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LIQUID CRYSTAL DISPLAYS AS AN EDUCATIONAL TOOL TO INTRODUCE AMPLITUDE AND PHASE CONCEPTS

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Abstract

In this work we show how liquid crystal displays can be a useful tool to introduce amplitude and phase concepts to students. Amplitude and phase play a very important role in the description of wave related phenomena, basic in many fields of Science and Engineering. Phase information is usually less evident than amplitude information since it is not directly related with the strength of the signal or wave. Actually, in this work we focus on a series of interferometric and diffractive experiences where the student can gain a deep insight of the importance of the phase content of a wavefront. The manipulation and/or measurement of the phase content are on the basis of many applications. In this paper we show some of these applications in metrology and in diffractive optics. Furthermore, these experiences are more clearly connected to modern applications and may also be more appealing for the student when using a well known commercial device, the liquid crystal display, in their development.

Keywords

Amplitude and phase, didactic experiments, liquid crystal displays, diffractive optics, interferences, wavefront modulation, metrology, diffractive optical elements.

1. INTRODUCTION

The concepts of amplitude and phase play a very important role in many fields of Science and Engineering as it can be experienced, for example, examining any general physics textbook [1]. These concepts originate in areas where oscillatory or wave movements are involved, as in electromagnetism, acoustics or signal theory to name a few. Amplitude and phase are also important in more modern areas like quantum mechanics where they are related with the description of a certain system as a linear combination of eigenstates. Oscillations and waves are two different phenomena, even though they are closely related in many situations (e.g. oscillations of an electrical charge generate the propagation of an electromagnetic wave). We note that this work can be applied to the description and interpretation of wave related phenomena [1][2].

In general, the amplitude of a signal, vector or scalar field, wave,…, can be easily understood by the students since it is related to the strength of the physical magnitude. However, the role played by the phase is somehow more mysterious. In general, the phase value is related to a time delay in the physical magnitude. How these time delays are introduced and how they can be used in applications is more difficult to perceive than the importance of the amplitude. In this sense, the realization of laboratory practices where phase information is directly applied provides a more effective comprehension of its importance both in Science and in Technology.

In this paper we show a lab practice where students manipulate the shape of a light beam (phase and amplitude). We use a liquid crystal display (LCD) [3][4], previously calibrated, to work as some typical devices such as diffraction gratings or diffractive lenses [5][6]. The LCD can be used as an amplitude or as a phase dynamic transparency, where the information can be changed in real time. When used as a phase transparency, the LCD is a transparent device, thus no visible information can be seen onto its surface. The student can, however, experience how the incident beam is reshaped by the phase information. The information onto the LCD can be changed in real time, so the student can see how the shape of the transmitted beam is dynamically changing.

In general, Optics experiences are very effective to introduce new concepts since students can directly visualize the effects of manipulation of information with their own eyes [2][7]. The use of widespread consumer electronics devices, such as LCDs, in an educational lab is also very appealing since students can clearly see the connection between daily technology and the concepts learned in theoretical lectures.

The structure of the paper is as follows. In Section 2 we introduce the liquid crystal display as a device that can be used to control the phase and amplitude of a light beam. In Section 3, we show different phenomena directly related with the phase information contained in a wave. On the one hand, we show the application of interference phenomena in metrological applications. On the other hand, we demonstrate the application of diffraction to generate non-conventional optical elements to deflect (diffraction gratings) or to focus (diffractive lenses) a light beam. Eventually, the main conclusions of the paper are given in Section 4.

2. AMPLITUDE AND PHASE MODULATION WITH A LCD

In many fields of Science and Engineering, the effect of a certain medium or device on an incident wave or signal can be modelled as an absorption and a time delay. In this case, for a linear medium, the transmission between an input and an output plane can be expressed as a phasor,

$$M(x,y)=T(x,y)\exp[\varphi(x,y)] \tag{1}$$

where $M(x,y)$ is the function describing the action of the medium between the input and output planes at coordinates (x,y). The modulus $T(x,y)$ is related with the absorption in the medium and $\varphi(x,y)$ corresponds to the phase associated with the time delay introduced when traversing the medium.

If the properties of the medium can be dynamically controlled by an external signal s, then the modulation capability of the medium can be expressed by

$$M(s)=T(s)\exp[\varphi(s)] \tag{2}$$

where in general the value for the applied signal s may vary with the position $s(x,y)$. Let us continue the discussion using the particular example of visible light. A medium with a tunable absorption can be thought as a dynamic amplitude transparency. In the case when there is no absorption but the phase of the incident signal can be shifted, then we have a transparent device working as a phase dynamic transparency. Even though we know what is a time delay, the fact that the medium is transparent does not allow to have a direct perception of the effect of the medium on the incident wave.
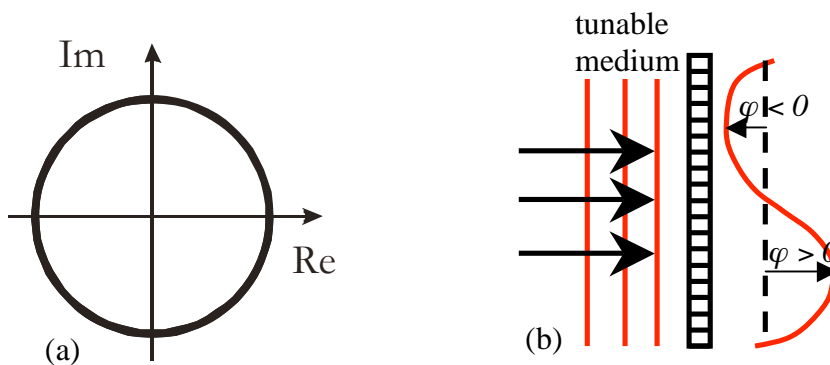

Fig. 1. Phase-only modulation. (a) Complex plane representation. (b) Diagram showing the time delay introduced by a phase-only device and its relation with the phase value across the wavefront.

In Fig. 1 we represent the action of a tunable phase medium. In Fig. 1(a) we show the curve corresponding to a phase-only device in the complex plane. The signal of control s modifies the phase φ of the phasor function in Eq. (2) while maintaining a constant magnitude T. In Fig. 1(b) the diagram shows the relation between the time delay introduced by the device onto a plane wave and the phase associated with the wavefront. We will consider the following convention in this work: points with a lower phase φ indicate a greater delay in the transmitted wave.

Even though the phase value can not be appreciated visually, its effects may provide a good insight of the importance of phase information in many applications. In visible light the effects of phase information have a direct impact onto the interferences and diffraction phenomena [2]. Useful applications can be envisioned taking advantage of both interferences and diffraction. Liquid crystal displays (LCD) enable to present these applications in real-time, i.e. direct control from a computer enables the refreshing of the information displayed at video rates.

In general, LCDs allow to modify in real time the amplitude, phase and/or the state of polarization of a light beam [2][4][8][9]. This capability can be used to design programmable optical elements, such as lenses, apodizing filters, data pages, or simply binary gratings, useful in diffractive optics, imaging systems, and in holographic data storage. In this work, the use of LCDs (widespread in commercial electronic devices) with its real-time capability allows an appealing presentation of phase-related applications to students and to non-experts in general.
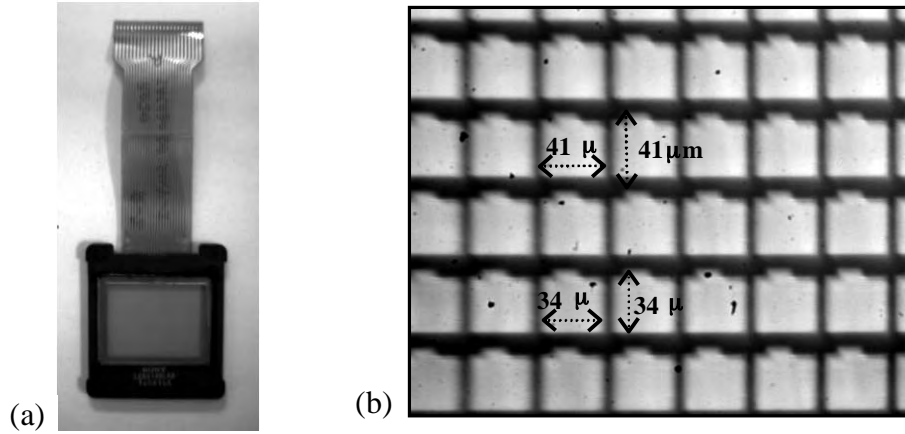

Fig. 2. (a) LCD Sony Model LCX012BL. (b) Magnified image of the pixelation of the LCD. Dark areas correspond to the electrode wires, and to the thin film transistor (TFT) and the capacitor for each pixel.

In Fig. 2 we show the detail of the LCD used in this work. It is a Sony LCD, model LCX012BL, with a VGA resolution (640x480 pixels), extracted from a Sony video projector, model VPL-V500. In Fig. 2(a) the LCD panel used is shown. In Fig. 2(b) a magnified image of the panel is presented, where the pixelated structure of the device can be seen. The interpixel spacing is about 41 μm with a pixel clear aperture of 34 μm. To use the LCD panel in an optical set-up we extract it from the video projector and proceed with some technical preparations (connection to a longer cable, removal of the sheet polarizers attached to the windows of the panel, etc). For more details see Ref. [8]. We use LCDs extracted from commercial LCD-video projectors due to their low cost and large availability. They can also be bought as ready to use LCD kits at a significant higher cost [10].
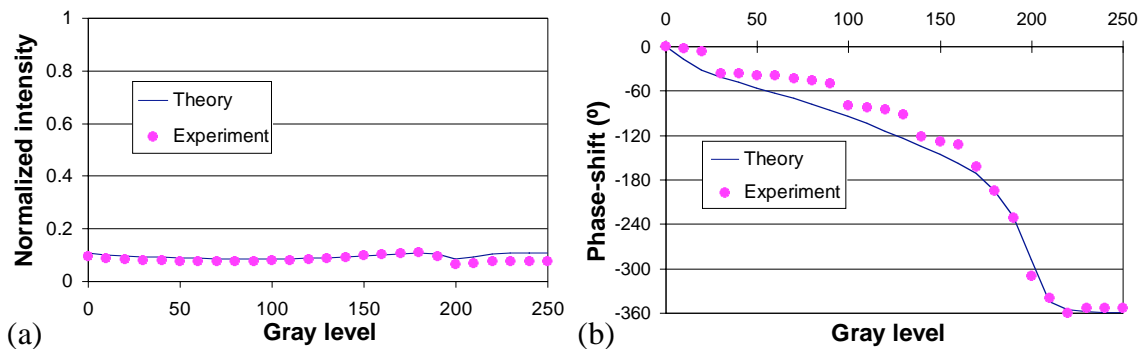

Fig. 3. Phase-only modulation used in this work. (a) Normalized intensity. (b) Phase-shift.

The modulation properties of the LCD can be characterized by a number of techniques [8]. This characterization enables us to use the panel as an amplitude-only modulator or as a phase-only modulator. The absorption and the time delay (phase-shift) produced by the LCD can be controlled as a function of the voltage applied to the pixel. In general, the LCD is inserted between a pair of linear

polarizers to obtain amplitude-only modulation, and between a pair of linear polarizers and a pair of wave plates to obtain phase-only modulation [8]. In Fig. 3 we show the modulation curves for the LCD used in this paper, enabling for phase-only modulation. We use the incident light beam from a Nd:YVO4 laser (λ=532 nm). In Fig. 3(a) and (b) we show respectively the intensity and the phase-shift as a function of the gray level (which is related with the applied voltage). The phase modulation depth is 360º and the intensity is almost constant. In Fig. 4 we plot a complex plane representation of the amplitude and phase-shift modulations: the curve has the shape of a closed circle with a constant radius, as it has to be for a phase-only modulation. In Fig. 3 and 4 the continuous line corresponds to the theoretically predicted values using the model described in Ref. [8], and the points correspond to the values measured experimentally. There is a good agreement between theory and experiment.
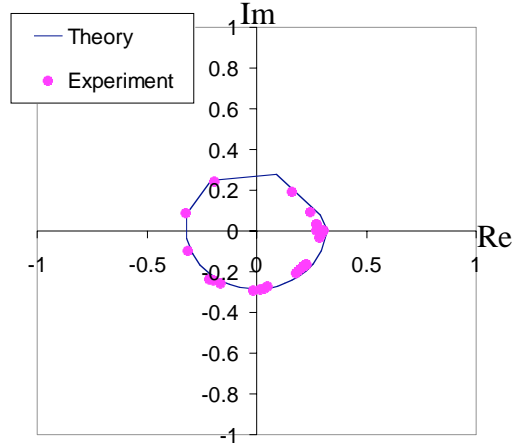

Fig. 4. Complex plane representation of the phase-only modulation used in this work.

Different applications of the phase content in a signal can be demonstrated using the phase-only modulation curves described in Figs. 3 and 4.

3. EXPERIENCES: CONTROLING THE PHASE OF A WAVEFRONT

3.1 Two beams interferometer to measure the phase modulation

Interferometric experiences are a useful approach to understand the information provided by the phase in a wavefront. In this sense interferometry is usually applied in metrological applications. In these applications the phase value of the wavefront serves as the probing magnitude to measure a certain property in the sample under study. Now we show the application of interferometry to measure the phase-shift introduced by the LCD on the incident wavefront as a function of the gray level.
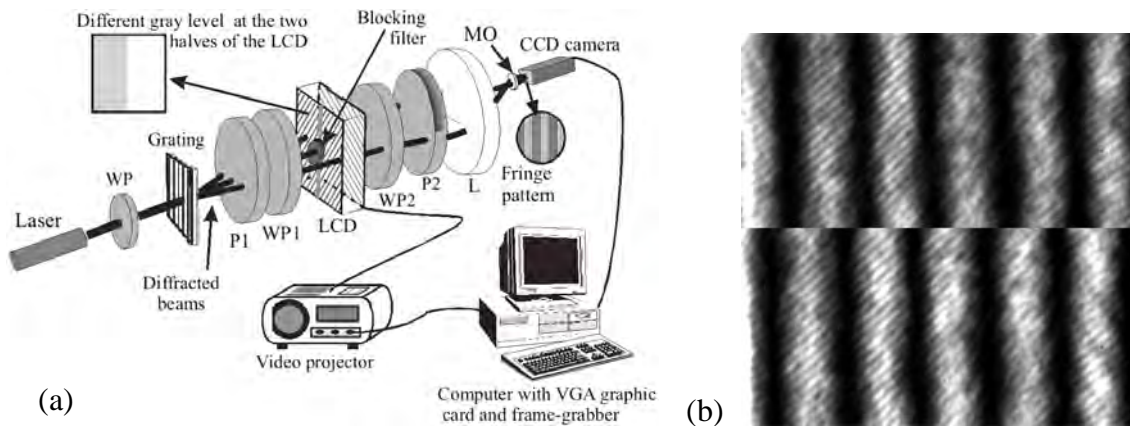

Fig. 5. (a) Phase modulation measurement set-up using the double slit interferometer: WP is a wave plate, P are polarizers, L is a converging lens, and MO is a microscope objective. (b) Fringe displacement due to the change of gray level in one side of the screen of the LCD.

In Fig. 5(a) we show the interferometric set-up used to measure the phase-shift curve shown in Fig. 3(b). It corresponds to a two beams interferometer (or a double slit interferometer). The LCD is inserted between the polarizing devices (linear polarizers, LP, and wave plates, WP) in the desired configuration. An unexpanded laser beam is diffracted by a low frequency phase diffraction grating. The two diffraction maxima corresponding to the first diffraction orders are incident onto the LCD. The rest of the diffraction orders are blocked. The lens L recombines the two beams after their passage through the LCD. The interference fringes produced are magnified with a microscope objective (MO) onto the sensor array of a CCD camera. The input aperture of the microscope objective serves as a spatial filter that only transmits the zero-order component of the diffraction pattern produced by the pixelated structure of the LCD.

Thus, the pattern produced at the CCD camera is a two-beam interference pattern like the one produced by a double slit [2]. The position of this interference fringe pattern on the camera is directly related to the relative phase-shift φ between the two beams that form the pattern. It is easily shown that

$$\varphi = 2\pi\Delta / \Lambda \tag{3}$$

where Δ is the interference fringe displacement, and Λ is the fringe period, both measured in CCD pixels. The two beams pass through opposite halves of the LCD. A different gray level signal is addressed to each half of the LCD. Thus, the relative phase-shift φ caused by the gray level can be obtained by observing the fringe translation. In principle we maintain one half of the screen at a gray level equal to zero, and the gray level at the other half of the screen is changed from 0 to 255 to obtain the data plotted in Fig. 3(b). In Fig. 5(b) we show two interference patterns corresponding to two different gray levels addressed to one half of the screen whereas the other half is kept at 0 gray level.

3.2 Deflection and focusing of a wavefront

Diffraction can be used in applications such as deflection or focusing of a light beam [5][6]. In these applications the modulating element, which in this paper is addressed onto the LCD, modifies the phase value along the wavefront in a very specific manner. The elements generated are usually called diffractive optical elements (DOEs), being the diffraction grating and the diffractive lens the basic ones.
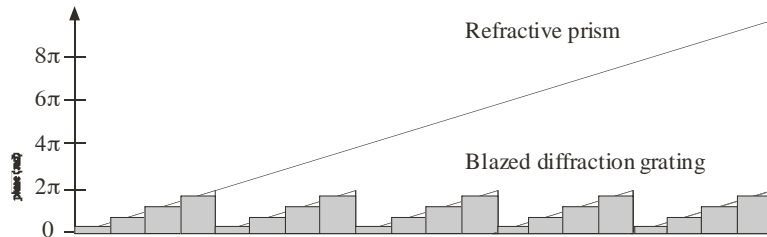

Fig. 6. Analogy between phase profiles for the prism (refractive) and the blazed grating (diffractive).

In deflection the goal is to shift angularly the path for the incident beam. This is what a refractive prism does. The equivalent device in diffraction is the blazed (or sawtooth) grating. In Fig. 6 we represent the phase profile for a prism and for a blazed grating. If we cut the prism in small prisms of 2π radians height, we obtain the periodic structure of a blazed grating. In the case of the LCD this periodic structure is furthermore sampled by the pixelation (e.g. in Fig. 6 each period is composed by four pixels). Two parameters are of interest: the deflection angle and the amount of energy deflected into the primary diffraction order. The deflection angle is given by the grating equation,

$$sen\theta_m = m\frac{\lambda}{\Lambda} \tag{4}$$

where m is the diffraction order, λ is the incident wavelength, Λ is the period of the grating and θ_m is the deflection angle for the order m. If the phase depth of the blazed grating is 2π, then all the incident

light is deflected to the first order. If the blazed profile is not continuous but it is quantized, as in Fig. 6, then a small amount of light is also directed to the other diffraction orders.

In Fig. 7 we show the experimental images obtained when addressing a blazed grating to the LCD. For the sake of comparison we show in Fig. 7(a) the image when no grating is addressed, thus the original beam is observed. In Fig. 7(b) we address a blazed grating with a phase depth of π radians. We see that part of the light from the original beam is redirected to the diffraction orders. In Fig. 7(c) a blazed grating with a phase depth of 2π is addressed. Now we observe that practically all the light is deflected to the first order. The period for the blazed grating addressed in these results is 4 pixels per period.
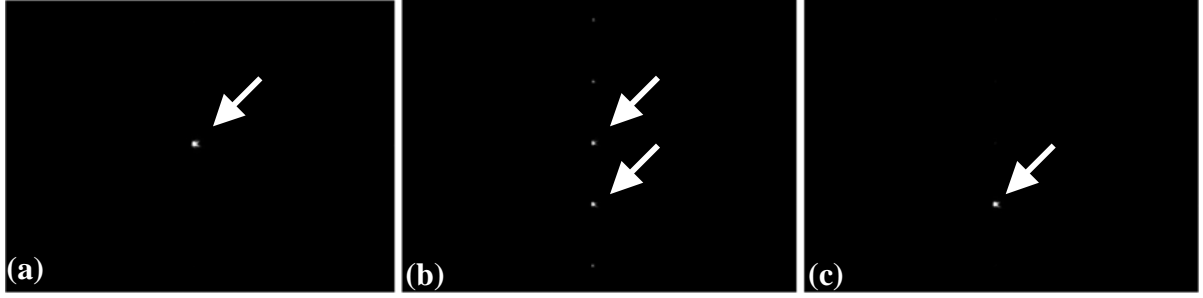

Fig. 7.(a) Original beam. Images (b) and (c) correspond to the diffraction orders generated by a blazed grating with a phase depth of π and 2π radians respectively. The arrows in the figures indicate the location of the original incidence and the designed deflection.

Let us show some results related with focusing. The lens is the element responsible for focusing. In Fig. 8 we show the phase profile for a refractive lens and for its diffractive equivalent. As in Fig. 6, the diffractive equivalent is obtained by cutting the phase profile of the refractive lens in steps with a 2π radians height. The diffractive lens can be thought as a blazed grating with a decreasing period as the distance from the symmetry axis increases. The phase profile introduced on the incident wavefront by a refractive lens is given by,

$$\varphi(r) = \frac{\pi}{\lambda f'} r^2 \tag{5}$$

where λ is the incident wavelength, f' is the focal length of the lens and r is the radial coordinate. In the case of cylindrical lenses the radial coordinate is substituted by one of the two Cartesian, x or y, coordinates.
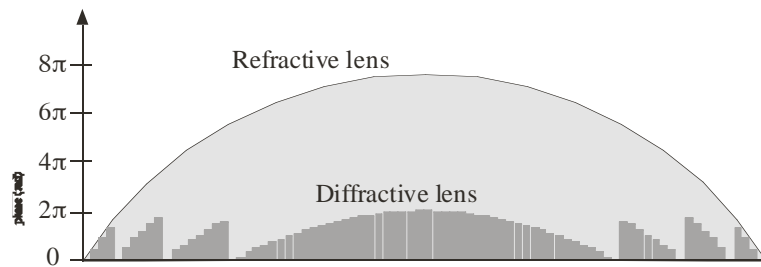

Fig. 8. Analogy between phase profiles for the refractive lens and the diffractive lens.

In Fig. 9 we show some experimental results obtained when addressing a cylindrical lens with a 1 meter focal length to the LCD. The phase profile for the lens varies along the vertical coordinate, thus the focusing is a horizontal line. In Fig. 9(a) we show the focusing line when the phase depth in the diffractive lens is π radians, and in Fig. 9(b) when the phase depth is 2π radians. Both images where obtained with the same incident intensity onto the LCD. When the phase depth is less than 2π diffractive lenses generate secondary focusing planes. We see that in Fig. 9(b) the focusing line is clearly more intense since almost all the energy is directed to the main focus.
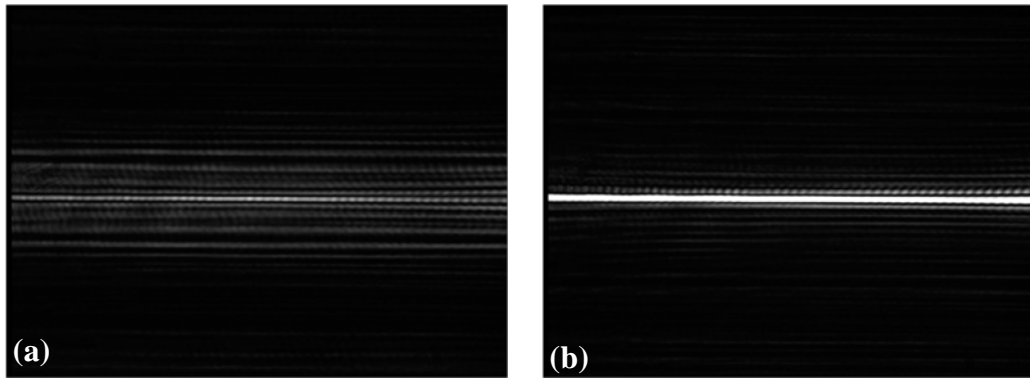
Fig. 9. Images obtained when addressing a cylindrical lens to the LCD with
a phase depth of π radians and 2π radians respectively in (a) and (b).

4. CONCLUSIONS

We have used a liquid crystal display working in the phase-only regime to provide a deeper insight into the meaning and importance of the phase content of a wavefront or signal. We use visible light in the experiences since it allows a more direct perception of wave related phenomena. We focus on experiences in interferometry and in diffractive optics based on the measurement and/or manipulation of the phase content. These didactic experiences are also directly connected to real applications. In interferometry we demonstrate a procedure to measure the phase-shift provided by the LCD as a function of the gray level addressed. In diffractive optics we show how depending on the phase profile addressed to the LCD we can perform the deflection or the focusing of a light beam. We think that these experiences are more clearly connected to modern applications and may also be more appealing for the student when using a well known commercial device, the liquid crystal display, in their development.

ACKNOWLEDGMENTS

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