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Pulse-width modulation drive technique for high-resolution liquid-crystal gratings

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We report the use of a pulse-width modulation drive technique for high-resolution liquid-crystal gratings and show how the grating diffraction efficiency depends on the duty cycle of the drive signal. We identify a regime in which the diffraction efficiency is linearly proportional to the duty cycle, thereby providing a linear drive characteristic.

Recently there has been a significant effort to integrate liquid-crystal devices directly on silicon backplanes to take advantage of the optical detection and digital memory and processing capabilities of VLSI circuitry.^{1,2} Currently we are investigating a complementary approach in which high-resolution liquid-crystal gratings on silicon electronics are used to form a real-time three-dimensional diffractive display based on previously reported partial pixel architecture.^{3,4} The liquid-crystal gratings are formed in a thin nematic liquid-crystal layer by fringing electric fields. They ultimately will be controlled by a processor in a silicon die that computes the requisite pixel gray levels.

In such devices, as well as in other smart-pixel devices, pixel data are generated and stored at each pixel site. Hence a liquid-crystal drive technique is required that is compatible with the conversion of locally stored data to local drive signals. The widely used passive and active matrix-addressing methods are unattractive for this purpose because the required drive signals are generated externally to the display region. Instead, local digital-analog conversion is preferable. Because digital techniques typically are easier to implement and more compact in VLSI circuitry than the generation of analog voltages, digital drive schemes such as pulse-width modulation (PWM) and pulse density modulation offer an attractive approach. In this Letter we investigate the use of PWM to drive liquid-crystal gratings. Specifically, we show how the diffraction efficiency of a liquid-crystal grating depends on the duty cycle of the PWM drive envelope, and we identify a regime in which the diffraction efficiency is linearly proportional to the duty cycle, thereby providing a linear drive characteristic. In addition, we investigate the relationship of the carrier frequency and the envelope frequency to the relaxation dynamics of the liquid crystal, which affects the maximum number of allowable gray levels.

A single partial pixel grating formed in a homeotropically aligned film of nematic liquid crystal is illustrated in Fig. 1. Fringing electric fields from a set of interdigitated electrodes provide a torque force that rotates the local director axis of the liquid-crystalline material in the direction of the field. The rotation of the local director axis results in a periodic variation in the effective refractive index of the

medium such that a highly anisotropic phase grating is formed.⁵ The local director axis rotation depends on the rms voltage of the drive signal rather than on its instantaneous voltage, provided that the drive signal oscillates faster than the turn-on and relaxation times of the nematic liquid crystal, which are typically between 1 and 100 ms.

The PWM drive technique is a method of controlling the rms voltage of the drive signal without modulating its peak amplitude. For example, consider a periodic carrier signal, $v(t)$, gated by a periodic pulse envelope, $A_{\text{env}}(t)$, as illustrated in Fig. 2. The pulse width of the envelope's high state is given by DT , in which D is the duty cycle and T is the fundamental period of the envelope function. If the pulse width is an integer multiple of the period of the carrier signal, the rms voltage of the gated drive signal, $V_{\text{gated-rms}}$, is

$$V_{\text{gated-rms}} = \left[\frac{1}{T} \int_0^{DT} v^2(t) dt \right]^{1/2} = D^{1/2} V_{\text{cw-rms}}, \quad (1)$$

in which $v(t)$ is the instantaneous voltage of the carrier signal and $V_{\text{cw-rms}}$ is the rms voltage. The rms voltage of the gated drive signal, $s(t)$ [which is illustrated in Fig. 2(c)], thus is proportional to the square root of the duty cycle of the envelope signal.

Because the liquid crystal responds to the effective rms voltage, the choice of the ac carrier waveform,

Fig. 1. Grating formation in a homeotropically aligned liquid-crystal film through the use of electric fringing fields from interdigitated electrodes. E and H are the electric- and magnetic-field vectors, respectively, of the incident readout beam.

Fig. 2. Illustration of the PWM drive scheme. The drive signal is composed of a periodic envelope function (a) with a varying pulse width that is used to gate (b) a sinusoidal or (c) a binary carrier wave.

$v(t)$, is arbitrary, except that it must not have a dc bias (to avoid a charge buildup that is deleterious to nematic liquid crystals). This mandates the use of a bipolar waveform. For purposes of this Letter, diffraction efficiency measurements were made with a gated bipolar sinusoidal wave applied to one of the electrodes, while the other electrode was held at ground.

To illustrate the PWM drive technique, we measured the diffraction efficiency of two liquid-crystal grating cells that were operated in a transmission geometry (as illustrated in Fig. 1) and that had different electrode pitches. Both cells consisted of a 4- μm -thick film of homeotropically aligned nematic liquid crystal (Merck BL009, $\Delta n = 0.29$) sandwiched between two glass plates. Each cell had a set of indium tin oxide (ITO) interdigitated electrodes patterned on one of the glass plates, with no ITO on the other plate. In Cell A, the electrode fingers were 6 μm wide with a 12- μm center-to-center spacing, and Cell B had 0.4- μm -wide fingers and a 2- μm center-to-center spacing. The ITO electrodes of Cell A were fabricated at Diffraction Limited, Inc. The electrodes of Cell B were patterned at the National Nanofabrication Facility at Cornell University.

The diffraction efficiency was measured as a ratio of the +1-order diffracted power to the incident power for a normally incident beam at 633 nm. The solid curves in Fig. 3 show the diffraction efficiency of each cell as a function of the rms drive voltage for a continuous 5-kHz sinusoidal drive signal. Cell A had a threshold voltage of ~ 1.4 V and a peak diffraction efficiency of 14.5% at 4.8 V. Cell B exhibited significantly lower diffraction efficiency at any given drive voltage, despite having a smaller separation between the electrode fingers and hence larger-magnitude fringing electric fields directly between the electrodes. This is mostly likely due to the electric field not penetrating as far into the bulk of the liquid-crystal layer as in Cell A, because the finger separation was less than the cell thickness.

As illustrated in Fig. 4, the diffraction efficiency for Cell A was measured as a function of duty cycle by use of the PWM drive technique. In this

case the PWM drive signal was a 5-kHz sinusoidal waveform gated by a 200-Hz square-wave envelope function. The curves in the figure correspond to sinusoidal carrier waves with amplitudes of 5 and 10 V. The duty cycle of the envelope signal was varied between 8% and 100%. The diffraction efficiency for any duty cycle on each of these curves is consistent with the diffraction efficiency of Cell A shown in Fig. 3, with the rms voltage of the PWM signal as calculated by Eq. (1). We illustrate this by converting the duty cycle for each PWM signal into the equivalent rms voltage and plotting the diffraction efficiency as a function of this voltage in Fig. 3. There is close agreement between the diffraction efficiency curves, thus indicating that the liquid crystal responds as expected to the rms voltage of the drive signal, regardless of the signal's specific temporal shape.

A comparable measurement of the diffraction efficiency of Cell B for the same PWM drive signals as those used for Cell A is shown in Fig. 5. The striking feature of these curves is their linearity with respect to the duty cycle of the drive signal's envelope function. This occurs because the diffraction efficiency of Cell B exhibits a quadratic dependence on the rms drive voltage over most of the voltage range shown in Fig. 3. Thus, $\eta \propto V_{\text{rms}}^2$ (in which η is the diffraction efficiency), and substitution of Eq. (1) yields $\eta \propto D$. Although Cell B exhibits a

Fig. 3. Diffraction efficiency as a function of rms voltage for Cells A and B with amplitude-modulation and PWM drive techniques.

Fig. 4. Diffraction efficiency as a function of duty cycle for Cell A (PWM drive technique).

Fig. 5. Diffraction efficiency as a function of duty cycle for Cell B (PWM drive technique).

Fig. 6. Diffraction efficiency as a function of drive frequency for Cell B.

lower diffraction efficiency than Cell A, the linearity of its drive characteristic makes it an attractive modulating element for our display application. As with Cell A, converting the duty cycle into the equivalent rms drive signal voltage and plotting the diffraction efficiency as a function of this rms voltage in Fig. 3 shows excellent agreement with the amplitude modulation curve.

In addition to the amplitude of the carrier signal, two other key parameters of the PWM drive signal are the frequencies of the envelope and carrier signals. These parameters determine the maximum number of gray levels that can be supported by the liquid-crystal gratings. Assuming that the minimum pulse width is the fundamental period of the carrier signal, the number of possible gray levels is equal to the number of pulses that can fit in the fundamental period of the envelope function. Therefore the number of gray levels, n , can be determined as $n = T_{\text{env}}/T_{\text{carrier}} = f_{\text{carrier}}/f_{\text{env}}$, in which T_{env} , T_{carrier} , f_{env} , and f_{carrier} are the periods and the

frequencies of the envelope and carrier waveforms, respectively.

The minimum envelope frequency is determined by the relaxation dynamics of the nematic liquid crystal. In the fringing-field configuration, the dominant relaxation process is splaylike. We measured relaxation times of approximately 50 and 5 ms for Cells A and B, respectively. In the case of Cell B, the minimum envelope frequency is thus ~ 200 Hz.

The maximum carrier frequency is related to the frequency dependence of the diffraction efficiency. For example, the diffraction efficiency of Cell B is shown in Fig. 6 as a function of the drive frequency for two constant-amplitude sinusoidal drive signals. In both cases, the diffraction efficiency drops significantly after 100 kHz. If this is used as the maximum carrier frequency, the liquid-crystal dynamics indicate that Cell B could support approximately 500 gray levels (~ 9 bits), which would be adequate for a gray-scale display. Realization of this number of gray levels depends on the achievable contrast ratio and on the level of diffraction from the ITO electrodes, which have yet to be examined.

In summary, the PWM technique offers an attractive alternative to amplitude modulation for driving liquid-crystal gratings. This technique should be equally applicable to conventional liquid-crystal pixels that are integrated with local memory and to processing elements such as those found in smart-pixel arrays. We are currently fabricating small-area integrated drive circuits using MOSIS that will allow the integration of large numbers of such gratings on silicon backplanes.

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