5-22-2009

Design of a Wide Bandwidth Switchable Mirror Based on a Liquid Crystal Etalon

Enkh-Amgalan Dorjgotov
Kent State University - Kent Campus

Philip J. Bos
Kent State University - Kent Campus, pbos@kent.edu

Achintya Bhowmik

Follow this and additional works at: http://digitalcommons.kent.edu/cpippubs

Part of the Physics Commons

Recommended Citation

This Article is brought to you for free and open access by the Department of Chemical Physics at Digital Commons @ Kent State University Libraries. It has been accepted for inclusion in Chemical Physics Publications by an authorized administrator of Digital Commons @ Kent State University Libraries. For more information, please contact earicha1@kent.edu, tk@kent.edu.
Design of a wide bandwidth switchable mirror based on a liquid crystal etalon

E. Dorjgotov, A. Bhowmik, and P. Bos

Chemical Physics Interdisciplinary Program, Liquid Crystal Institute, Kent State University, Kent, Ohio 44242, USA

Intel Corporation, Santa Clara, California 95054, USA

(Received 23 January 2009; accepted 8 April 2009; published online 22 May 2009)

We propose the design for a switchable mirror with high efficiency and a 30 nm bandwidth. The device is based on a liquid crystal filled etalon. Broad bandwidth is achieved through the use of integrated half-wave layers into the dielectric stack design, while high efficiency is achieved using a polarization independent liquid crystal effect. Potential applications in the area of displays are also presented. © 2009 American Institute of Physics. [DOI: 10.1063/1.3130122]

I. INTRODUCTION

Etalons are usually considered as narrow bandwidth transmission filters whose transmission is not very high. However, they can be designed for broader bandwidth, high transmission applications, and can also be considered as high reflectivity pixels for color displays. With the rapid commercialization of portable electronic devices such as portable media players, cell phones, personal digital assistants, mobile internet devices, netbook, and notebook computers, the need for sunlight readable power efficient displays is becoming ever more important. Constant improvements in contrast, color saturation, and viewing angle properties made thin-film transistor liquid crystal (LC) displays the dominant technology in both portable and large screen direct view display applications. However, polarization dependent operation of LC displays combined with side-by-side color pixel structure makes the current technology very inefficient for use in battery operated portable devices. Current devices lose more than ~50% of the light due to absorption of polarizers and lose additional ~67% due to the color filters in the side-by-side subpixel structure. As a result new technologies are being considered such as the iMoD displays from Qualcomm. 

Their device works in the same way as Fabry–Perot interferometer or an etalon such that the reflected light is tuned by mechanically changing the spacing between parallel mirrors.

In a LC based etalon, unlike conventional LC displays, tunability is achieved directly by phase retardation rather than polarization rotation effect and as a result it can be made polarization insensitive. In addition, refined mirror design and advanced LC materials with high birefringence would open possibility for stacked pixel design, which would further increase the efficiency of the color display to unparalleled level.

In this paper we will explore a LC etalon device that employs low loss dielectric mirrors and high birefringence nematic LC mixture. We have considered different approaches to design a tunable LC etalon device. First, design of a simple quarter wave (λ/4) stack with LC layer in the middle is considered. We calculated relative brightness and contrast ratio for 30 nm wide green spectrum and investigated ways to optimize them. We then propose a λ/4 stack mirror design with integrated half-wave (λ/2) layers and LC layer. The contrast ratio of this design is significantly better. Finally, a modification that allows for a polarization independent operation is demonstrated.

II. DESIGN OF LIQUID CRYSTAL ETALON DEVICE

In this section we will introduce the basics of tunable parallel-plate etalon device with the cavity filled with LC material. In a simple parallel-plate etalon incident light undergoes multiple reflections within the cavity and interferes with itself (see Fig. 1). Transmittance of the etalon is determined by several parameters including reflectivity of the plates, cavity thickness, and refractive index of the medium. For normally incident light transmittance can be written as follows:

\[ T = \frac{T_a T_b}{(1 - \sqrt{R_a R_b})^2} \left[ 1 + \frac{4R_a R_b}{(1 - \sqrt{R_a R_b})^2} \right] \times \sin^2 \left( \frac{\phi_a + \phi_b - \delta}{2} \right) \]  

(1)

Here, \( T_{a,b} \), \( R_{a,b} \) are transmittance and reflectance of parallel mirrors, \( \phi_{a,b} \) is phase shift on reflection from the mirrors and \( \delta = (2 \pi d / \lambda) \). If the absorption is negligible, then reflectance of the etalon is simply \( R = 1 - T \), which has minimums and

![FIG. 1. Parallel plate Fabry–Perot etalon.](image-url)
maximums under conditions given by Eq. (2),
\[
(nd)_{\text{dark}} = \frac{\lambda_0}{2} m, \quad (nd)_{\text{bright}} = \frac{\lambda_0}{2} \left( m - \frac{1}{2} \right)
\]
where,
\[
m = 1, 2, 3 \ldots
\]

Optical path length of the cavity, \(nd\), is the primary variable by which the etalon reflectance is tuned. In mechanical etalon device tunability is achieved by changing the physical thickness of the cavity, whereas in LC etalon device reflectance is tuned by switching effective index of the cavity by applied electric field. Nematic LC is characterized by an orientational ordering, which is defined by unit vector (the director) along the average direction of elongated molecules’ long axis. Light polarized along and perpendicular to the director axis experiences different indices of refraction, which are called the extraordinary and ordinary LC indices.

It can be seen from Eq. (2) that the ratio between effective indices of the dark and bright states reduces as the order of the device gets higher \((n_{\text{dark}}/n_{\text{bright}} = m/(m-1/2))\) \(m = 1, 2, 3 \ldots\). This means that if the LC index is to switch from first order \((m=1)\) dark state to first order bright state then the required change in index is much larger than if it is to switch between higher order dark and bright states. It should be noted here, however, that the condition for high reflectivity is valid only at the center wavelength, \(\lambda_0\), so for other wavelengths the condition may not be met. This wavelength dispersion effect of reflectance gets severe as the order of the device increases and as a result lowest possible order device, which requires high birefringence LC material is needed. Although state of the art materials with birefringence as high as 0.6 is reported, current commercially available LCs have birefringence not more than around 0.3.

For high efficiency devices the simplest solution is to use dielectric mirrors that consist of stack of alternating high and low index material. In this design LC layer in the etalon cavity (between two mirrors) switches between \(\lambda/4\) and \(\lambda/2\) states to get high and low reflectances. When the LC layer is in \(\lambda/4\) state constructive interference of reflections from each dielectric interface result in reflectance maximum, and when it switches to \(\lambda/2\) state reflection from top half of the mirror destructively interferes with that from bottom half and reflectance minimum occurs. However, reflectance rises as the wavelength diverges away from the center wavelength where the dielectric stack is tuned. Such light leakage outside the center wavelength but within the operating spectrum decreases the contrast of the device.

In order to increase the contrast of the device light leakage outside the center wavelength in the dark state must be suppressed. For broader dark state it is possible to couple several \(\lambda/4\) stacks separated by \(\lambda/2\) layers in order to get multiple reflection minimums. This is referred to as a multiple cavity filter. For example, Fig. 2 shows a simple series in which three reflector stacks consisting of alternating \(\lambda/4\) layers (in dark) conjoined by two \(\lambda/2\) layers (in white). It is intuitive to think of the total reflection from the series as the sum of reflections from individual parts. Then reflection from the subseries, which consist of top two reflectors sandwiching the first \(\lambda/2\) layer, has minimum at the center wavelength (V-shaped reflection), whereas reflection from the bottom reflector has maximum at the center wavelength. Total reflection of the series is the difference between reflections from the subseries and the bottom reflector because they are conjoined by the second \(\lambda/2\) layer and are out of phase. If the amplitudes of these reflections are comparable, then there will be two minimums in the total reflection at the intersection points where these reflections are equal (W-shaped reflection). Similarly if third \(\lambda/2\) layer and another reflector consisting of \(\lambda/4\) stack are added in the series, then the resultant total reflectance would be the difference between W-shaped reflection coming from the subseries, which consist of three reflectors and two \(\lambda/2\) layers, (the stack of Fig. 2) plus the reflection from the fourth reflector. In this case it is not hard to imagine that depending on the reflection amplitudes, it is possible to have up to four minimums in the total reflection.

In our proposed design we integrated two \(\lambda/2\) layers within the dielectric mirrors and tuned the LC cavity between \(\lambda/2\) and \(\lambda/4\) states (see Fig. 3). When the LC is in \(\lambda/2\) state, etalon resembles the series with three \(\lambda/2\) layers.
[Fig. 3(a)], whereas when the LC is in \( \lambda/4 \) state, etalon becomes series with two \( \lambda/2 \) layers [Fig. 3(b)]. The main goal of the design is to achieve broadband dark state with minimum light leakage when the LC is in \( \lambda/2 \) state and to maximize the bright state reflection when the LC switches to \( \lambda/4 \) state. In order to increase the bandwidth of the dark state, total reflectance minimums, where reflectance 1 and 2 intersect, must be far apart [right plot in Fig. 3(a)]. This means the width of W-shaped reflection from the subseries, which consist of two \( \lambda/2 \) layers and three reflector stacks, must be increased. This in turn requires the width of V-shaped reflection from the sub-subseries, which consist of single \( \lambda/2 \) layer and two reflector stacks, to be wide (the “reflectance 1” curve in Fig. 2). There are two ways to increase the width of this reflection, which are to increase the ratio of high and low index materials, or to decrease the number of layers in the \( \lambda/4 \) stack. In addition to increasing the dark state bandwidth, it is also important to keep the light leakage in the dark state as low as possible, which means the amplitude of reflections from the subseries (W-shaped reflection) and the bottom reflector stack must be comparable near their intersection points. In general this is done by keeping the reflections of two inner \( \lambda/4 \) stack reflectors comparable to those of two outer \( \lambda/4 \) stack reflectors, which in effect reduce the difference between reflectance 1 and 2 within their intersection points [right plot in Fig. 3(a)]. As for the bright state, the reflection would be maximized if all of the \( \lambda/2 \) layers switched to \( \lambda/4 \). However if only the middle \( \lambda/2 \) layer (the LC etalon) switches to \( \lambda/4 \), then the series becomes similar to that shown in Fig. 2. In this case however, the reflectance of the middle \( \lambda/4 \) stack reflector is much higher than that of the outside \( \lambda/4 \) stack reflectors and reflections from two parts of the series do not intersect [right plot in Fig. 3(b)]. As a result total reflectance of the series has slight dip at the center wavelength without touching zero.

In summary, the dark state bandwidth of a \( \lambda/4 \) dielectric
stack with triple \(\lambda/2\) layers increases with increasing ratio of high and low index materials and with lowering of reflectivities of the two inner \(\lambda/4\) stack reflectors. However, reflectivities of the two inner \(\lambda/4\) stack reflectors must be comparable to those of outer \(\lambda/4\) stack reflectors for minimum light leakage. If all reflectivities are reduced, then the reflectance in the bright state is also reduced. As a result the bandwidth and the light leakage of the dark state and the reflection of the bright state must all be balanced according to the specific application requirements.

In these etalon designs the theoretical reflectance is limited to less than 50% of an unpolarized incident light because polarization sensitive LC operation requires a polarizer that absorbs more than half of the incident light. If the tunable LC layer within the etalon cavity has made polarization insensitive, then the etalon brightness will be enhanced by twofold. A method to achieve polarization insensitive transmissive LC etalon operation has been published by the authors.7 In this paper we extend the method to reflective LC etalon operation.

It was shown in Eq. (2) that the reflectance is maximized when \(nH_{\perp} = \) an odd multiple of a quarterwave. In a homogeneous nontwist LC medium, the eigenmodes of light propagation are linearly polarized modes corresponding to LC ordinary and extraordinary indices. The total reflectance becomes the sum of these modes, only one of which is tunable. Previously it was shown by the authors that polarization independent LC etalon operation can be achieved if the phase shift on reflection from the mirrors and the phase conditions for etalon resonance for the two eigenmodes is tuned by having twist LC structure.7 Instead of reducing the phase difference between the eigenmodes, polarization independent LC etalon operation is achieved by simultaneously satisfying different orders of resonances for the elliptically polarized eigenmodes. Phase shift on reflection from the dielectric mirrors required the difference in the phases of the eigenmodes to be integer multiple of \(2\pi\). For reflective LC etalon, eigenmodes of the light propagation must acquire different orders of resonance condition where \(nH_{\parallel} = \lambda n/2\) and \(nH_{\perp} = \lambda n/2\) with \(m = 1, 3, 5\) and \(n = 1, 3, 5\) but \(n \neq m\). This means the difference between \(m\) and \(n\) is an even number and the condition arising from the phase shift on reflection from the dielectric mirrors is always satisfied. Once the mirror reflectivity, LC cavity thickness, and material parameters are known, the LC twist angle that reduces the polarization sensitivity will be found and be implemented in the design.

In our design we will optimize the etalon mirrors for green wavelength region ranging from 510 to 540 nm. In Sec. III, we will numerically calculate reflectance of different designs of LC etalon and will analyze them in terms of brightness and contrast.

III. NUMERICAL MODEL

In this section we will numerically simulate two different LC etalon designs for green wavelength region from 510 to 540 nm. Optical reflectance of the LC etalon was calculated by dividing the entire structure into finite number of layers of individual optical elements. Numerical method that we used was \(4 \times 4\) matrix formulation,8 which is a direct solve of Maxwell’s equations in one dimension. First we consider a polarization dependent LC etalon where dielectric mirrors consist of stack of alternating high and low index \(\lambda/4\) materials. Then we consider our proposed design with integrated \(\lambda/2\) layers, which has wider dark state and better contrast. For these designs homogeneous LC structure was modeled for polarized light source as dielectric medium with constant refractive indices and total reflectance is halved for polarization loss. After introducing these designs we will modify the design to be polarization independent. In this case twist LC director structure was calculated by minimizing the free energy, which consists of Frank–Oseen9,10 elastic energy and electric energy due to applied field. Material parameters of the modeled LC were same as that of BL009 from Merck \((\varepsilon_{||} = 21, \varepsilon_{\perp} = 5.5, \gamma \sim 0.083\) Pa S, \(K_{11} \sim 14.6\) pN, \(K_{22} \sim 7\) pN, \(K_{33} \sim 29.9\) pN), which has birefringence near 0.29. We modify the birefringence and keep other material parameters the same for high birefringence designs. We ignore the effects of glass substrates, conducting and alignment layers in the optical calculations because they can be minimized and or compensated in real devices. Calculated reflectances were normalized by incident unpolarized light.

It is preferable to have a low order etalon device in order to minimize the wavelength dispersion effects on reflectance. A typical nematic LC material has ordinary index of refraction around 1.53, and if we choose to make this index correspond to dark state, then thickness of the first order device for 525 nm wavelength is calculated using Eq. (2) to be \(\sim 0.172\) \(\mu m\). Using the same equation we can calculate the required extraordinary index of the LC to tune from first order dark state to first order bright state to be around \(\sim 2.29\). This is birefringence in excess of 0.7, which is not practical and as a result order of the device is increased to reduce the required birefringence. It can be further calculated using Eq. (2) that the required birefringence for second order device is \(\sim 0.4\) and that for third order device is \(\sim 0.3\). In our design etalon mirrors are modeled as stack of alternating layers of high and low index \((n_{H} \sim 2.27, n_{L} \sim 1.63)\) dielectric materials tuned to be \(\lambda/4\) at 525 nm. For enhanced reflectivity we simply increased the ratio between high and low indices of the dielectric materials.

Calculated reflectance spectrum of unpolarized incident light for first to third order LC etalon devices are shown in Fig. 4. It shows that low order device has better contrast as a result of small light leakage in the dark state. In addition low order device has higher reflectance in the bright state because of the increased index mismatch at the interface of dielectric mirror and LC layer. Note that the dielectric mirrors were designed only for 30 nm wide green region of the visible spectrum and LC etalon reflectance is optimized in this region only. The inset in Fig. 4 shows reflections outside the optimized region (in gray shade). Figure 5 shows the reflectance spectrum of LC etalon with high reflectivity mirrors. In this design mirror reflectivity is enhanced by increasing the ratio between high and low index materials. In comparison to the previous design the reflectance of the etalon in the bright state is increased considerably. However, light leakage out-
side the center wavelength region in the dark state is elevated and as a result contrast of the device is not so high.

It was mentioned in Sec. II that etalon with single $\frac{\lambda}{2}$ layer sandwiched between two $\frac{\lambda}{4}$ reflector stacks, as shown in Figs. 4 and 5, has low contrast because of the reflection rise outside the center wavelength. If additional $\frac{\lambda}{2}$ layers and reflector stacks are inserted within the etalon, then the contrast is improved as a result of wider dark state bandwidth. With the constraints introduced in Sec. II we have modeled LC etalon with two integrated $\frac{\lambda}{2}$ layers in the dielectric mirrors. Index ratio was maximized ($n_H \sim 2.27$, $n_L \sim 1.38$) for broad dark state at the same time maximizing the bright state reflectivity. Number of layers in the inner and outer $\frac{\lambda}{4}$ stacks was optimized so that reflectance in the bright state is maximized at the same time keeping the light leakage in the dark state minimized. Figure 6 shows reflectance spectrum of unpolarized incident light on third order etalon device with integrated half-wave layers. Design IIA (solid curve) has considerable light leakage in the dark state that goes up to 10% along the edges of the spectrum. Dashed curve shows increased dark state bandwidth as a result of reduction in the reflectivity of the inner $\frac{\lambda}{4}$ stacks. This is done by changing the indices of the two dielectric materials next the LC layer (...$n_Ln_{LC}n_H$...) from 2.27 to 1.95. However, reduced inner $\frac{\lambda}{4}$ stack reflectivity results in drop in the bright state reflectance at the center wavelength region. Similarly reflectivity of the outer $\frac{\lambda}{4}$ stack can be reduced by lowering the index of the outermost high index materials from 2.27 down to 1.95. In this case dark state bandwidth is narrowed and the reflectance in the bright state is higher (dotted curve). As with the previous design reflections outside 30 nm wide green region must be suppressed (shaded area in the inset of Fig. 6) with the help of additional absorptive color filters in a display device.

It is interesting to see how the order of the etalon affects the reflectance spectrum in integrated half-wave design. Figure 7 shows reflectance spectrum of the same LC etalon that is shown in Fig. 6 except this time LC layer thickness is decreased by one order. As with the $\frac{\lambda}{4}$ stack mirrored etalon design integrated half-wave etalon design has broader dark state as the order of the device decreases. At the same time however, light leakage is slightly increased just outside the 525 nm region and the average reflectance is lowered in the bright state.

For high efficiency, as mentioned in the introduction, we consider a twisted LC device to yield a polarization independent device. As the LC twist angle increases, the polarization of eigenmodes changes from pure linear modes to elliptically polarized modes and the effective indices approach the average of ordinary and extraordinary indices. This means that the effective index in the field off state decreases with high twist rate, whereas that in the field on state stays the same. As a result switching between $\frac{\lambda}{2}$ and $\frac{\lambda}{4}$ states requires
higher birefringence material in twisted LC etalon than in nontwist LC etalon. In the quarter-wave stack LC etalon design, first and second order etalons require birefringence $\Delta n / H \approx 0.4$ and $\Delta n / H \approx 0.7$ for a nontwisted LC layer (see Fig. 2). A twisted configuration would require even higher value of birefringence, which is not practical. However, the third order device with integrated half-wave stack design shown in Fig. 6 requires birefringence of only $\Delta n / H \approx 0.25$. For this device we need to find the twist angle that satisfies the resonance condition, which is consistent with the requirements of the phase shift on reflection from the mirrors. Using Eq. 6 in the reference paper we have calculated the relative phase difference between the eigenmodes as function of twist angle (left plot in Fig. 8) and found the lowest twist angle at which the phase difference is integer multiple of $2\pi$ (at $\approx 170^\circ$). We then calculated the acquired phases of the eigenmodes at this twist angle (right plot in Fig. 8) using Eq. 5 in the reference paper and found them to be $4.4\pi$ and $2.4\pi$. They are not odd multiple of $\pi/4$ and as a result resonance condition for reflectance maximum is not fully satisfied. However, if the material birefringence is 0.25, then at this twist angle LC etalon is least polarization sensitive for the wavelength region near 525 nm. To confirm our result we calculated the average reflectance for different twist angle and plotted in Fig. 9. It shows that the optimum twist angle at which the reflectance is maximum is between $150^\circ$ and $180^\circ$, which is consistent with our predictions. Although reflectance is increased significantly compared to design IIA in Fig. 6, it is not twice higher than the polarization sensitive reflectance. This is due to the fact that effective birefringence of the twist LC structure is much lower than the nontwist LC structure. As a result higher birefringence LC material is needed in order to further increase the reflectance of the polarization insensitive etalon. Figure 10 shows the reflectance of polarization insensitive etalon where the birefringence of the material is 0.3 and 0.4.

IV. DISCUSSION

In Sec. III, the numerical calculation results of a modeled etalon that operates over 30 nm wide spectrum spanning...
In the designs of LC etalon device we did not discuss about unwanted reflections outside the spectrum bandwidth. The simplest solution would be to have cutoff color filters that absorb incident light outside the design spectrum. However, such design would force side-by-side color pixel structure as in conventional LC displays, which would reduce the reflectance efficiency by more than 1/2. If dielectric mirrors are designed such that incident light outside the design bandwidth is transmitted, then it would result in stackable device where brightness efficiency would be near to those shown in Table I over the working wavelength regions.

In calculating the reflectance spectrum of above designs we did not consider the effects of alignment and conducting layers. However, it is possible to incorporate them into the design of the dielectric mirrors. Alignment and conducting layers can be substituted for either high or low index material by adjusting their optical thickness to be λ/4. Further optimizations can be done with precisely tailored dielectric mirror designs where index mismatch and order of the device better serve the overall brightness and contrast of the device.

Finally, we would like to comment on the effects of viewing angle and dielectric mirror dispersion as well as the order selection of the LC etalon on the performance of the device. As Fig. 3(a) shows the reflectivity of the device sharply increases outside the 30 nm design bandwidth. This means that the contrast of the device is reduced for obliquely incident light as a result of increased light leakage coming from the change in apparent thickness of the dielectric stack. Figure 11 shows the comparison reflectances of design IIE for on-axis (solid) and for off-axis incident light (10°-dotted, and 15°-dashed). Numerical calculations indicate that the contrast of the design IIE drops down to about 30 for 10° off-axis light and to mere 10 for 15° off-axis light. Similarly, dispersion of high index dielectric materials can decrease the brightness and contrast of the device. In order to illustrate this effect we modeled dielectric materials of the design IIE as Ta2O5, MgF2, and high birefringence LC mixture of which indices are calculated using Cauchy equation, \( n(z) = A + Bz^2 + Cz^4 \), with \( A_H = 2.16, B_L = -2.00E3, C_H = 3.16E9, A_z = 1.35; B_z = 4.07E3, C_z = 0; \) and \( A_{olr} = 1.44/1.76, B_{olr} = 2.50E4/3.50E4, C_{olr} = 0/3.00E9 \). Dashed line in Fig. 11 shows that the dispersion of the dielectric indices caused the dark and bright state reflectances to shift slightly to the longer wavelength region. In this case average reflectance and contrast of the design IIE is decreased down to ~70% and 55%, respectively. It was shown in Sec. II that the lower order LC etalon has wider dark state bandwidth. As a result of this constraint LC cavity thickness in our design is thinner.

From 510 to 540 nm were shown. We considered different designs for LC etalon device. A quarter-wave stack design with single tunable LC layer has narrow dark state where light leakage outside the center wavelength was quite high. On the contrary λ/4 stack with integrated multiple λ/2 layers had much broader dark state even for high order devices that are required due to the limited birefringence of available LC materials.

Table I summarizes the results of numerical modeling for difference LC etalon device designs. Integrated multiple half-wave design has higher reflectance and contrast compared to λ/4 stack mirror design. Even when the order of the etalon is low (design IB) reflectivity is not as high as the multiple λ/2 design (design IIA). Note that the design IIB has lower reflectance and contrast compared to design IIA even though it is lower order device. This is due to reduced reflectance as a result of lower index mismatch at the LC and high index dielectric interface, as well as elevated light leakage outside the center wavelength region in the dark state.

For polarization independent designs we optimized the twist angle that results in the highest reflectance in the integrated λ/2 design. Reduced effective birefringence due to twist LC structure requires higher LC material birefringence. This can be clearly seen in the Table I as birefringence of the LC approaches 0.4 reflectivity is double that of the polarization dependent design IIA.

<table>
<thead>
<tr>
<th>Design</th>
<th>Polarization sensitive</th>
<th>Polarization insensitive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta n = 0.25 )</td>
<td>( \Delta n = 0.38 )</td>
</tr>
<tr>
<td>Operative spectrum</td>
<td>30 nm</td>
<td>30 nm</td>
</tr>
<tr>
<td>Average reflectance</td>
<td>25%</td>
<td>30%</td>
</tr>
<tr>
<td>Contrast ratio</td>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>
than in most of the commercially available products. However, while manufacturing of thin cells is difficult, the authors have shown elsewhere that the requirement for thickness nonuniformity for submicron cells is not necessarily severe.\textsuperscript{11} In addition, top-end manufacturers are currently producing cells that are 0.7 m thick in high volumes and have stated that thinner cells are possible.\textsuperscript{12}

V. SUMMARY

We have demonstrated LC etalon based switchable mirror, which in one state reflects 30 nm region of the visible spectrum and in the other state transmits it. Bandwidth of the operational spectrum and the amplitude of the reflection were optimized and inclusion of multiple half-wave passive layers found to have superior performance. In addition, polarization independent transmissive etalon operation reported previously by the authors has been extended for reflective device. For reflective etalon relative phase difference between the eigenmodes has to be integer multiple of 2\pi, which satisfies both the requirement for etalon reflectance maximum and the requirement for constructive interference of reflected light from the mirrors.

Numerical model demonstrates that polarization independent reflective device can be designed with reflectance \textasciitilde 70\% and with contrast ratio of 50:1 for 30 nm wide spectrum for LCs with birefringence \textasciitilde 0.3. If high birefringence (\textasciitilde 0.4) LC becomes commercially available, then the reflectance and the contrast can be increased further to 75\% and 60:1, respectively.

\textsuperscript{1}M. Miles, SID Int. Symp. Digest Tech. Papers, 7,3, 71 (1997).
\textsuperscript{5}Licristal-Liquid Crystal Mixtures for Electro-Optic Displays (May 2002, Merck Catalog).
\textsuperscript{12}M. Handschy, Displaytech, Inc., private communication.