optical system, the radius, \( r \), should increase to keep the ratios \( \frac{r}{w} \) constant \[15\]. The terms inside parenthesis in the denominator relate the effect of the beam length and head areas to the deflection due to an applied voltage. Note that if the head area is too large when compared to the beam mass, the Young’s modulus and the material density will be independent of width \( w \).

\[
\omega_0 = 2 \pi f_0 = \sqrt{\frac{k}{m}} = \sqrt{\frac{k}{m}} \left( \frac{k}{m} \lambda_c \right)^2 \left( \frac{\lambda_c}{w} \right)^2 \tag{1}
\]

where \( k \) is the beam spring constant, \( k_0 \) a factor dependent on topology \( 0.14 \) for the cantilever, see Table 1, \( m \) the beam mass, \( E \) the Young’s modulus and \( \rho \) is the material density. As length is proportional to the inverse of square root of frequency, this calculation will give an upper bound and beams smaller than the calculated will always be faster.

The last parameters to be determined are \( d \) and \( w \). The designer has some degree of freedom to choose them. At \( \lambda_c \), the gap should be an integer multiple, \( n \), of \( \lambda_c/2 \). The gap is also dependent on \( \lambda_{opt} \) which determines the mechanical excursion the filter’s top DBR needs in order to cover the entire range. The total excursion can be at most \( \sqrt{3} \) of the total gap

\[
\omega_{pull-in} = \frac{2k(d - z)^2}{\epsilon_0 (w/4 + \pi r^2)} \tag{2}
\]

where \( z \) is the beam displacement from the initial position and \( \epsilon_0 \) is air permittivity. The derivation for Eq. (2) is out of the scope and can be found elsewhere \[17\]. The terms inside parenthesis in the denominator relate the effect of the beam and head areas to the deflection due to an applied voltage. Note that if the head area is too large when compared to the beam area, the deflection will be independent of the beam width. If the value obtained for \( w \) is too small for the available lithography, a trade-off among \( \lambda_{opt}, f_0 \) and voltage will be necessary in order to increase \( w \).

Different types of tunable filters can be easily compared. If we take the first three types from Table 1, readily see that simple cantilever is the easiest to fabricate. Looking at the spring constants from Table 1 and Eq. (2) we can also

\[
V_{pull-in} = \frac{2k(d - z)^2}{\epsilon_0 (w/4 + \pi r^2)} \tag{2}
\]
conclude that the cantilever is the one that requires the smallest voltage for a similar layer structure. However, the cantilever structure may be most sensitive to tension or stress in the mechanical structure, inadvertently caused by epitaxy or processing. This may adversely affect process yield. The advantage of the other two types is to keep the mirror surfaces parallel while the top mirror is moving. However, the tilt angle is very small and has been proved not to affect the simple cantilever [18].

3. Design examples

In order to demonstrate the above design rules we will use the flow chart from Fig. 2 for two different wavelengths: 850 nm and 4 μm. Both examples consider a cantilever design. These wavelengths are suitable for different applications: in the case of 850 nm, the filter may be used to identify a trace such as the one given by Cunningham et al. [19] when monitoring protein–protein interaction; in the case of 4 μm case, the tunable filter may be used to acquire multispectral IR images in the MWIR range. These applications may give us the requirements for the two different filters, which are given in Table 2. In the following, the filters will be designated as A (850 nm) and B (4 μm).

The tuning range requirement determines the material system to be used (step 1). From Fig. 3, any of the examined systems can be used for 850 nm but AlGaAs, Si/TiO2 and ZnSe/CaF2 cannot be used for 4 μm as these materials do not give 2 μm of tuning range. Let’s choose AlGaAs (GaAs substrate) for 850 nm and Si/SiO2 (Si substrate) for 4 μm.

The computation of the transmission matrices is straightforward once the variation of the index of refraction with wavelength is given [13,14]. The number of DBR pairs can then be determined based on the linewidth requirement (step 2). Actually, the reflectivity of the mirrors is not constant throughout the entire tuning range, which also makes linewidth not constant. Choosing the central wavelength to match the requirement, filter A will require 20.5 pairs of Al0.9Ga0.1As/Al0.7Ga0.3As in the top mirror and 25 pairs in the bottom mirror. Note the different number of pairs to match mirror reflectivities. The interfaces with air are always in the bottom mirror. For filter B, the central wavelength is exactly at the center of the stop band and 1 μm of tuning is allowed to each side, as shown in Fig. 4b. Note that as the mirrors from filter A have a good match, the transmission for this filter is nearly 1 while for filter B it is ~0.95.

The top DBR mirror gives the filter beam thickness. Each 1/4 layer of Al0.9Ga0.1As @850 nm has 69.8 nm and Al0.7Ga0.3As has 61.1 nm so that the total thickness for filter A beam is 2.68 μm. At 3.7 μm, the 1/4 layers of Si/SiO2 have 270/618 nm. Thus, the thickness of the filter beam is 1.158 μm.

The filter radius follows the diffraction loss limit. If the numbers given in the previous section are used together with a gap of λc/4, 0.85 μm for filter A and 4 μm for filter B, the results are 5.5 μm radius for filter A and 25.8 μm radius for filter B. Those are lower bound values that can give a first number to work with. Let’s choose 7.5 μm for filter A and 26 μm for filter B. The designer should have in mind that the smaller the radius, the more difficult to couple light inside the cavity (requires high NA lenses) and the larger the radius, the more difficult to etch the sacrificial layer and release the device.

### Table 2

<table>
<thead>
<tr>
<th>Specifications for filter design examples</th>
<th>850 nm (A)</th>
<th>4 μm (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central wavelength</td>
<td>850 nm</td>
<td>4 μm</td>
</tr>
<tr>
<td>Tuning range</td>
<td>±0.3 μm</td>
<td>±1 μm</td>
</tr>
<tr>
<td>Linewidth</td>
<td>1 μm</td>
<td>30 nm</td>
</tr>
<tr>
<td>Resonance</td>
<td>50 kHz</td>
<td>50 kHz</td>
</tr>
<tr>
<td>Voltage</td>
<td>±20 V</td>
<td>±30 V</td>
</tr>
</tbody>
</table>

Fig. 4. Transmission spectra for the filters at (a) 850 nm and (b) 3.7 μm.
The length of the beams is determined with respect to the resonance frequency. For filter A, using data from bulk GaAs \((E = 82 \text{ GPa }, \rho = 5630 \text{ kg/m}^3)\), results \(l = 127.6 \text{ m}\).

For filter B, using data from bulk silicon \((E = 150 \text{ GPa}, \rho = 2330 \text{ kg/m}^3)\), results \(l = 121.6 \text{ m}\). As those are upper bounds for the beam length, let's choose \(100 \text{ m}\) for both filters.

In order to determine the gap size, the mechanical excursion should be determined first. For filter A, the mechanical excursion has to tune from 820 to 880 nm and for filter B from 3 to 5 μm. Using transmission matrix theory again, one can determine the Fabry-Pérot wavelength as function of the gap size and then determine the mechanical excursion. Fig. 5 shows the result for the example filters. Fig. 5a reveals a smooth difference among the different orders. To tune along the 1st mode \((n = 1)\), the mechanical excursion is \(\sim 0.15 \text{ μm}\) and the initial gap should be \(0.5 \text{ μm}\). Thus, any choice of initial gap would allow the necessary excursion as limited by the 1/3 rule. However, the gap for the first mode is rather small and would etch very slowly. Following the above suggested ratio of \(r/d \leq 5\), let's choose \(1.4 \text{ μm}\) for the gap size of filter A \((n = 3)\) and confirm later if this value obeys the voltage requirement. Fig. 5b shows that for large gaps the filter will be multimode and may transmit more than one wavelength for a given gap. However, if the smallest gap is chosen \((n = 1)\), \(\sim 3 \text{ μm}\), the 1/3 rule will limit the excursion up to 2 μm of gap and the desired tuning range will not be covered. Thus, filter B needs an initial gap (sacrificial layer thickness) of at least 5 μm so that it can move up to 3.33 μm and cover all wavelengths from 3 to 5 μm. However, it will transmit two modes for some gap sizes. One alternative to this problem is to use some technique that overcomes the 1/3 rule \([20,21]\) and start with an initial gap of 3 μm. Let's not consider this option and choose the gap for filter B to be 5 μm, large enough for the diffusion of reactants.

Table 3 summarizes the designed values for both filters.

### Table 3

<table>
<thead>
<tr>
<th>Designed parameters for the cantilever type filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central wavelength 850 nm (A) 4 μm (B)</td>
</tr>
<tr>
<td>Material system (\text{A}<em>{0.9}\text{Ga}</em>{0.1}\text{As/Al}<em>{0.2}\text{Ga}</em>{0.8}\text{As/SiO}_2)</td>
</tr>
<tr>
<td># DBR pairs (top/bottom) 20.5/25 1.5/2</td>
</tr>
<tr>
<td>Filter radius ((r)) 7.5 μm 6 μm</td>
</tr>
<tr>
<td>Beam length ((l)) 100 μm 100 μm</td>
</tr>
<tr>
<td>Beam thickness ((t)) 2.68 μm 1.15 μm</td>
</tr>
<tr>
<td>Beam width ((w)) 4 μm 5 μm</td>
</tr>
<tr>
<td>Gap size ((d)) 1.4 μm 5 μm</td>
</tr>
<tr>
<td>Maximum voltage 19.9 V 23.3 V</td>
</tr>
</tbody>
</table>

4. Summary

We presented the design sequence for micromechanical tunable optical filters and scaling laws as function of wavelength. The systematic method was demonstrated through two examples of cantilever type operating at different wavelengths: 850 nm and 4 μm. The simple cantilever topology is the easiest to fabricate and the one that requires minimum voltage among the possible different structures.

Acknowledgements

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### References