MOEMS vertical-air-cavity filters are widely and continuously tunable around 1.55 microns

Hartmut Hillmer, Sören Irmer, Friedhard Römer, Andreas Hasse, J. Daleiden, C. Prott, S. Hansmann, and M. Strassner

Micromachined vertical-resonator-based filters—capable of wide, continuous, and kink-free tuning at 1.55 μm using a single control parameter—have been designed, implemented, and characterized. Tuning is achieved by mechanically actuating at least two membranes in a vertical air-gap resonator including two highly-reflective distributed-Bragg-reflector (DBR) mirrors. Electrostatically-actuable single-chip filters including InP/air-gap DBRs (3.5 periods) provide continuous tuning up to 14% of the absolute wavelength. By varying the reverse voltage from 0V to -3.2V between the membranes of one design, a tuning range as wide as 142nm was obtained. By varying it from 0V to -28V in another design, a tuning range as wide as 221nm was measured. Strain in the membranes plays a major role in the filter performance.

Tunable devices based on micro-opto-electro-mechanical systems (MOEMS), such as vertical-cavity filters and surface-emitting lasers (VCSELs), have attracted much interest because of their unique features: a wide continuous tuning range and two-dimensional array integration. Tunable devices with a wide tuning range and high spectral purity have many applications: these include dense wavelength division multiplexing (DWDM) for optical communications, sensing, analytic instruments, confocal microscopy, process control applications, as well as medical diagnostics. We are particularly interested in the former.

DWDM revolutionized data transmission technology by increasing the signal capacity of embedded fiber. Incoming optical signals are encoded at specific wavelengths within a designated frequency band, and then multiplexed onto a single fiber. This process allows for multiple video, audio, and data channels to be transmitted over one fiber while maintaining system performance and enhancing transport systems. The ability to provide potentially unlimited transmission capacity is the most obvious advantage of DWDM.

figures and diagrams as described in the text

Here we present our recent results on tunable vertical cavity filters, which show a tuning rage of 221nm. Our filters consist of top and bottom In(GaAs)P/air DBR mirrors that provide high reflectivity and wide stopbands: for a three-period DBR, the theoretical reflectance is 0.997 and the filter’s stopband is 1000–1500nm. The DBRs are separated by a cavity. Electrostatic actuation is enabled by n-doping the bottom DBR mirror and p-doping the top mirror. By reverse biasing this pn-junction and varying the voltage, the cavity length can be controlled. Depending on the cavity length, the filter can be adjusted to be transparent to only one of the wavelength channels while blocking the others.

Growing the structures requires epitaxy to deposit interleaved binary—In(GaAs)P membrane—and ternary (InGaAs sacrificial) layers. Arsenic carryover keeps the interface from being abrupt. Due to this intermixing at the interface of membrane-sacrificial layers,
Figure 2. Scanning-electron micrographs of multiple air-gap filters with membranes 40 μm in diameter and four suspensions. (a) An InGaAsP/air-gap filter with 30 μm-long suspensions. (b) A closer view of the layers (c) A spiral-shaped suspension InP/air-gap filter. (d) An InP/air-gap filter with 10 μm-long suspensions.

Figure 3. (a) Measured tuning of an InP/air multiple membrane (type 1) filter under electrostatic actuation (nearly-flat membranes in the unactuated condition at U = 0 V). (b) Measured tuning and corresponding reflectance spectra (inset) of an InP/air multiple membrane (type 2) filter under electrostatic actuation (strained and bent membranes in the unactuated condition at U = 0 V).

layers, underetching produces an inhomogeneous surface on both sides of each membrane. Thus, within the InP-membranes, the material composition is most likely slightly inhomogeneous in the vertical direction. Suspended multiple membrane structures (Figures 1 and 2) are sensitive even to extremely small vertical compositional variations, since they cause slight bending in the membrane after release. As a consequence, the filter properties can be varied widely, including the spectral tuning range, filter line transmission, filter linewidth, and lateral mode structure.

We fabricated two types of filters. Filter type 1 was grown with several minutes of epitaxial growth interruption prior to each InP deposition, to reduce the carry-over that allows arsenic to incorporate into the InP layers. Filter type 2 was grown with short growth interruptions and tensile-strained GaInAs sacrificial layers to generate a compensating interface layer between the GaInAs and InP layers that remains after the underetching process. Type 1 causes less net strain accumulation and thus less membrane bending but type 2 has the potential for larger wavelength tunability.

The micromachined fabrication is based on three main steps: defining the multiple-layer structure by epitaxy or other deposition methods; dry etching to define the lateral structure (vertical patterning of the mesa) and removing the sacrificial layers by selective wet-chemical underetching to define the air-gaps. The surface-micromachining fabrication process requires no micromounting since the entire structure is fabricated in a batch process: the filter can only be low-cost if many devices are batch-fabricated simultaneously. Our process is therefore compatible with mass production.

Figure 3a displays the experimental results obtained for a type-1 filter suspended from four beams, each 40 μm long. The membrane is 40 μm in diameter. The filter has three λ/4 InP membranes separated by λ/4 air-gaps, a λ/2 cavity, and an air-gap of 637.5nm to the InP substrate. Because this filter has almost no strain, the membranes are nearly flat when the applied voltage is 0V. The transmission dip of the device is located at λ = 1.599 μm for non-actuated membranes (U = 0V) and at λ = 1.457 μm in the case of actuation by U = −3.2 V, covering a tuning range of 142nm. The type-2 filters have four 30 μm-long suspensions and a 20 μm membrane diameter. Three λ/4 InP membranes are separated by λ/4 air-gaps, and this filter has a λ-cavity and a spacing of 465nm to the InP substrate. We obtained a larger tuning range. The filter is weakly strained and thus at U = 0 V has curved membranes. Using an electrostatic tuning voltage of 28V, we obtained a 221nm tuning range: see Figure 3(b). To the best of our knowledge, this is a record value for air-gap-based micromachined DBR filters demonstrating fast tuning.

Our experimental and theoretical calculations indicate that the tuning range and the required voltage range are sensitive to a large number of parameters such as suspension lengths, number of suspensions, suspension widths, membrane diameter, membrane and suspension thickness, as well as cavity length. Less evident is the fact that we found a strong dependence on the layer strain and thus the membrane and suspension pre-bending in the unactuated state, i.e. at U = 0V. The images show a much stronger bending of the top membrane and the corresponding
suspensions for type 2. Due to the miniaturization of the filters, the efficiency of the electrostatic force increases considerably. Table 1 compares a selection of DBR-based tunable filters.

Our filters (the 10th and 14th lines in Table 1) are batch-process compatible and, thus, can potentially be produced at low-cost. They show very-fast tuning, low actuation voltages, and extremely-wide tuning ranges. Due to the very-high mechanical resonance frequencies, the tuning speed is very high: more than high enough for today’s DWDM system requirements.

Support by the German BMFB and DFG funding is gratefully acknowledged. The authors wish to thank K. Streubel, D. Gutermuth, H. Schröter-Hohmann, I. Kommallein, I. Wensch, W. Scholz for technical support and stimulating discussions.

### Table 1.

<table>
<thead>
<tr>
<th>FP air gaps</th>
<th>DBR material system</th>
<th>starting wavelength λ</th>
<th>tuning range Δλ</th>
<th>electrostatic actuation voltage range AL</th>
<th>tuning speed</th>
<th>structure</th>
<th>FWHM fsr</th>
<th>affiliation [Ref.]</th>
<th>disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AlAs/ GaAs</td>
<td>937 nm</td>
<td>53 nm</td>
<td>14 V</td>
<td>medium</td>
<td>membrane</td>
<td>3ns FSR?</td>
<td>U. Stanford[1]</td>
<td>wavelength range</td>
</tr>
<tr>
<td>1</td>
<td>AlAs/ GaAs</td>
<td>972 nm</td>
<td>70 nm</td>
<td>8 V</td>
<td>medium</td>
<td>cantilever</td>
<td>8ns FSR?</td>
<td>U. Stanford[1]</td>
<td>wavelength range</td>
</tr>
<tr>
<td>1</td>
<td>AlAs/ GaAs</td>
<td>1.635 μm</td>
<td>105 nm</td>
<td>35 V</td>
<td>medium</td>
<td>two chips</td>
<td>1.2 μm</td>
<td>U. Darmstadt[2]</td>
<td>micro mounting</td>
</tr>
<tr>
<td>1</td>
<td>SiO₂/ Si</td>
<td>1.585 μm</td>
<td>70 nm</td>
<td>27 V</td>
<td>medium</td>
<td>membrane</td>
<td>0.5-0.7μm FSR</td>
<td>CoreTek[3]</td>
<td>relatively high voltage</td>
</tr>
<tr>
<td>1</td>
<td>SiO₂/ Si</td>
<td>1.55μm</td>
<td>45 nm</td>
<td>40 V</td>
<td>medium</td>
<td>membrane</td>
<td>10μm FSR</td>
<td>KTH[4]</td>
<td>relatively high voltage</td>
</tr>
<tr>
<td>6</td>
<td>InP/fair</td>
<td>1.35 μm</td>
<td>62 nm</td>
<td>14V</td>
<td>fast</td>
<td>membrane</td>
<td>0.6-3nm FSR</td>
<td>CNRS Lyon[5]</td>
<td>membrane bending</td>
</tr>
<tr>
<td>1</td>
<td>AlAs/ GaAs</td>
<td>1.60 μm</td>
<td>100nm</td>
<td>23 V</td>
<td>medium</td>
<td>torsion</td>
<td>1μm</td>
<td>UC Berkeley[7]</td>
<td>relatively high voltage</td>
</tr>
<tr>
<td>1</td>
<td>dielectric</td>
<td>1.55μm</td>
<td>30 nm</td>
<td>29 V</td>
<td>medium</td>
<td>membrane</td>
<td>0.2-1μm</td>
<td>Yokogawa[8]</td>
<td>relatively high voltage</td>
</tr>
<tr>
<td>6</td>
<td>InP/fair Filter type 1</td>
<td>1.60 μm</td>
<td>142nm</td>
<td>3.2V</td>
<td>fast 4m-0.4MHz</td>
<td>membrane</td>
<td>3-5nm</td>
<td>U. Kassel, INA[9]</td>
<td>membrane bending control required</td>
</tr>
<tr>
<td>6</td>
<td>InP/fair</td>
<td>1.528 μm</td>
<td>46nm</td>
<td>8V</td>
<td>fast</td>
<td>membrane</td>
<td>4μm</td>
<td>KAIST Korea[10]</td>
<td>FWHW large</td>
</tr>
<tr>
<td>6</td>
<td>InP/fair Filter type 2</td>
<td>1.66 μm</td>
<td>221 nm</td>
<td>28V</td>
<td>fast 4m-0.4MHz</td>
<td>membrane</td>
<td>4-15nm</td>
<td>U. Kassel INA this work</td>
<td>membrane bending, relatively high voltages</td>
</tr>
<tr>
<td>-</td>
<td>external cavity</td>
<td>1.59μm</td>
<td>190nm</td>
<td>20V</td>
<td>medium</td>
<td>MEMS mirror</td>
<td>14nm</td>
<td>Yokogawa[11]</td>
<td>FWHW large</td>
</tr>
<tr>
<td>-</td>
<td>PMMA/PS</td>
<td>900nm</td>
<td>274nm</td>
<td>6000 ppm (no electrostatic actuation)</td>
<td>slow</td>
<td>polymer</td>
<td>20nm</td>
<td>U. Friefborg IMTEC[12]</td>
<td>tuning speed and FWHM</td>
</tr>
</tbody>
</table>

### Author Information

Hartmut Hillmer, Sören Irmer, and Friedhard Römer
Institute of Nanostructure Technologies and Analytics (INA)
University of Kassel
Kassel, Germany

Prof. Dr. Hartmut Hillmer is co-director of the Institute of Nanostructure Technologies and Analytics. He has published a number of papers in SPIE journals and given invited talks at SPIE conferences.
SPIE Newsroom

Andreas Hasse
IPAG Innovative Processing AG
Darmstadt, Germany

M. Strasser
CNRS-LPN
Route de Nozay
Marcoussis, France

J. Daleiden
Infineon Technologies
Dresden, Germany

References


