Demonstration Polarization Phenomenon and Laser System Simulation by Software in University Lecture Course

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ABSTRACT

Traditional physics or engineering education mainly describes the photonics phenomenon through complex mathematical formula and calculations, or with diagram to explain the phenomenon. The photonics phenomenon is usually not easy to imagine. Many physical models are relatively complicated for many students. We want to provide a self-developed interactive photonics program by LabVIEW, and demonstrate in the lecture. Students can also download these programs, and observe the simulator by changing the physical parameters. We demonstrate two topics in the university lecture. The first is the phenomenon of polarization, by using software to present the relationship of polarization and Poincare Sphere. Another is diffraction and its application the laser dots projector system. Finally, through the teaching analysis questionnaire, we quantify the degree of understanding of students. This result can be used as the reference for direction of improvement.

Keywords: Simulation, Optics Education, Photonics Education, LabVIEW, Visualization, Diffraction, Polarization

1. INTRODUCTION

For university professors, the job consists of at least three aspects, administration, academia and teaching. In administration part, teachers are responsible for enrolling students, reviewing scholarship applicants, or seeking funding from the government and companies. In academic part, it is responsible for designating research topics, developing theories, conducting simulations, and experiments. Some of the works are done by professor themselves, while some works require graduate student, post-doc or other technician. Then, when the research work have some achievement, they will the publish journal papers or apply patents. If the patent has commercial value, professor will transfer this technology to the appropriate manufacturer to develop the product. Sometimes, professors will participate in conference and publish their research result. The administration and academic occupied most of the time for the professors. Therefore, professors have limited time to prepare the teaching slides or notes for the class. Since the time for homework assignments, test papers, and review reports occupied the major time of teaching. Even if the professors want to use multi-media material to enrich content of the lectures, it is very hard for them to do so.

Animated video is a very good resource for education. Abstract principle analysis and complicate and expensive equipment can be shown in video, but video is not a multi-medium for interaction. Student sometimes want to ask question. If the professor can repay instantly, it will be very helpful for education. For engineering education, the professor can explain the conceptual idea, but if students want to see the change of a certain parameter in physical phenomenon. The software simulator is a very good choice, but most of the current photonics simulation software is for computer aid design (CAD) simulation, and there is lack of simulation on specific topics. Moreover, professional software is expensive so it is unlikely for education. If the professors are familiar programming, they can develop educational simulator on their own. Orquín [1] uses LabVIEW multimedia to educate quantum physics courses. Another way is to find a cooperate partner to develop, and now there are many small software studios can help. Some of studios also are familiar with photonics, and they are good partners for multimedia education project. The teaching cooperate with the software studio can create a different teaching experience.

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2. TEACHING WITH LABVIEW VISUALIZATION

The current way for teaching students to understand physics is mainly through classroom lectures. Professors state the physical phenomena or problems and use analytical formulas to describe problems, also supplemented by diagrams or pictures. Students write notes or copy the lecture notes prepared by the class teacher. Now with the popularity of laptop and the invention of the graphical programming language LabVIEW. Creating a GUI software that can interact instantly is much simpler than in the past. It is allowing students to interact with light wave parameters and feel the change of light waves. I had made similar attempts in the past [2]. For example, diffraction need to mention about Fourier Transform. However, the Fourier transform can be analytically calculated only on specific function. By software, students can calculate numerical result of Fourier Transform of any function. If we made a slide bar of those parameters. Student can manipulate signal frequency, aperture size and see the diffraction pattern. In the lecture, some simple experiment can be done for experiment the physics in lecture. For example, you can use the camera's CPL filter, or polarized sunglasses to interact with the student's laptop screen. In laser projector system, diffraction and convolution concept can be observed from diffractive optical element (DOE) placed on the laser pen. In the lecture, I will focus on two topics, polarization optics and laser diffraction optics. I give the simulator on the cloud drive for student download and install. Those students came to class with laptop install LabVIEW runtime and the simulator file.

3. OPTICS SIMULATION AND EXPERIMENT IN LECTURE

3.1 Polarization wave and Poincare sphere

Polarization is an abstract concept for many student. Student know the electric field has the vector form [3], as shown in eq.(1).

$$\boldsymbol{E} = \begin{pmatrix} E_x \cos(kz - \omega t) \\ E_y \cos(kz - \omega t + \delta) \end{pmatrix} \tag{1}$$

Electric field E_x and E_y and their amplitude A_x and A_y.There are phase retardation between E_x and E_y and the retardation value is δ. The value of E_x, E_y and δ can categorize these waves into linear polarization, circular polarization or elliptical polarization. The total electric wave is the combination of x and y direction field, and it is very difficult to draw a circular polarization in a blackboard. Some animation is helpful for construction this geometric relationship between the electric field in x, y and the combination.

Another important concept of polarization is Poincare sphere. Different polarization state can also describe on the point of the sphere. The sphere is in Cartesian coordinates with three axes s_1, s_2, and s_3. The positive s_1 axis direction is horizontal polarization, while vertical polarization is in the opposite direction of s_1 axis. The positive s_2 axis direction is linear polarization in 45 degree, while the opposite direction is linear polarization in 135 degree. The positive s_3 axis direction and negative s_3 axis direction are north pole and south pole, which are left hand and right hand circular polarization. In eq.(2), the inverse tangent of the amplitude ratio A_y over A_x makes ψ.

$$\psi = \tan^{-1}\left(\frac{A_y}{A_x}\right) \tag{2}$$

The azimuthal angle is 2ψ which describes the latitude where the point lies on the sphere and the retardation δ describe the angle between the point and S_3 axis. With 2ψ and retardation δ, user can point out the polarizaiton state in Poincare sphere as eq.(3). Without computer visualization, it is not easy for student to understand.

$$\begin{pmatrix} s_1 \\ s_2 \\ s_3 \end{pmatrix} = \begin{pmatrix} cos2\psi \\ sin2\psi cos\delta \\ sin2\psi sin\delta \end{pmatrix} \tag{3}$$

Linearly polarized wave is the electric field oscillate in a constant plane (in xy-plane). The phase retardation between x and y polarized light is $\delta = \delta_y - \delta_x = 0 \ or \ \pi$.

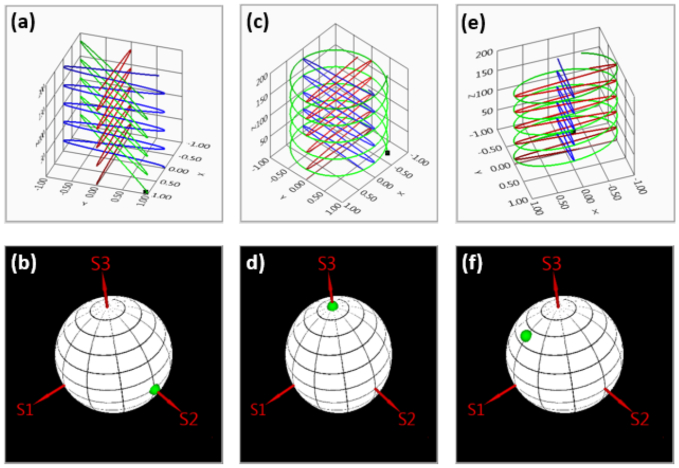

Figure 1 (a) linear polarized wave (b) linear polarization state on Poincare sphere (c) circular polarized wave (d) circular polarized wave on Poincare sphere (e) elliptical polarized wave (f) elliptical polarization state on Poincare sphere

Circularly polarized wave is the electric field vector propagate with uniform rotation electric field in the xy-plane. This occurs when $A_x = A_y$ and $\delta = \delta_y - \delta_x = \pm\frac{\pi}{2}$. The relationship between E_x and E_y is a circle, as shown in eq.(4).

$$\mathrm{E_x = Acos(\omega t - k)} \quad \text{and } \mathrm{E_y = Acos}\left(\omega t - kz - \frac{\pi}{2}\right) = \mathrm{Asin(\omega t - kz)}$$

$$E_x^2 + E_y^2 = A^2cos^2(\omega t - kz) + A^2sin^2(\omega t - kz) = A^2 \tag{4}$$

Through derivation calculations, students can understand that this is a circle equation. Circular polarization wave is hard to imagine how it works. I tried to use interactive software in teaching. You can use the mouse to change the angle of view angle. For example, observe the wave on xy plane from z direction. It is much easier to understand the left-handed and right-handed circular polarizations. The polarization state on Poincare sphere at the right side of program changes according to the amplitude and relative retardation, as shown in Figure 2. Moreover, it is easier to observe the polarization state change from circular polarization to the linear polarization. Also, the electric field shown in eq.(1) can be written as an elliptic function, such as eq.(5). Through the continuous changing processor parameter, we can let students operate various polarization states.

$$\left(\frac{E_x}{A_x}\right)^2 + \left(\frac{E_y}{A_y}\right)^2 - \frac{2cos\delta}{A_xA_y}E_xE_y = sin^2\,\delta \tag{5}$$

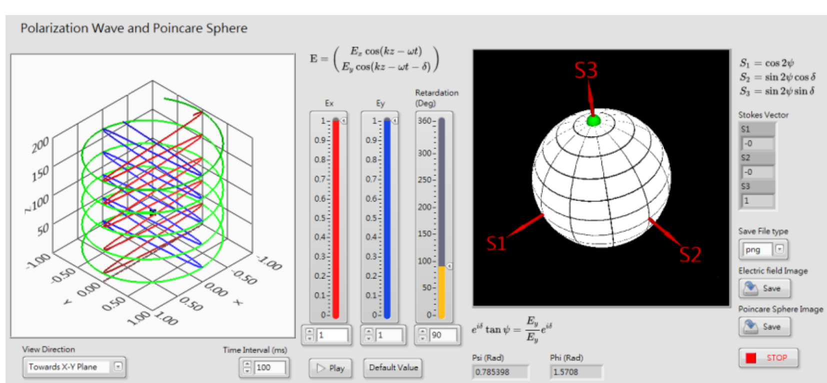

Figure 2 Polarization Wave and Poincare Sphere

Therefore, the polarization state is not only a mathematical form, but also an object, which can be manipulate. Student use the simulator in the classroom, as shown in Figure 3(a). In the classroom, you can also do simple experiment. Many students have mobile phones. Nowadays, mobile phone screen is polarized light. Teachers can prepare polarized sunglasses or circular polarizer lenses for cameras to show this phenomenon. The brightness of the screen laptop changes as shown in Figure 3(b).

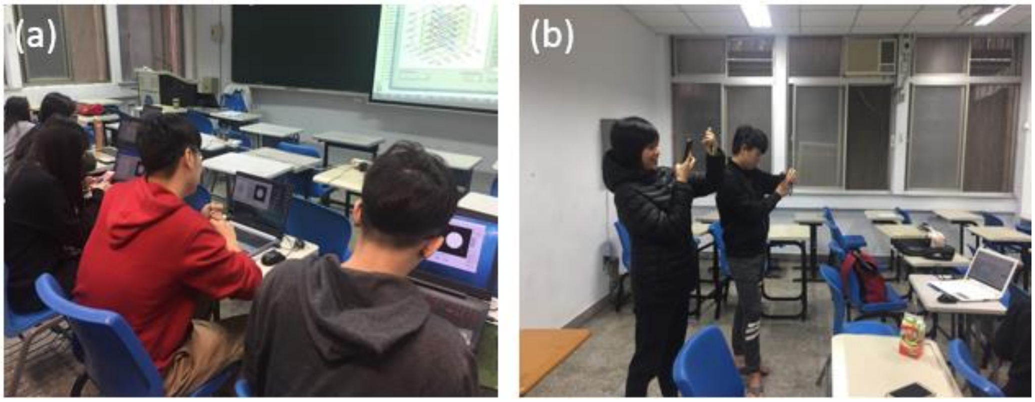

Figure 3 (a) student use laptop to manipulate the polarization state and Poincare sphere (b) student observe the brightness of laptop screen when the sunglass and circular polarizer plate with different rotating angle

How do we generate polarization? Sometimes I ask student this question. We can use a polarizer to absorb specific polarization direction, or we can generate polarization state by reflection. For example, we can use Fresnel equation to describe the light transmitted and reflected from surface. The s-polarization and –polarization states have different reflection coefficient as shown in eq. (6) (7).

$$R_s = \left|\frac{n_1 cos\theta_i - n_2 cos\theta_t}{n_1 cos\theta_i + n_2 cos\theta_t}\right|^2 \tag{6}$$

$$R_p = \left|\frac{n_1 cos\theta_t - n_2 cos\theta_i}{n_1 cos\theta_t + n_2 cos\theta_i}\right|^2 \tag{7}$$

Students can observe the reflection, relation coefficient and the Brewster Angle by actually operating the angle of incidence or changing the refractive index of the medium, as shown in Figure 4

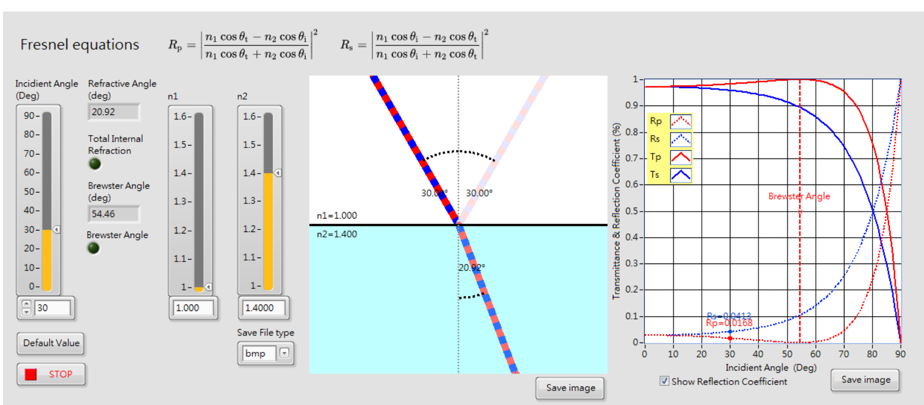

Figure 4 Fresnel equation for reflection and transmittance intensity

In daily life, the LCD screen is the application of polarization light. Changing the brightness by change the polarization after pass through liquid crystal. Optical structure of LCD is two orthogonal polarizers, with a transmission axis at 0 and 90 degrees. A liquid crystal act as a wave plate sandwiched between polarizers. By changing the optical axis of the liquid crystal, while the phase retardation $\Gamma = 2\pi(n_e - n_o)d/\lambda$. The parameters n_e ,n_o and λ represent the extraordinary,

ordinary refractive index and wavelength, respectively. The transmittance can be explain Jones calculus as shown in eq. (8) [4]. The transmittance intensity is shown in eq. (9).

$$E' = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \frac{cos\Gamma}{2} & -\frac{isin\Gamma}{2} \\ -\frac{isin\Gamma}{2} & \frac{cos\Gamma}{2} \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \frac{-i}{\sqrt{2}} \begin{pmatrix} sin\frac{\Gamma}{2} \\ 0 \end{pmatrix} \tag{8}$$

$$I = \frac{1}{2} sin^2 \left(\frac{\Gamma}{2}\right) = \frac{1}{2} sin^2 \left(\frac{\pi (n_e - n_o) d}{\lambda}\right) \tag{9}$$

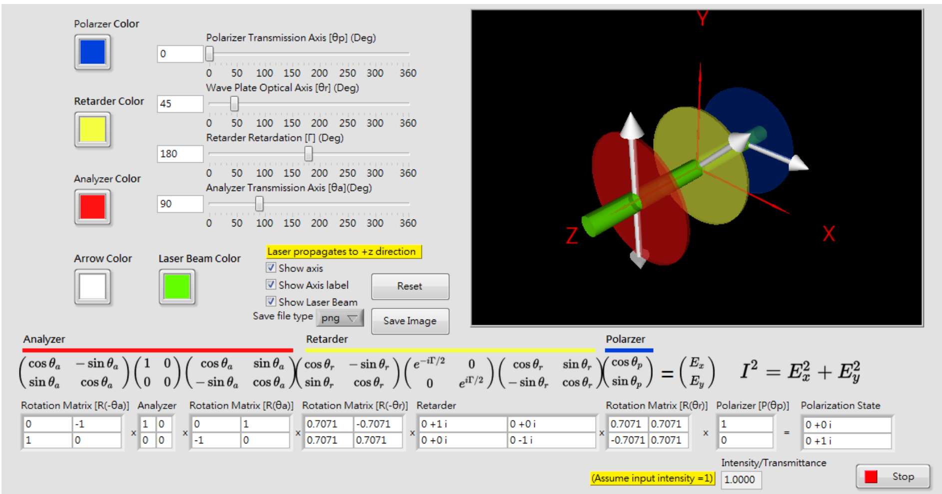

Figure 5 Transmittance simulation of a wave plate between polarizer and analyzer

The students actually change the value of the transmittance axis angle of polarize and analyzer, retardation and optics axis angle of wave plate in simulator as shown in Figure 5. According to Fresnel equation, we explained that most of the ground reflections are s-polarization that is why sunglasses has horizontal absorption axis. Students rotated polarized sunglasses and observed the brightness change of laptop, as shown in Figure 6.

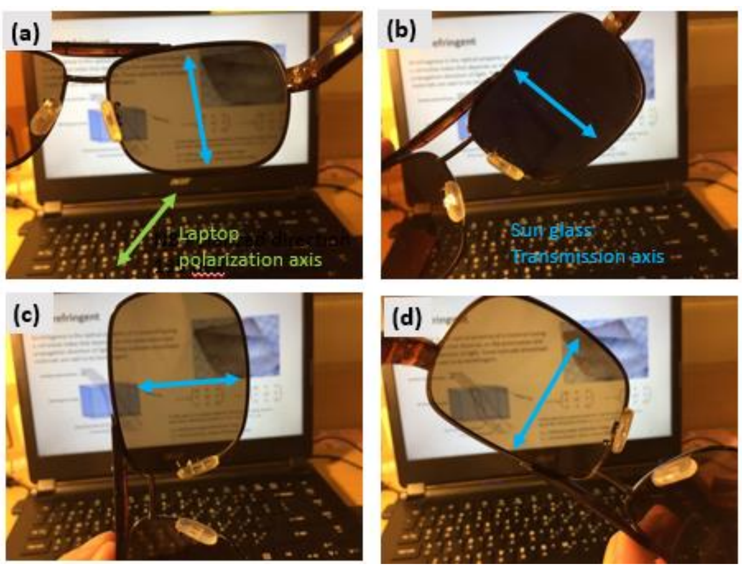

Figure 6 A simple experiment of transmittance of a polarized light pass through a polarizer- sunglass. The green arrow is the polarization direction of laptop while the sunglass transmission axis is (a) 90 degrees (b) 135 degrees (c) 180 degrees (d) 225 degrees

3.2 Diffraction and laser dots projector System

Diffraction is also a common topic in the photonics. When I teaching this topic, I started from Fourier series, and then introduced the Fourier transform. Finally explained an application of diffraction, the 3D sensing structure light in the mobile phone. Series expansion of the periodic square wave as shown in eq. (10), can be expanded into the sum of many different frequency sine functions. The coefficients of each sinusoidal wave have different coefficients as shown in eq. (11).Superposition of those different frequency sinusoidal waves can reconstruct the original square wave, as shown in Figure 7 (a).

$$f(x) = \begin{cases} 1, \; if \quad n\pi < x < (n+1)\pi \\ -1, \; if \quad (n-1)\pi < x < n\pi \\ \quad 0, \; if \; x = n\pi \end{cases} \tag{10}$$

$$f(x) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4}{n\pi} \sin(nx) \tag{11}$$

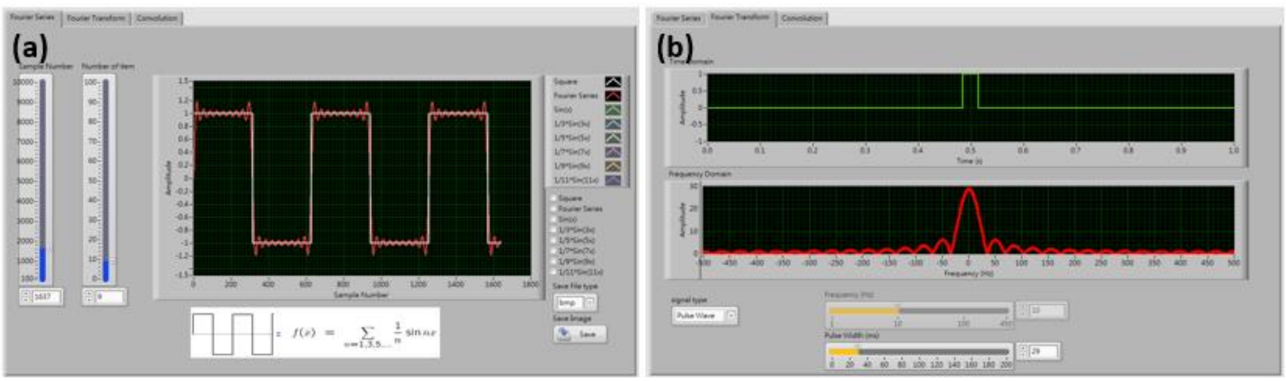

Figure 7 (a) Series expansion of periodic step function (b) The Fourier transform of a rectangular function rect(x/A), and the amplitude in frequency domain is |Sinc(Af)|

Similarly, we can also use any function to analyze the amplitude of each of its frequencies, and plot the frequency of each component against the intensity. It is the Fourier transform of the original function. For example, the rectangular function, whose relationship is shown in eq. (12),

$$g(x) = rect\left(\frac{x}{A}\right) = \begin{cases} 1, |x| < \frac{A}{2} \\ 0, |x| \geq \frac{A}{2} \end{cases} \tag{12}$$

Through the Fourier transform, you can transform the rect function to a sinc function on the frequency domain, as shown in eq.(12). Only a few specific functions have analytic Fourier transforms pairs. For example, rect function and sinc function are a pair of quite important Fourier transform pairs as shown eq.(13). This function is very important for optics, because sinc function is the electric field distribution from the single slit diffraction. The intensity distribution of diffraction is the square of the sinc function. In Figure 7 (b), it shows the original function g(x) and its amplitude |G(f)| in the frequency domain. In this case, it is |G(f)|= |Asinc(Af)|.

$$G(f) = \int_{-\infty}^{\infty} g(t)\, e^{-i2\pi f t} dt = \int_{-\frac{A}{2}}^{\frac{A}{2}} e^{-i2\pi f t}\, dt = \frac{1}{-i2\pi f}\left[e^{-\frac{i2\pi f A}{2}} - e^{\frac{i2\pi f A}{2}}\right] = \frac{A\sin(\pi A f)}{\pi A f} = A sinc(Af) \tag{13}$$

In the integral transform, the convolution integral is also very often used. It is defined as the integral of the product of the two functions after one is reversed and shifted. As shown in eq. (14). This is a very dynamic concept. It has not been easy for students to understand such concepts. Teachers often explain this process to students by constantly changing τ. I think this is also a mathematical concept that is quite suitable for introduction with interactive software. Through the change of τ parameter, h(t-τ) will be in different positions, we can observe this change phenomenon in time. Such as Figure 8 (a).

$$g * h(t) \equiv \int_{-\infty}^{\infty} g(\tau)\, h(t-\tau) d\tau = \int_{-\infty}^{\infty} g(t-\tau)\, h(\tau) d\tau \tag{14}$$

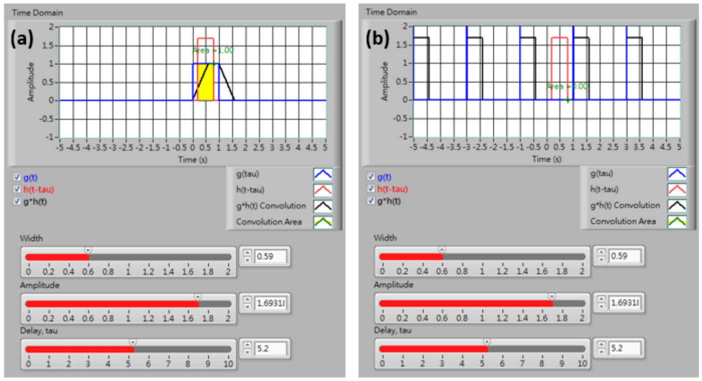

Figure 8 (a) convolution of two rectangular function (b)

The Fourier transform can change the complex convolution integral into a simple multiplication, $\mathcal{F}\{g * h\} = \mathcal{F}\{g\}\mathcal{F}\{h\}$. The function I want to use here is Comb function $III_T(t)$. The definition of Comb function is shown in eq.(15), which is a pulse train of delta function.

$$Comb_T(t) = III_T(t) = \sum_{n=-\infty}^{\infty} \delta(t - nT) \tag{15}$$

The convolution of g(x) and $III_T(t)$ will be, g(x) is copied to each pulse train. As shown in Figure 8 (b), the mathematical formula can be written as eq.(16).

$$g * III_T(t) = g * \sum_{n=-\infty}^{\infty} \delta(t - nT) = \sum_{n=-\infty}^{\infty} g(t - nT) \tag{16}$$

The Fresnel diffraction formula, such as eq. [5], can also be written in the form of convolution. The electric field in the initial position convolute with the transfer function $h(x, y, z) = \frac{e^{ikz}}{i\lambda z} e^{\frac{ik}{2z}(x^2+y^2)}$. Therefore, he Fresnel diffraction formula can be rewritten into the form of eq. (18). Another method is to take the x, y terms out of eq.(17) and make eq.(17) become form of a two-dimensional Fourier transform, as shown in eq.(19). The mathematical formula is concise and symmetry, but for students still feel obscure about the distribution. Therefore, students can use software and change the aperture size and then observed the diffracted image directly, as shown in Figure 9 (a) and (b). To deepen the students' understanding of diffraction optics, it is relatively helpful.

$$E(x, y, z) = \frac{e^{ikz}}{i\lambda z} \iint_{-\infty}^{+\infty} E(x', y', 0) e^{\frac{ik}{2z}\left[(x-x')^2 + (y-y')^2\right]} dx'dy' \tag{17}$$

$$E(x, y, z) = E(x, y, 0) * h(x, y, z). \tag{18}$$

$$\frac{e^{ikz}}{i\lambda z} e^{\frac{i\pi}{\lambda z}(x^2+y^2)} \iint_{-\infty}^{\infty} E(x', y', 0) e^{\frac{i\pi}{\lambda z}\left(x'^2+y'^2\right)} e^{i2\pi\left[\frac{x}{\lambda z}x' + \frac{y}{\lambda z}y'\right]} dx'dy' \tag{19}$$

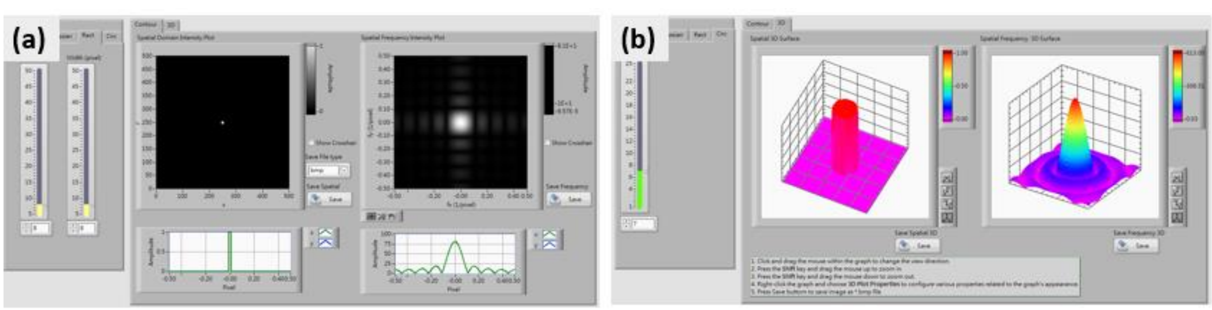

Figure 9 (a) Diffraction of square aperture in 2D intensity plot (b) Diffraction of circular aperture in 3D intensity plot

After some lecture and simulator operation, we can use the laser pen with DOE to demonstrate the relationship between the diffraction and the convolution. A simple demonstration is shown in Figure 12 (a). Finally, I will briefly introduce how to generate structured light and its application 3D Sensing on the mobile phone, such as iPhone X Face ID. The laser dots projector can be divided into three parts [6]: patterned-VCSEL, collimated lens and impulse DOE, As shown in Figure 10.

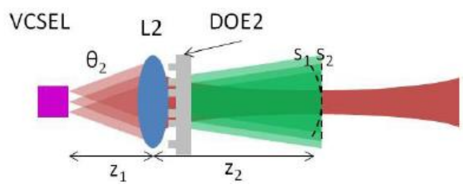

Figure 10 Patterned-VCSEL structured light system

The patterned-VCSEL array in dot projector is shown in Figure 11 (a). The diffraction pattern of the DOE is fan-out pattern similar to 2D Comb function as shown in Figure 11 (b). The diffraction pattern of the VCSEL array pass through the DOE is like copy the VCSEL pattern to every pulse on the pulse train as shown in Figure 11 (c). For large angle diffraction, we can imagine that the pattern of Figure 11 (c) is imaged on a spherical surface. This, when the spherical image is turned to the plane image, some pincushion distortion occurred, and the final image is as shown in Figure 11 (d). This is how laser dots projector works in consumer electronics. Figure 12 (b) is the laser dot projector pattern of OPPO Find X on the market.

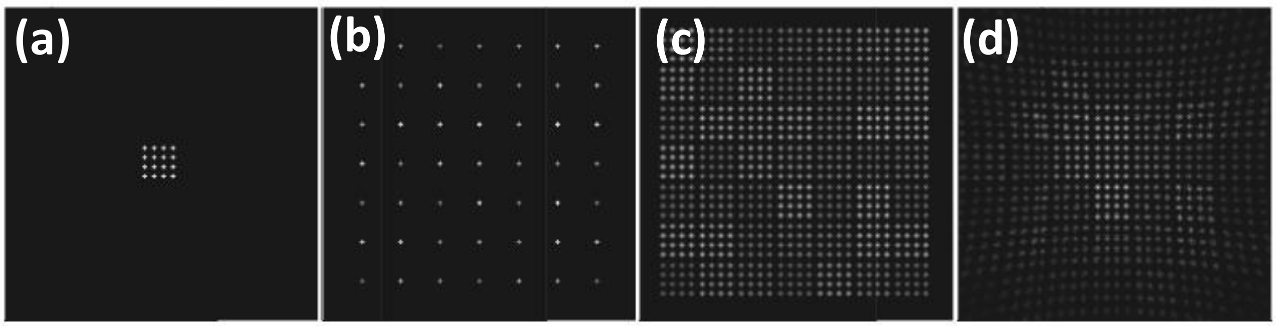

Figure 11 (a) patterned VCSEL array (b) impulse of DOE (c) image of spherical surface s_1 (d) image of planar surface s_2.

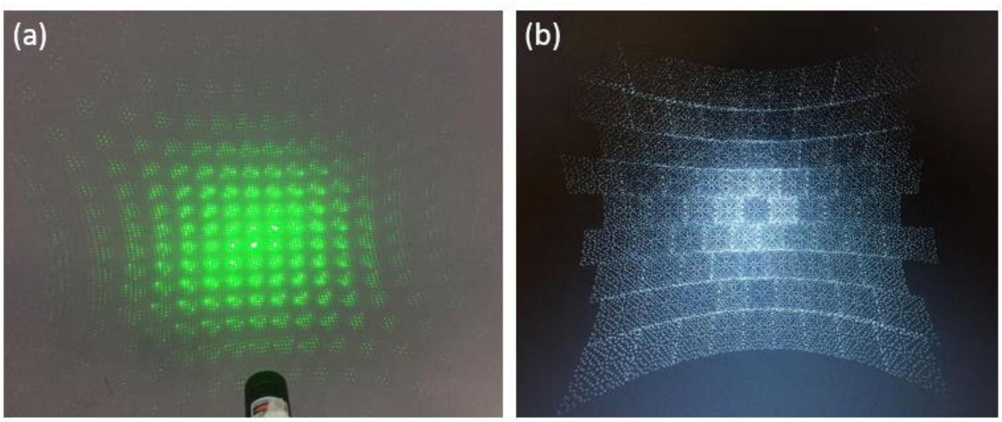

Figure 12 (a) Diffraction image of laser projector from daul DOE (b) Diffraction image from pattern VCSEL and fan-out DOE in OPPO mobile phone Find X.

4. TEACHING ANALYSIS QUESTIONNAIRE

I design teaching questionnaire to understand the students' feedback on teaching. I have some questions about polarization and use the Likert scale to understand the student's reaction. The format of a typical five-level Likert item and the option are

1. Strongly disagree
2. Disagree
3. Neither agree nor disagree
4. Agree
5. Strongly agree

The odd questions Q1, Q3, Q5 and Q7 of questionnaire are asking, “Can students understand the physics meaning of the slide?” The next questions such as Q2, Q4, Q6 and Q8 are asking students “With the simulator, can students understand the physical meaning and mathematical formula?”

Table 1 Questionnaire about polarization wave and Poincare sphere

Q1	When using physical formulas to explain the theory of linear polarization, circular polarization, and elliptical polarization of electromagnetic wave, I think I have understood the relationship between them.
Q2	It is helpful to use animation to explain the linear polarization, circular polarization, and elliptical polarization of electromagnetic fluctuations.
Q3	When using physical formulas to explain the electromagnetic wave polarization state and the Poincare Sphere, I think I have understood the relationship between them.
Q4	It is helpful to use software simulation to understand the relationship between the polarization state of electromagnetic waves and Poincare Sphere when it comes to software simulation.
Q5	When using physical formulas to explain how the Jones Matrix operates, I think I understand the relationship between polarization, transmittance axis, wave plate, and optical axis.
Q6	Using simulation software to explain how the Jones Matrix operates is helpful for understanding the relationship between polarization, transmittance axis, wave plate, and optical axis.
Q7	When using physical formulas to explain how the Fresnel equation operates, I think I have understood the relationship between reflectivity and polarization.
Q8	Using simulation software to explain how the Fresnel equation works is helpful for understanding the relationship between reflectivity and polarization.

Table 2. Questionnaire about diffraction and laser dots projector system

Q1	I can understand the Fourier series decomposition of periodic function.
Q2	It is helpful to understand the Fourier series through software interaction.
Q3	Through the lecture, I can understand the Fourier transform and Convolution.
Q4	It is helpful to understand Fourier transform and Convolution through software interaction:
Q5	Through the lecture, I can imagine the 2-dimensional Fourier transform.
Q6	It is helpful to understand 2-dimensional Fourier transform through software interaction.
Q7	Through lecture, I can understand the relationship between diffraction and Fourier transform.
Q8	It is helpful to understand the relationship between diffraction and Fourier transform through software interaction,

From Figure 13(a) polarization wave and Poincare sphere, we can see that the interaction of software is helpful for students' understanding, especially the use of software to explain Poincare sphere (Q4) than just through mathematical calculations (Q3). The difference in scores is over 0.7, and the results seem to be significant. However, from the student's reaction, Figure 13 (b) diffraction and laser dots projector system. The difference in scores is less than 0.5. The possible reason is that the mathematics of diffraction is more complicated, not every student is familiar with the Fourier transform. The simulator is not intuitive enough, so that students cannot easily understand that the concept convey by the lecture. If the intuition of the simulator improved, and I believe that the lecture with simulator will be better than only textbook and blackboard note.

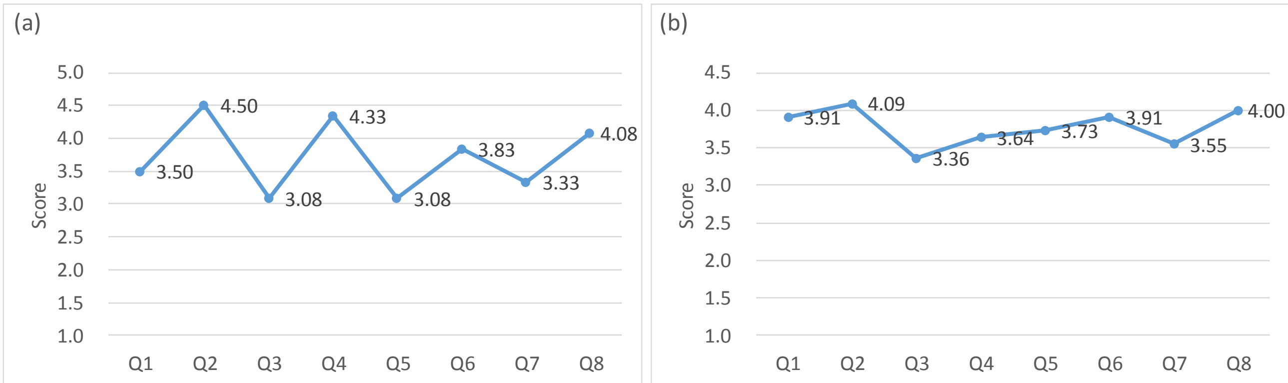

Figure 13 average score of students' response of (a) polarization wave and Poincare sphere (b) Diffraction and laser dots projector system

5. CONCLUSION

The progress of the education field is a long-term work. It is not only a school educator, but also an externally invited lecturer. Can we make simply copy and write notes become an interactive teaching method? Let students explore classroom theory through operate some simulator, and to actually see the visualization image of the physical math formula. We have tried this concept in the lectures of university and share the simulator program to student. We have made two main topics about polarization optics simulator and diffractive optics simulator. Questionnaire had been made for analyzing the student's learning situation and feedback. The result show that simulator about polarization optics is better than simulator about diffractive optical. It might be result from the mathematics of Fourier transform and diffraction are complicate. We will increase the intuition of the simulator in the future.

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