# Optical Compensation Effects Induced by Dielectric Surface Gratings for Wide-Viewing Liquid Crystal Displays

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## Abstract

*We present wide-viewing characteristics of a twisted nematic liquid crystal display (TN LCD) achieved by adopting dielectric surface gratings (DSGs) as alignment layers. The experimental data and the numerical analyses consistently show that the optical compensation effect inherent to the TN LCD with the DSGs greatly reduces the contrast inversion of the TN LCD.*

## 1. Introduction

Nematic liquid crystal displays (LCDs) have severe drawbacks in the viewing characteristics because of asymmetric variations of the optical phase retardation at the different viewing angles [1]. In order to resolve this problem, the multi-domain method has been recognized as the most appropriate one [2]. However, as implicit in its name, the multi-domain method requires a formation of different easy-axes in adjacent domains, which usually involves complex processes such as multiple rubbing and photo-alignment.

Recently, mostly in the vertically aligned LCD configurations, the distortions of the electric potential in the LC layer have been utilized to obtain wide-viewing characteristics [3]. Since no complex surface treatment is involved, this method is known to be simple and cost effective. Through the systematic analyses of the distortions of the electric potential, we present wide-viewing characteristics of a twisted nematic (TN) LCD by adopting dielectric surface gratings (DSGs) as the alignment layers [4]. The wide-viewing characteristics are achieved by the spatial variations of the effective voltage across the LC layer ($V_{LC}$). We have developed a theoretical model for these spatial variations of the $V_{LC}$ [5] which can offer a basis for designing the LCD with the DSGs. However, the validity of our model for the TN LCD with the DSGs has not been fully explored yet.

In this paper, based on the basic concept of the spatial variations of the $V_{LC}$, we present the experimental data and the numerical analyses of the TN LCD with the DSGs. The experimental data and the numerical results consistently show that the optical compensation effect in the TN LCD with the DSGs greatly reduces the contrast inversion of the TN LCD.

## 2. TN LCD with DSG Alignment Layers

Let us consider the TN LCD which adopts the DSGs as the surface alignment layers. In Fig. 1, we show the surface profile of the DSG with hills and valleys utilized in our experiments. Since the periodicity of the DSG is 6μm, when such DSG is used as an alignment layer of the LCD, it aligns the LC director perpendicular to the grating vector through the topographical effect [6,7].

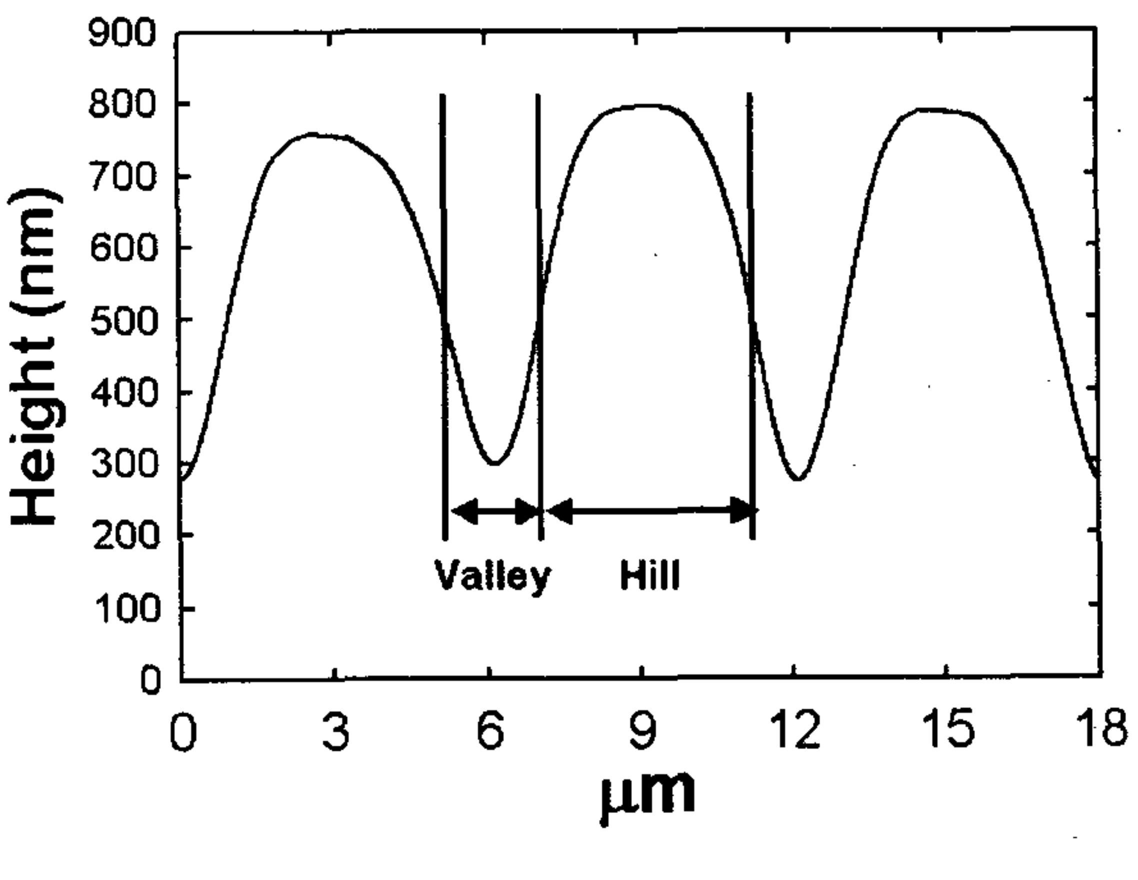
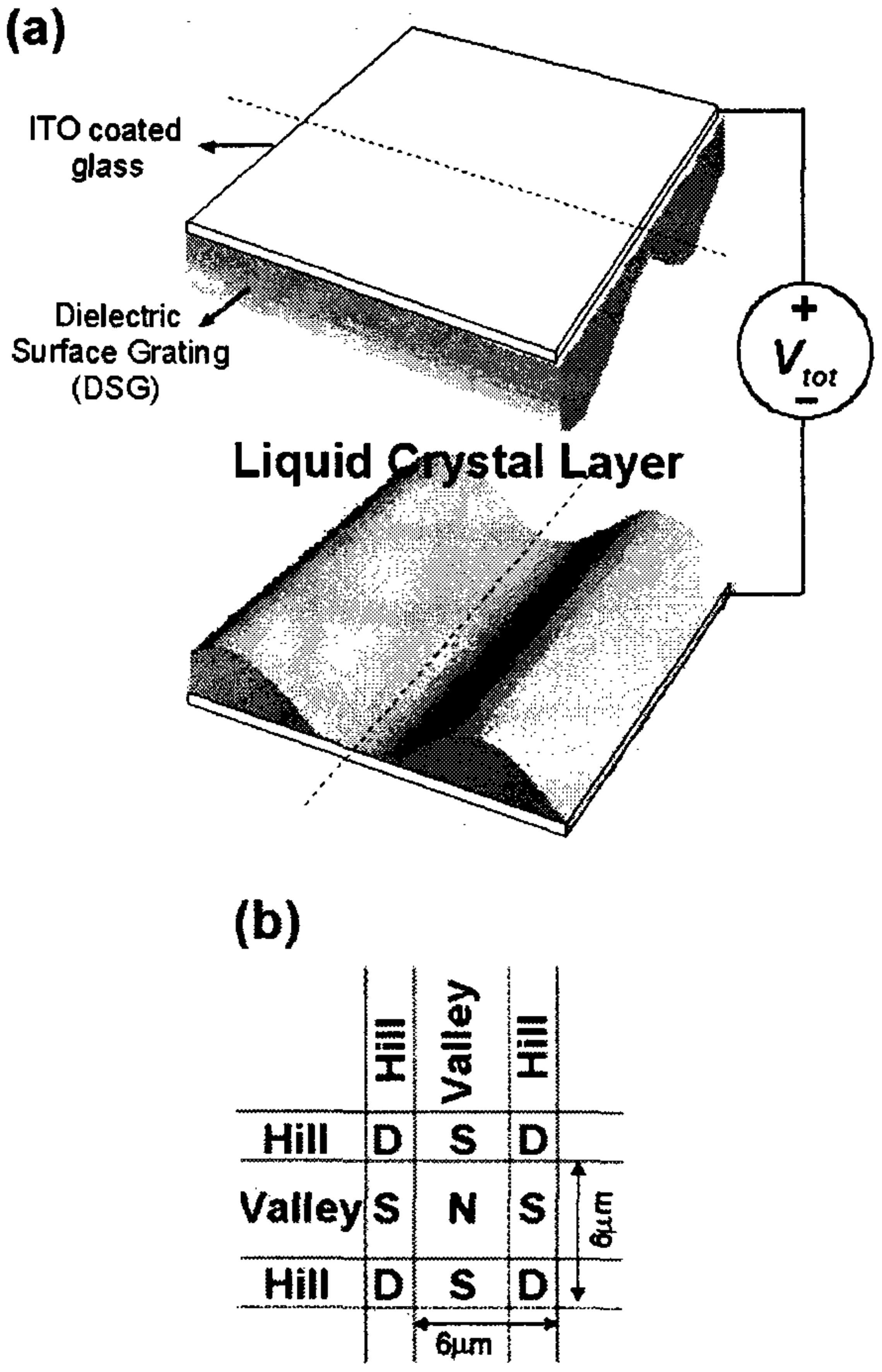


**Figure 1.** The surface profile of the DSGs utilized in our experiments.



| | Hill | Valley | Hill |
|---|---|---|---|
| Hill | D | S | D |
| Valley | S | N | S |
| Hill | D | S | D |

**Figure 2.** The schematic diagram of the TN LCD with the DSG alignment layers: (a) the 3-dimensional and (b) the top view. The DSG configurations in D, S, and N regions are two-sides occupied, one-side occupied, and not occupied, respectively.

In the configuration of assembling two DSG alignment layers perpendicular to each other as in Fig. 2, the TN LCD with the DSG alignment layers can be obtained. And the distortions of the electric potential take place over the whole cell in the presence of the applied voltage ($V_{tot}$). The distortions of the electric potential by the DSGs are found to critically depend on a dimensionless parameter, $\xi$, defined as the effective voltage per unit thickness across the DSG, $V_{DSG}/h$, scaled by the voltage across the LC layer, $V_{LC}/l$ [4]. After simple calculations, the expression for $\xi$ is given as

$$\xi = \frac{\langle \varepsilon_{LC} \rangle}{\varepsilon_{DSG}}, \qquad (1)$$

where $\varepsilon_{LC}$ and $\varepsilon_{DSG}$ are the effective dielectric constants of the LC layer and the DSG, respectively. The bracket denotes the spatial average over one period of the DSG. This parameter, $\xi$, can be used to describe the main features of the distortions of the electric potential. For $\xi \approx 1$, the distortions barely exist. However, for $\xi >> 1$ as well as $\xi << 1$, strong distortions are produced. In the case of $\xi << 1$, the distortions by the DSGs resemble what are induced by a nonplanar electrode. When $\xi >> 1$, the spatial variations of $V_{LC}$ are largely enhanced due to the distortions of the electric potential by the DSGs. Due to these spatial variations, the value of $V_{LC}$ periodically varies in the microdomains such as the $D$, $S$, $N$ regions defined in Fig. 2(b).

The expressions for these spatial variations of $V_{LC}$ can be found elsewhere [5]. For simplicity, we consider each domain as a locally flat domain and assume that $V_{tot}$ is divided into $V_{LC}$ and $V_{DSG}$. Under the assumptions of no external source except for $V_{tot}$ and no spontaneous polarization in the LC layer in a macroscopic scale, the electric displacement vector has only the $z$-component and its magnitude ($D_z$) becomes constant. In general, $\varepsilon_{DSG}$ is not a function of $V_{tot}$ and thus the expression for $V_{DSG}$ is simply given as $(D_z / \varepsilon_{DSG}) \cdot h$. By the application of Gauss's law, the value of $D_z$ can be obtained as the multiplication of the net capacitance per unit area by $V_{tot}$. Since the net capacitance per unit area comes form a connection of the LC layer and the DSG in series, the expression for $V_{LC}$ is then given as

$$V_{LC} = V_{tot} \cdot [1 + \xi \cdot \left(\frac{l}{h}\right)]^{-1}, \qquad (2)$$

where $l$ and $h$ are the thickness of the LC layer and that of the DSG, respectively. Eq. (2) clearly shows that without any change in the geometrical parameters, i.e., $l$ and $h$, the spatial variations of $V_{LC}$ can be enhanced by increasing the value of $\xi$.

## 3. Fabrication of the TN LCD with DSGs

Based on the above ideas, we fabricated the TN LCD with the DSGs of $\xi > 1$. The DSGs as shown in Fig. 1 were used as the alignment layers. The TN cell was assembled as shown in Fig. 2. The photoresist material AZ-6612 and the commercial LC material ZLI-4900-100 were used. The physical parameters of the LC are $\varepsilon_{DSG} = 5.1$ at 1 kHz, $(\varepsilon_{LC\perp}, \varepsilon_{LC\parallel}) = (7.9, 37.7)$ at 1 kHz, and the elastic constants $(K_1, K_2, K_3) = (16.5, 9.5, 23.3)$ in units of $10^{-7}$ dyn. The measured values of $(h_{Hill}, h_{Valley}) = (0.79, 0.28)$ μm and $(l_D, l_N) = (5.22, 6.24)$ μm, giving the cell gap of 6.8 μm.

Figure 3 shows a photograph of the fabricated TN LCD taken under crossed polarizers at $V_{tot} = 2.1$ V, corresponding to $\xi = 3.8$. A spontaneously formed array of microdomains as shown in Fig. 2(b) were observed and the transmitted light intensity through the cell varies periodically with the DSGs. It is clear that this spontaneously formed microdomains results from the spatial variations of the midplane tilt in the LC layer. This is consistent with the theoretical results of our TN LCD with the DSGs.

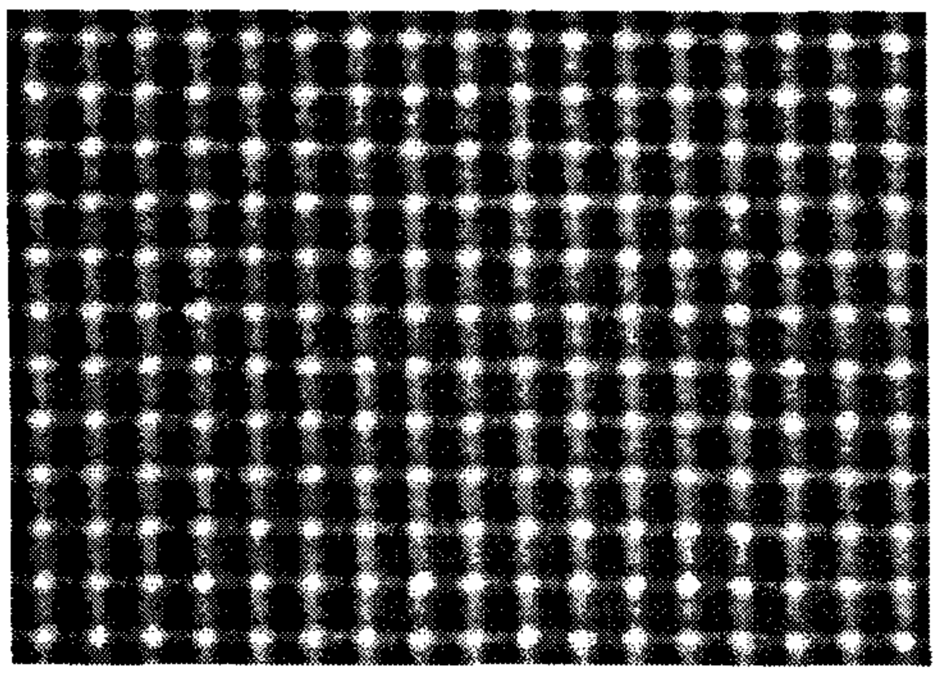


**Figure 3.** The photograph of the fabricated TN LCD with the DSGs under crossed polarizers at $V_{tot} = 2.1$ V ($\xi = 3.8$). The spontaneously formed microdomain array has the same structural symmetry as that shown in Fig. 2(b).

## 4. Optical Compensation Effect in TN LCD with DSGs

The microdomain array observed above has an intrinsic optical compensation effect which is useful for obtaining wide-viewing characteristics of the LCD. This optical compensation effect naturally comes from the spatial variations of the midplane tilt in the microdomain array. Since the midplane tilt abruptly changes just above the Fredericksz transition [8], variations of the midplane tilt are readily produced by the spatial variations of $V_{LC}$. Taking into account that the contrast inversion of the TN LCD essentially arises from the uniformity of the midplane tilt in the LC layer [1], the microdomains formed in our case are expected to eliminate the contrast inversion of the TN LCD through the different midplane tilts within the individual pixel. In Fig. 4, we present the experimental data of the luminance of the TN LCD with the DSGs along the positive vertical viewing angle. The luminance curves at various voltages do not intersect with each other up to 60°, meaning that the contrast inversion was greatly reduced.

The electrooptic characteristics of the TN LCD with the DSGs were numerically analyzed based on our theoretical model. First, one should find the spatial variations of $V_{LC}$. As pointed out previously [5], Eq. (2) does not have an analytic solution. Thus, $\langle \varepsilon_{LC} \rangle$ should be found as a function of $V_{LC}$ [9], and then the pair of ($V_{LC}$, $\langle \varepsilon_{LC} \rangle$) is inserted in Eq. (2) to obtain the corresponding $V_{tot}$. From this result, we can obtain the LC director distribution in each microdomain as a function of $V_{tot}$, respectively. Then, by applying the 2×2 Jones matrix formalism [10], the viewing characteristics of each microdomain can be obtained. Since no interference was assumed to exist between adjacent domains, the overall viewing characteristic of the cell was the average value of each locally flat domain. Since the LC director distribution in $S$ is the intermediate one between those in $D$ and $N$, apparently any physical property of the whole cell can be obtained from as the average over only $D$ and $N$. Based on the area occupied by each microdomain, the appropriate weighting factors of 0.25 and 0.75 are assigned to $D$ and $N$, respectively.

In Fig. 4, we present the numerical results for the normalized luminance at various voltages, represented by the solid lines. Some discrepancies observed at 1.68 V and 1.82 V depend on the weighting factor at each voltage. The agreement between the experimental data and the numerical results tells us that our simple theoretical model explains the essential features of the TN LCD with the DSGs.

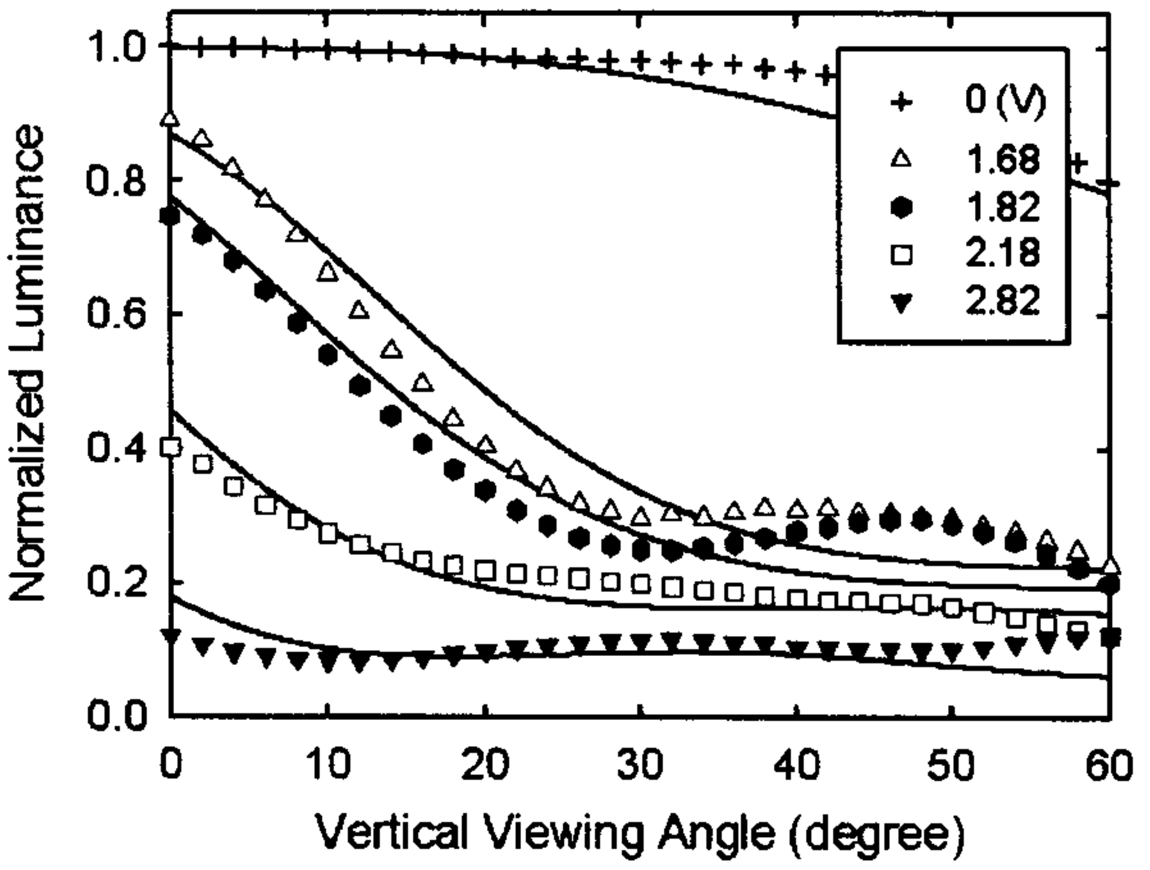


**Figure 4.** The normalized luminance of the TN LCD with the DSGs along the positive vertical viewing angle at various $V_{tot}$'s. The symbols and the solid lines denote the experimental data and the numerical results, respectively.

## 5. Conclusion

We have demonstrated that a simple concept of the spatial variations of the $V_{LC}$ explains all the essential features of the TN with the DSGs. Moreover, both the experimental data and the numerical results show that the optical compensation effect in the TN LCD with the DSGs greatly reduces the contrast inversion of the TN LCD.

As predicted previously [5], this microdomain array is also applicable for a 2-dimensional voltage-controlled diffraction devices. Therefore, the fabrication technique and theoretical model developed here should provide the basis for designing new LCDs as well as optical devices adopting the DSGs.

## 6. Acknowledgement

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