Tunable infrared detector with integrated micromachined Fabry-Perot filter

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Abstract. We report the design, fabrication, and test results of a tunable pyroelectric detector with an integrated micromachined Fabry-Perot (FP) filter for gas analysis in the mid-wave infrared (MWIR). The new approach is based on a bulk micromachined Fabry-Perot interferometer with an air cavity, which is electrostatically tuned. Various types of movable reflectors and spring configurations are fabricated to determine the optimum solution with respect to maximum tuning range, low gravity influence on center wavelength, and suitable filter bandwidth. Short and long cavity filters are designed for the spectral ranges of 3 to 4.3 \( \mu \)m and 3.7 to 5.0 \( \mu \)m, respectively. The tunable filter is arranged on top of a current mode pyroelectric detector with a flat spectral response. It is shown that the main challenge is to achieve a high finesse in spite of nonperfect parallelism, mirror curvature, and the additional phase shift caused by the Bragg reflectors. © 2008 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2909206]

Subject terms: Fabry-Perot filter; finesse; infrared filter; Bragg reflector; antireflection coating; bulk micromachining.

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1 Introduction

Infrared (IR) pyroelectric detectors equipped with narrow-band infrared fixed wavelength filters are widely used in infrared analyzers and flame-and-fire detection systems, and are characterized by room temperature operation, robustness, flat spectral response, and low costs. The center wavelength and bandwidth of the commonly used narrow-band infrared filters are selected in accordance to the substances to be analyzed. The more substances there are to be analyzed simultaneously, the more detectors or detectors with separate spectral channels are necessary. The application of an electrically tunable filter allows us to overcome this drawback. Higher flexibility and improved performance of a device equipped with a tunable filter are more sophisticated than a simple fixed filter approach. New measuring algorithms are possible, particularly if mixtures have to be analyzed, in which the substances are characterized by adjacent or overlapping absorption bands. The device could be operated like a spectrometer to obtain a spectral signature.

Many attempts toward this approach have been pursued. Micromachined Fabry-Perot interferometers (FPI) in combination with IR detectors have been investigated and reported by numerous reports.1,2

In addition to the choice of appropriate tuning ranges, for instance from 8 to 12 \( \mu \)m and 3 to 5 \( \mu \)m for the absorption spectroscopy, a small spectral width of transmission band, high maximum transmittance, large free spectral range, large optically active area, low tuning voltage for the full range, and negligible influence of gravitation and vibration are a matter of concern. One of the main difficulties is to fulfill the conflicting requirements originating from these demands. Despite mechanical film stress of the reflection layers enclosing the FPI cavity, which leads to warping, it is necessary to achieve extremely flat and parallel surfaces of the FPI reflectors. Relatively thick and mechanically stiff substrates would compensate this, but they cause sensitivity regarding gravity and vibration because of their weight. A stiff suspension of the movable reflector and higher actuation voltage are necessary.

A membrane-based design of the movable FPI reflector is described in Ref. 3, and a corrugated diaphragm used as a reflection carrier is shown in Ref. 4. The drawback in these cases is the weakness of membranes against film stress and against actuation forces, which lead to nonparallel reflectors when the device is actuated and to reduced performance regarding transmission and selectivity.

A different approach including the full integration of a FPI filter and detector is reported in Ref. 5. The movable FPI reflector is elastically suspended on structured \( \text{Si}_3\text{N}_4 \) beams and the reflector warp is significantly increased. The direct integration of the FPI and IR detector is advantageous in respect of the fabrication effort. However, the size of the optically active area of the reported device is as low as \( 100 \times 100 \mu \)m, and the generated total photocurrent is low.

This work discusses the design, fabrication, and integration of an improved tunable FPI IR filter and a pyroelectric detector. Design and fabrication sequences have been optimized to reach a \( 2 \times 2 \)-mm optically active area, high transmittance of at least 70%, low out-of-band blocking of at
least 0.5\%, and medium actuation voltage up to 60 V. The specification reflects the requirements of the integration of the FPI in a pyroelectric detector and the application in IR gas analyzers. These characteristic parameters have been achieved by a detailed analysis of the optical and mechanical systems, including a relatively thick carrier for the reflection layers, an antireflection coating of the reflector carrier, an extended tuning range by separation of actuation gap and optical resonator gap, and optimized fabrication technology sequence.

### 2 Fabry-Perot Filter Design

#### 2.1 Optical Considerations

A classical Fabry-Perot interferometer is the key element of the MEMS-based tunable IR filter, which is built from an optical resonator consisting of two coplanar reflectors with a separation distance \( d \) and a material with a refraction index \( n \) in-between them. By varying the separation distance \( d \), the filter can be spectrally tuned. In Fig. 1 the setup principle and the transmission as function of the wavelength \( \lambda \) is presented.

If we take into account the absorptance \( A \) and the reflectance \( R \) of the reflectors, the transmission \( T \) can be described with the Airy function:

\[
T = \left(1 - \frac{A}{(1-R)}\right)^2 \frac{1}{1 + F \sin^2 \delta/2} \tag{1}
\]

with

\[
F = \frac{4R}{(1-R)^2}, \tag{2}
\]

and

\[
\delta = 4\pi nd \sigma \cos \theta - 2\varphi(\sigma), \tag{3}
\]

where \( d \) and \( n \) are the physical thickness and refractive index of the resonant cavity, \( \theta \) is the angle of incidence, and \( \varphi \) is the phase shift on reflection. \( F \) is termed as \( F \)-value and \( \delta \) as optical phase.

The Fabry-Perot interferometer only transmits radiation, which satisfies the interference condition \( \delta = m \pi \). The form of individual peaks is \( \sin^2(1/\lambda) \) with the maximum transmittance at the center wavelength (CWL) \( \lambda_m \). The period of the Airy function is described as free spectral range (FSR) and is constant in respect to the wavenumber \( \sigma = 1/\lambda \), but is continuously decreasing as a function of the wavelength \( \lambda \). The bandwidth of the interference peak at the half-power transmittance \( T_{\text{max}}/2 \) is termed as full-width at half-maximum (FWHM). The finesse \( \tilde{F} \) of a Fabry-Perot interferometer is defined as the quotient of FSR/FWHM and is often used as a figure of merit. Simple relations for the center wavelength \( \lambda_m \), the free spectral range FSR, the full-width at half-maximum (FWHM), and the finesse \( \tilde{F}_R \) (finesse in terms of reflectance) can be deduced using air as a resonator medium, under the condition of normal incidence and by neglecting the effect of phase shift at the reflectors \( \varphi \). In Table 1, these functions Eqs. (4–8) and additionally the requirements for the filter and the resulting design parameters are listed.

The tunability of the filter between 5 and 3 \( \mu \)m requires an order number \( m = 1 \) and a physical tuning of the resonator cavity from 2500 to 1500 nm. Bandwidths of 100 to

### Table 1 Mathematical description, requirements, and design of a Fabry-Perot filter.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Design parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center wavelength</td>
<td>( \sigma_m = m/2d ) (4a)</td>
</tr>
<tr>
<td></td>
<td>( \lambda_m = 1/\sigma_m = 2d/m ) (4b)</td>
</tr>
<tr>
<td></td>
<td>( \lambda_m = 5 ) to ( 3 ) ( \mu )m</td>
</tr>
<tr>
<td></td>
<td>( d/m = 2.5 ) to ( 1.5 ) ( \mu )m</td>
</tr>
<tr>
<td>Free spectral range</td>
<td>( \text{FSR}_c = 1/2d ) (5a)</td>
</tr>
<tr>
<td></td>
<td>( \text{FSR}<em>c = \lambda_m/m+1 = \lambda</em>{\text{max}}/m ) (5b)</td>
</tr>
<tr>
<td></td>
<td>( \text{FSR}_c = 2 ) ( \mu )m</td>
</tr>
<tr>
<td></td>
<td>( m = 1 )</td>
</tr>
<tr>
<td>Full width half maximum</td>
<td>( \text{FWHM}_c = 1/2d \pi 1/\tilde{F}_R ) (6a)</td>
</tr>
<tr>
<td></td>
<td>( \text{FWHM}_c = \lambda_m/m1/\tilde{F}_R ) (6b)</td>
</tr>
<tr>
<td></td>
<td>( \text{FWHM}_c = 50 ) to ( 100 ) nm</td>
</tr>
<tr>
<td></td>
<td>( \tilde{F}_R = 40 ) to ( 80 )</td>
</tr>
<tr>
<td>Reflective finesse</td>
<td>( \tilde{F}_R = \text{FSR}/\text{FWHM} = \pi\sqrt{R}/1-R ) (7)</td>
</tr>
<tr>
<td></td>
<td>( R = 0.924 ) to ( 0.962 )</td>
</tr>
<tr>
<td>Contrast</td>
<td>( C = T_{\text{max}}/T_{\text{min}} = (1+R)^2/(1-R)^2 ) (8)</td>
</tr>
<tr>
<td></td>
<td>( C \geq 400 )</td>
</tr>
<tr>
<td></td>
<td>( R \geq 0.905 )</td>
</tr>
</tbody>
</table>
50 nm require a finesse between 40 and 80 or a reflectance of about 92.4 to 96.2%, where a transmission contrast of at least 400 can be obtained.

2.2 Mechanical Design

To achieve the tuning of the resonator cavity, an electrostatic actuation using a parallel plate design has been chosen. It fits the filter setup very well and can be easily integrated. Due to these advantages, electrostatic actuators are the most common micromachined drives. However, the achieved forces are lower in comparison to piezoelectric drives, which need additional materials and are difficult to integrate in the micromachining technology.

The design principle of the detector with a tunable filter is shown in Fig. 2. It is based on an approach using relatively thick reflector carriers, one of them being fixed and the other suspended by springs that allow vertical movement. The mechanically stiff reflectors with low curvature guarantee a high finesse and high aperture. The filter design is compatible to micromachining technology. A setup with a coated and etched wafer is bonded directly or by an intermediate SU-8 layer, which yields in medium fabrication complexity.

300-μm-thick silicon wafers with a resistivity of 5 to 10 Ω cm are used as carriers for both the fixed and movable reflector. The fixed reflector is located in the center surrounded by the driving electrodes. The movable reflector is suspended by diagonally arranged springs located in the corners of the outer frame. Various types of movable reflector and spring configurations, shown in Fig. 3, have been...
fabricated to determine the optimum solution with respect to maximum tuning range, low gravity influence on center wavelength and filter bandwidth, low deviation of reflector parallelism by mechanical stress, and low fabrication complexity. In the first type, the movable reflector carrier consists of two wafers with wet-etched springs. After direct bonding of the wafer, a parallel spring suspension with eight diagonal springs is formed. The parallel spring suspension will provide the necessary vertical movement and the necessary rigidity to minimize any tilting of the movable mirror carrier. In the second type, the movable reflector carrier consists of a single wafer. In this case, the parallel spring suspension is wet etched from both sides of the wafer. In the third type, dry-etched springs with stress compensating elements are used instead of parallel spring suspension, resulting in the most simplified design and technology.

The center of gravity of the movable reflector carrier was designed to be in the middle plane between the two bonded wafers and also in the middle of the single wafer to prevent tilting by gravity. The outer parts of the movable reflector carrier are used as movable electrodes. The polycrystalline silicon layers of the reflector stacks are connected to the wafer, keeping these layers free of electrostatic charges.

The parallel spring design results in a nearly ideal movement in the vertical direction. But this is only the case if the assembling of the planes succeeds in tension and warping free. Tensions lengthwise cannot be compensated by the springs. They lead to a deformation of the spring in the vertical direction. Alternatively, stress compensation elements can be integrated into the springs. The T-form facilitates the reception of compressive or tensile stress, as the small T side can be bent crosswise. Advantages of this modification are the simple and proven technology, a large freedom of the design parameters and high precision of the fabricated springs. Besides smaller dimensions of the spring, the dry etching allows smaller trenches as well. Thus the spring needs less space, even with complicated embodiment, and more area can be used for the electrostatic force generation. Combined with a wet etching process for the adjustment of the spring thickness, very precise spring mass systems can be produced. According to the actual design parameters, the measured resonance frequencies and the calculated spring stiffness are 7.7 kHz and 13.4 kN/m for the parallel springs, and 4.8 kHz and 7.4 kN/m for the stress compensated springs.

Both wafers with movable and fixed reflector carriers respectively are connected either by direct silicon bonding or with a SU-8 interface layer. Direct bonding is carried out after a surface activation in oxygen plasma at room temperature and impact of a marginal mechanical pressure. A sufficient rigidity and long-term stability is achieved by high temperature annealing at 400°C. However, a sufficient bond yield is difficult to ensure, because a perfect surface quality of the bonding areas must be maintained during the whole process flow.

SU-8 is spun on the wafer like a photoresist. It is offered in different nominal thicknesses; the desired layer thickness can be adjusted by changing the rotation speed of the spinning. For the layer thicknesses requested here, a SU-8 with a nominal thickness of 5 \( \mu \text{m} \) was chosen. The thickness accuracy of the spinning process was measured to be \( \pm 100 \text{ nm} \). The bonding was carried out after slow heating at 100°C under pressure and slow cooling down.

### 3 Bragg Reflector and Antireflection Coating Design

In Fig. 4 the absorption bands of some gases are shown in the range from 3 to 5 \( \mu \text{m} \) as an example. Combustible, toxic or environmental harmful gases like CH\(_4\), C\(_2\)H\(_6\), CO, and N\(_2\)O can be measured in the spectral range of 3 to 5 \( \mu \text{m} \). This spectral range is also easier to measure, because up to 4.5-\( \mu \text{m} \) low-cost miniature incandescent lamps can be used as an IR source.

Distributed Bragg reflectors are commonly used to generate a broadband reflector. Bragg reflectors are built up by alternating quarter-wave optical thickness (QWOT) layer.
ers with low and high refractive index. To generate a broad high reflective zone from 3 to 5 μm, even with a low stack number, thin films with as high as possible refractive index ratio \( n_\text{H}/n_\text{L} \) have to be applied. Potential thin films are silicon dioxide, silicon nitride, and SiO₂ aerogel as low refractive index material, and polycrystalline silicon as high reflective index material. The optical constants \( n \) and \( k \) were measured by an ellipsometer on QWOT layers in the wavelength range of 2 to 20 μm. The layers are deposited by CVD processes and spin-on technology (aerogel), and are compatible with the previously described micromachining process. Measured optical constants are plotted versus the wavelength from 2 to 20 μm within Fig. 5.

In the 3 to 5-μm range, all investigated thin films are characterized by a very low absorption and a moderate dispersion of the refractive index. The lowest refractive index of 1.22 was shown for aerogel films (highly porous silica), but the spin-on technology is not yet suitable for precise optical coating and structuring. Silicon dioxide with a refractive index of 1.38 at 4 μm is used as a silicon dioxide and polycrystalline silicon layers for the ARC. This double-layer design was refined to use only silicon dioxide with a refractive index of 1.38 as a Bragg layer of silicon dioxide with a refractive index of 1.85 for a silicon/air interface at a wavelength of 4 μm. Unfortunately, silicon nitride layers exhibit high intrinsic stress, which produces substrate bowing after deposition, and therefore makes them unsuitable for antireflection coatings of FP filters. Alternatively, a double-layer broadband ARC increases the transmittance in a broader wavelength range. The refractive indexes of the QWOT double-layer ARC must follow Eqs. (10) and (11):

\[ n_1 = (n_0 n_2)^{1/3} = 1.51, \tag{10} \]
\[ n_2 = (n_0 n_3)^{1/3} = 2.27. \tag{11} \]

This double-layer design was refined to use only silicon dioxide and polycrystalline silicon layers for the ARC. For the first layer, a QWOT silicon dioxide layer with \( n_1 \) of 1.38 was chosen. The second layer was synthesized with the backside of the wafer were antireflection coated to reduce reflection losses and ripples in the high reflective band caused by multiple reflections in the silicon substrate. A QWOT layer of silicon nitride with a refractive index of 1.89 would be a much better silicon ARC than a QWOT layer of silicon dioxide with a refractive index of 1.38 according to Eq. (9):

\[ n_L = (n_0 n_3)^{1/2}. \tag{9} \]

which results in a refractive index \( n_L \) of 1.85 for a silicon/air interface at a wavelength of 4 μm. Unfortunately, silicon nitride layers exhibit high intrinsic stress, which produces substrate bowing after deposition, and therefore makes them unsuitable for antireflection coatings of FP filters.

![Fig. 6](https://example.com/fig6.png)

(a) Reflectance and (b) phase shift of distributed Bragg reflectors with optical references at 3550 and 4400 nm for short and long cavity filters.

![Fig. 7](https://example.com/fig7.png)

Fig. 7 Reflectance of single- and triple-layer antireflection coating.
very thin films of silicon dioxide and polycrystalline silicon fulfilling the condition \( nd \ll \lambda \). The overall physical thickness of the refined triple-layer broadband ARC is only about 1000 nm. In Fig. 7, the single-layer ARC is compared with the broadband triple-layer ARC. Whereas the reflectance of the single-layer ARC has a minimum only at the reference wavelength. The reflectance of the refined triple-layer ARC has an average of 0.6% in the hole spectral range of 3 to 5 \( \mu \text{m} \) and a minimum of 0.3%. The transmittance characteristics in Fig. 8 indicate key benefits of the triple-layer ARC. Compared to a single layer ARC, which was designed for a reference wavelength \( \lambda_{\text{REF}} \) of 3900 nm, the ripple amplitude of the triple-layer ARC is reduced and the transmittance is increased.

The necessary air gap size of the short and long cavity Fabry-Perot filters was designed with a commercial optical thin film software, considering the influence of the additional phase shift \( \varphi \), which appears by the reflection at the dielectric reflectors.

Although the correlation of center wavelength versus cavity spacing is determined by a slope of 2 for perfect reflectors without additional phase shift, the actual design shows a slope of 1.3 considering the phase shift (Fig. 9).

This increases the necessary cavity tuning to about 155% compared to perfect reflectors, which is illustrated in Table 2 and illustrates explicitly that the influence of phase shift \( \varphi \) cannot be neglected for small interference orders.

<table>
<thead>
<tr>
<th>Type</th>
<th>Center wavelength [nm]</th>
<th>Cavity spacing without phase dispersion [nm]</th>
<th>Cavity spacing with phase dispersion [nm]</th>
<th>Required increasing of cavity spacing [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>3000</td>
<td>1500</td>
<td>1369</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4100</td>
<td>2050</td>
<td>2225</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Difference 550</td>
<td>856</td>
<td>156</td>
<td></td>
</tr>
<tr>
<td>Long</td>
<td>3900</td>
<td>1950</td>
<td>1845</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5000</td>
<td>2500</td>
<td>2693</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Difference 550</td>
<td>847</td>
<td>154</td>
<td></td>
</tr>
</tbody>
</table>

The mismatch of both functions is caused by different absolute phase shifts because of different design wavelengths, already shown in Fig. 6(b).

### 4 Detector Design

The tunable filter is arranged on top of a current mode pyroelectric detector with a flat spectral response, shown in Fig. 10. The transimpedance amplifier (TIA) is connected to a blackened 2 \times 2-mm² pyroelectric chip of lithium tantalate, which is the radiation sensitive element. A second chip, which is connected antiparallel and shielded from the radiation, compensates signals due to temperature changes of the surroundings and of the package without reducing the responsivity. A low-noise, low-power complementary metal-oxide semiconductor (CMOS) op-amp with a 100-GΩ feedback resistance and a very low parasitic 40-\( \text{fF} \) feedback capacitance converts the pyroelectric current into a high signal voltage. The op-amp operates with a minimum supply voltage of \( \pm 2.2 \) V and a quiescent current of 70 \( \mu \text{A} \). The low power dissipation in connection with the thermal compensation results in a very short warm-up time of several seconds. To avoid capacitive coupling from the electrostatic driving circuitry of the tunable filter, the pyroelectric chips and the input of the TIA are completely shielded. The wiring of the detector is shown in Fig. 11.

Both the tunable filter and the detector are packaged in a TO-8 housing with a broad bandpass filter.

![Fig. 8 Transmittance fringes of FP filters with Si₃N₄ single-layer and multilayer ARC.](image8)

![Fig. 9 Simulated dependence of the center wavelength of the peak transmittance from air cavity spacing of short and long cavity filters.](image9)

![Fig. 10 Schematic drawing (left) and picture of a sample (right) of a tunable pyroelectric detector with integrated filter.](image10)
pass filter transmits only in the 3.0 to 4.3-μm range for the short cavity filter and 3.7 to 5.0-μm range for the long cavity filter, and blocks higher interference orders and long wave radiation from UV to 12 μm.

5 Detector Performance

The transmittance of the Fabry-Perot filters was measured using a FTIR interferometer at a resolution of 8 cm⁻¹ before packaging into the detector. The results of the optical measurements of the short and long cavity filters presented in Fig. 12 confirm the optical design to achieve a high transmittance and low bandwidth.

The typical bandwidths FWHM of the long cavity and short cavity filters are 100 ± 20 nm and 80 ± 20 nm, respectively. The voltage dependence of the filter’s CWL features the typical square root function of an electrostatic actuator. The decreasing transmittance during tuning, visible in Fig. 12, is probably a result of nonperfect parallel deflection of the moveable reflector. Stiffness tolerances of the individual springs as well as electrode area and gap inhomogeneities can cause this effect. The different design approaches with spring stiffnesses of 13.4 and 7.4 kN/m result in different maximum driving voltages of 60 and 27 V, respectively, to provide a tuning range of about 1300 nm.

The voltage responsivity and the noise density of the tunable detector are presented in Figs. 13(a) and 13(b). As a result of the low electrical time constant of 4 ms, the normalized responsivity is flat up to a frequency of 40 Hz. The responsivity $R_V$ (400°C, 10 Hz, 25°C) of the detector, measured with a 400°C blackbody as a radiation source at a room temperature of 25°C and a modulation frequency of 10 Hz including the tunable filter, is about 2500 V/W for the short cavity FP filter, 1500 V/W for the long cavity FP filter, and 160,000 V/W for the detector without the tunable filter, respectively. The significant reduction of the responsivity is effected by the filter, which transmits only a small band of the incident broadband blackbody radiation. The specific detectivity of the tunable detector is higher than $8 \cdot 10^6$ cm Hz¹/₂/W for the short cavity FP filter and $4.5 \cdot 10^6$ cm Hz¹/₂/W for the long cavity FP filter, respectively.

Tunable detectors and stand-alone filters were applied in infrared analyzers and spectrometers to quantify single gases like ethanol and carbon dioxide, as well as gas mixtures of methane and propane and anesthetic gases of halothane, laughing gas, and different fluranes. The tests confirmed the higher performance and flexibility of the tunable detector approach in comparison to detectors equipped with fixed narrowband filters.

6 Discussion

Comparing the measured finesse and the peak transmittance of the FP filters with the theoretical data, the influence of...
defects (deviations from the ideal filter characteristic) can be evaluated by introducing an effective finesse $F_{\text{E}}$. The effective finesse $F_{\text{E}}$ can be understood as quadratic interaction of the distinct terms $F_{\text{X}}$:

$$F_{\text{E}} = \left[ \sum \frac{1}{F_{\text{X}}^2} \right]^{-1/2},$$  \hspace{1cm} (12)

with the reflective finesse $F_{\text{R}}$, the spherical finesse $F_{\text{S}}$, the roughness (Gaussian) finesse $F_{\text{G}}$, and the parallelism finesse $F_{\text{P}}$. The collimation finesse is not considered here.

The reflective finesse $F_{\text{R}}$ can be calculated with Eq. (7) and is 77 for a reflectance $R$ of 0.96. For the terms of the effective finesse $F_{\text{X}}$ caused by the defects $\delta_{\text{X}}$, the following relations can be deduced:

spherical finesse $$F_{\text{S}} = \frac{\lambda}{2\delta_{\text{S}}},$$ \hspace{1cm} (13)

roughness (Gaussian) finesse $$F_{\text{R}} = \frac{\lambda}{22^{1/2}\delta_{\text{G}}},$$ \hspace{1cm} (14)

parallelism finesse $$F_{\text{P}} = \frac{\lambda}{3^{1/2}\delta_{\text{P}}}. \hspace{1cm} (15)$$

Assuming that a degradation of the effective finesse to 90% compared to the reflective finesse ($F_{\text{R}}$ of 77) can be accepted, the defect terms $F_{\text{X}}$ should be greater than 275. Therefore, considering Eqs. (13)–(15) at a wavelength of 4 $\mu$m, the warping $\delta_{\text{S}}$ should be less than 7.3 nm, the roughness $\delta_{\text{R}}$ smaller than 3.1 nm, and the tilting $\delta_{\text{P}}$ smaller than 8.4 nm. This is a great challenge in combination with an aperture of $2 \times 2$ mm$^2$. However, as the effective finesse $F_{\text{E}}$ is determined by the smallest term $F_{\text{X}}$, the definition of the major defect $\delta_{\text{X}}$ is essential for the practical application.

Although the roughness of the dielectric layer stacks $[\text{LH}]^2$ could be reduced to 1.7 nm due to an improved deposition of the polycrystalline silicon, the warping $\delta_{\text{S}}$ measures typically about 35 nm (shown in Fig. 14), reducing the defect term $F_{\text{S}}$ to 57. Even without including a tilting $\delta_{\text{P}}$, a dramatic decrease of the effective finesse $F_{\text{E}}$ to 45.6 has to be noticed. This leads to an increase of the bandwidth to 86 nm at 4 $\mu$m wavelength and 107 nm at 5 $\mu$m wavelength, respectively. These calculated bandwidths conform well to the measured typical bandwidths. Therefore, we can conclude that mainly the warping of the reflectors essentially determines finesse and bandwidth. Further effort...
should be put on reducing this warp by optimization of the layer deposition process, because it is mainly caused by stress in the silicon dioxide layers. A higher finesse will also enhance the peak transmittance of the FPI and the system performance.

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References
12. H. A. MacLeod, Thin-Film Optical Filters, IoP, Bristol, UK (2001).
15. The Essential Macleod, “Optical coating design program,” Thin Film Center Inc., Tucson, AZ.

Norbert Neumann has been in the field of infrared detectors for the last 25 years. He graduated in electrical engineering and received the diploma degree (Dipl-Ing) in 1979, the Dr-Ing degree in 1984, and the Dr-Ing habil. degree in 1991. He started his career at the Dresden University of Technology working on infrared detectors, pyroelectric, arrays, and ferroelectric thin films. Currently he is the head of research and development of InfraTec, Dresden, Germany, which he cofounded in 1991. His scientific activities are mostly directed toward pyroelectric detectors for gas analysis, fire and flame detection, as well as MOEMS components for infrared applications.

Martin Ebermann graduated in electrical engineering and received the Dr-Ing degree in 1995, both at Chemnitz University of Technology. He was with Fraunhofer IZM since 2001 and active in the fields of design and test of MEMS components like accelerometers, vacuum pressure sensors, scanning mirrors, and other MOEMS components. His current research focuses on the development of test methods for MEMS components at wafer level and their integration in the fabrication process. He is a lecturer at Chemnitz University of Technology and has supervised more than 30 graduate students for diploma and DrIng degrees.

Steffen Kurth graduated in electrical engineering and received the Dr-Ing degree in 1995, both at Chemnitz University of Technology. He was with Fraunhofer IZM since 2001 and active in the fields of design and test of MEMS components like accelerometers, vacuum pressure sensors, scanning mirrors, and other MOEMS components. His current research focuses on the development of test methods for MEMS components at wafer level and their integration in the fabrication process. He is a lecturer at Chemnitz University of Technology and has supervised more than 30 graduate students for diploma and DrIng degrees.

Karla Hiller received her diploma degree (Dipl-Ing) in electrical engineering from Dresden University of Technology, Germany, in 1988, and her Dr-Ing degree in 1994 from Chemnitz University. Since 1994 she has been working in the field of MEMS fabrication, development of MEMS technologies, and wafer bonding at the center for Microtechnologies (ZIM) of Chemnitz University. In 2004 she earned her qualification for lectureship (Dr-Ing habil.) and became a senior scientist at ZIM. Presently, she is involved in the development of inertial sensors (accelerometers and gyroscopes) as well as optical components (especially Fabry-Perot filters). She is the coordinator of several research projects together with industrial partners in Germany as well as within the sixth framework of the European Commission.