Improvement for the steering performance of liquid crystal phased array*

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Optical phased array technology is introduced and the steering performances of liquid crystal phased array are discussed, several factors affecting the beam steering performances are analyzed completely, also simple models for some typical factors are developed. Then, a new method based on iterating and modifying the output phase pattern of liquid crystal phase shifters is proposed. Using this method, the modified voltages applied on electrodes of liquid crystal phase shifters can be obtained, after applying the voltages, the influence of factors can be compensated to some extent; the steering angle accuracy and efficiency with liquid crystal phased array can be improved. Through the simulation for the angle range from 0° to -1°, the error of steering angle can be reduced three orders of magnitude, and the efficiency can be increased almost 30% after several iterations.

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Optical phased array (OPA) technology is a key of laser phased array radar, and it was first introduced into beam steering by Paul F. McManamon etal[1]. For OPA components, liquid crystal (LC) is commonly used because of low driving voltage, large birefringence, and low cost fabrication techniques. Therefore, by applying appropriate driving voltages, the desired output phase pattern can be obtained and a deflection of the beam can be performed.

Here, the exact driving voltages are called wave-control data. Generally two important issues related with wave-control data in LC phased array-based beam steering are the steering efficiency and the steering accuracy.

However, little work has been done on wave-control data [2], most studies used the response curve of voltage vs. phase retardation for LC cell to get the wave-control data[3,4], but if the response curve has errors, the corresponding wave-control data will bring efficiency loss and angular deviation to the LC phased array. Even though the response curve is exact, other factors such as fringing fields, Gaussian phases, fabrication error etc also will produce unneglected influence to the LC phased array.

Some factors have been studied before, such as the effect of fringing fields[5] and fabrication error[6], but previous research failed to develop an effective method to compensate them completely. Other studies have shown some compensation methods[7,8], but they failed to consider the realizability of technique[14] or comprehensive compensation in the actual situation. Further, Chen[2] first proposed the frame configuration of obtaining the wave-control data method, but the steering efficiency and the steering accuracy are still needed to improve.

So, in this paper factors that influence the performance of LC phased array completely are discussed. Then a new method is proposed, which can compensate the total influencing factors and improve the accuracy and efficiency significantly. Finally, simulations are used to quantify the impact of error factors and present the improvements in performance of LC phased array.

A LC phased array steers beam by appropriate adjustment of the addressable voltages of electrodes which can produce corresponding phase shifts. The concepts of tunable wave plate derive from microwave phased-array beam steering technology, and have been previously described in detail[9].

Two important issues in performance of LC phased array steer the angle accuracy and efficiency. However, for the phase shifters in a 1-D array, the steering angle can be given by:

$$\sin\theta = \lambda\phi/(2\pi d) \ , \tag{1}$$

where θ is the steering angle, d is the spacing of phase shifters which are assumed to have uniform phase difference φ be-

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tween elements. From the equation, the steering angle is determined by the mean slope of output wavefront[10].Moreover, for an ideal beam steering phase front that is all modulo-2π resets of the original ideal phase profile fall between electrodes, the steering efficiency in the first order can be written as[1]

$$\eta = \left(\frac{\sin(\pi / q)}{\pi / q} \right)^2 , \tag{2}$$

where q is the number of steps in the blazed profile. However, due to the fringing field and the viscosity of liquid crystals, the phase resets are caused to occur over a finite spatial extent, when the phase shift of 2π is subtracted from the phase front. This variation in phase reset values causes dispersion that means steering the beam in a different direction.

For laser phased array radar, the fraction of the incident light that is actually steered in the desired direction can be the criteria to evaluate the efficiency of the system. We define steering efficiency as the ratio of intensity in main lobe width means minimum 3 dB band width and total intensity in the entire field of view.

Since, in order to provide the maximum signal intensity to the receiver at the exact desired angle, the factors which will influence the performance of the LC phased array must be discussed.

From a system viewpoint, LC phased array offers improved pointing performance and reliability compared with conventional mechanical gimbal systems for laser radar. Theoretically, pointing accuracy greater than 1/4 beamwidth can be achieved[10], the energy in the first diffraction order can be calculated by equation (2), which allows the device to be used for both coarse, large angle steering and rapid, fine grain steering. But there are many factors influencing the performance of LC phased array.

First, the fringing electric fields and LC elasticity are caused by the voltage leakage between adjacent pixels "smears out" the desired phase pattern due to unwanted rotation of the LC molecules at the edges of electrodes. This area can smooth the phase profile, improve the fill factor[11] and reduce the negative influence of the pixel structure, but it also creates what has been termed a flyback region at the 2π reset. As shown in Fig.1, this flyback is not normal with respect to the backplane, but is instead sloped with an opposite blaze, which decrease the diffraction efficiency of high spatial frequency components from the applied phase patterns[12].

It is essential to model the effects of the fringing fields in order to predict the performance and construct different compensation schemes to increase the steering efficiency. To simulate the effect of voltage leakage it has been assumed that the effect on the phase distribution approximately corresponds to a convolution by a Gaussian kernel. The resulting phase delay φ then could be described by,

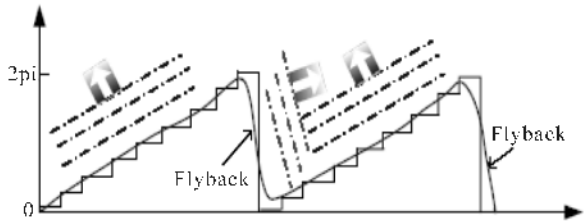

Fig.1 Ideal blazed profile and phase profile with flyback

$$\varphi(x) = \varphi_{\text{ideal}}(x) \otimes G(x) , \tag{3}$$

where φ_{ideal} is the ideal phase ramp and G is a Gaussian kernel with 1/e width χ defined by,

$$G(x) = e^{\frac{x^2}{\chi^2}} , \tag{4}$$

where x is the position relative to the step in electrodes.

Second, the fabrication error, such as cell thickness variation and electrodes defect, also can cause the phase aberration and reduce the amount of energy delivered to the intended direction. Here, the phase profile of such phase undulations, concave at the centre of the aperture diameter, can be described by

$$\varphi_{\text{undulation}}(x) = 2\pi A \cos\left[2\pi \left(\frac{x - x_{\text{midpoint}}}{D} - 0.5 \right) \right] , \tag{5}$$

where A is one-half of the peak-to-valley amplitude of the undulation, x is the surface location, x_{midpoint} is the centre of the aperture, D is the aperture diameter.

Third, the input beam of laser radar is Gaussian beam that is already formed. It's not necessary to electrically program the beam amplitude across the output aperture to achieve low sidelobe levels, but because of the Gaussian phase brought to the input phase profile, the offset between actual steering and desired angles will be caused. Thereby, the control method of the LC phased array of phase shifters will differ from many modern microwave phased arrays. Assuming that the laser beam is collimated the array, from the equation (6), the Gaussian phase of input beam can be calculated[13].

$$E = \frac{c}{w(z)} e^{-\frac{r^2}{w^2(z)} - i[k(z + \frac{r^2}{2R(z)}) + \phi(z)]} , \tag{6}$$

where c is constant factor, r is the propagation distance and k is the wave number; $w(z)$, $R(z)$ and $\Phi(z)$ are sectional radius of Gaussian beam, curved surface radius and phase factor of wavefront curved surface respectively.

Finally, the voltage quantification bits are limited for the technics restriction, not all the phase retardations can be performed for the realizable digitized voltages, those cannot be performed are instead by the nearest phase retardation, thereby, some electrodes will be applied on the same voltage.

Furthermore, the response curve of phase vs. voltage can have errors because of the restriction of the metrical technology. Hence, the applied voltages on electrodes corresponding to phase retardation cannot be obtained by the response curve. There is needed to find out a new method to apply the voltages correctly.

The quantificational computation and simulation of the influence factors are discussed in detail in future. Depending on single compensation for single factor, the correct voltages applied on electrodes cannot be obtained, a new method is needed to achieve the exact steering angles and large energy on the desired diffraction order. In the next section, we will propose an effective method.

Since, no effective method is proposed to compensate these influence factors, further studies are still necessary.

The main idea is to compare the modified phase pattern with the simulated one and iteratively modify the phase pattern, namely modify the applied voltage. For each pixel, the voltage is increased if the phase is too low and decreased if the phase is too high. If V_{n+1} and V_n are the phase patterns at iteration step n+1and n respectively, p_{n+1} is a proportionality factor at iteration step n+1, Φ'_{ideal} is the ideal phase pattern which has the same phase ramp with Φ_{ideal} after unwrapping and Φ_n is the simulated phase pattern, a simple algorithm would be

$$V_{n+1} = V_n - p_{n+1} \times (\Phi_n - \Phi'_{ideal}) . \quad (7)$$

The processing flow is shown in Fig.2.

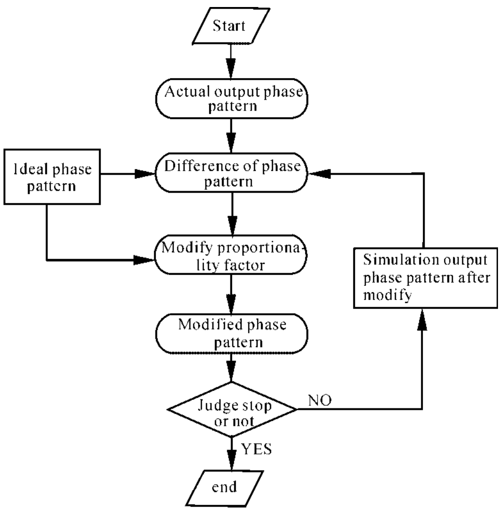

Fig.2 Processing flow of obtaining wave-control data

The realization process can be described as:

1) Getting the testing response curve of $\varphi \backsim v$ of LC and the ideal phase pattern Φ_{ideal} for desired angle θ. Considering the Gaussian phase $\Phi_{Gaussian}$ of input beam, the phase retardations are defined as $\varphi = \Phi_{ideal} - \Phi_{Gaussian}$. Then looking up the applied voltages v=V_1 .

2) Because of the errors between the testing response curve and the actual character curve, after loading the digitized voltages on the electrodes, We get the phase φ' and form the output pattern Φ'.

3) According as the above mentioned influence model, various phase undulation is added to Φ', and the first iteration Φ_1 of phase pattern Φ_n is formed. Here, p_1 is a constant of 0.5.

4) In the followed iteration ($n \geqslant 2$), the proportionality factor p_n is defined as

$$p_{n+1} = a \times p_n + b \times K , \quad (8)$$

where a and b are constant and satisfy a+b=1. K is defined as K=k/max(k) and is the normalization of k. Here k is

$$k = \frac{\Delta \Phi_t}{\Delta \Phi_n + m} . \quad (9)$$

where $\Delta\Phi_n = |\Phi_n - \Phi_{n-1}|$, $\Delta\Phi_t = |\Phi_n - \Phi_{ideal}|$ and in order to avoid the denominator of k appearing zero, m is defined as a constant, and satisfies m>0.

5) From equation (7),(8) and (9), we can get the modified voltages. When the steering accuracy and efficiency are satisfied, the modified voltages are desired wave-control data and the iteration process will be stopped.

It's important to mention that the management of the ideal phase pattern is written as

$$\Phi'_{ideal} = \mathrm{mod}\,(\Phi_{ideal} - \Phi_{Gaussian}, 2\pi) + \Phi_{Gaussian} , \quad (10)$$

and has the same far field intensity distribution with Φ_{ideal}, so the intention is to adjust the voltages to make the actual output phase pattern approach Φ'_{ideal} .

In order to validate the validity of this algorithm, some simulation results will be carried out.

Here, through the simulation of this algorithm, the performances of the LC phase array applying unmodified voltages v and modified voltages V_n are compared. The simulation parameters are set as:

Tab.1 Simulation parameters

Simulation parameters	numerical value
number of electrodes	1440
width of electrode	5 μm
wavelength	1.064 μm
sectional radius	675 μm
desired steering angle	-0.1°

After applying unmodified voltages, the simulation of far field intensity with ideal phase pattern and actual output phase pattern are shown in Fig.3(a). The desired and actual steering angles are -0.1° and -0.092639 °, the maximal side-lodes are on the order of -13.3 dB and -3.9 dB, and the steering efficiencies are 72.4% and 31.1% respectively.

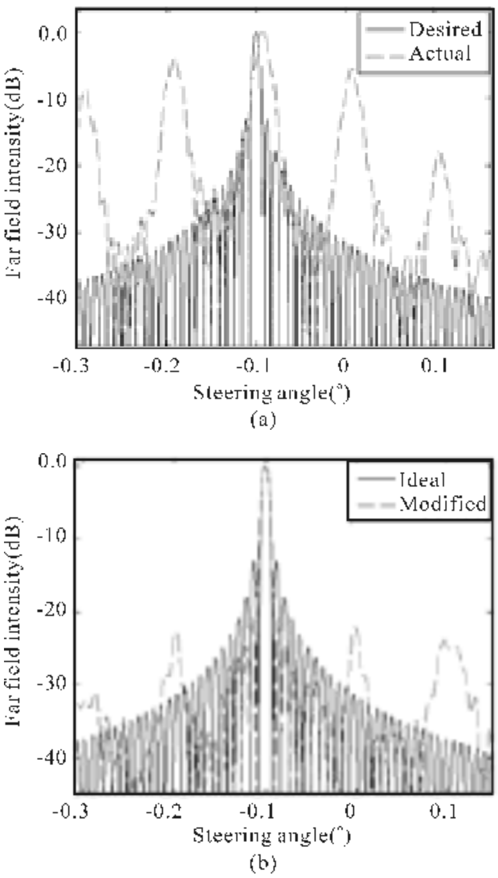

Fig.3 (a) Far field intensity of ideal and actual output phase pattern (b) Far field intensity of ideal and corrected output phase pattern

After 10 iterations, applying modified voltages, the error between modified and desired steering angle is minimum, the modified angle is -0.099997°, the maximal side-lobe is -22.8 dB and the steering efficiency is 62.5%. Their intensity distributions are shown in Fig.3(b).

The varieties of modified steering angles in 50 iterations are shown in Fig.4.

In the range 0°- -1° of steering angle, the steering accuracy and efficiency after 10 iterations are shown in Fig.5(a) and (b).

From the simulation, we can conclude the error between modified and desired steering angle is on the order of 10^{-6}, and the efficiency can be improved almost 30%.

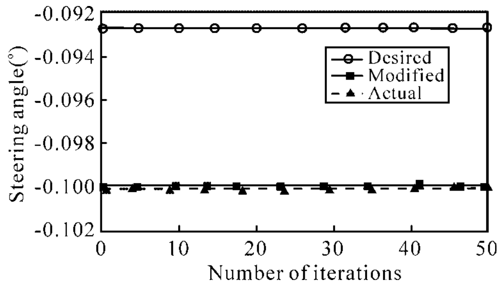

Fig.4 The variety of steering angles

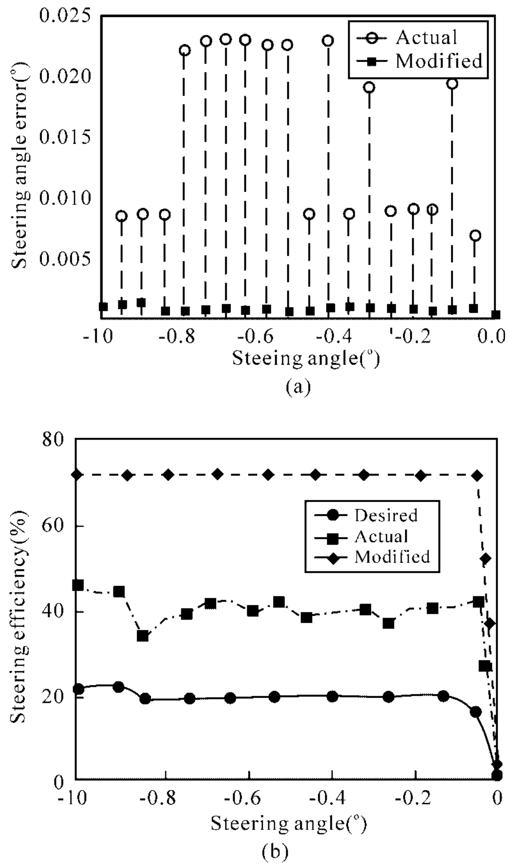

Fig.5 (a) Steering accuracy (b) Steering efficiency

The performance of LC phased array, namely steering angle and efficiency and the influence factors that include the fringing fields and elastic behaviour, fabrication error, Gaussian beam, voltage quantification, and the error of character curve etc are analyzed. Consequently, in order to compensate the factors and improve the performance, a new method based on iteration correction of the output phase pattern and modifying the applied voltages is proposed. Through the simulation, the error of steering angle can be reduced and the efficiency can be increased effectively, which can prove the validity of this algorithm.

However, when the impact of influence errors increases, the proportionality factor needs to be adjusted; in addition, the treatment to ideal phase pattern and the selection of proportionality factor are key problems, we will discuss them in the future. Also, the error factors which our method based on are further discussed in our next study.

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