# Fast, large and controllable phase modulation using dual frequency liquid crystals

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**Abstract:** We report on a method for high speed, large stroke phase modulation using dual frequency control of liquid crystals. Our system uses an all-electronic feedback system in order to simplify the control. We show half wave phase modulations of ~120Hz with the operating point varying over nearly the full dynamic range of the device, and demonstrate larger phase shifts (2.5 waves) at a frequency of 37Hz. For large phase shifts, the speeds are an order of magnitude faster than existing techniques.



**OCIS codes:** (230.0230) Optical Devices, (230.3720) Optical Devices, liquid crystal Devices

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## 1. Introduction

High-speed phase modulation using nematic liquid crystals (LCs) is desirable for a range of optical applications, and is an area in which much work has been published. Our interest in nematic LCs is as spatial light modulators for adaptive optics [1] where their relatively slow switching speed is a serious limitation. Published switching speeds of nematic LCs vary widely, since some authors quote results (~10ms) requiring a phase shift of only half a wave, and others describe results associated with larger phase shifts, where the switching speed is much slower (~ seconds). It is therefore only meaningful to quote switching speeds of phase shifting nematic LCs when also quoting the phase shift. Methods for improving the switching speed include pi-cells [2] and the transient nematic effect [3], but the method reported to give the fastest phase shift is the dual frequency effect [4,5,6].

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In a dual frequency LC the sluggish molecular realignment is improved by using a LC material which exhibits a low frequency inversion of the sign of the dielectric anisotropy, allowing the cell to be driven both on and off using electric fields of low and high frequency, respectively. However, dual frequency control has not widely been used due mainly to the complexity of the control method. It is simple to turn off an LC cell fully using the dual frequency effect, but a more practical scenario involves switching from one arbitrary phase value to another, which is complicated because;

- There is not a simple relationship between the starting phase, the next desired phase and the required voltage sequence.
- The LC must not be used near to saturation, otherwise the plane of the director can become undefined and scattering occurs.
- High frequency high amplitude voltages must be applied with care, otherwise damage due to heating in the LC cell can occur.

Some of the problems associated with dual frequency control can be circumvented if the LC is used as a wavefront controller in an adaptive optics system [6,7], in which case high speed high dynamic range switching can occur. Similarly, results using a closed loop optical system [7] to compensate for vibrations in an interferometer have been reported. However the results quoted in [6,7] are not suitable for non-closed loop adaptive optics applications requiring high speed high stroke phase shifting.

## 2. Experimental work

An alternative technique for maintaining the advantages of stability and controllability associated with closed loop control, whilst dispensing with the technological problems of using an optical closed loop system is to use an electronic-closed loop system.

The equivalent circuit of a simple LC cell is shown in Fig. 1.

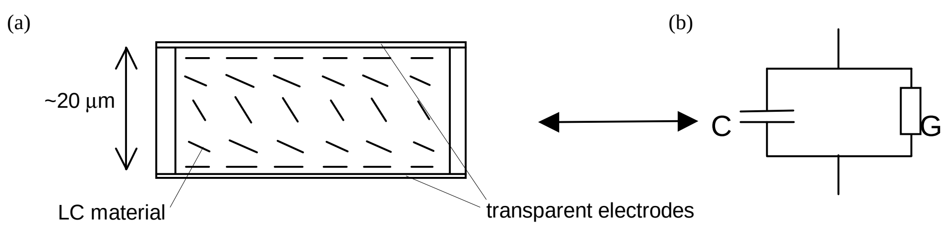


Fig. 1 (a) A simple LC cell structure schematic, and (b) the approximate equivalent circuit, where C is the equivalent parallel capacitance and G is the equivalent conductance

The capacitive component C in the equivalent circuit is due to the parallel plates of the transparent electrodes, separated by the dielectric media of the LC material. The conductive component G is due to the dielectric losses in the LC material. Strictly, there should be a second conductive component due to the DC conductivity of the LC material, but in practice this is small enough to be negligible.

As the cell is actuated, the LC molecules rotate, and the effective dielectric constant of the material in the direction of the applied field changes, giving the change in the refractive index required for the cell to operate. However, the change in the dielectric constant also results in a change in the capacitance of the cell [8]. The capacitive component of the cell can be measured and can be used as a feedback signal in a closed loop control system.


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The closed loop control system can be made transparent to the end user. This basic concept was suggested by Esposito *et al* [9] but this paper contains the first results using the technique.

A block diagram of the control system is shown in Fig. 2.

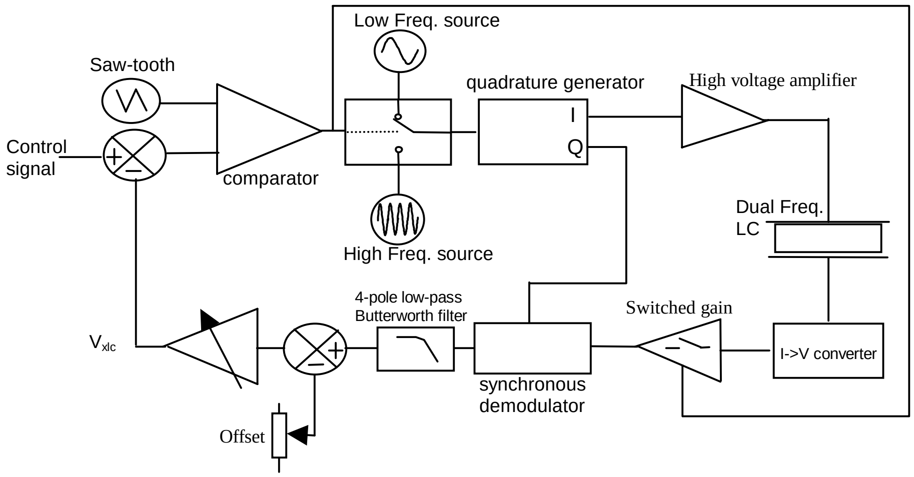


Fig 2. Block diagram showing the simplified electronic closed loop system. The cell capacitance is measured and is compared to the control input to generate an error signal. A comparator, operating on inputs from the error signal and a saw-tooth generator, provides the appropriate mark-space ratio between the high and low frequency voltages to be applied to the LC cell.

When driven with a low-frequency signal, the LC ‘turns on’, and when driven with a high frequency signal the LC ‘turns off’. The state of the LC can therefore be controlled by adjusting the relative periods for which it is driven with a high frequency and a low frequency source, in a manner analogous to pulse-width modulation.

In the system shown in Fig. 2, the ‘control signal’ input voltage represents the desired level of optical phase shift. The voltage $V_{xlc}$ is proportional to the measured reactance of the cell. The system produces an error signal by measuring the difference between the two signals.

The error signal is compared to a reference saw-tooth signal, and the resultant is used to select between a high- and a low-frequency source. The selected signal source is fed into a ‘quadrature generator’ which produces two outputs; one output (I) is in phase with the input and the other (Q) is in quadrature (i.e. has a $\pi/2$ phase shift relative to input). Output I is fed through a high-voltage amplifier to drive the LC cell and output Q is passed to the trigger input of a synchronous demodulator.

The current flowing through the LC is measured using a current to voltage converter. The reactive component of any system will result in a component of the current flowing through it being in quadrature to the voltage applied to it. Thus by extracting the magnitude of the component of the current signal which is in quadrature with the LC driving voltage, a value proportional to the reactive component of the LC can be obtained. This function is performed by the synchronous demodulator, using the quadrature signal (Q) mentioned previously, and the low-pass filter.

In the case of a simple LC cell, the reactive component is simply the capacitance due to the parallel electrodes, mentioned previously. Since the change in the capacitance of the LC is small relative to the at-rest value, an offset and a gain stage are included in the feedback path.

A closed-loop control system will operate so as to minimise the error signal. In this case, the system will drive so as to make the measured capacitance signal ($V_{xlc}$) equal to the

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‘control signal’ voltage. It was found that the relationship between optical phase shift and capacitance is linear to a good approximation, and so the system can be considered to drive such that the desired optical phase shift is obtained, i.e. that it operates in closed loop mode with respect to the optical phase shift.

The Liquid crystal material used in the dual frequency experiments was Niopik LC1001, the relevant physical properties of which are summarized in Table 1.

Table 1. Niopik LC1001 parameters.

| n‖ | n⊥ | ε‖ | ε⊥ | Rotational viscosity (Pa s) | Crossover Freq. (Hz) |
|---|---|---|---|---|---|
| 1.79 | 1.53 | 9.53+0.63*i* | 5.1+0.45*i* | 0.377 | ~7000 |

In all cases ‖ indicates ‘parallel to’ and ⊥ indicates ‘perpendicular to’ the LC director

### 3. Results

Figure 3 shows an oscillogram of the system operation, for an 800-mVpp triangular wave ‘control signal’ input.

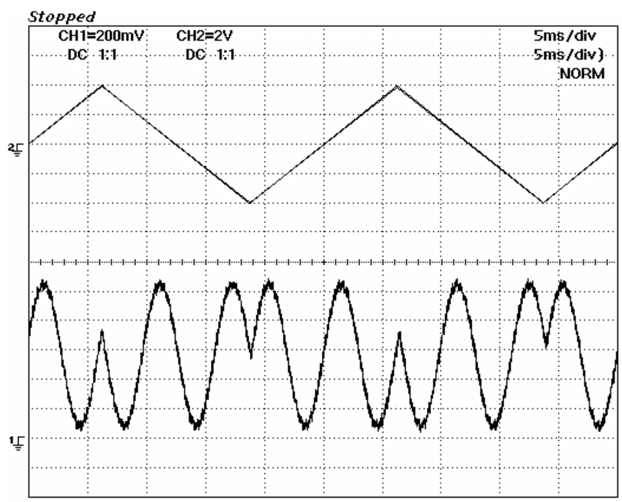


Fig. 3. Oscillogram illustrating high-speed large phase modulation with closed-loop control. Upper trace shows input (control) signal. Lower trace shows measured optical signal. The time-base is 5ms/division.

The upper trace shows the ‘control signal’ input. The lower trace shows the optical response from a photodiode, illuminated by light passing through the LC sandwiched between crossed polarizers. A phase shift of slightly over 2 waves (i.e. a round trip of just over 4 waves per cycle) can be seen.

The slope of the triangular control signal input wave is uniform on each half of the cycle, and the corresponding optical trace is sinusoidal over each corresponding half cycle, as would be expected if the system were operating in control loop mode with respect to the optical phase shift. This confirms the linear relationship between measured cell capacitance and optical phase shift.

The small ripple visible on the optical trace is due to the high-speed switching between high- and low- frequency drive signals. The amount of ripple can be reduced by increasing

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the frequency of the saw-tooth source, and thus the switching frequency, or by reducing the drive voltage.

Figure 4 gives quantitative results for the maximum achievable phase shift with respect to frequency for the system in dual-frequency closed loop operation (using dual frequency LC material LC1001), and for an LC cell (LC material E49) operated in the transient nematic mode, which is the fastest possible mode of operation for conventional cells.

The cyclic operation speed of a cell operated in the conventional way is limited by the relaxation speed of the cell when the driving voltage is removed. The relaxation speed of the cell is fastest at the saturation point of the cell. Thus the fastest possible cyclic operation is achieved when the cell is operated near saturation. This is the 'transient nematic' mode of operation.

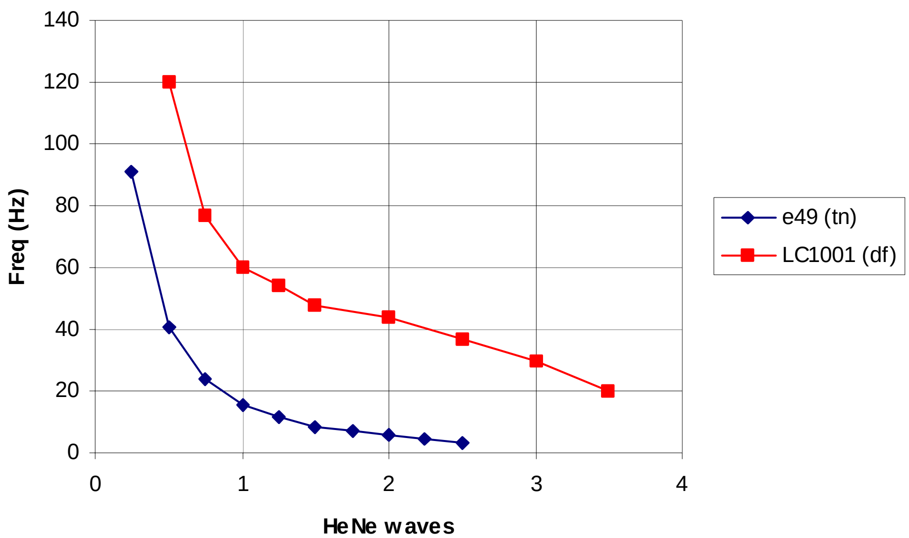


Fig. 4. A comparison of maximum achievable phase shift, with respect to frequency, for LC1001 in closed loop dual frequency control (triangles) and LC-E49 using the transient nematic effect (diamonds).

The induced phase shifts were sinusoidal and so, for a given phase shift, the LC has to cycle through twice that value (i.e. on and off).

There is a clear improvement for the dual frequency mode of operation at all phase shifts. These results were taken using voltages of up to 264Vpp. The useable operating optical phase shift of the cell drops as the driving voltage increases, but if one were only interested in small phase shifts, then a larger driving voltage could be used and faster results obtained.

It should be noted that these results were taken for a single pixel LC cell. For incorporation into a spatial light modulator, with numerous and/or closely packed elements, the high voltages used could be problematic, especially for silicon backplane liquid crystal devices.

The results in Fig.4 actually reflect unduly favourably on the non dual-frequency mode of operation, due to the nature of the transient nematic mode of operation. From the graph it can be seen that a half wave phase change using E49 is possible at a frequency of 41Hz. However, this is only achievable if the cell is used at saturation. The speed is much slower if the same half wave operation is required, but using a different part of the optical phase shift range (necessary, e.g., in adaptive optics).

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This is reflected in Fig. 5, which shows the achievable frequency for a half-wave phase shift as a function of nominal operating point (bias) on the optical phase shift range. Note that separate vertical scales are employed for the dual frequency and transient nematic modes.

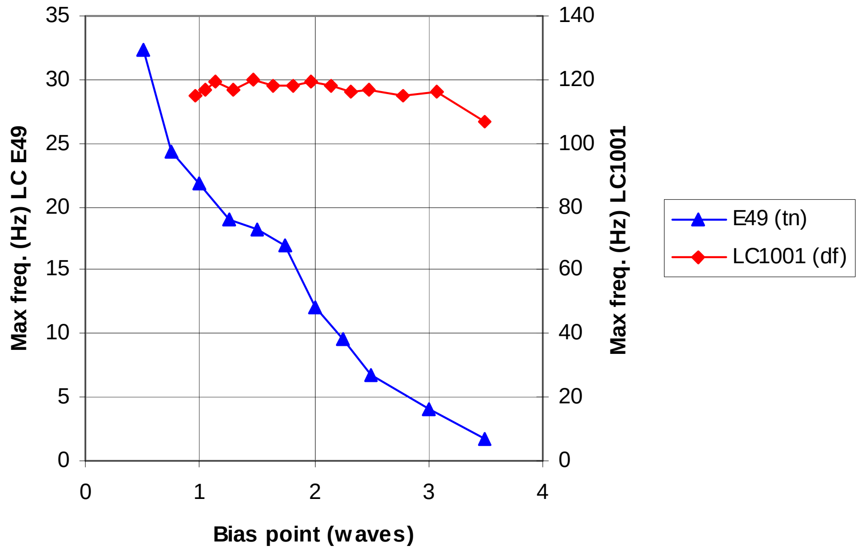


Fig 5. A comparison of maximum frequency of operation for a half wave phase shift versus the center operating point (bias) on the phase-voltage range, for LC1001 operated with closed-loop dual frequency control (diamonds) and LC-E49 operating in transient nematic mode (triangles). A nominal operating point of zero is defined when the cell is fully on. Note different frequency axes for dual frequency and transient nematic results.

A dramatic improvement in maximum operating speed is clearly achievable using the dual frequency mode. Furthermore, the maximum operating speed is largely independent of the bias point of the cell, and when the system is operating in closed loop control, cyclic rates of any frequency between DC and the maximum frequency can be achieved.

## 4. Conclusion

In summary, we have shown half wave phase modulations of ~120Hz with the operating point varying over nearly the full dynamic range of the device. For comparison, a normal nematic LC would give a frequency of up to ~50Hz, but only when the range of operation is limited to be near the saturation point.

We have demonstrated larger phase shifts (2.5 waves) at a frequency of 37Hz, compared to about 3Hz using the transient nematic effect, and much less than 1 Hz using a simple LC control method. We have demonstrated that, using closed-loop control, it is possible to produce arbitrary optical phase shift waveforms, which is not possible by transient nematic and conventional LC control methods.

Finally, using cell-capacitance measurement as a measurement mechanism, the desired optical phase shift can be obtained without interference with the end-user's optical design.


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