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PROGRESS

Display technique based on surface plasmon resonant effect

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In a surface plasmon resonant (SPR) configuration, real part in refraction coefficient of modulation layer material is monotonic with resonant wave length, while imaginary part is monotonic with resonant magnitude. Based on the fact above, a new type of display is proposed and designed. Firstly, a display pixel with either controllable color or controllable brightness is discussed, and then a display pixel with both controllable color and brightness is proposed in detail. At last, an SPR display with 8×8 pixels is developed and simulated. The results show that color and brightness of each display pixel in an SPR display can be tuned directly, with no need of synthesizing three basic colors, traditionally. Moreover, the display has many merits, such as high color resolution, high contrast, high brightness, fast response, etc. Yet practical usage of SPR display demands deeper study on properties of modulation layer material and fabrication techniques.

SPR effect, display, natural color

OPTICS

In 1897, a display device was invented by Braun in Germany. This device can transform electrical signal to optical signal by emitting electronic bundle generated by a gas discharge on the fluorescence materials. It could be regarded as the debut of electronic display. In 1933, Zworykin, "Father of the TV", invented the photoelectric vidicon and kinescope. It uncovered the veil of electronic epoch. Ever since, human beings stepped into the time of black and white TV. In 1950, Radio Company of America (RCA) developed the first color kinescope. Therefore color display time came. Since the 1960s, many kinds of new flat panel displays (FPD) have popped up one after another, such as liquid crystal display (LCD) invented by Heilmeiler in RCA in 1968, electroluminescent device (ELD) by Deb in 1969 and plasma display panel by Bitzer and Slottow at University of Illinois in USA in 1966. Contrasted with traditional CRT devices, such plane displays have smaller volume, lower power consumption, and lower driver voltage, completely solid state and easier fabrication process by the integrated circuit technique, etc.

New technology combining computer with display marked the history of display. This new application demands higher performance of display than general TV. Besides, popularity of micro computers calls for the appearance of varied and abundant graphic or word display with excellent performance. Therefore following this trend, it is natural that FPDs are more popular in computer display.

From the brief history of electric display, it can be seen that display development has the following characteristics: (i) A display based on a new principle may start a new epoch; (ii) development of the display has a very close relation with other fields, such as materials science, electronics and semiconductor integral circuit; (iii) displays hold promising future. If CRT technique that appeared at the beginning of the 20th centenary is considered as the first display revolution, the plane LCD technique can be viewed as the second one. Obviously, the

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advent of next generation display technique used for multimedia will be the third display revolution.

Today display techniques are primarily dominated by CRT and FPD, and the former has become mature while the latter is still in rapid and attractive development. Generally, CRT and FPD can be divided into many categories. Based on different principles, displays can be classified into active or passive display. Active display refers to the one that can be lighted by itself. The group of active display includes CRT, PDP, vacuum fluorescence device (VFD), filed-emitting device (FED), light-emitting diode (LED), the organic LED (OLED), etc. While Passive one refers to the one that cannot be lighted by itself but modulates surrounding or external optical source to let it show on a panel. In the process, it is supposed to control optical character of luminescence materials with electrical signals. LCD, digital micromirror device (DMD), ELD, etc., are just representatives of passive display.

About 90% of the objects seen by human beings belong to passive display group, so looking at passive display is consistent with human visual habits, which is more important today because of much more display applications. Furthermore, the passive display excels in anti-optical interference. Consequently, LCD has dominated very large market because of its many merits today. Unfortunately, it has a slower response to transmitting signal.

In a word, almost all color display devices are based on RGB synthesis system and the corresponding color band scope is very limited. Is it possible to invent a new type of display with high color resolution, high contrast, separation of color and brightness and fast response? Surface plasmon resonance effect (SPRE) gives an optimist answer[1−11].

Up to now, SPRE has been used to design biosensors widely. This kind of biosensor determines refractive coefficient by testing SPR wavelength. On reverse, given measured object's controllable refractive coefficient, the resonant wavelength is controllable too. This physical phenomenon makes SPRE very attractive in the display field. In the 1990s, Wang at JPL of California Institute of Technology had conducted research on SPRE display technique and designed electronically tunable color filter[4−8] and SPR RGB display device[9]. Moreover, he had made some study on electro-optic materials used for SPR display device[7,10]. This paper was initially inspired by the previous work of Wang. In my opinion, although his work is magnificent, separate study of color control and brightness control is not fitting into practical application of display. In this paper, combination of color and brightness control will be analyzed theoretically and simulated. Some key techniques will be presented and the future research target will be discussed.

1 SPR display principle

1.1 SPR display pixel configuration and classification

The basic SPR display pixel takes form of prism. Its fundamental operation principle is that real part in refractive coefficient of modulation layer controls resonant wavelength, while the imaginary part can control resonant magnitude. In other words, real part of refractive coefficient can control display color, while the imaginary part can control display brightness[11]. For a practical display pixel, output color and brightness are, in general, controlled by electrical signals, but not by refractive coefficient. Thus both real and imaginary parts of refractive coefficients should be controlled by electrical signals as well, which means that the used modulation layer should be a kind of electro-optic material whose refractive coefficient is a function of an electrical signal. Because it is difficult to control color and brightness simultaneously by a single modulation layer, two modulation layers are proposed in the paper, where one layer's refractive coefficient has constant imaginary part but electrically controllable real part for color control and another layer's refractive coefficient has constant real part but electrically controllable imaginary part for brightness control.

Firstly, the relation of refractive coefficient's real part and resonant wavelength, as well as the relation of imaginary part and resonant peak value will be discussed separately. Thus a configuration including just one modulation layer is enough to explain the SPR display principle, where the configuration shown in Figure 1 consists of prism 1, metal film 1, modulation layer, metal film 2 and prism 2. For the basic SPR display pixel, the process can be described as follows: a light with TM mode inputs into the prism 1 from one edge at a certain incident angle and then a surface plasmon wave (SPW) with a very narrow band will be excited at the interface of the metal film 1 and modulation layer, which will induce a coupled SPW with the same character as above one at the interface of the modulation layer

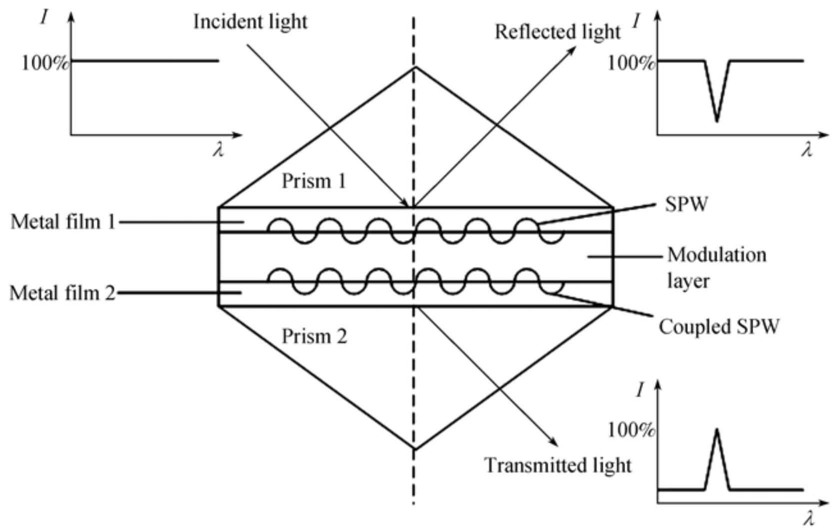

Figure 1 Basic SPR display pixel configuration.

and metal film 2 as long as the thickness of the modulation layer is thin enough, where the coupled SPW will be outputted from the opposite edge of the prism 2 and the reflected light will be outputted from another edge of prism 1 at the same time. The incident, reflected and transmitted lights are shown in Figure 1 respectively. In the configuration, both metal films are plamon layers as well as electrical poles.

According to different imaging methods, the SPR display can be classified into transmission mode and reflection mode. If the imaging is based on the transmitted light, it is defined as a transmission mode; if the imaging is based on the reflected light, it is defined as a reflection mode. For the reflection mode, the output light has a wider bandwidth, which controls display color by correspondent complementary color. And the brightness is controlled by the light source intensity. For the transmission mode, the output light has a very narrow bandwidth if a wonderful design is adopted, i.e. it can obtain very high color resolution and good contrast. In theory, both modes follow the same principle. However, it is more attractive for the transmission mode because it can be used to design a new FPD, is easier to implement and has higher color resolution.

1.2 Relationship of the modulation layer refractive index real part to resonant wavelength

Consider eq. (2.75) in ref. [11], suppose the real part in refractive coefficient of the used modulation layer is electrically controllable, the imaginary part is zero and other relative parameters have been appropriately selected. Then the resonant wavelength λ is a function of the refractive index real part n_{tr}, as expressed in eq. (1) and displayed in Figure 2:

$$\lambda = \lambda(n_{tr}). \qquad (1)$$

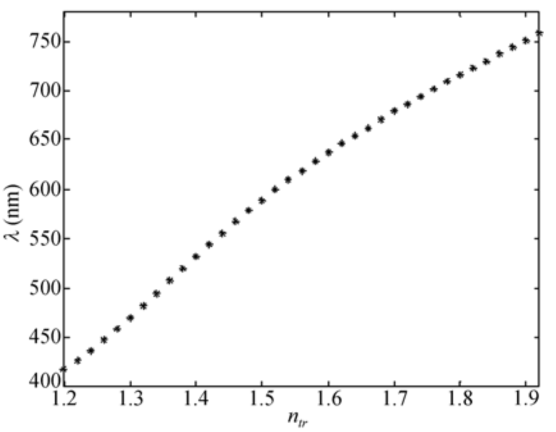

Figure 2 The relationship curve of λ and n_{tr}.

Figure 2 shows that λ is a monotonic function of n_{tr} under certain conditions, where the former is within 410 and 760 nm and the latter is within 1.2 and 1.95 RIU. It proves that controlling SPR display color by altering n_{tr} is possible in theory. By now, another question should be further discussed again. The question is how to create a function of n_{tr} to an electrical signal v_c, which can be expressed as

$$n_{tr} = n_{tr}(v_c). \qquad (2)$$

This question is very vital for practical SPR display design, but it is very hard to find an appropriate electro-optic material, whose refractive coefficient's real part is electrically controllable. At present, liquid crystal is often used as the modulation layer[7,10].

Combining eq. (1) with eq. (2), the function of the wavelength λ and the electrical signal v_c can be expressed as eq. (3). It is a key technique to create an optimal function of λ and v_c which will bring much work such as parameter optimization and material selection.

$$\lambda = \lambda(n_{tr}(v_c)). \tag{3}$$

1.3 Relationship of the resonant peak value to the refractive index imaginary part

Like in Section 1.2, another condition is discussed. Under this condition, refractive coefficient's imaginary part is electrically controllable, real part stays constant and other relative parameters have been appropriately selected. Then the resonant peak value $R_{\min}$ is a function of the refractive coefficient's imaginary part n_{ti}, which can be expressed as below and displayed by Figure 3.

$$R_{\min} = R_{\min}(n_{ti}). \tag{4}$$

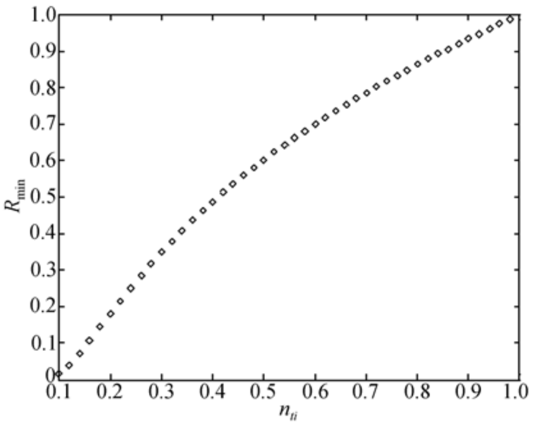

Figure 3 The relationship curve of $R_{\min}$ and n_{ti}.

Figure 3 shows that $R_{\min}$ is a monotonic with n_{ti} under certain conditions where the former is within 0 and 1 and the latter is within 0.1 and 1. It proves that SPR display brightness can be controlled by altering n_{ti}. According to the theory, the contrast can be up to 90%. And the experiment result shows that 50% contrast has been obtained[7,10]. Similarly, another question should be further discussed. It is about to create a function of n_{ti} to electrical signal v_l, which can be expressed as

$$n_{ti} = n_{tic} + n_{tiv}(v_l), \tag{5}$$

where n_{tic} is the constant part and n_{tiv} is the electrically controllable part.

Eq. (5) is pivotal for practical SPR display design as well, but it is very hard to find an appropriate electro-optic material whose imaginary part of the refractive coefficient is electrically controllable. So far liquid crystal, KDP, EO polymer, organic crystal and organic salt, etc., are often used as the modulation layer and Ni, Rh and Pt are used as a metal film[7].

By combining eqs. (4) and (5), the function of peak value $R_{\min}$ and electrical signal v_l can be rearranged as

$$R_{\min} = R_{\min}(n_{tic} + n_{tiv}(v_l)). \tag{6}$$

It is key to create an optimal function of $R_{\min}$ and v_l.

1.4 Combination relationships of λ, $R_{\min}$, n_{tr} and n_{ti}

Relation between material characteristic and color, as well as characteristic and brightness are independently discussed in the above sections to explain SPR basic principle, but it does not meet practical requirement for simultaneous control of n_{tr} and n_{ti} to change λ and $R_{\min}$. Although Figures 2 and 3 show very ideal results as expected, the performance will be worse under the combination of λ, $R_{\min}$, n_{tr} and n_{ti}. Thus the configuration in Figure 1 should be revised as Figure 4 including two modulation layers. One's real part of refractive coefficient is controllable and the other's imaginary part is controllable. Contrasted with Figure 1, all components have the same functions except an added insulation layer 5 sandwiched within metal films and two added transition layers 2 in Figure 4. Insulation and transition layers should be transparent in the visible light waveband and the transition layers are used to enhance the reliability of the configuration.

Based on eq. (2.75) in ref. [11], the function relation of the wavelength λ to n_{tr} and n_{ti} can be expressed as eq.

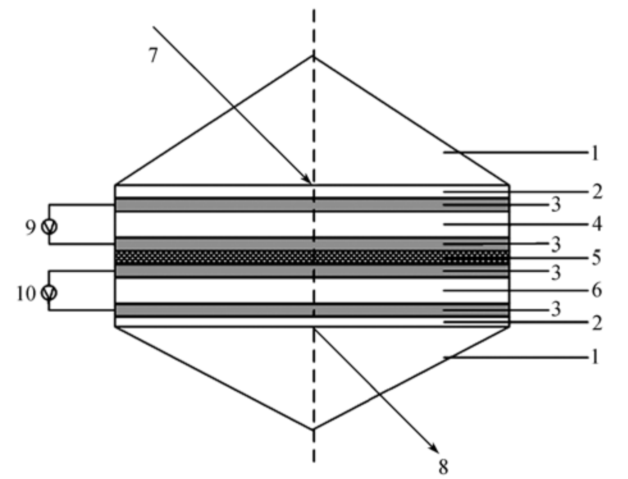

Figure 4 Combined SPR display pixel configuration. 1, Prism; 2, transition layer; 3, metal films (i.e. electric poles); 4, modulation layer with a controllable refractive index real part; 5, insulation layer; 6, modulation layer with a controllable refractive index imaginary part; 7, incident light; 8, transmitted light; 9, electrical signal to control layer 4; 10, electrical signal to control layer 6.

(7) and the function relationship of the peak value $R_{\min}$ to n_{tr} and n_{ti} can be expressed as eq. (8):

$$\lambda = \lambda(n_{tr}(v_c)) + \delta_i \lambda(n_{tic} + n_{tiv}(v_l)), \quad (7)$$

$$R_{\min} = R_{\min}(n_{tic} + n_{tiv}(v_l)) + \delta_r R_{\min}(n_{tr}(v_c)). \quad (8)$$

Differing from eqs. (3) and (6), there is an added item in both eqs. (7) and (8) because in modulation layer 4, n_{tr} and $R_{\min}$ are dependent and in modulation layer 6, n_{ti} and λ are dependent either. Specifically, while controlling brightness by altering imaginary part of the layer 6, the color will change very little and while controlling color by altering real part of layer 4, the brightness will change very little as well.

The relation of the layer 4 n_{tr} and λ, and of the layer 6 n_{ti} and $R_{\min}$ can be simulated by selecting appropriate parameters. The relative curves are shown in Figure 5, in which the x-coordinate denotes λ in nm and the y-coordinate denotes transmitted light intensity R. There are 8 clusters from left to right corresponding to 8 different n_{tr} values, and there are 8 curves from bottom to top corresponding to 8 different n_{ti} values in each cluster in Figure 5. It can be observed that for a fixed n_{ti}, the resonant wavelength λ will change a little and for a fixed n_{tr}, the peak value $R_{\min}$ will change very slightly in Figure 5. Obviously, mutual effect of both n_{tr} and n_{ti} has negative effect on the design of SPR display but can be reduced effectively by selecting appropriate materials and relative parameters. Therefore mutual-effect reduction is a key technique for the SPR display design. Moreover, the pixel's dimension is in the order of several micrometre[11] which can satisfy the SPR display design request.

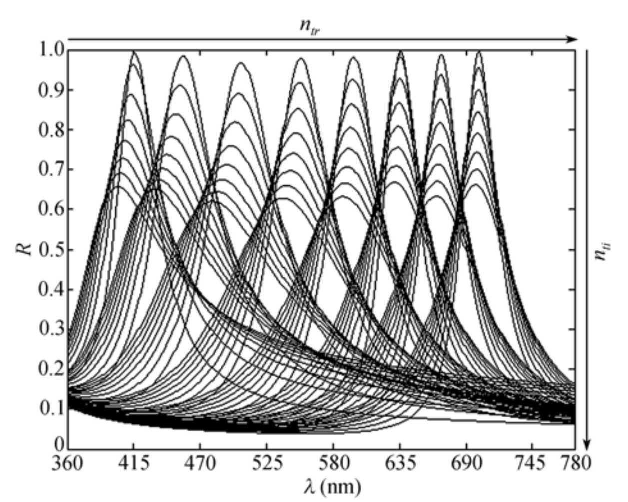

Figure 5 The relationship of the layer 4 n_{tr} and λ, and the relationship of the layer 6 n_{ti} and $R_{\min}$ based on the configuration of Figure 4.

2 Design of a transmission mode SPR display

In general, a display is composed of many pixels and it is the same for an SPR display. A transmission mode SPR display with $N\times N$ pixels will be discussed to prove the feasibility of the idea.

2.1 SPR display structure design

Side elevation of transmission mode SPR display with $N\times N$ pixels is shown in Figure 6. Prism 1 with a special structure in Figure 6 is used to realize FPD easily and the polarization lens is added to pass TM mode light and prevent TE mode light.

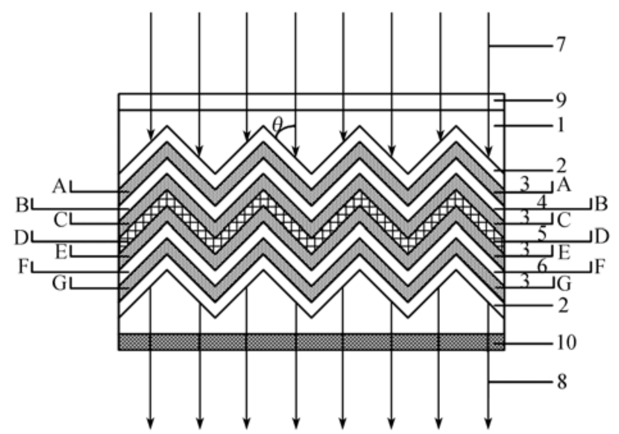

Figure 6 Side elevation of a transmission mode SPR display with $N\times N$ pixels. 1, Prism; 2, transition layer; 3, metal films (i.e. electric poles); 4, modulation layer with a controllable refractive index real part; 5, insulation layer; 6, modulation layer with a controllable refractive index imaginary part; 7, incident light (white light); 8, transmitted light (color light); 9, polarization lens; 10, imaging board. θ, incident angle; A, B, C, D, E, F and G denote different layer section planes respectively, where sections A-A, B-G, F-F and G-G have the same structure and sections C-C, D-D and E-E have the same structure.

In Figure 6, A, B, C, D, E, F and G denote different layers, where sections A-A, B-B, F-F and G-G have the same structure shown in Figure 7 and sections C-C, D-D and E-E have the same structure shown in Figure 8. A-A section plane includes $N\times N$ pixels whose dimension can be determined from ref. [11] and interval between two neighbor pixels can be selected according to the designed display characteristic. There are four metal layers in Figure 6, where both metal layers at the A-A section and G-G section are used not only as plasmon layer but also as electrical poles. They also connect with outside control signals (Figure 7). Sections C-C and E-E are ground layers and all pixels can use a common layer (Figure 8).

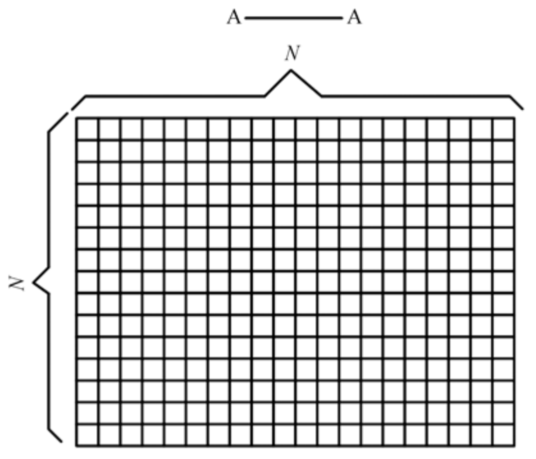

Figure 7 Section A-A structure.

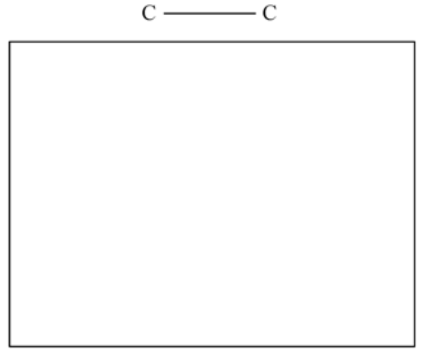

Figure 8 Section C-C structure.

2.2 Control circuit

For a basic combined SPR display pixel, it is easy to control color and brightness by adding electrical signals to the metal poles. But for a combined SPR display with $N\times N$ pixels, array control signals are responsible for adjusting each pixel. Array driving circuits shown in Figure 9 can be adopted, which is similar to the LCD driving circuit[12]. A basic driving unit of the array circuits is shown in Figure 10.

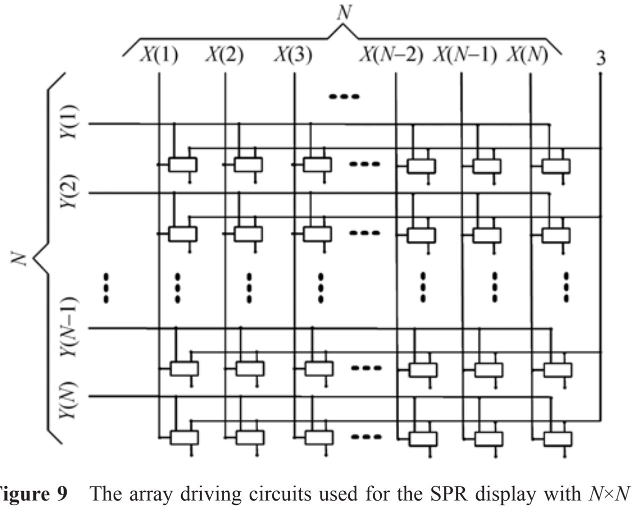

Figure 9 The array driving circuits used for the SPR display with $N\times N$ pixels.

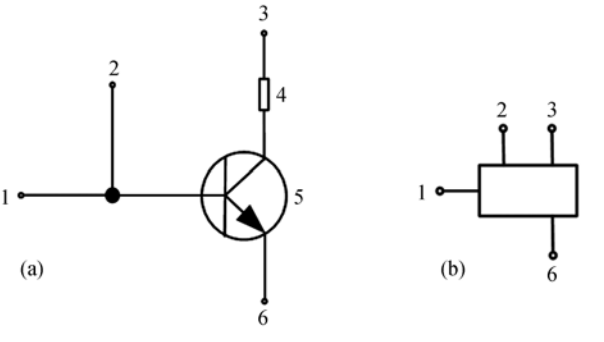

Figure 10 Driving circuit used for an SPR display pixel. (a) Circuit; (b) simplified denotation. 1, Line scan signal; 2, row scan signal; 3, color or brightness control signal; 4, load; 5, control gate; 6, loading electrical pole.

The control circuit operation process for a combined SPR display pixel can be described as follows: Connect input terminals with line scan signal 1 and row scan signal 2. In Figure 10(a), when signal 1 or signal 2 is at a high level, gate 5 opens and control signal can pass the gate circuit to control color or brightness. The control signal is digital. For simplicity, the driving circuit can be expressed by Figure 10(b). In the whole SPR display, there are two group control circuits, section A-A to control color and section G-G to control brightness. The circuit in Figure 9 can work column by column or row by row.

2.3 Simulation result of the SPR display with 8×8 pixels

At present no practical sample is available for test. However, some performances of the SPR display can be observed by simulation. Just as discussed above, the displayed image pixel is controlled by the resonant wavelength and peak value in the SPR display system. To observe the performance of the SPR display using traditional displays such as a CRT or LCD, it is necessary to transform special SPR signal format (λ, Y) corresponding to color and brightness into traditional image format (R, G, B):

$$(R, G, B) = \boldsymbol{H} \times (\lambda, Y), \tag{9}$$

where $\boldsymbol{H}$ denotes a transform array of RGB signal to color and brightness (λ,Y) signal (http://cvision.ucsd.edu/index.htm).

In the simulation model, the transmission mode SPR display is set at 8×8 pixels and the relative data used to control color and brightness is from Figure 5. Firstly, the data from color and brightness (λ, Y) format is transformed into RGB format using eq. (9). Secondly, the transformed RGB signal is displayed in traditional LCD, as shown in Figure 11. In the figure, the 8 clusters listed from top to bottom are corresponding to a group wavelengths from 400 to 700 nm and the 8 pixels in each cluster arranged from left to right are corresponding to a normal peak value from 0.4 to 0. It is easy to find that color changes from top to bottom and brightness changes from left to right. Only considering the image quality, it is not ideal, simply because the transformation array $\boldsymbol{H}$ is not very precise. In theory, a higher-quality image can be obtained from a real SPR display.

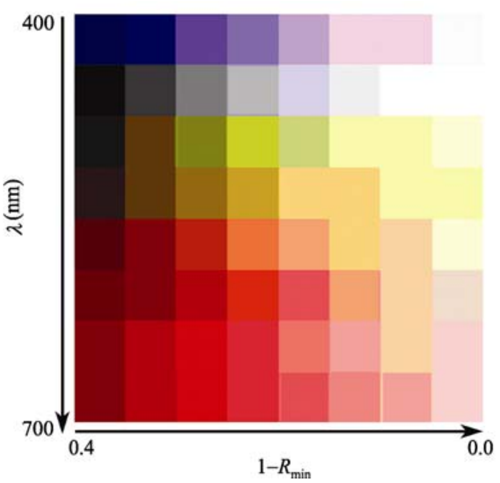

Figure 11 Simulated display of a combined SPR display with 8×8 pi.

3 Potential applications and advantages

As far as we know, the SPR display technique can be used to (i) design and manufacture electronically tunable color filter; (ii) design and manufacture an SPR display with RGB format; (iii) design and manufacture a real-color SPR display with color and brightness format.

Thus the SPR display has the following advantages: wide bandwidth, high contrast and independent control of color and brightness, etc. Meanwhile, if an appropriate material is selected as the modulation layer, it has a very fast response[7]. Due to the independent control of color and brightness, it should have such advantages as below.

(i) Simple transmission and display system

The three color components in the traditional RGB space have a very strong relation; thus it is necessary to reduce it or make color-brightness separate in the TC technique. It is not only compatible with black and white TV but also can reduce redundancy information so as to compress video signal bandwidth. In general, image signal is often transformed from RGB space into other color and brightness space such as YUV and YC_TC_b spaces for transmission and then transformed back into RGB space for display. Obviously, these two transforms render hardware more complex, leading to brightness-color garbling and color distortion, but for SPR display, no transform is needed.

(ii) Simple identification of color

Similarly, sometimes image has to be transformed into other spaces such as HIS and YIQ spaces to get better color identification or segmentation in order that mode identification of a color image can be accomplished. For the SPR display system, its color component is a real color corresponding to a certain waveband without any color distortion. Thus using color identification or segmentation it will be more effective to make mode identifiable in the SPR display system.

Of course these two advantages are potential and the current main work is to study display and imaging system based on the SPR effect.

4 Problems of the SPR display

The SPR display technique has been demonstrated as feasible in theory and some experiments. But there is still a long way to go before we implement such a practical SPR display. This paper only provides a theoretical discussion. Some key technical issues are listed below.

(i) How to reduce dependence between real part and imaginary part of modulation layers as much as possible by optimizing structure and parameters.

(ii) How to find appropriate materials with controllable real part of refractive coefficient.

(iii) How to find an appropriate material with controllable imaginary part of refractive coefficient.

(iv) Although no ideal material has been found as yet, liquid crystal can be used in experiments at present. Fortunately, it is easy to control brightness by substituting Ni, Pt, Rh and Rh-Ni alloy for Ag and Au as plasma layer and metal pole[2−10].

(v) How to determine optimal parameters for the SPR display.

(vi) How to overcome the difficulty in the SPR display manufacture.

(vii) It is easier to create an SPR display with 2 or 4 pixels in theory.

(viii) Investigate imaging system based on the SPR effect, which is more demanding than the display.

There are many other problems and many other difficulties pending to be explored, studied and overcome step by step.

5 Conclusion

Based on the published references, basic principle of the SPR display is discussed in detail. A theory regarding about controlling color and brightness simultaneously for the SPR display is presented firstly. Then the parameter optimization and theoretical simulation have been examined and control circuit scheme is provided. Finally, advantages, potential applications and current difficulties are stated as well. Although SPR display lies at the initial stages and many difficulties remain to be solved, a number of advantages and theoretical feasibility will bring SPR display a very attractive and promising future.

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