The PHASAR exhibits a TE-TM shift of 1.37 nm due to the waveguide birefringence. This could be overcome by the compensation technique reported in [6] or by another such technique.

![Comparison of classical and double phasar](image)

**Fig. 4** Compared response of classical and double phasar

- Classical phasar, \( \eta = 17\% 
- Double phasar, \( \eta = 50\% 

Flattening loss penalty: 2.2 dB

**Conclusion:** We have proposed a new design to realise a phased array with a flattened spectral response. The multigrating method has been implemented on an InP/InGaAsP based device. The bandwidth at -1 dB is 0.94 nm and the figure of merit is 50%, which is an improvement of more than double compared with a conventional phasar. Fibre-to-fibre losses are 12 dB for TE and TM polarisation, including a 2.2 dB loss penalty for the channel flattening and without anti-AR coating.

**Acknowledgment:** The authors acknowledge F. Olivier-Martin and M. Carré for accurate photolithography. The authors would also like to thank A. Carenco for useful discussions.

© IEE 1997

**ELECTRONICS LETTERS 25th September 1997** Vol. 33 No. 20

**Widely tunable 1.5μm micromechanical optical filter using AlOx/AlGaAs DBR**

M.S. Wu, G.S. Li, W. Yuen and C.J. Chang-Hasnain

**Indexing terms:** Micromechanical devices, Optical filters

The authors demonstrate, for the first time, a wavelength tunable optical filter at 1.55 μm using micromechanical tuning of a Fabry-Perot resonator with an AlOx/AlGaAs distributed Bragg reflector (DBR). The use of thermally oxidised AlAs layers, resulting in an ultrawide bandwidth, dramatically increased the tuning range and efficiency of the resonator. Very efficient continuous tuning of > 90 nm with only a 0.95 V tuning voltage was achieved. The tuning range, limited by our test laser, is expected to be expandable to hundreds of nm.

**Introduction:** Wavelength division multiplexing (WDM) has shown great promise for increasing the transmission bandwidth and the routing capability in optical communications [1]. An ideal filter for WDM applications would have a wide and continuous tuning range, low tuning power, low insertion loss, high extinction ratio, no polarisation dependence, simple coupling and simple fabrication to facilitate 2D arrays. Recently, using a micromechanical tunable Fabry-Perot (FP) as the basic structure, widely tunable surface-normal filters [2], detectors [3, 4], and lasers [5, 6] have been demonstrated, all with record tuning ranges and possessing many of the desirable attributes.

These micromechanical tunable resonators typically have an air-gap cavity sandwiched by dielectric or semiconductor distributed Bragg reflectors (DBR). A semiconductor DBR consists of alternating mirror layers with desired reflectivity. For a double phasar DBR, for example, the dielectric characteristics are given by the double phasar reflectivity over its dielectric counterparts [4, 6].

In this Letter, we report the first operation of a micromechanically tuned wavelength-tunable resonant cavity device employing deflection of an oxide-based DBR. We demonstrate a wavelength tunable filter operating at 1.55 μm with a wide continuous tuning range of > 50 nm. We further demonstrate very efficient tuning which requires only a 0.95 V change in tuning voltage to cover the entire 50 nm range.

**Design and fabrication:** The filter was designed to use a p-doped AlOx/AlGaAs top DBR and an n-doped regular semiconductor bottom DBR. The top mirror is freely suspended above the bottom mirror using a cantilever geometry [2] to form an air-cavity FP resonator. By reverse biasing the pn-junction, the voltage potential between the two DBRs causes electrostatic deflection of the cantilever and the top DBR towards the substrate and consequently tuning of the resonant wavelength.

To illustrate the advantages of thermally oxidised mirrors, we first compare the predicted performance of three tunable resonator designs. The number of mirror pairs for each resonator was chosen to give a reflectivity of ~0.985. The resonator designs are outlined in Table I. Design A uses a material choice which was previously used to form a tunable filter [2]. Design B uses materials that provide the maximum index difference that can be achieved in the AlGaAs system. Design C uses materials to illustrate the potential performance of AlOx/AlGaAs DBR.

The use of the oxide DBR yields three primary advantages. First, the bandwidth is much wider than that of AlGaAs mirrors. For the bottom mirror of each design outlined above, the mirror
incorporating thermal-oxide based DBRs with micromechanical structure design results in a dramatic increase in tuning efficiency, with a potential range of hundreds of nm. This design can be readily adapted to tunable vertical cavity lasers and detectors, and opens a wide window of opportunities for wavelength translation.

**Conclusion:** We have demonstrated, for the first time, the successful fabrication and operation of a novel tunable optical filter using AIO/AlGaAs DBR on a movable mechanical cantilever. We achieved > 50nm tuning with < 1V tuning voltage at 1.55μm. The tuning range is currently limited by our test laser and the tuning efficiency is the highest reported to date. This oxide DBR micromechanical structure design results in a dramatic increase in tuning range and tuning efficiency, with a potential range of hundreds of nm. This design can be readily adapted to tunable vertical cavity lasers and detectors, and opens a wide window of opportunities for wavelength translation.

**Table 1: Resonator designs**

<table>
<thead>
<tr>
<th>Resonator</th>
<th>DBR material</th>
<th>Index ratio</th>
<th>No. of mirror pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Al₉Ga₈As/Al₉Ga₈As</td>
<td>3.32/3.07</td>
<td>20 1/2 22</td>
</tr>
<tr>
<td>B</td>
<td>GaAs/AlAs</td>
<td>3.37/2.89</td>
<td>12 1/2 15</td>
</tr>
<tr>
<td>C</td>
<td>Al₉Ga₈As/Al₂O₃</td>
<td>3.32/1.55</td>
<td>2 1/2 3</td>
</tr>
</tbody>
</table>

Secondly, because of the large index difference, high mirror reflectivity can be obtained with very few mirror pairs. To form a 98% reflector, only two mirror pairs are required if thermal oxide is used. In contrast, 12 GaAs/AlAs pairs and 20 AlGaAs pairs are required. The small number of pairs required allows for much shorter growths and a shorter mirror penetration depth.

Finally, variations in air spacer thickness are more efficiently translated into variations in resonant cavity wavelength, resulting in a higher tuning efficiency, as illustrated in Fig. 1. For a 300nm tuning of the air gap spacer thickness, 55, 80 and 220nm of resonant wavelength tuning is achieved for designs A, B and C, respectively. The effect of spacer thickness variation is much stronger for the thermal oxide DBR, resulting in a lower voltage for a given tuning range. Furthermore, as illustrated in Fig. 1b, the FSR of the thermal DBR structure is > 500nm. Therefore, single wavelength tuning can be achieved over a 500nm spectral observation window.

![Fig. 1 Resonant wavelength against air gap thickness for each cavity design](image)

- Oxide mirror (design C) shows more efficient tuning
- FSR of oxide mirror cavity (design C)

![Fig. 2 SEM photograph of oxide-DBR filter](image)

- 3D view showing tuning contact
- Profile view of mirror showing that only 2 1/2 mirror pairs are required for high reflectivity mirror

A wavelength tunable filter using a thermally oxidised layer in the top DBR was implemented to demonstrate the feasibility of incorporating thermal-oxide based DBRs with micromechanically tuned Fabry-Perot resonators. The filter was designed to operate at a centre wavelength of 1.5μm. The filter epitaxial structure is composed of a 14 period GaAs/AlAs bottom DBR, a 2 1/2 period movable oxide DBR and a 1.4μm sacrificial GaAs layer which forms the tunable air spacer and cavity after being etched away. Gold contacts were deposited and patterned using standard lift-off techniques. The cantilevers were defined using an anisotropic dry etch and released using selective isotropic dry etching to remove the GaAs layer. The devices were then exposed to steam at 400°C to oxidise the top DBR. An SEM photograph of the finished device and a close-up of the top oxidised DBR are shown in Fig. 2. Only 2 1/2 mirror pairs are required to form a high reflectivity mirror.

![Fig. 3 Filter tuning spectra](image)

Measurement tuning range is limited by laser tuning range

**Experimental results:** The device performance was measured using a wavelength tunable laser from EOSI Inc. The laser is tunable from 1580 to 1530nm which substantially limited the testable range of the filter. The filter tuning spectra is illustrated in Fig. 3. Tuning was observed over a wavelength range of 50nm, limited by the tuning range of the laser source. Very efficient tuning was observed, with only a 0.95V change in applied tuning voltage required to tune across the entire 50nm range. The reduced transmission at wavelengths < 1550nm was due to the reflectivity mismatch between the top and bottom mirrors caused by a growth error in the bottom semiconductor mirror which led to red-shifting of the DBR band. This reflectivity mismatch could be removed in filter designs by using thermal oxide mirrors for both the top and bottom mirror to ensure a better reflectivity match, or by more stringent control of the epitaxial growth. The insertion loss is 5–10dB, mostly due to the lack of antireflection coating, mirror band mismatch, optical coupling loss and n-substrate absorption. All of these could easily be improved. Finally, the passband width is ~8nm. It can be made narrower by improving the mode-matching between the input fibre optics and the FP cavity, and by increasing the DBR reflectivity.

M.S. Wu, G.S. Li, W. Yuen and C.J. Chang-Hasnain (EECS Department, University of California at Berkeley, Berkeley, CA 94720, USA)
Hybrid dielectric/metal reflector for low threshold vertical-cavity surface-emitting lasers

M.R. McDaniel, D.L. Huffaker and D.G. Deppe

Indexing terms: Vertical cavity surface emitting lasers, Semiconductor device manufacture, Semiconductor device metallization

Data are presented on a hybrid dielectric/metal reflector made from MgF/ZnSe/MgF/Au for use on vertical-cavity surface-emitting lasers. This hybrid design can reduce the thickness of the top mirror to 0.75 μm for a wavelength of 1.5 μm, while also achieving high reflectivity. The authors demonstrate a mirror on vertical-cavity surface-emitting lasers with a sub-100 μA threshold.

The mirrors of vertical-cavity surface-emitting lasers (VCSELs) have a great impact on the device fabrication and performance. Although the most common approach used today involves p and n-doped semiconductor distributed Bragg reflectors (DBRs), these mirrors are limited by their optical loss due to doping [2], diffusion loss due to low contrast [1], and thickness due to low contrast. As active region sizes in VCSELs are reduced and new applications evolve such as flip-chip mounting onto Si, there will be renewed motivation for developing very low loss mirrors for ultra small, low threshold, and low profile designs for easy device integration. Reducing the mirror thickness is especially important for the top side of the device to facilitate intracavity electrical contact while maintaining surface planarity.

One approach for reducing the mirror thickness is with high contrast dielectrics and with dielectrics with metal overcoating. Of the high contrast dielectrics, MgF/ZnSe DBRs formed by electron beam deposition [3] and AlOx/AlAs DBRs [4] formed by selective oxidation [5] have been successfully applied to VCSELs, while dielectrics with metal overcoating have used TiO2/SiO2/AU and AlAs/ GaAs/Ag [6, 7]. The hybrid dielectric/metal combination presents an interesting limit in reducing the mirror thickness while achieving high reflectivity, and in this Letter we present studies of a new dielectric/hybrid reflector based on MgF/ZnSe/MgF/Au, demonstrating a lasing threshold of sub-100 μA. The device structure has attractive features for flip-chip mounting onto Si integrated circuits.

A schematic cross-section illustrating the VCSEL structure is shown in Fig. 1. The device is grown by molecular beam epitaxy and is based on a single 60 Å In0.53Ga0.47As quantum well placed at the edge of a GaAs half-wave spacer. Electrons are injected into the quantum well through a 30 Å AlAs tunnel barrier on the n-side of the device [8]. The bottom mirror consists of an n-type 26 pair AlAs/GaAs DBR. The semiconductor structure is completed with a 2 μm GaAs layer followed by a 200 Å thick p-AlxGa1-xAs etch stop and a 2 μm p-GaAs contact layer. The device processing proceeds by first defining lift-off Ti/Au/Ni metal ring contact on the p-type GaAs, with the metal having a 30μm outer and a 10μm inner diameter. Reactive ion etching is then used to form a 30μm outer/10μm inner diameter mesa from the 2μm thick p-type GaAs using the metal contact as a mask. The inner 10μm hole is then covered with photoresist, and the remaining p-GaAs, p-AlxGa1-xAs etch stop, and 2μm p-GaAs layers outside the mesa are removed by selective wet etching. Oxidation is performed for ~3min at 465°C to form 3-5μm square apertures, and provide current and index confinement. Using a photore sist mask and the p-GaAs mesa to facilitate lift-off, the p-AlxGa1-xAs etch stop layer is selectively removed from the 10μm inner diameter region with the recessed region and then filled with dielectric or hybrid dielectric/metal reflectors, completing the lasing cavity illustrated in Fig. 1.

Reference

Fig. 1 Schematic cross-section of VCSEL structure

Fig. 2 Continuous-wave, room temperature light against current curves for 2.5 and 3.5 pair MgF/ZnSe/MgF/Au mirror VCSELs

300 K, CW
(i) 2 pairs MgF/ZnSe/Au, 5μm
(ii) 3 pairs MgF/ZnSe/Au, 3μm

Light against current curves under continuous-wave, 300K operation for devices with 2.5 and 3.5 pair MgF/ZnSe/MgF/Au mirrors are shown in Fig. 2. The last MgF layer thickness for each mirror is adjusted to yield a constructive phase shift when combined with the Au. The output powers are low due to the small transmission through the n-doped AlAs/GaAs DBR. The total thickness for the 2.5 pair MgF/ZnSe/MgF/Au mirror is 0.725μm, and for the 3.5 pair MgF/ZnSe/MgF/Au mirror is 0.98μm. The differences in the maximum power outputs are due to the difference in device sizes. The 3μm diameter VCSEL with the 3.5 pair MgF/ZnSe/MgF/Au mirror exhibits a slightly higher slope efficiency of 5% and a sub-100μA threshold current of 91μA. The 5μm diameter VCSEL with the 2.5 pair MgF/ZnSe/MgF/Au mirror has nearly the same threshold current density but a higher threshold current of 296μA. The oscillations in the above threshold light against current curves are due to reflections from the n-