Simulation and Discussion of Spatial Coherence of Light Field Based on the Seelight Platform

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In Young's double-slit interference experiment, under the irradiation of an ideal monochromatic extended light source, the contrast of the interference fringes is related to the width of the light source. In this paper, the influence of light source width on the contrast of interference pattern is discussed when two incoherent point light sources are used as ideal monochromatic extended light sources, and the simulation results are carried out by using Seelight software. The simulation results are helpful for us to understand and master the clarity of the interference patterns of monochromatic extended light sources, and semi-quantitatively and semi-qualitatively obtain the relationship between the spatial coherence of the light field and the intrinsic parameters of the light source.

I. EXPERIMENTAL OBJECTIVE

1. Understand the physical principle of the wave-splitting surface interference.

2. Establish the Seelight structure model for the interference of space point light source.

3. Calculate the visibility of stripes quantitatively.

4. The relationship between fringe visibility and the width of the one-dimensional extended light source was examined semi-quantitatively.

II. THEORETICAL BASIS

In Young's interference experiment, the light intensity distribution function on the light screen satisfies the relationship[1]:

$$I(x,\delta s) \propto 1+\cos\left(\frac{2\pi xd}{\lambda D}\right)\cos\left(\frac{2\pi d}{\lambda R}\delta s\right) - \sin\left(\frac{2\pi xd}{\lambda D}\right)\sin\left(\frac{2\pi d}{\lambda R}\delta s\right) \tag{1}$$

where d is the distance between the slits, x is the coordinate on the screen, D is the distance between the slits and the screen, R is the distance between the light source and the double slit, λ is the wavelength of the light source, δs is the offset of the point light source from the principal optical axis.

Here, we simply use two point light sources separated by a certain distance to represent the extended light source. In this way, the total light intensity distribution after superposition is

$$I(x) = I\left(x,+\frac{b}{2}\right) + I\left(x,-\frac{b}{2}\right) \tag{2}$$

where b represents the width of the light source. As a result, the specific expression of the total light intensity distribution is

$$I(x) \propto 1+\cos\left(\frac{2\pi xd}{\lambda D}\right)\cos\left(\frac{2\pi d}{\lambda R}\frac{b}{2}\right) \tag{3}$$

Combined with the definition of contrast γ

$$\gamma = \frac{I_{max}-I_{min}}{I_{max}+I_{min}} \tag{4}$$

we get the contrast γ of the stripes

$$\gamma = \left|\cos\frac{\pi db}{R\lambda}\right| \tag{5}$$

If we give the value of contrast and other parameters, the width of the light source that meets the condition can be obtained by

$$b = \frac{\lambda R}{\pi d}\left|\arccos\gamma + k\pi\right| \tag{6}$$

III. SET UP THE SIMULATION

We use seelight system to build simulation environment (FIG.1).

In the simulation, we use the combination of directional light and negative lens to replace the point light source. In our theory, the distance between the light source and the double slit is expressed as

$$R = h - f \tag{7}$$

where f is the focal length of the ideal lens, note that it is a negative value, and h represents the distance of vacuum transmission from the beam combiner to the double slit.

It is worth noting that in our optical path diagram, the vacuum transmission module between the laser beam combiner and the beam modulator has been discarded, and the reasons will be analyzed later. So, we have $h = 0$.

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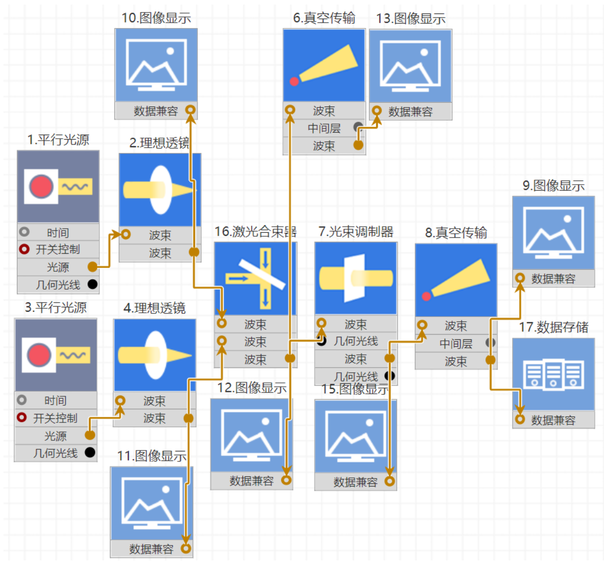

FIG. 1. **Simulation Data Stream on Seelight.** We suppose $d = 0.15 \times 10^{-4}\ m$, $f = -9.8 \times 10^{-2}\ m$, $D = 1\ m$ and $\lambda = 550\ nm$. Other parameters in details can be seen in our project document.

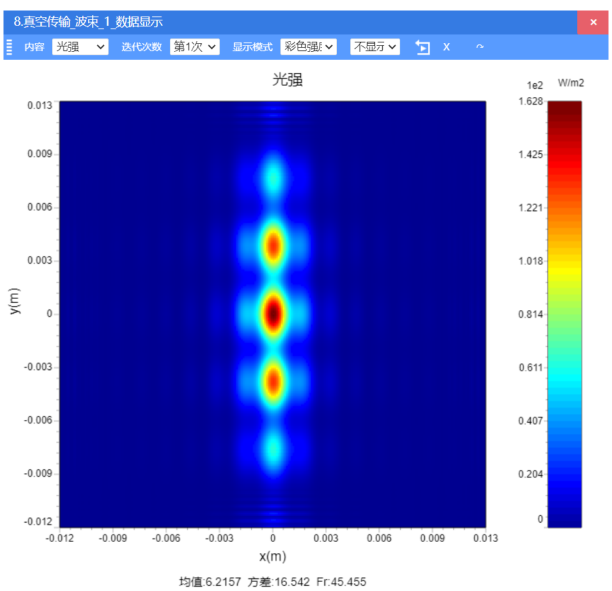

FIG. 2. **Interference Image with Contrast as** 0.5**.** The coloring in the picture is distinguished according to the light intensity. The interference fringes are arranged longitudinally. Diffraction occurs both transversely and longitudinally.

IV. SIMULATION RESULTS

A. The Case of Contrast as 0.5

According to the result given by the equation (6) when we choose $k = 0$, we suppose $b = 1.1978 \times 10^{-4}\ m$, with the interference image shown in (FIG.2) obtained.

Because the width and length of the slit are finite, diffraction will occur both transversely and longitudinally. We will analyze the effect of diffraction later.It is worth noting that the image of Young's double-slit interference should be striped, but what we show here is the interference spot, which is deliberately set through the diffraction effect.

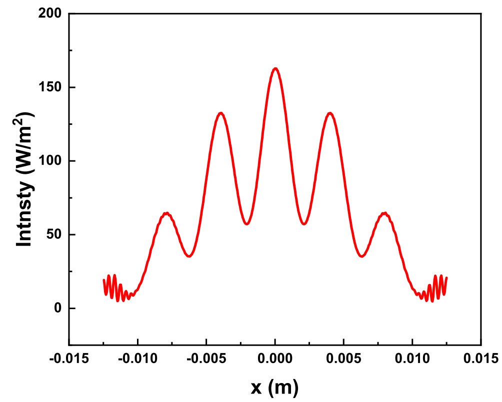

FIG. 3. **Distribution Curve of Light Intensity with Contrast as** 0.5**.** Taking the central peak of the curve as the maximum light intensity and the adjacent trough as the minimum light intensity, the contrast is 0.4807.

By analyzing the middle column of the light intensity distribution matrix, we can get the light intensity distribution curve (FIG.3). Then, the contrast at this time can be measured to be $\gamma_m = 0.4807$. There is no obvious difference between it and the theoretical value $\gamma = 0.5$, and the relative error is 3.86%. The amplitude of the intensity distribution curve attenuates to both sides, which is due to the influence of diffraction. We will consider correcting this effect later. However, we will find that this correction is a small amount if we use our current method of measuring contrast.

B. The Case of Contrast as 0.7

According to the result given by the equation (6) when we choose $k = 0$, we suppose $b = 9.0977 \times 10^{-5}\ m$, with the interference image shown in (FIG.4) obtained.

Because the width and length of the slit are finite, diffraction will occur both transversely and longitudinally. We will analyze the effect of diffraction later.It is worth noting that the image of Young's double-slit interference should be striped, but what we show here is the interference spot, which is deliberately set through the diffraction effect.

By analyzing the middle column of the light intensity distribution matrix, we can get the light intensity distribution curve (FIG.5). Then, the contrast at this time can be measured to be $\gamma_m = 0.7224$. There is no obvious difference between it and the theoretical value $\gamma = 0.7$, and

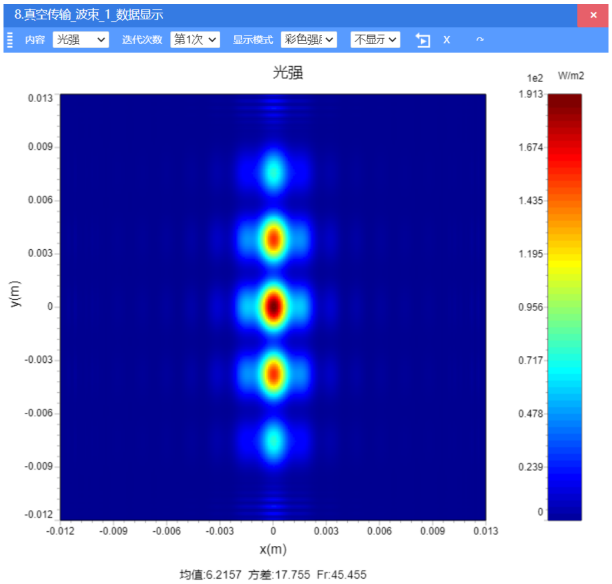

FIG. 4. **Interference Image with Contrast as** 0.7**.** The coloring in the picture is distinguished according to the light intensity. The interference fringes are arranged longitudinally. Diffraction occurs both transversely and longitudinally.

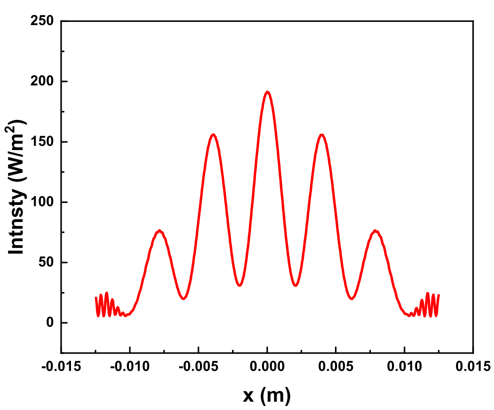

FIG. 5. **Distribution Curve of Light Intensity with Contrast as** 0.7**.** Taking the central peak of the curve as the maximum light intensity and the adjacent trough as the minimum light intensity, the contrast is 0.7224.

the relative error is 3.20%. The amplitude of the intensity distribution curve attenuates to both sides, which is due to the influence of diffraction. We will consider correcting this effect later. However, we will find that this correction is a small amount if we use our current method of measuring contrast.

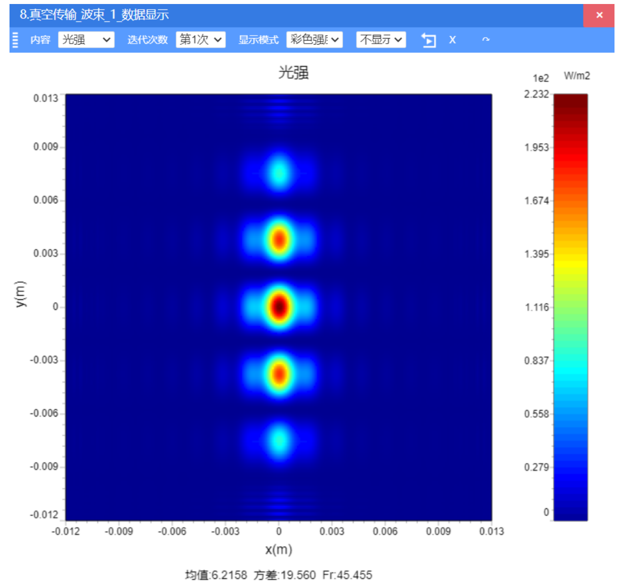

FIG. 6. **Interference Image with Contrast as** 0.95**.** The coloring in the picture is distinguished according to the light intensity. The interference fringes are arranged longitudinally. Diffraction occurs both transversely and longitudinally.

C. The Case of Contrast as 0.95

According to the result given by the equation (6) when we choose $k = 0$, we suppose $b = 3.6322 \times 10^{-5}\ m$, with the interference image shown in (FIG.6) obtained.

Because the width and length of the slit are finite, diffraction will occur both transversely and longitudinally. We will analyze the effect of diffraction later.It is worth noting that the image of Young's double-slit interference should be striped, but what we show here is the interference spot, which is deliberately set through the diffraction effect.

By analyzing the middle column of the light intensity distribution matrix, we can get the light intensity distribution curve (FIG.7). Then, the contrast at this time can be measured to be $\gamma_m = 0.9876$. There is no obvious difference between it and the theoretical value $\gamma = 0.95$, and the relative error is 3.96%. The amplitude of the intensity distribution curve attenuates to both sides, which is due to the influence of diffraction. We will consider correcting this effect later. However, we will find that this correction is a small amount if we use our current method of measuring contrast.

V. DISCUSSION

A. The Relationship between the Linearity of Light Source and the Spatial Coherence of its Light Field

This is the core of this article.

In our life experience, we know that, in general, the

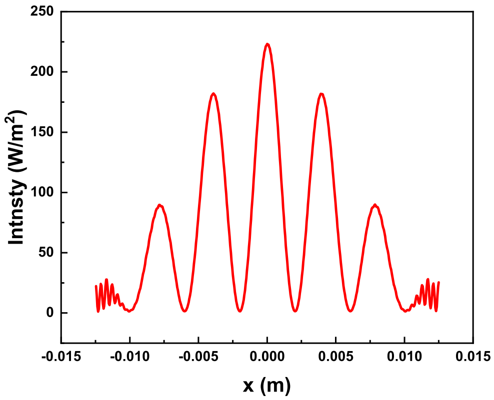

FIG. 7. **Distribution Curve of Light Intensity with Contrast as** 0.95**.** Taking the central peak of the curve as the maximum light intensity and the adjacent trough as the minimum light intensity, the contrast is 0.9876.

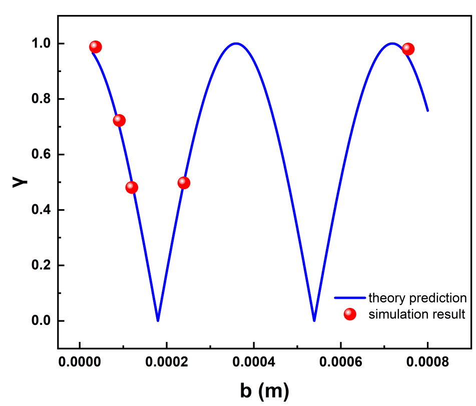

FIG. 8. **Comparison between Theory and Experiment about the Relationship between Light Source Width and Spatial Coherence** Here, the extended light sources here are two incoherent point lights.

larger the width of the extended light source, the less the spatial coherence of the light field. According to our theory (5), it can be found that when the width of the light source is small, the spatial coherence of the light field does decrease with the increase of the width of the light source (FIG. 8). However, when the width of the light source continues to increase, the contrast (we use the contrast of interference fringes to represent the spatial coherence of the light field) will rise in the form of the absolute value of the cosine function, which is the result of using two point light sources to represent the extended light source. In fact, if we replace the sum in equation (2) with an integral, we can get the following contrast

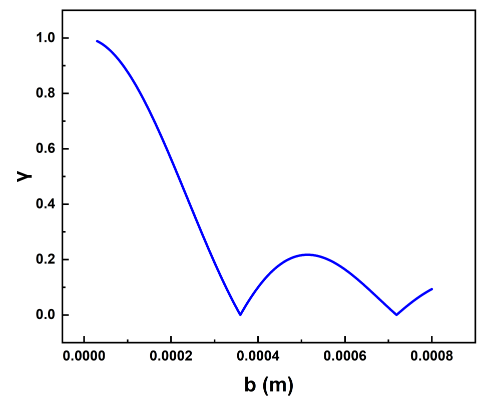

FIG. 9. **Theory Curve of the Relationship between Light Source Width and Spatial Coherence** Here the extended light source here is a series of point light sources with continuous and uniform distribution.

relation,

$$\gamma = \left| \frac{R\lambda}{\pi b d} \sin \frac{\pi d b}{R\lambda} \right| \tag{8}$$

and it will also show a rebound in contrast, but the overall amplitude will attenuate very quickly (FIG. 9), thus returning to our common sense of life and physical intuition.

We still discuss the case of two incoherent point sources. Comparing the simulation results of the previous section with our theoretical curve (FIG. 8), we can find that when the width of the light source is small, the spatial coherence attenuates with the increase of the width. In order to verify that the contrast will rise when the width of the light source is large, we add two sets of simulation data, which are the corresponding simulation results. This validates the predictions made by our theory.

I would like to emphasize here that compared with the projects of some students, our simulation results can verify the prediction of our theory. Although some students (perhaps the vast majority) use theoretical analysis to make predictions in advance, their final simulation results are not based on the parameters of theoretical predictions. In other words, their theories and experiments cannot form a closed loop. They often change the parameter values predicted by the theory in order to get the contrast results required by the homework, and as a result, they get scores that they do not deserve.

B. Considering the Influence of Single Slit Diffraction Factor

1. Correction of Amplitude

In the ideal Young's double-slit interference model, the amplitude of our interference intensity distribution should be uniform, as described in our equation (3). However, in our simulation results, we see that the amplitude of the light intensity distribution attenuates at both sides, because our double slit is not an ideal double slit.

Because the width of the slit is finite, we will observe the influence of the single slit diffraction factor in the direction of the distribution of the interference fringes. If we consider the single-slit diffraction of each of the two slits, it becomes a multi-beam diffraction model, similar to a grating. So we can get its light intensity distribution:

$$I(x) \propto \left(\frac{\sin u}{u}\right)^2 \left[1 + \cos\left(\frac{2\pi x d}{\lambda D}\right) \cos\left(\frac{2\pi d}{\lambda R}\frac{b}{2}\right)\right] \tag{9}$$

when

$$u = \frac{\pi a}{\lambda} \cdot \frac{x}{D} \tag{10}$$

where a is the width of the slit, established under paraxial conditions.

In order to obtain the ideal interference fringes and calculate the contrast of the interference fringes, we can modify our light intensity simulation results. By dividing the original light intensity by the diffraction factor, the uniform intensity distribution of amplitude can be obtained (FIG. 10), from which we can take multiple peaks and troughs to calculate the contrast, so as to reduce our experimental error. And we find that for the peaks and troughs closest to the center, the influence of the diffraction factor is small, so our previous contrast measurement method will not bring visible errors.

However, it is interesting that in order to make the corrected amplitude uniform, we find that the slit width an in the diffraction factor can not take the actual slit width given in our project, but should take about 68.6% of its actual value. This law is true for different parameter conditions. This may mean that the width of the slit participating in the diffraction in the simulation calculation should be the effective width, which is different from the value given in our project.

2. Concentrate Energy through Diffraction Effect

Although diffraction usually interferes with our interference results, we can still make reasonable use of the influence of diffraction to improve our simulation results.

Because the length of the slit is limited, there will be diffraction in the direction perpendicular to the distribution of the interference fringes. This kind of diffraction can be avoided. If we set the spot diameter to be less than the slit length, diffraction will not occur in this direction.

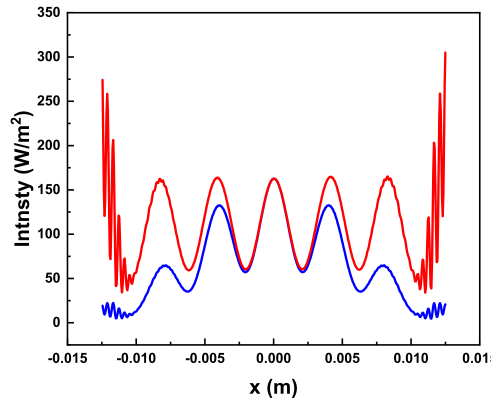

FIG. 10. **Comparison before and after Diffraction Correction** The red line is the modified curve and the blue line is the pre-modified curve. Here we select an example with a contrast of 0.5 to correct it. The correction effect of the edge is not very good, this is because our diffraction factor is already too small, and it is on the denominator, so the error will be magnified a lot.

However, because there are many loopholes in the algorithm of the vacuum transmission module of the Seelight simulation platform, if we keep the fringe interference pattern, the error will be larger in the end. We will also analyze these errors in detail later. On the one hand, this is not conducive to our contrast measurement, on the other hand, the simulated interference image will have non-physical results. Therefore, we need to make rational use of diffraction to control the shape and scope of the interference pattern.

We know that reasonable diffraction can concentrate more of the surrounding energy on the zero-order fringes. Therefore, we control that the length of the slit is not too long (the specific value can be seen in our engineering file) to get the speckle-like interference pattern. In this way, the loss of interference beam quality can be reduced, so as to avoid getting noisy results like some classmates.

On the other hand, we control the reasonable slit width so that the amplitude of the light intensity distribution can attenuate quickly. In this way, the number of interference fringes displayed on the screen will not be too large, so as to avoid the problem of insufficient resolution of the simulation and reduce the measurement error of contrast. At the same time, some calculation errors of the vacuum transmission module can be avoided (which will be analyzed later).

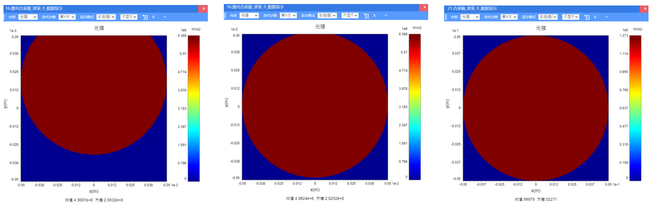

FIG. 11. **Symmetry breaking** The order of magnitude of the size of point light is much larger than that of the light spot will make the figure more symmetry. Considering the situation when the magnitude of the spot spacing is 10^{-5}. Here, from left to right, the order of magnitude of the spot diameter is 10^{-4}, 10^{-3}, 10^{-2}.

C. Symmetry breaking

The parameters setting with an unsuitable size will cause symmetry breaking in the simulation process. That is, when we input exactly the same beam to the two inputs of the laser beam combiner, and the setting of the laser beam combiner is symmetrical, the spot coming out of the laser beam combiner will shift upward. If the offset is too obvious, it will lead to asymmetric results in the subsequent simulation calculation. The setting of the size of the point light and the spot spacing produced by the laser combiner plays a key role in the process. Qualitatively, the order of magnitude of the size of point light is much larger than that of the spot spacing will make the figure more symmetry (FIG. 11).

D. Calculation Error of Vacuum Transmission

We have mentioned many times that in the Seelight simulation platform, the vacuum transmission module often has serious calculation errors and produces non-physical simulation results. The algorithm loopholes of vacuum transmission module are mainly reflected in the following two aspects:

1. *Grid-like self-intervention*

In life, after a beam of light travels a short distance in a vacuum, the beam quality, spot pattern and intensity distribution will not change. However, the spot pattern and light intensity distribution will change significantly in the vacuum transmission module of Seelight simulation platform. Let's give an example to illustrate this point.

From the comparison before and after vacuum transmission shown in FIG.?, it seems that the beam will self-interfere when it passes through the vacuum. In fact, in the actual physical situation, we can also regard the straight-line propagation of parallel light in a vacuum as continuous self-interference, but this interference should be isotropic, so the spot pattern will not change in the propagation time. Or at least symmetry breaking does not occur when non-parallel light is propagating. We can see that the originally uniform and rotationally symmetrical light spot becomes a grid after vacuum transmission, which is not physical. This can not be explained by Fraunhofer circular hole diffraction or Fraunhofer moment hole diffraction. If such deformed light spots are allowed to participate in the subsequent interference, it will naturally produce non-physical simulation results.

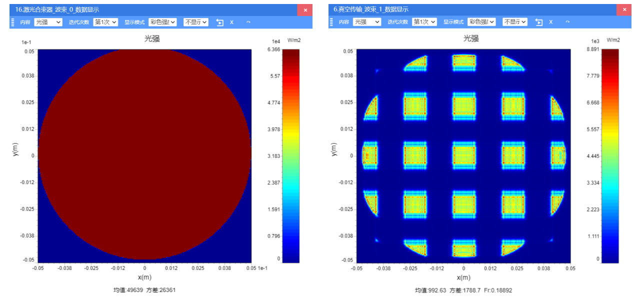

FIG. 12. **Comparison of Light Spots before and after Vacuum Transmission** The picture on the left shows the spot image before vacuum transmission, and the picture on the right shows the spot image after vacuum transmission. The distance of vacuum transmission is 4 m.

In order to avoid the error of vacuum transmission as much as possible, we try to reduce the use of vacuum transmission module. In the equation (7), we make $h = 0$, that is, we do not add this vacuum transport module to the optical path. In this way, the light entering the slit has better beam quality.

2. *Calculation of boundary value of vacuum transmission screen*

In vacuum transmission, the size of the screen must be set reasonably. If the light spot covers the boundary of the vacuum transmission screen, it will make a serious error in the calculation of the vacuum transmission module. If we want to see the local details of the interference fringes, we want to reduce the screen size of the vacuum transmission, but at this time, we often see the deformed spot or even only a piece of noise due to the calculation error of the vacuum transmission module.

Therefore, in order to ensure that the vacuum transmission module does not have this kind of calculation error, the screen size must be larger than the size of the interference pattern. Because the resolution is limited, to ensure that we can see a wealth of details, we need to control the length and number of stripes by diffraction, which we have analyzed earlier.

E. The Influence of the Dimension of Light Source

The dimension of the light source determines the resolution of the simulation results. Physically speaking,

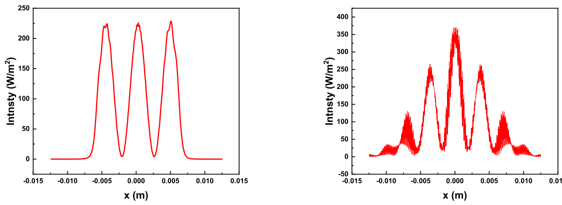

FIG. 13. **Comparison of Different Light Source Dimensions** The light source dimension of the left picture is 256, and the light source dimension of the right picture is 1024. It can be seen that when the dimension of the light source is low, the diffraction effect can not appear. When the dimension of the light source is too high, the self-interference of vacuum transmission is too obvious.

changing the dimension of the light source will not change the simulation results greatly. However, our simulation is a process of numerically solving partial differential equations, and the degree of discretization of our calculations sometimes has a great impact on the correctness of the results.

The simulation results corresponding to different light source dimensions are compared (FIG. 13). We can see that when the dimension of the light source is too small, the simulation error is large because too much information is ignored. Even, because it does not calculate the diffraction effect, we say that the simulation result is non-physical. When the dimension of the light source is too large, the grid self-interference fringes generated by the vacuum transmission module will be superimposed on our simulation results, which is also non-physical.

F. The Relationship between the Angle of the Light Source to the Field Site and its Spatial Coherence

According to our theory (5), just like the the relationship between the linearity of light source and the spatial coherence of its light field, the relationship between the angle of the light source to the field site and its spatial coherence should obey cosine function relation, since the angle of the light source to the double slits is just $\frac{b}{R}$.

However, our simulation observations are not like this! We have to admit that the experiment is in good agreement with the theory only under a specific combination of parameters.

If we increase the values of b and R proportionally at the same time, according to our theory, the contrast will not change. After all, the angle of the light source to the double slits has not changed. But in fact, we find that if we make such a change, the contrast is likely to change considerably. In figure (FIG. 14), we describe the simulation measurement of contrast given different light source and slit distance R, and then give b (6) according to the desired theoretical values of contrast (such as 0.95,

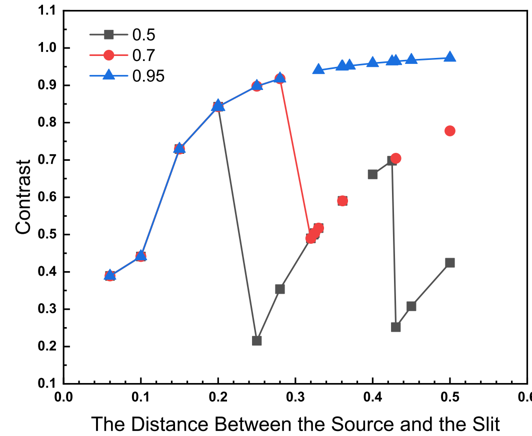

FIG. 14. **The Variation of Contrast with the Distance R from the Light Source to the Double slit** Given a different R, we also give the value of b in proportion to the theoretical value of contrast. The illustration gives our theoretical expected contrast corresponding to each curve. Note that the three curves coincide in many areas. According to our theory, the obtained curve should be three horizontal curves which are stable near the theoretical value.

0.7 and 0.5).

This is disastrous for our theory, our theory is completely unable to explain such a result, and we have not yet found out the reason for this. And we find that when the value of b is changed in a certain range in the case of a given R, the contrast and interference image do not change at all. It seems that in some range, the interference has a shielding effect on the change of b, or the interference is stable in this range. Even when the threshold is beyond this range, the resulting interference image and contrast will jump with the change of b. I think maybe this is not because our theory is flawed. After all, from the point of view of physical intuition, these phenomena are impossible to happen in real life.

Admittedly, according to the law shown by (FIG. 14), we can find several groups of parameters, which can accurately meet the contrast requirements of this operation. Under these groups of parameters, the experiment is in good agreement with the theory. In fact, the contrast measurement of the simulation results obtained from the parameters I left in my simulation project is exactly equal to 0.9500. However, I think this is meaningless. We hope that our theory can fully explain the experimental phenomena under any conditions that meet the requirements, rather than just happen to coincide with the experiment under some specific parameters. Unfortunately, so far, we have not found out the cause of this phenomenon. I just hope it's not a matter of our theory.

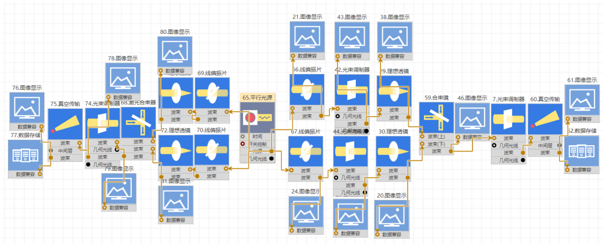

FIG. 15. **The Interference Light Path of Incoherent Light Source is Obtained by Polarization.** In fact, the picture shows two paths of light. The light path on the left attempts to make an extended light source through the coherent superposition of the laser beam combiner (after all, the polarization components are different and should still be irrelevant). The light path on the right attempts to prepare an extended light source through two small holes with a certain space distance.

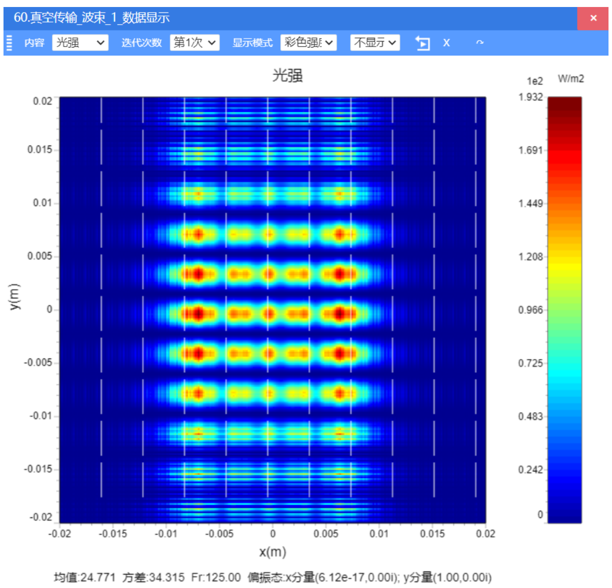

FIG. 16. **Interference Image of Extended Light Source Prepared by Polarization** The contrast of the interference fringes is always maintained at a high level, which looks like the coherent superposition of the beam after passing through the polarizer.

G. A New method of obtaining coherent Light Source

We know that one of the conditions under which light can be coherent is that it has a parallel polarization component. Then we can consider using two vertical linear polarizers to obtain incoherent light sources. So we built such a simulated optical path. Unfortunately, although this kind of optical path can also obtain a better interference image, we can not get the desired contrast by adjusting its parameters. Perhaps this method can not get an incoherent light source, the exact reason is not clear.

H. Some Opinions about Seelight Simulation System

1. *What I Want to Say to My Classmates*

I know the students feel very hard about this assignment. I think the requirements of this assignment are really beyond the current ability of most students. In order to complete this task, we should not only skillfully master the elementary wave optics theory, but also need full patience to deal with a variety of non-physical problems encountered in the simulation process. This really makes people feel hard and tired, but also wastes a lot of precious time of the students.

Below, I would like to talk about some experience gained in the process of simulation for your reference:

a. Experiments should not be carried out blindly. Any experimental operation or parameter change must have clear theoretical guidance. When setting the screen size of each module, make sure that the dimensions match. The image obtained by the simulation results has the superposition of interference and two kinds of diffractions. the distance between the fringes can be estimated by the theoretical value to determine which one is the interference fringe we want to use to measure the contrast.

b. Pay attention to the correct correspondence between theoretical parameter values and experimental parameter values. In our simulation experiment, the distance between the adjacent beams in the laser beam combiner module corresponds to half of our theoretical parameter b. If we don't even figure this out, then the simulation is completely random. The gap in the beam modulator refers to the interval between the inside of the two slits, which is also different from our theoretical parameter d.

c. It is necessary to operate boldly and be flexible. For example, our vacuum transmission module is a difficult guy, we should make rational use of diffraction to get better results. For the peculiar phenomenon of symmetry breaking, it is also necessary to make rational use of the order of magnitude relationship between the parameters to avoid skillfully.

2. *What I Want to Say to My Teacher*

I fully understand the teacher's original intention of assigning this kind of simulation homework. Let students use the tools and methods of scientific research to carry out physical experiments from the beginning of the lower grade, which can effectively promote the cultivation of their research ability and innovation ability[2].

However, I think such assignments must be carefully designed and tested by the teaching team. As far as this assignment is concerned, most of the problems encountered by the students are not physics problems. Even a considerable part of the problem is not the operation of the students, but the problem of the simulation software.

The students spent a lot of time on this assignment, but it did not help to consolidate the knowledge of physics, and they did not learn much about the details of the operation of scientific research experiments. A lot of energy is wasted on adjusting the parameters, but the theory and experiment can not form a closed loop. This homework not only dampens the students' interest and enthusiasm for physics, but also encourages some academic misconduct. This is very serious, very terrible.

3. *What I Want to Say to Seelight*

I just want to say one sentence:
If you cannot stand the heat, get out of the kitchen.

VI. ACKNOWLEDGMENTS

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[1] K. H. Zhao and X. M. Chen, *A Course in New Conceptual Physics: Electromagnetism* (Higher Education Press, 2003).

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