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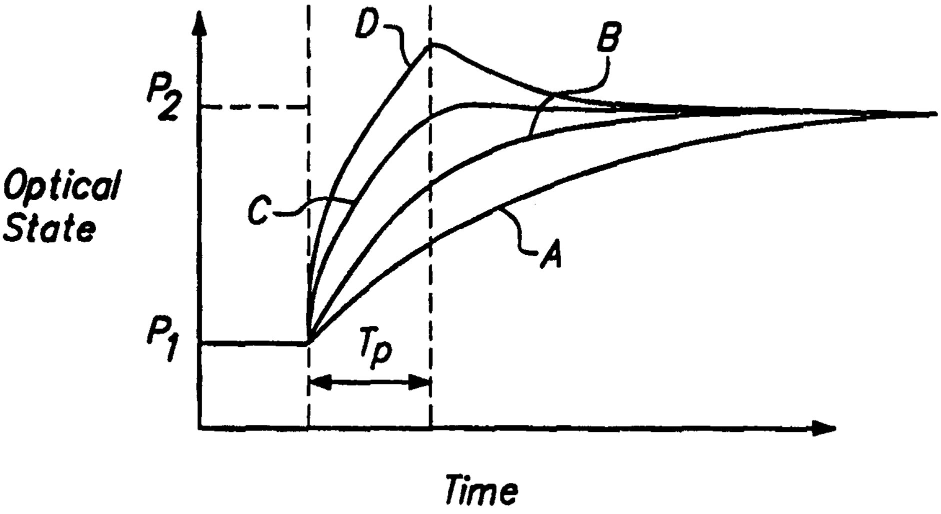

(57) Abstract

An improved driving method is described for increasing the switching speed of gray-scale liquid crystal displays. By applying a pulsed electric field greater than the desired final electric field at the start of the driving cycle, a boost in the initial switching impetus is provided that increases the switching speed.

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METHOD OF DRIVING A LIQUID CRYSTAL DISPLAY

TECHNICAL FIELD OF THE INVENTION

The present invention relates to a method of driving a liquid crystal display to improve its gray scale switching speed.

BACKGROUND OF THE INVENTION

High resolution, high speed liquid crystal displays for depicting graphical or linguistic information comprise many pixels, each of which may be driven or controlled by an active matrix element such as a transistor. Illustrative publications relating to such displays include Edmonds, US 3,832,034 (1974); Hamaguchi, US 4,838,654 (1989); Bowman et la., US 4,910,579 (1990); Shannon, US 4,931,787 (1990); Te Velde, US 5,005,951 (1991); Flasck, US 5,022,750 (1991); Flasck, US 5,024,524 (1991); Flasck, US 5,108,172 (1992); Kamath et al., US 5,233,445 (1993); IBM, EP 0,112,417 (1984); N.V. Philips, EP 0,294,898 (1988); Garwin, IBM Technical Disclosure Bulletin, Vol. 22, no. 8A, pp. 3447-8 (Jan. 1980); and Huntley, IBM Technical Disclosure Bulletin, Vol. 23, no. 1, pp. 347-8 (Jun. 1980).

The active matrix elements are disposed in an array, each element helping define a pixel and controlling the optical state of liquid crystal material associated therewith. Depending on the desired optical state of an active matrix element, a voltage (electric field) is applied or not to the liquid crystal material. In turn, the liquid crystal material is switched from one optical state to another. For example, a pixel in the "field-on" state may permit incident light to be transmitted through the liquid crystal material and to be specularly reflected by a reflector positioned behind it, back towards the incidence side (albeit angularly displaced by operation of the laws of reflection), while a pixel in the "field-off" state may prevent such reflection by scattering or absorbing the light. Generally, the optical effect is associated with a reorientation of the alignment directors of the liquid crystal material. The combination of many "on" and "off" pixels generates an image that can be viewed directly, or projected onto a screen for viewing, or viewed as a virtual image with the aid of appropriate optics. In many instances it is desirable that the display present a gray scale image, in which pixels are not either entirely "on" or "off" but only partially so, with the result that an image having subtle shades of gray is presented, instead of a stark black-and-white image.

A schematic illustration is shown in Fig. 1, in the form of a simplified liquid crystal display 1 consisting of four pixels 2a, 2b, 2c, and 2d. Pixel 2a is in the "field-off" state and is, in this depiction, arbitrarily shown as white. Pixel 2d is in the full "field-on" state and is shown arbitrarily as black. Pixels 2b and 2c are in intermediate switching states, corresponding to respective intermediate voltages that are non-zero but are less than the "field-on" voltage, and have progressively darker gray tones (the voltage applied to pixel 2c being greater than that applied to pixel 2b). (The electric field experienced by the liquid crystal material depends on the applied voltage and the thickness of the liquid crystal material. Two specimens of the same thickness will experience the same field if the voltage is the same; conversely, specimens of different thicknesses will experience different fields for the same applied voltage.)

For some liquid crystal materials, the gray scale rise time (the time needed to drive a pixel from one optical state to another by the application of an electric field thereto) is a non-monotonous function of the applied electric field. Fig. 1 illustrates this relationship for one type of liquid crystal material, a liquid crystal composite comprising plural volumes or droplets of liquid crystals contained within a polymer matrix, such as disclosed in Fergason, US 4,435,047 (1984). Increasing the applied voltage (i.e., the electric field across the liquid crystal material) increases the driving force for the reorientation of the alignment directors, but at the same time a greater extent of realignment is required to reach the equilibrium position. These opposing factors result in a maximum in the rise times at intermediate voltages. In other words, gray scale response can be much slower than full off/on response. In this particular instance the time needed for a pixel to switch from the field-off optical state to the intermediate optical state corresponding to 2.5 volts is about 1,100 msec, compared to the 100 msec required for full field-on switching at about 4.0 volts.

Slow gray scale rise times can result in problems such as "image sticking" for static images and "image ghosting" for moving images. These effects are aesthetically unpleasant and their elimination is desirable.

Further, field sequential color approaches for generating intermediate gray scale color images in a projection display or virtual display require fast speeds in order to generate pure colors. Slow response times will produce color blending.

BRIEF SUMMARY OF THE INVENTION

In view of the foregoing, it is desirable to develop a method for improving the gray scale switching speed, or response, of a liquid crystal display. Accordingly, this invention provides a method of driving a pixel in a liquid crystal display having a plurality of pixels, comprising the steps of:

a. providing a liquid crystal display comprising a plurality of pixels comprising liquid crystal material and having a plurality of optical states that differ in their transmittivities to incident light as a function of the electric field to which the liquid crystal material is subjected;

b. selecting a pixel to be driven, the pixel being at a first optical state P_1 and the liquid crystal material therein being subjected to a corresponding first electric field E_1;

c. selecting, for the pixel, a desired second optical state P_2 and a corresponding second electric field E_2, wherein

$$E_2 > E_1 \quad ;$$

d. subjecting the liquid crystal material of the pixel to a pulsed electric field E_P wherein

$$E_P > E_2 \quad ; \qquad \text{and}$$

e. thereafter subjecting the liquid crystal material of the pixel to the second electric field E_2.

BRIEF DESCRIPTION OF THE DRAWING(S)

Fig. 1 shows a liquid crystal display having four pixels displaying varying degrees of a gray scale.

Fig. 2 shows how the gray scale response time of a liquid crystal display varies with the applied electric field.

Fig. 3a illustrates the pulsed driving method of this invention. Fig. 3b shows how the pulsed driving method of this invention lowers the switching time of a liquid crystal display.

Fig. 4 shows an embodiment of this invention with a fixed pulse duration but a variable pulse amplitude.

Fig. 5 shows an alternative embodiment of this invention with a variable pulse duration but a fixed pulse amplitude.

DETAILED DESCRIPTION OF THE INVENTION

Figs. 3a and 3b show how the driving method of this invention leads to lower switching times (i.e., faster switching speeds or responses) in a gray scale liquid crystal display. The figures depict, plotted against a common time X-axis, the electric field applied to a pixel of a liquid crystal display (Fig. 3a) and the pixel's optical state (Fig. 3b). The pixel is initially at a first optical state P_1 corresponding to a first electric field E_1. The scale of the electric field axis in Fig. 3a is arbitrary, so first electric field E_1 can be zero (i.e., no electric field has been applied and the pixel is in the field-off state), or it can be non-zero (i.e., the pixel is at an intermediate gray scale state). It is desired to switch the pixel to a second optical state P_2, corresponding to a second electric field E_2, where E_2 is greater than E_1. In a conventional driving method, the electric field applied to the pixel is simply increased from E_1 to E_2 and the optical state of the pixel is permitted to transition from P_1 to P_2 at its intrinsic switching speed. This process, shown as curve A in Fig. 3b, is not instantaneous. As noted hereinabove during the discussion of Fig. 2, the switching speed can be relatively very slow for intermediate gray-scale optical states.

According to this invention, a pulsed electric field E_P is applied the pixel, the pulsed electric field being greater than second electric field E_2. Then, the electric field applied to the pixel is reduced to second electric field E_2, corresponding to the desired second optical state P_2. The application of pulsed electric field E_P has the effect of giving the pixel a greater initial switching impetus towards second optical state P_2, although the equilibrium optical state eventually reached is that determined by the second electric field E_2, namely P_2. The result is that the pixel reaches second optical state P_2 faster, as shown by curve B of Fig. 3b.

If the amplitude of pulsed electric field E_P is increased, the boost in initial switching impetus is greater, resulting in even faster switching. This effect is illustrated by curve C in Fig. 3b, where the pulsed electric field E_P applied is greater in the instance of curve C than in the instance of curve B.

The waveform of pulsed electric field E_P is not critical, although a rectangular waveform is typical. Its duration (indicated as T_P in Figs. 3a and 3b) is preferably between 1 and 16 msec.

Curve D in Fig. 3b illustrates an overshoot situation that is preferably avoided. The amplitude and duration of pulsed electric field E_P are such that the optical state of the pixel passes beyond P_2 before returning to P_2. While a modest overshoot (for example, preferably less than about 10% and more preferably less than about 5%) is not detrimental, a significant overshoot can be optically noticeable and is therefore undesirable. Thus, preferably the duration of the pulsed electric field E_P no greater than the time required for the pixel to switch from first optical state P_1 to second optical state P_2 when subjected to the pulsed electric field E_P. Or, expressed mathematically,

$$T_P \leq T(P_1 \rightarrow P_2)\big|_{E_P}$$

where T_P is the duration of the pulse of pulsed electric field E_P and $T(P_1 \rightarrow P_2)\big|_{E_P}$ is the time required for the pixel's optical state to transition from P_1 to P_2 under an applied electric field equal in amplitude to E_P.

Fig. 4 shows how a pulse of constant duration (15 msec) but varying amplitude can be used to increase gray-scale switching speed. Five sets of curves, I through V, corresponding to increasing second electric fields E_2, are shown. For each set of curves, the solid line represents the calculated optical response upon the application of a voltage equal to second electric field E_2, while the dotted line (absent in set V) represents the calculated optical response upon the application of a pulsed driving method according to this invention. The pixel's switching time under a given set of conditions may be approximated as the time taken for the optical response to reach the "knee" of a curve. Line E links the switching times for the instances in which no pulsing is employed (i.e., conventional driving) and line F links the switching times needed to reach the same optical response when pulsing is employed. Switching times read from Fig. 4 is tabulated in Table IA below.

Table IA
Pulsed Driving With Variable Pulse Amplitude and Constant Pulse Duration (Using "Knee" Definition of Switching Speed)

Curve No.	Second Electric Field (V/μm)	Pulsed Electric Field (V/μm) [a]	Switching Time without Pulse (msec)	Switching Time with Pulse (msec)
I	0.60	0.65	17	15
II	0.80	0.95	39	17
III	0.90	1.15	45	18
IV	1.00	1.20	40	15
V	1.20	(none)	23	n/a

[a] Pulse duration 15 msec

An alternative definition of switching speed is often used in the art, instead of the above "knee" definition, in which the switching speed is defined as the time required for the transmission to increase from

$$P_1 + 0.1(P_2 - P_1)$$

to

$$P_1 + 0.9(P_2 - P_1) \quad .$$

Table IB provides information on the switching speed using this alternative definition (referred to herein as the $\Delta_{0.1\text{–}0.9}$ switching speed):

Table IB
Pulsed Driving With Variable Pulse Amplitude and Constant Pulse Duration (Using $\Delta_{0.1-0.9}$ Definition of Switching Speed)

Curve No.	Second Electric Field (V/μm)	Pulsed Electric Field (V/μm) [a]	Switching Time without Pulse (msec)	Switching Time with Pulse (msec)
I	0.60	0.65	25	19
II	0.80	0.95	48	15
III	0.90	1.15	42	15
IV	1.00	1.20	31	15
V	1.20	(none)	16	n/a

[a] Pulse duration 15 msec

It can be seen from a comparison of Tables IA and IB that, while the values of the switching speeds will be slightly different depending on the definition employed, the same pattern of improved switching speeds is observed. The Tables show how pulsed pixel driving according to this invention has the effect of lowering the switching time, the pulsed switching times being significantly lower than those without pulsing. Consistent with Fig. 2, the maximum effect is at the middle of the gray scale range. Another noteworthy effect of pulsing is that it substantially equalizes the pixel switching time of the pixel at all gray scale levels (in Fig. 2, line F is much less curved than line E).

Fig. 5 shows an alternative embodiment of the invention, in which the pulse amplitude is held constant, but the pulse duration is varied for different second electric fields E_2. Curves sets VI through X correspond to increasing second electric fields E_2 (with the solid and dotted lines having the significance as in Fig. 4). Line G connects the switching times in the absence of pulsing, while line H connects the switching times with pulsing.

Relevant information on switching speed improvement under constant-amplitude pulsing is provided in Tables IIA (using the “knee” definition) and IIB (using the $\Delta_{0.1-0.9}$ definition).

Table IIA
Pulsed Driving With Constant Pulse Amplitude and Variable Pulse Duration (Using a "Knee" Definition of Switching Speed)

Curve No.	Second Electric Field (V/μm)	Pulse Duration (msec) [a]	Switching Time without Pulse (msec)	Switching Time with Pulse (msec)
VI	0.60	2	9	2
VII	0.80	7	34	7
VIII	0.9	10	40	10
IX	1.00	15	33	15
X	1.20	0	22	n/a

[a] Pulse amplitude 1.2 V/μm

Table IIB
Pulsed Driving With Constant Pulse Amplitude and Variable Pulse Duration (Using a $\Delta_{0.1-0.9}$ Definition of Switching Speed)

Curve No.	Second Electric Field (V/μm)	Pulse Duration (msec) [a]	Switching Time without Pulse (msec)	Switching Time with Pulse (msec)
VI	0.60	2	25	17
VII	0.80	7	48	6
VIII	0.9	10	42	18
IX	1.00	15	31	15
X	1.20	0	16	n/a

[a] Pulse amplitude 1.2 V/μm

The effects shown in Tables IIA and IIB are generally similar to those shown in Tables IA and IB. Tables IA/B and IIA/B in combination show that the benefits of pulsed driving are available either in a constant pulse duration/variable pulse amplitude embodiment, or in a variable pulse duration/constant amplitude embodiment. Generally, the extent of the pulsing effect depends on the pulse duration and the pulse amplitude.

As noted above, the advantages of this invention are most noticeable in the middle of the gray scale range. If E_S is the saturation electric field, corresponding to a full "field-on" optical effect, then it is preferred that

$$0.8E_S > E_2 > 0.1E_S$$

There is no advantage in the method of this invention where a pixel is to be switched from an optical state corresponding to a higher electric field to an optical state corresponding to a lower electric field — i.e., where the switching is to be effected by decreasing the electric field applied to the pixel. Referring back to Fig. 2, the fall times — i.e., the switching times of the pixel in response to removal of or a decrease in the electric field — are relatively fast and generally insensitive to the applied electric field. Thus, in such an instance there is no need to increase the switching speed, and, even if a pulsed driving method were employed, it would be ineffective because of the insensitivity of fall times to the applied electric field.

One type of liquid crystal display for which the present invention is especially suitable employs a liquid crystal composite comprising plural volumes (or droplets) of liquid crystals contained (i.e., dispersed, encapsulated, or embedded) within a polymer matrix. Such composites have been referred to in the art alternatively as encapsulated liquid crystal material, nematic curvilinear aligned nematic (NCAP) materials or as polymer dispersed liquid crystal (PDLC) materials. Exemplary disclosures include Fergason, US 4,435,047 (1984); West et al., US 4,685,771 (1987); Pearlman, US 4,992,201 (1991); Andrews et al., US 5,202,063 (1993); Kamath et al., US 5,233,445 (1993); Reamey, US 5,328,850 (1994); Reamey et al., US 5,405,551 (1995); Wartenberg et al., US 5,427,713 (1995); Reamey et al., US 5,543,944 (1996); Havens et al., US 5,585,947 (1996); Cao et al., US 5,738,804 (1998); Raychem WO 96/19547 (1996); and Dainippon Ink, EP 0,313,053 (1989); the disclosures of which are incorporated herein by reference. Generally, such composites are light scattering and/or absorbing in the absence of a sufficient electric field (the field-off state), but are substantially light transmissive in the presence of such electric field (the field-on state). The present invention is particularly advantageous with NCAP/PDLC materials, as they are susceptible to stress-whitening even at fairly low stress levels.

The foregoing detailed description of the invention includes passages that are chiefly or exclusively concerned with particular parts or aspects of the invention. It is to be understood that this is for clarity and convenience, that a particular feature may be relevant in more than just the passage in which it is disclosed, and that the disclosure herein includes all the appropriate combinations of information found in the different passages. Similarly, although the various figures and descriptions herein relate to specific embodiments of the invention, it is to be understood that where a specific feature is disclosed in the context of a particular figure or embodiment, such feature can also be used, to the extent appropriate, in the context of another figure or embodiment, in combination with another feature, or in the invention in general.

Further, while the present invention has been particularly described in terms of certain preferred embodiments, the invention is not limited to such preferred embodiments. Rather, the scope of the invention is defined by the appended claims.

CLAIMS

What is claimed is:

1. A method of driving a pixel in a liquid crystal display having a plurality of pixels, comprising the steps of:
   a. providing a liquid crystal display comprising a plurality of pixels comprising liquid crystal material and having a plurality of optical states that differ in their transmittivities to incident light as a function of the electric field to which the liquid crystal material is subjected;
   b. selecting a pixel to be driven, the pixel being at a first optical state P_1 and the liquid crystal material therein being subjected to a corresponding first electric field E_1;
   c. selecting, for the pixel, a desired second optical state P_2 and a corresponding second electric field E_2, wherein

$$E_2 > E_1 \quad ;$$

   d. subjecting the liquid crystal material of the pixel to a pulsed electric field E_P wherein

$$E_P > E_2 \quad ; \qquad \text{and}$$

   e. thereafter subjecting the liquid crystal material of the pixel to the second electric field E_2.

2. A method according to claim 1, wherein the pulsed electric field E_P has a duration of between 0.1 and 16 msec.

3. A method according to claim 1, wherein the duration of the pulsed electric field E_P is no greater than the time required for the pixel to switch from first optical state P_1 to second optical state P_2 when subjected to the pulsed electric field E_P.

4. A method according to claim 1, wherein the pulsed electric field E_P has a substantially rectangular waveform.

5. A method according to claim 1, wherein first electric field E_1 is zero.

6. A method according to claim 1, wherein first electric field E_1 is greater than zero.

7. A method according to claim 1, wherein the second electric field E_2 has an amplitude satisfying the inequality

$$0.8E_S > E_2 > 0.1E_S \quad ,$$

where E_S is the saturation electric field for the pixel.

8. A method according to claim 1, wherein the liquid crystal display has a reflector positioned therebehind.

9. A method according to claim 1, wherein the liquid crystal display has a light absorber positioned therebehind.

10. A method according to claim 1, wherein the liquid crystal material of the pixel is encapsulated liquid crystal material.

11. A method according to claim 10, wherein the pulsed electric field E_P has a duration of between 0.1 and 16 msec.

12. A method according to claim 10, wherein the duration of the pulsed electric field E_P is no greater than the time required for the pixel to

switch from first optical state P_1 to second optical state P_2 when subjected to the pulsed electric field E_P.

13. A method according to claim 10, wherein the pulsed electric field E_P has a substantially rectangular waveform.

14. A method according to claim 10, wherein first electric field E_1 is zero.

15. A method according to claim 10, wherein first electric field E_1 is greater than zero.

16. A method according to claim 10, wherein the second electric field E_2 has an amplitude satisfying the inequality

$$0.8E_S > E_2 > 0.1E_S \quad ,$$

where E_S is the saturation electric field for the pixel.

17. A method according to claim 10, wherein the liquid crystal display has a reflector positioned therebehind.

18. A method according to claim 10, wherein the liquid crystal display has a light absorber positioned therebehind.

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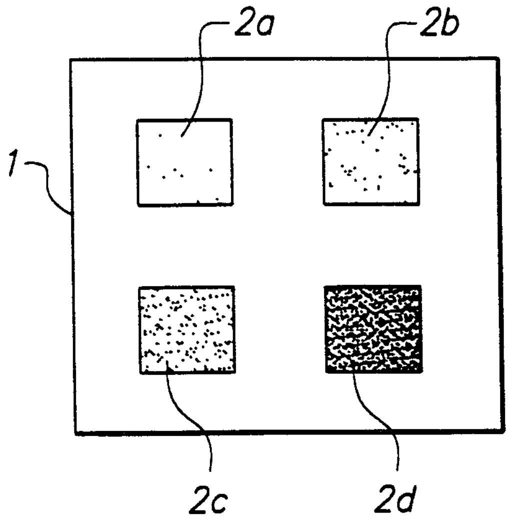


FIG. 1 (PRIOR ART)

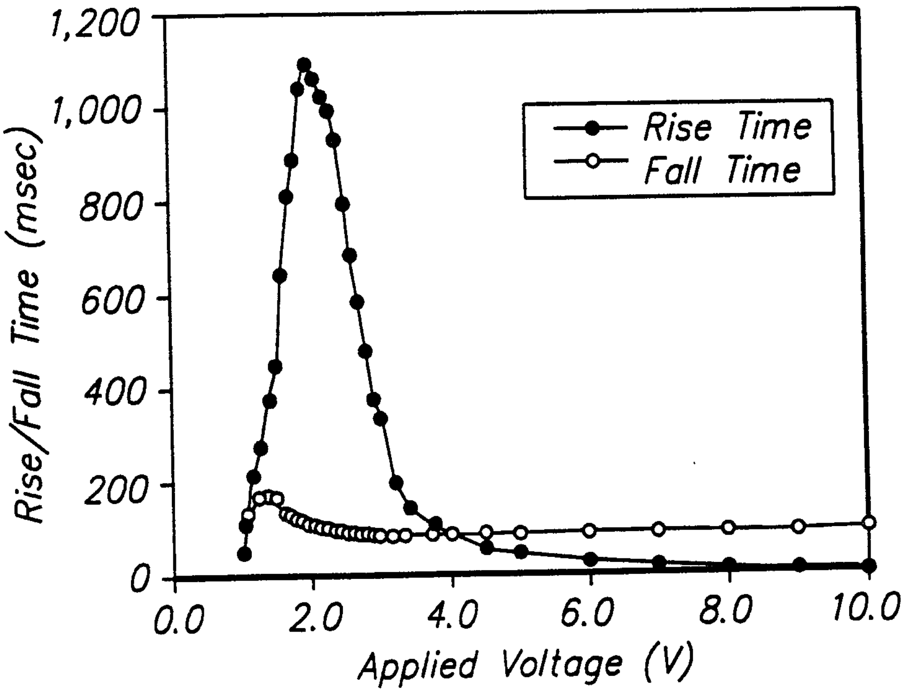
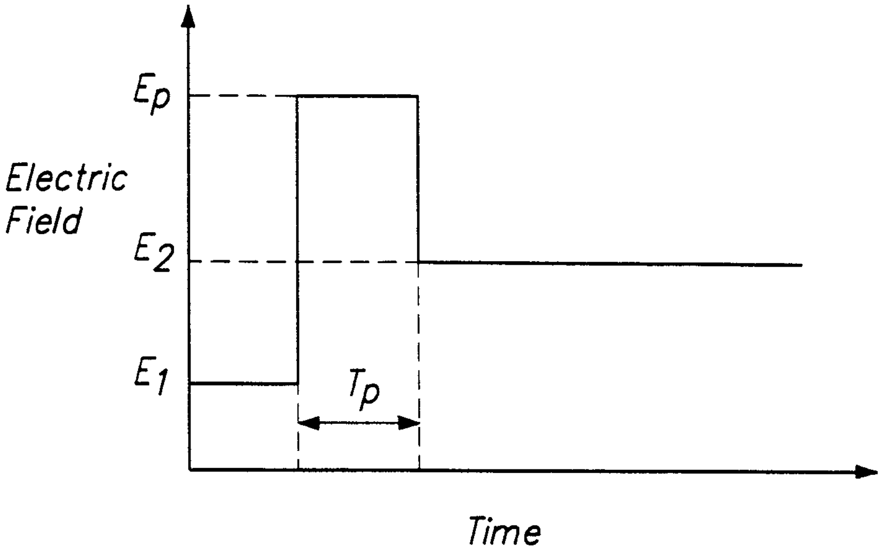


FIG. 2 (PRIOR ART)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Electric Field
E_2
E_1
T_p
Time

FIG. 3A

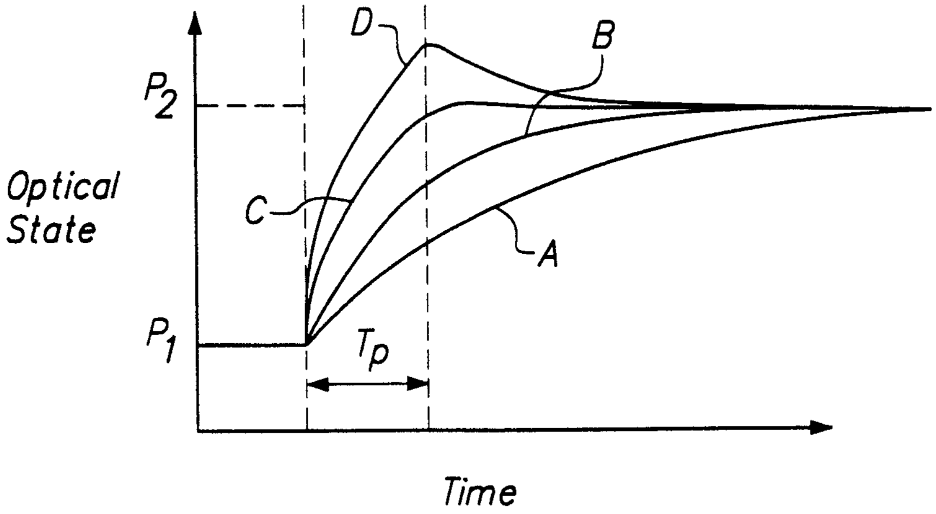
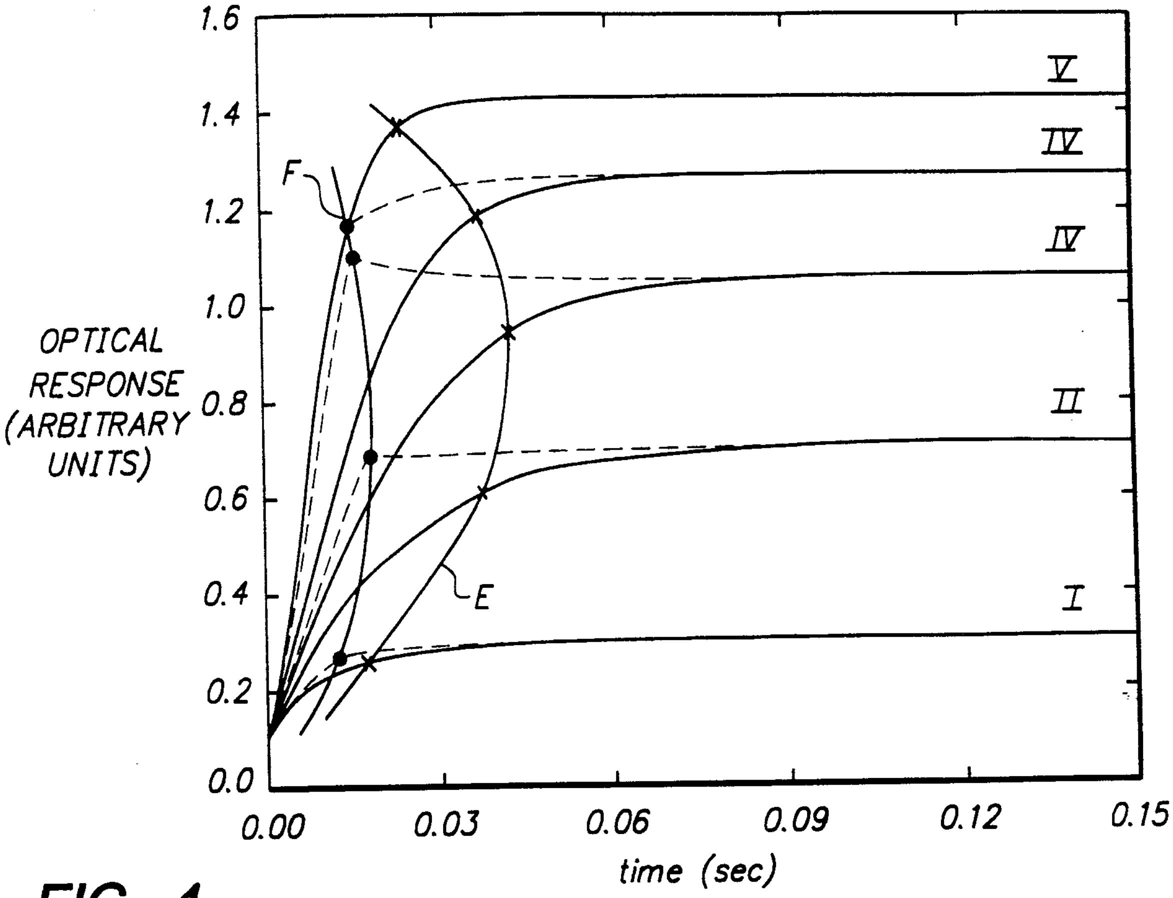

D
B
P_2
Optical State
C
A
P_1
T_p
Time

FIG. 3B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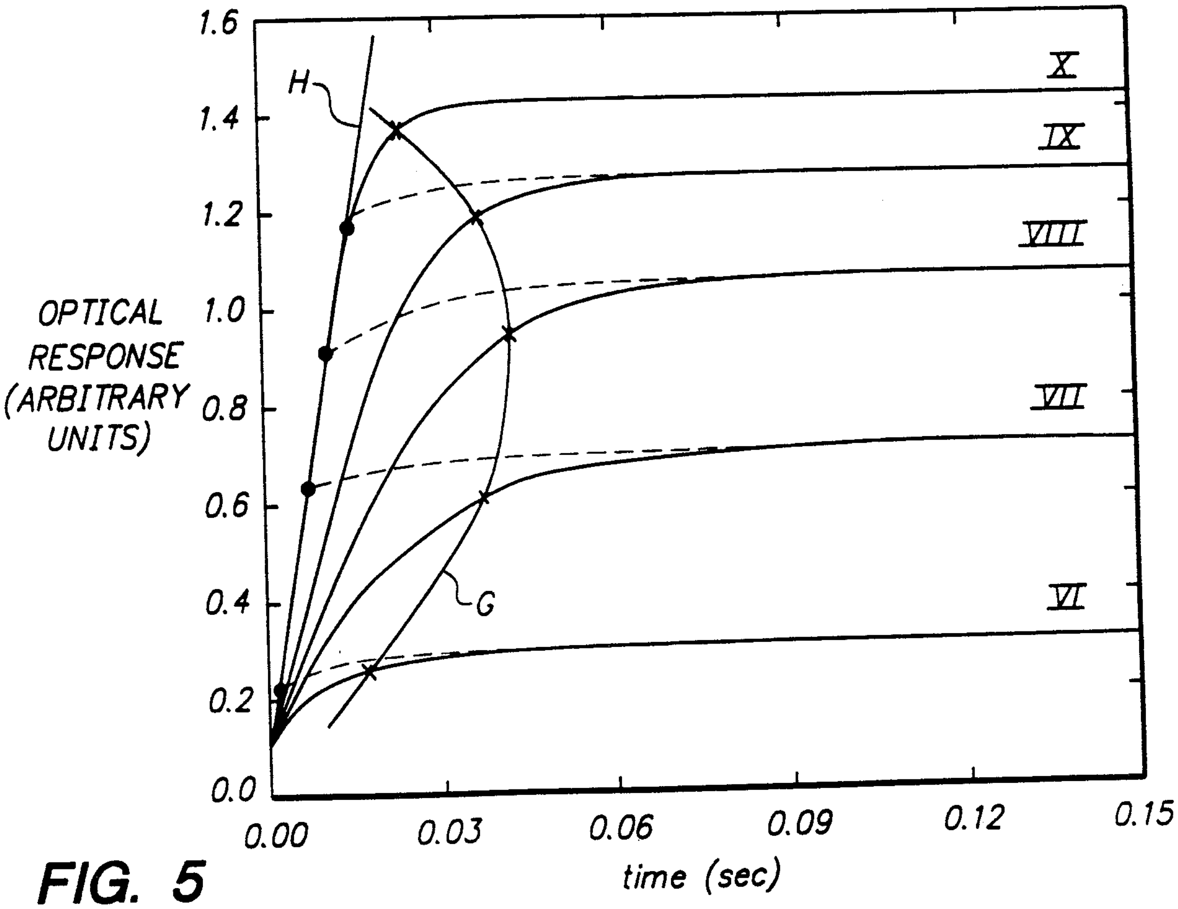
IV
II
I
F
E

FIG. 4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0.03
0.06
0.09
0.12
0.15
time (sec)
X
IX
VIII
VII
VI
H
G

FIG. 5

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/12521

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G09G3/36

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G09G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 521 611 A (OKADA HISAO ET AL) 28 May 1996 (1996-05-28) column 1, line 13 - line 38 column 5, line 9 - line 57 figure 2	1,4-6, 8-10, 13-15, 17,18
Y		2,3,7, 11,12,16

Y	WO 87 01468 A (CONS TECHNOLOGY PTY LTD) 12 March 1987 (1987-03-12) page 4, line 25 -page 4A, line 1 page 8, line 3 - line 22 page 11, line 21 -page 12, line 3 figure 4	2,3,7, 11,12,16
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Date of the actual completion of the international search 24 September 1999	Date of mailing of the international search report 05/10/1999
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