APPLIED PHYSICS LETTERS **87**, 201106 (2005)

# Fringing-field minimization in liquid-crystal-based high-resolution switchable gratings

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(Received 8 April 2005; accepted 19 September 2005; published online 9 November 2005)

A liquid-crystal (LC)-based high-resolution switchable grating is proposed by using a double-sided structure, where striped electrodes are patterned on both sides of the LC cell. A unique biasing configuration is employed to successfully minimize the distortion of the LC director profile due to the fringing-field effects under two-dimensional electric fields. A first order diffraction angle of 14.5° with a diffraction efficiency of 33% for transmission light at 1.55 $\mu$m is experimentally achieved. This result approaches the theoretical upper limit of 33.8% for a sinusoidal phase grating. The device efficiency is enhanced 80 times compared to a conventional single-sided device. Experimental results indicate the tolerance of electrode misalignment is 2 $\mu$m. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2130729]

Programmable liquid-crystal (LC) based gratings have been reported for numerous applications, such as three-dimensional displays, reconfigurable optical interconnects, and beaming steering.[1–5] Current efforts have been focused on high-resolution (grating pitch size is comparable to LC cell thickness), two-level and multilevel LC gratings due to the potentials for more switching ports in the optical network and a larger beam deflection tuning range. Investigations of the fringing-field effect, which severely degrades the phase modulation depth of the high-resolution LC grating, were reported by a few groups.[6–9] However, to our knowledge, no efficient solution has yet been found. The conventional structure of a one dimensional, two-level (or binary) LC grating, as shown in Fig. 1(a), consists of a continuous ground plane, a sandwiched nematic LC layer, and an array of striped electrode pixels. LC molecules are initially homogenously aligned in the horizontal direction. By applying a biasing voltage between the ground plane and the electrode pixels, the LC molecules tend to align with the electric field lines and form a specific distribution of the molecule director. In reality, the phase profile of the transmission light is broadened undesirably due to the fringing fields which leak from the edge of the electrode pixels. Especially in high-resolution LC gratings, where the pixel spacing is small, the overlap of the fringing fields from the adjacent openings significantly reduces the modulation capacity and thus limits the diffraction efficiency of the device. A method to increase the resolution was reported where an interdigitated structure, utilizing lateral (fringing) fields rather than transverse (vertical) fields to align LC, was reported.[1,10] However, the modulation capacity of this device is still insufficient to achieve high device efficiency because the effective modulation layer in such a device is much thinner than the actual thickness of the LC cell. This is particularly true for long working wavelengths in the near-infrared (IR) and IR regions. In this letter, we propose a double-sided device structure to solve the problem of the low phase modulation depth in the high-resolution LC gratings working at 1.55 $\mu$m. The schematics of the proposed device configurations are shown in Figs. 1(b) and 1(c). Unlike the conventional structure, where the electrodes are patterned only on one side of the device, our structure has electrode pixels patterned on both the top and bottom sides. By using biasing configuration (A), where all of the pixels on the top side are grounded while all of those on the bottom side are applied by the same voltage, a smaller lateral leakage of the electric fields between adjacent pixels is expected since the transverse fields are more confined between the opposite discrete electrodes. Further improvement can be achieved by using biasing configuration (B), where the biasing voltages are applied between the adjacent electrodes lying in the same plane and also applied between the facing electrodes in the opposite plane. This biasing scheme simultaneously develops a lateral electric field between adjacent

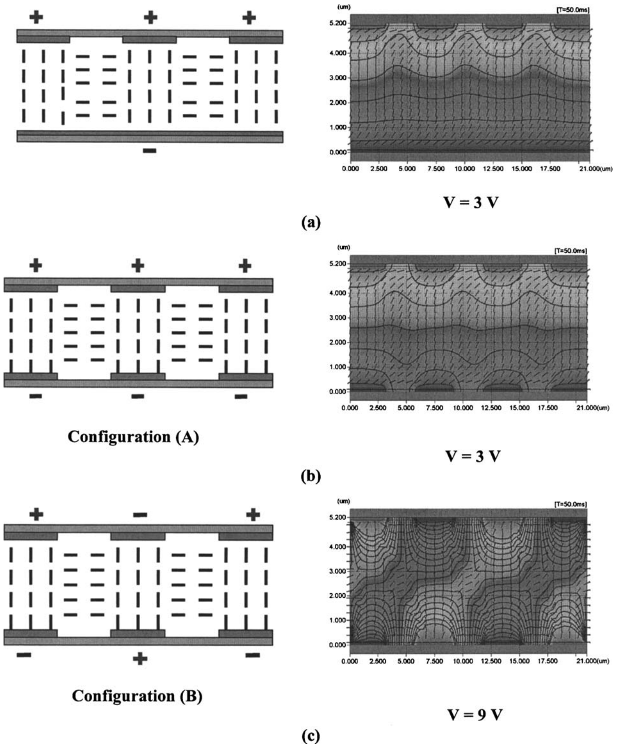

FIG. 1. Schematics of device configurations and the simulated corresponding LC director profiles. (a) Conventional single-sided structure; (b) double-sided structure in biasing configuration (A); (c) double-sided structure in biasing configuration (B).

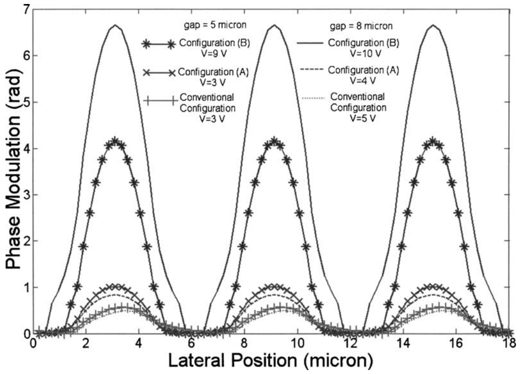

FIG. 2. Simulated phase modulations of the transmitted TE wave under the optimized biasing voltage for the single-sided and double-sided structures with LC layers of 5 $\mu$m and 8 $\mu$m, respectively.

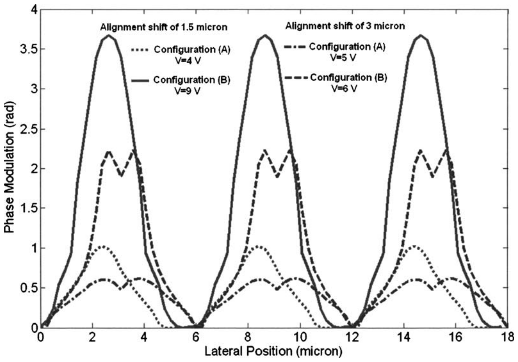

FIG. 3. Simulated phase modulations for double-sided structures in biasing configurations (A) and (B) with electrode misalignments of 1.5 $\mu$m and 3 $\mu$m, respectively.

electrodes and a vertical electric field between opposite electrodes. The distortion of the LC director profile is minimized by the lateral fields and the transverse fields. The lateral fields help maintain the initial alignment of the LC director in the horizontal direction between adjacent pixels and the transverse fields force the LC director above the pixels to align vertically. It is theoretically and experimentally confirmed that this scheme provides an efficient solution to the fringing-field effects in high-resolution LC gratings. With each grating pixel dynamically addressed by a multi-channel electric switch, an efficient beam steering device with large scanning angles can be achieved using the device configuration presented here.

In this work, we use a simulation tool called LCD Master (Shintech Ltd., Japan) to simulate the LC director profile of the devices. This simulator has been shown to be accurate in simulating the LC phase gratings under two-dimensional electric fields.[2,3,6,11] The input parameters for simulating the LC material E7 (Merck) include elastic constants of $k_{11}=11.1$ pN $k_{22}=17.1$ pN, $k_{33}=9$ pN; dielectric constants of $\varepsilon_s=19.0$, $\varepsilon_p=5.2$; and viscosity of $\gamma=0.038$ Pa s. Phase modulation profiles for a normally incident TE wave ($p$-wave) under various biasing conditions are calculated based on the simulated director distribution. High-resolution LC gratings with a pitch size $p_0=6$ $\mu$m, electrode width of 3 $\mu$m, and LC thickness of both 5 $\mu$m and 8 $\mu$m are simulated in this work. Simulated results of the director profile for a 5 $\mu$m thick cell under the optimized voltage, which provides the maximum phase modulation depth, for each configuration are shown in Fig. 1. It is observed that the modulation in the conventional single-sided structure is very weak. The LC director in the lateral region is severely distorted from its desired orientation in the horizontal direction due to the fringing fields. For this conventional structure, the simulation indicates that the best modulation condition occurs under a low biasing voltage of 3 V since a larger voltage introduces even stronger fringing fields. A slight improvement can be observed in the double-sided structure in biasing configuration (A). However, the director distribution is still far from the ideal profile. A much more efficient director modulation, which approaches the perfect spatial alignment, can be achieved with the double-sided structure in biasing configuration (B) by choosing the right biasing voltage. Figure 2 presents the corresponding phase modulations of the transmitted TE wave under the optimized biasing voltages. For the 5 $\mu$m thick LC cell, the maximum phase modulation depths for the single-sided structure and the double-sided structures in configuration (A) and (B) are 0.54 rad, 1.01 rad, 4.15 rad, respectively. One can find the phase profiles are more or less sinusoidal, where the far-field diffraction pattern can be simplified as the first-order Bessel function.[12] The theoretical upper limit of the first order diffraction is 33.8% when the phase modulation depth reaches 3.67 rad (1.17 $\pi$). As shown in Fig. 2, this required 1.17 $\pi$ phase-shift can be fully covered by configuration (B). It is also shown by Fig. 2, that the modulation depth for both the conventional single-sided structure and double-sided structure in configuration (A) decreases when the LC thickness increases. This effect is common for a high-resolution LC grating since the fringing-field effect usually increases with the cell thickness.[1,6,7,10] However, the phase modulation depth of configuration (B) increases to 6.65 rad when the LC thickness increases to 8 $\mu$m. This is because the fringing-field effect has been efficiently suppressed in this unique design. This makes the device more attractive for working in the long wavelength near-IR and IR regions, where the large phase modulation depth is usually even harder to achieve. A thin phase-grating analysis is performed to simulate the far-field pattern by using the Fast-Fourier-Transfer (FFT) algorithm.[12] The simulated maximum first order diffraction efficiencies (not shown here) are ~2% and ~6% for the single-sided structure and double-sided in configuration (A), respectively. In configuration (B), it increases to ~34% which is close to the theoretical upper limit of a sinusoidal phase grating.

The alignment tolerance of the electrode pixels is also investigated. Simulation results of the maximum phase modulation for the double-sided structures, where the top and bottom electrodes are misaligned by lateral shifts of 1.5 $\mu$m and 3 $\mu$m, are shown in Fig. 3. Compared with the phase modulation of the accurately aligned structure shown in Fig. 2, a slight degradation of the phase modulation is observed for the device with a misalignment of 1.5 $\mu$m. When the lateral misalignment increases to 3 $\mu$m, which is the maximum value of the possible misalignment in our structure, the phase modulation of configuration (B) is still much higher than the single-sided structure. The simulated far-field pattern shows that a maximum first order diffraction efficiency of 22% can be achieved in our double-sided structure with a misalignment of 3 $\mu$m, which is much larger than the simulated maximum efficiency of 2% for the conventional single-sided device.

Both the single-sided and double-sided devices (with and without lateral misalignment) were fabricated. An array

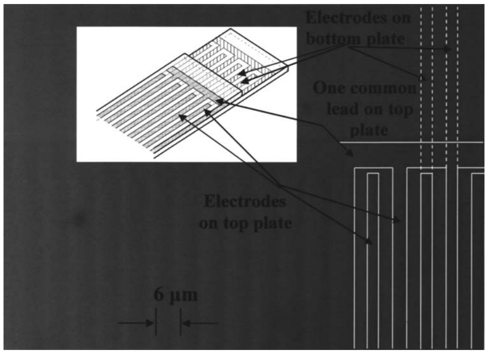

FIG. 4. Top view of the accurately aligned electrodes. Each plate has two groups of interdigited electrodes, each group being connected by a common lead. The frames are added for visual guide. The bottom plate is shifted toward the top of the picture to show the electrodes on the bottom plate, which have a less vivid green color than the ones on the top.

of 3 $\mu$m wide and 2 mm long striped electrodes were patterned on ITO coated glass by conventional photolithography and wet etching techniques. For the double-sided grating, the top electrodes and bottom electrodes were aligned by using a conventional photolithography mask aligner. A fixture is designed to attach the top glass plate to the mask holder of the aligner, and the bottom glass plate sits on the wafer holder. Figure 4, taken through the microscope of the aligner, shows the accurate alignment of the top and bottom striped electrodes. 5 $\mu$m glass microbeads were used to form a uniform cell gap. A nematic LC material with a positive dielectric anisotropy E7 (Merck) was filled into the cell. A TE wave of 1.55 $\mu$m was used for the optical characterization. An ac voltage at 150 Hz was provided by a function generator.

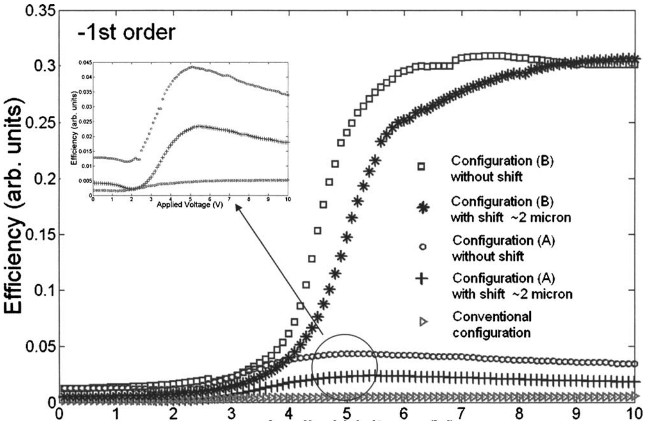

FIG. 5. Measured values of the first order diffraction efficiencies of the conventional single-sided structure and the proposed double-sided structures, with and without electrode misalignments.

The primary diffraction of the device, i.e., the first order diffraction at 14.5°, for the single-sided and double-sided structures (with and without lateral misalignment) in biasing configuration (A) and (B) are characterized. The diffraction intensity is normalized to the transmission intensity of the grating when there is no biasing voltage applied. The measurement results are plotted in Fig. 5. Compared with the single-sided structure, which has a maximum diffraction efficiency of 0.4%, the diffraction efficiency of the double-sided devices is greatly enhanced. For the double-sided structure with precise electrode alignment, the maximum diffraction efficiencies in biasing configuration (A) and (B) are 4.5% and 33%, respectively. Both results match well with the simulated results of 6% and 34%. An 80-time enhancement of the diffraction efficiency of the newly designed structure, with respect to the conventional single-sided structure, is experimentally confirmed. The influence of electrode misalignment on the device efficiency was experimentally studied. When there is a 2 $\mu$m lateral shift between the opposite electrodes, the diffraction efficiency of configuration (A) decreases by half, which is clearly shown in the inset of Fig. 5. However, no significant reduction of the efficiency occurs in configuration (B). This can be well explained by the simulated phase profiles under electrode misalignments, which are shown in Fig. 4. As shown in Fig. 5, a misalignment of 2 $\mu$m can be fully compensated by increasing the biasing voltage from ~7 V to ~9 V, which considerably relaxes the alignment stringency in device assembly.

In conclusion, we have proposed and fabricated a two-level LC grating working at 1.55 $\mu$m. By applying a unique biasing configuration to a double-sided structure, the distortion of the LC directors due to the fringing-field effect is significantly suppressed, which leads to a much larger phase modulation depth and higher diffraction efficiency. A diffraction efficiency of 33% at the first order diffraction angle of 14.5° was experimentally achieved. The efficiency has been enhanced 80 times compared with the conventional structure and approaches the theoretical limit. Experiments have confirmed that no significant performance degradation occurs under an electrode misalignment of 2 $\mu$m. For the current device to work as a programmable grating, a common method is to selectively activate a subset of electrodes, whose pitch $p$ is a multiple of the fundamental pitch $p_0$. Our structure ensures that the programmed state with the smallest $p$ $(=p_0)$ and therefore the worst fringing-field effect has high phase modulation depth, the other states are generally better, which was confirmed by simulations.

This research is supported by the Air Force Research Lab.

[1] Jeffrey H. Kulick, Jphn M. Jarem, Robert G. Lindquist, Stephen T. Kowel, Mark W. Friends, and Thomas M. Lesile, Appl. Opt. **34**, 1901 (1995).
[2] Ichiro Fujieda, Appl. Opt. **40**, 6552 (2001).
[3] Ichiro Fujieda, Osamu Mikami, and Atsushi Ozawa, Appl. Opt. **42**, 1520 (2003).
[4] I. G. Manolis, T. D. Wilkinson, M. M. Redmond, and W. A. Crossland, IEEE Photonics Technol. Lett. **14**, 801 (2002).
[5] D. P. Resler, D. S. Hobbs, R. C. Sharp, L. J. Friedmanks, and T. A. Dorschner, Opt. Lett. **21**, 689 (1996).
[6] Manuel Bouvier and Toralf Scharf, Opt. Eng. **39**, 2129 (2000).
[7] Boris Apter, Uzi Efron, and Eldad Bahat-Treidel, Appl. Opt. **43**, 11 (2004).
[8] Emil Hallstig, Johan Stigwall, Torleif Martin, Lars Sjoqvist, and Mikael Lindgren, J. Mod. Opt. **51**, 1233 (2004).
[9] Richard James, F. Anibal Fernandez, and Sally E. Day, Mol. Cryst. Liq. Cryst. **422**, 209 (2004).
[10] R. G. Lindquist, J. H. Kulick, G. P. Nordin, J. M. Jarem, S. T. Kowel, and M. Friends, Opt. Lett. **19**, 670 (1994).
[11] M. Kitamura, SID-IDRC, 350, presented at the International Display Research Conference, Monterey, CA, 1994.
[12] J. W. Goodman, *Introduction to Fourier Optics* (McGraw-Hill, New York, 1996).