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Abstract. A photon model is proposed, and the parameter equations of the photon are obtained. This model can explain the polarization, total reflection, evanescent wave, and Goos-Hanchen shift of a single photon. The evanescent waves of photons with different frequencies are refractively dispersed. The Goos-Hanchen shift is dependent on the difference between the two refractive indices of media, the incident angle, and the frequency of the photon. According to this model, an evanescent wave of light does not decay exponentially along the *z* direction and does not propagate along the *x* direction infinitely. The laws of refraction and reflection for a single photon can be derived. The refractive dispersion of light can be explained. According to this model, every photon is polarized. Polarization is the intrinsic nature of the photon. The motion of a single photon is either clockwise or counterclockwise. The so-called unpolarized light refers to light that consists of an equal number of photons with clockwise motion and counterclockwise motion. The trajectories of two photons with the same frequency but opposite spiral directions are mirror-image isomers. They cannot be superimposed upon each other. [DOI: 10.1117/1.OE.52.7.074103]

Subject terms: photon; refraction; reflection; dispersion; evanescent wave; Goos-Hanchen shift.

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1 Introduction

Almost everybody knows what light is. Actually, though, no one knows what the light really is. There are many theories that have been proposed explanations of the sophisticated phenomena of light. For instance, during the 18th and 19th centuries, four main theories: projectile theory, fluid theory, vibration theory, and wave theory, were employed. However, none of them could solve the problem completely.[1] James Clerk Maxwell considered that light consists of alternating electromagnetic waves. In this way, the observed actions of reflection and refraction, interference, and diffraction and polarization could all be explained,[2] but it could not explain photoelectricity. Einstein took the energy of a light ray spreading out from a point source as a finite number of energy quanta and solved the phenomena of photoemission perfectly.[3,4] Now, we consider that light has dualistic nature as wave and particle.[2,3,5] However, we neither use its wave property to explain its particle behaviors nor use its particle property to explain its wave behaviors. We have no reason to suppose that the present concepts represent an ultimate description.[2]

For an evanescent wave of light, many interesting studies have been done. For instance, by using the Goos-Hanchen shift to design high-power superluminescent diodes of up to 115 mW, a low thermal resistance of 4.83 K/W in active multimode interferometer (active-MMI) superluminescent light-emitting diodes (SLEDs) and a high coupling efficiency of 66% of the fiber-coupled power of active-MMI SLEDs into single-mode fiber have been obtained.[6–8] However, I do not think that the problem of the evanescent light wave has been solved satisfactorily. According to the electromagnetic wave theory, an evanescent wave of light should decay exponentially along the z direction and move forward infinitely in the x direction. However, the experiment results showed that an evanescent wave does not decay exponentially along the z direction,[9] and moves only one Goos-Hanchen shift Δx along the x direction. Hongrui[10] proposed a new classical photon model. In this paper, using that model, I derived the laws of reflection and refraction for a single photon. I can also explain why the evanescent wave does not decay exponentially along the z direction, and only moves one Goos-Hanchen shift Δx along the x direction. A new formula for calculating the Goos-Hanchen shift Δx was obtained. According to that model, the boundary of an evanescent wave of light is clear.

2 New Classical Photon Model

Based on Einstein's idea of the photon, I suppose that a photon spirals forward with energy $E = h\nu$, the linear velocity of spiral motion υ and momentum $p = m\upsilon$, where m is the moving mass of the photon, h is Planck's constant, and ν is the frequency of the light which is the number of the oscillations that the photon experienced per second (see Fig. 1). The distance between the two spirals (one oscillation) is the wavelength λ of the light. There are only two spiral directions for photons. One is clockwise and the other is counterclockwise. Different photons with different energies have different linear velocities of spiral motion. A photon with a high frequency ν (more spiral cycles per unit time) has a high energy E and a short wavelength λ. Different photons with different energies have different ν, but they have the same component of the linear velocity c in the forward direction in vacuum. In other words, they have different υ_a but the same $\upsilon_b (= c)$ [see Fig. 1(b)]. Figure 1(a) represents the motion of a clockwise

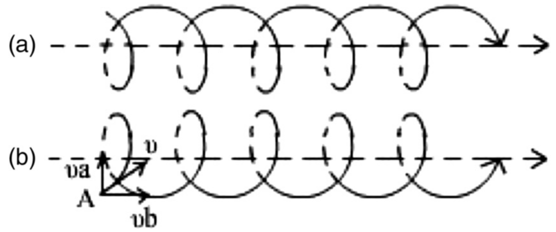

Fig. 1 The new photon model: (a) clockwise spiralling photon and (b) counterclockwise spiraling photon.

spiral photon, and Fig. 1(b) represents a counterclockwise spiral photon. In Fig. 1(b) at point A, the linear velocity υ of the spiral photon is divided into two parts υ_a and υ_b; in vacuum υ_b is always equal to c, and υ always exceeds c.

Now we can get the parameter equations for the spiral motion of one photon:

$$\begin{cases} x = r\cos\omega t & \text{wave nature of light} \\ y = r\sin\omega t & \text{wave nature of light} \\ z = k\omega t = ct & \text{particle nature of light} \end{cases}.$$

In these equations, $x = r\cos\omega t$ and $y = r\sin\omega t$ are both cyclical fluctuation functions. They represent the wave properties of the light. $P = m\upsilon$ and $z = k\omega t$, which is a linear function of time, can represent the particle properties of the light. Thus, these parameter equations show the dual nature of the photon as it travels. More generally, the equations become:

$$\begin{cases} x = r\cos(\omega t \pm \varphi) \\ y = r\sin(\omega t \pm \varphi) \\ z = k\omega t \pm \delta = ct \pm \delta \end{cases}, \tag{1}$$

where r is the radius of the spiral motion of the photon, ω is the angular frequency of the spiral motion of the photon, k is a constant, and φ is the initial phase.

3 Reflection of a Single Photon by an Elastic Collision at the Interface Between Vacuum and Glass

When a photon spiralling forward is obliquely incident onto glass from a vacuum, the photon collides with the surface of the glass at point A (shown in Fig. 2) along the direction of the tangent linear velocity of the spiral motion at that point. The collision is elastic because no kinetic energy of the system is lost. The laws of conservation of momentum and of kinetic energy hold. For the surface of the glass, its velocity and kinetic energy are not changed by the collision. For the photon, we obtain

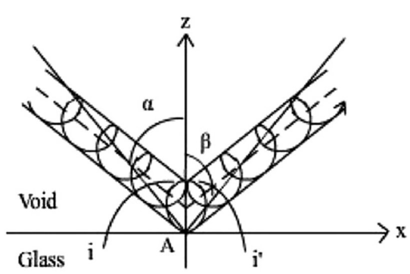

Fig. 2 The elastic collision of one photon onto a glass surface.

$$\frac{1}{2}m\upsilon_1{}^2 = \frac{1}{2}m\upsilon_2{}^2,$$

so $\upsilon_1 = \upsilon_2$.

The scalars of the tangent linear velocities of the spiralling photon are unchanged by the collision. Now let us consider the conservation of momentum of the system. Applying the conservation of momentum, we obtain two scalar equations. For the x-component of the collision, we have

$$m\upsilon_{1x} = m\upsilon_{2x}, \tag{2}$$

where $\upsilon_{1x} = \upsilon_1 \cdot \sin\alpha$, $\upsilon_{2x} = \upsilon_2 \cdot \sin\beta$ (shown in Fig. 3). Substituting into Eq. (2), we have

$$m\upsilon_1 \cdot \sin\alpha = m\upsilon_2 \cdot \sin\beta,$$

where $\upsilon_1 = \upsilon_2$ because of the conservation of kinetic energy. One photon has the same m with the same υ, so $\alpha = \beta$.

Also for the z-component, we have

$$m\upsilon_{1z} = m\upsilon_{2z}, \tag{3}$$

and from Fig. (3), we obtain

$$\upsilon_{1z} = \upsilon_1\cos\alpha, \qquad \upsilon_{2z} = \upsilon_2\cos\beta.$$

Substituting into Eq. (3), we have

$$m\upsilon_1\cos\alpha = m\upsilon_2\cos\beta,$$

and $\alpha = \beta$ again.

Because the angle between the tangential velocity and the axis of the spiralling motion of the incident photon before the collision is equal to the angle between the tangential velocity and the axis of the spiralling motion of the reflected photon after the collision at point A (shown in Fig. 2), the angle of incidence of the photon i is equal to the angle of reflection of the photon i'. This is the law of reflection for a single photon.

4 Refraction of a Single Photon

Figure 4 shows how refraction takes place when an incident photon enters the glass from a vacuum. In Fig. 4, line MP represents the interface between the vacuum (above MP) and glass (below MP). When a photon spiralling forward is obliquely incident from a vacuum onto glass as shown in Fig. 4, its spiral motion plane must move from CD to EF. The photon should experience the distance DF in the vacuum, the propagating speed is c, and at the same time it should also travel the distance CE in the glass with forward velocity υ_m. If the resistance in the glass to the photon is

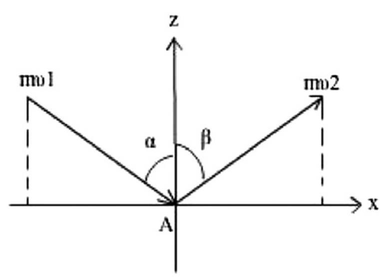

Fig. 3 The conservation of momentum of the system.

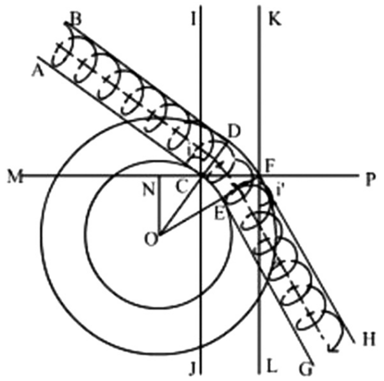

Fig. 4 The refraction of a photon.

equal to that in vacuum, $\upsilon_m = c$, we have DF = CE. The photon spirals forward in its original direction. There is no refraction at all. If the resistance of the glass is greater than that of vacuum, we have $\upsilon_m < c$, and CE < DF. Therefore, the propagation direction of the photon should bend toward the normal line in the glass. That is the refraction of the photon. Now, let us derive Snell's law from this model. In Fig. 4, the angle ACI is the angle of incidence i, and the angle HFL is the angle of refraction i'. The arcs DF and CE have the same center O, so we have $\mathrm{OC}/\mathrm{OD} = \mathrm{CE}/\mathrm{DF} = \upsilon_m/c$, and we also have $\mathrm{OC}\sin i = \mathrm{OF}\sin i' = \mathrm{ON}$, with OD = OF, so we get, $\sin i/\sin i' = \mathrm{OF}/\mathrm{OC} = \mathrm{OD}/\mathrm{OC} = c/\upsilon_m = n_1/n_2$. This is Snell's law (where n_1 and n_2 are the refractive indices of glass and vacuum, respectively).

A photon passing from a denser to a rarer medium is refracted away from the normal to the surface. The angle of refraction in the rarer medium increases more rapidly than the angle of incidence. In Fig. 5, when the angle of incidence i is outside of the critical angle i_c (where $i' = 90$ deg, $\sin i_c = \upsilon_m/c$), the photon turns back into the glass. In this case, some part of the trajectory of the photon is in vacuum, and the rest of the trajectory of the photon is in the glass. This is the total reflection of a single photon (shown in Fig. 5).

5 Dispersion of Light

When a photon from a vacuum passes obliquely through a prism, the refractive index of the glass is greater than that of a vacuum, so the motion of the photon is like the case shown in Fig. 6. When the photon spirals through the distances AB and DE during the same time interval, the velocity of the photon in the glass is slower than that in vacuum caused by the different resistances of the glass and vacuum ($\upsilon_m < c$), so DE is shorter than AB, DE < AB. The direction of propagation of the photon bends downward. The same thing happens again when the photon leaves the prism; HI < FG, so the propagation direction of the photon bends downward again. Two refractions occur for the photon passing through the prism. In addition, photons with different frequencies have different distances DE and HI. The higher the frequency the light has, the more oscillations are made by the photon when it passes through the distances DE and HI, and the bigger the effect of the resistance of the glass should be. The distances DE and HI are shorter, and the direction of propagation of the photon bends much more downward compared with a low-frequency photon. Therefore, photons with higher frequencies have larger indices of refraction. This is the refractive dispersion of light. When we let a beam of white light pass through the prism obliquely, photons with different colors are refracted at different angles according to their frequencies and are therefore separated or dispersed into a band of colors.

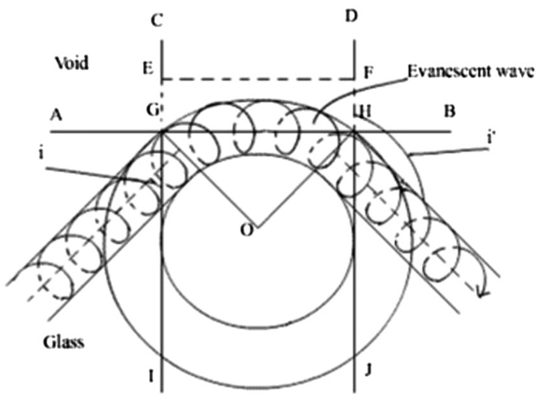

Fig. 5 The total reflection of a single photon.

6 Evanescent Wave of a Single Photon

6.1 *Evanescent Wave of a Single Photon*

In Fig. 5, the trajectory of the photon within the length of the dashed line is the evanescent wave of the photon, but it is only part of the trajectory. It cannot be the whole trajectory of the total reflection of the photon. If the whole trajectory of the photon appeared in the rarer medium, the total reflection of the photon would not occur.

When total reflection of a single photon occurs, the photon must passes through the interface; sometimes it is in the rarer medium, and sometimes it is in the denser medium. The resistance of the denser medium to the photon is greater than that of the rarer medium. This forces the photon to bend downward back into the denser medium causing total reflection. It seems that the denser medium draws the photon back from the rarer medium. The part of the trajectory of the photon in the rarer medium is the so-called evanescent wave. The depth of the photon entering into the rarer medium is dependent on the incident angle $i(\geq i_c)$, the difference of $n_1 - n_2$, and the frequency ν (or the wavelength λ) of the photon. The larger the value of $n_1 - n_2$ is, the greater the depth ($i \to i_c$) would be. The smaller the angle of incidence $i(\geq i_c)$ is, the greater the depth would be, also. However, the depth should be less than $2r$ if the spiral plane of the photon is not changed (r is the radius of the spiral motion of the photon).

When a photon is totally reflected (as shown in Fig. 5), the left portion of the photon's trajectory is like the case in which

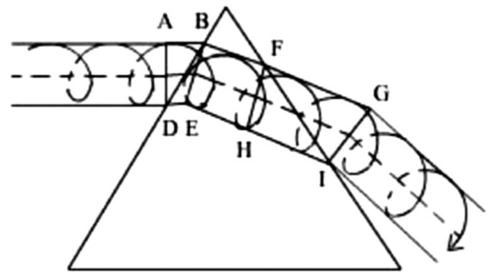

Fig. 6 The dispersion of light.

the photon emerges from the glass into the vacuum as in Fig. 6. Therefore, if we use a beam of white light as the incident light for total reflection, we can obtain one band of colors of evanescent waves. That means the white light is dispersed when it becomes evanescent waves. Because of that, photons with different frequencies experience different resistances emerging from the denser medium; the higher frequency the photon is, the greater the resistance the photon should experience, so the direction of the propagation of the photon bends much more downward back into the denser medium compared to a low-frequency photon. Therefore, the evanescent waves are the dispersion of the incident light in this case, which is refractive dispersion.

Now let us consider the relation between the depth of the photon moving into the rarer medium and the refractive indices. If the spiral plane of the photon is not changed when the total reflection occurs, the photon takes place the total reflection like the case showed in Fig. 7. When the photon goes through from point C to point E passing by point D, we suppose that it moves just for one wavelength λ. The middle point between C and E is F. We suppose that F is the top point of the evanescent wave of the photon. Drawing a line from F to point D, line FD intersects line AB at point O perpendicularly. AB represents the interface of the glass and the vacuum. The depth of the photon moving into the rarer medium is determined by the refractive indices of the mediums at a certain incident angle and the frequency of the photon. When the two total forces of the photon suffering in the different mediums are equal, the depth of the photon moving into the rarer medium is the biggest ($i \to i_c$). Thus, we have

$$\mathrm{OD} \times n_1 = \mathrm{OF} \times n_2. \tag{4}$$

Defining $\mathrm{OD} = z_1$ and $\mathrm{OF} = z_2$, Eq. (4) becomes $z_2 n_2 = z_1 n_1$ and $z_1 = 2r - z_2$ (the spiral plane of the photon is not changed). Then we have

$$z_2 = (2r - z_2)n_1/n_2 \quad \text{and} \quad z_2 = 2rn_1/(n_1 + n_2)(i \to i_c). \tag{5}$$

Here, r is constant when λ is given. If n_2 is given ($n_2 = 1$ in vacuum), z_2 increases as n_1 increases, i.e., the depth that the photon moves into the rarer medium increases. The maximum of z_2 is $2r$ when n_1 is considered to be infinite ($n_1 \to \infty$). That is the diameter of the spiral plane of the photon.

6.2 *Explanations of Experiments*

6.2.1 *Isaac Newton's experiment*

If we let one spiralling photon entering the prism as shown in Fig. 8, total reflection of light would take place. Let us place a positive lens near the prism as shown in Fig. 8. When the lens does not touch the trajectory of the photon ($d > 4\lambda$),[11] no change in the total reflection occurs. However, if the lens intersects the trajectory of the photon ($d < 4\lambda$),[11] the direction of the photon changes to enter the lens as shown in Fig. 9. Then another refraction occurs (from the rarer medium to the denser medium, i.e., the lens). In this case, there is no reflection at all.

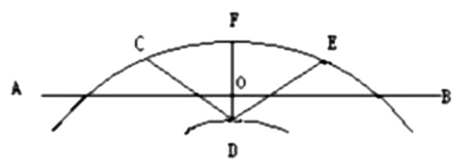

Fig. 7 The greatest depth of the photon in the rarer medium.

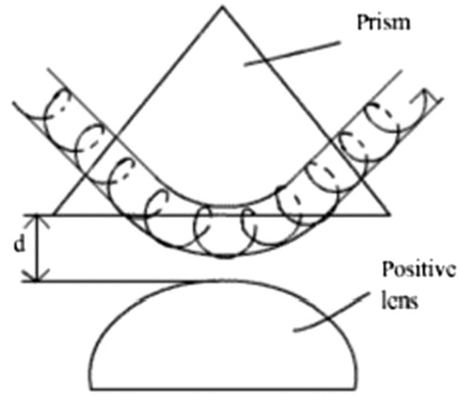

Fig. 8 The lens does not touch the trajectory of the photon.

6.2.2 *Experiment of sensitization*

If we put the prism on a slab with some part of it coated with photosensitive material, where the refractive index n_2 of the photosensitive material is less than the refractive index n_1 of the prism (as shown in Fig. 10), neither total reflection nor an evanescent wave occurs in this case, because the photon is absorbed by the photosensitive material. We only have the chemical reaction:

$$\mathrm{AgBr(s)} + h\nu \to \mathrm{Ag(s)} + \frac{1}{2}\mathrm{Br_2(1)}.$$

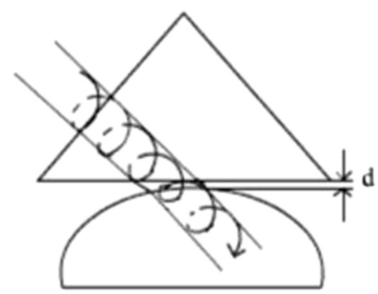

Fig. 9 The lens touches the trajectory of the photon.

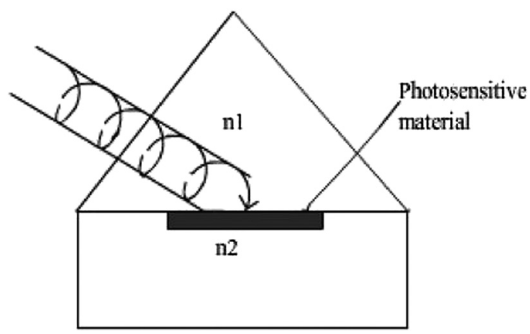

Fig. 10 The photon is absorbed by the photosensitive material.

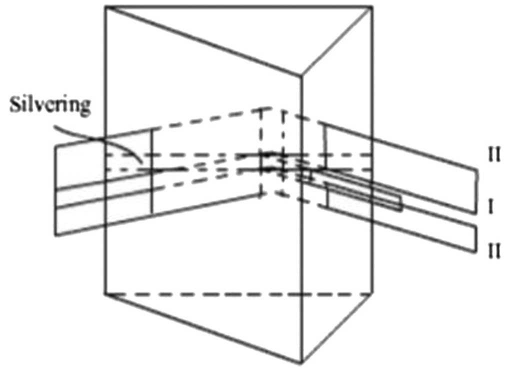

Fig. 11 The lateral beam shift of total reflection.

7 Goos-Hanchen Shift of a Single Photon

Figures 11 and 12 illustrate the Goos-Hanchen effect of a single photon. When a beam of light is incident from an optically denser medium to a rarer medium with the angle of incidence outside of the critical angle ($i > i_c$), total reflection takes place. Goos and Hanchen found that there was a lateral beam shift in this case (1947).[12] This phenomenon is the so-called Goos-Hanchen shift. Now let us explain this phenomenon by using the propagation of a single photon.

We let a beam of light pass through the prism as in the case shown in Fig. 11. When the angle of incidence is outside of the critical angle ($i > i_c$), total reflection occurs. If we coat one part of the base of the prism by silvering (as shown in Fig. 11), the base of prism is divided into two parts: I and II. Part I is silvered, and part II is not. When a forward-spiralling photon is incident from the glass onto the silvering, the photon is reflected back into the glass; the reflection of an elastic collision occurs, and the angle of reflection is equal to the angle of incidence ($i = i'$). There is no evanescent wave in this case (case I). If the photon is incident from the glass into the vacuum with $i > i_c$, total reflection takes place (case II).

Case I begins the transition at point B, and case II begins the transition at point C (as shown in Fig. 12). For the reflection in case I, the photon goes through the distance AB + BE, and in the case II, the photon must go through the distance AC + CD which is longer than AB + BE. BC + CF is the excess distance in case II compared to case I. The distance BF along the interface is the Goos-Hanchen shift Δx. $\Delta x = 2ct \sin i$. Here, c is the velocity of light in a vacuum, $2t$ is the time of the total reflection for one spiralling photon, where t is dependent on the frequency of the photon, the angle of incidence, and the difference between n_1 and n_2.

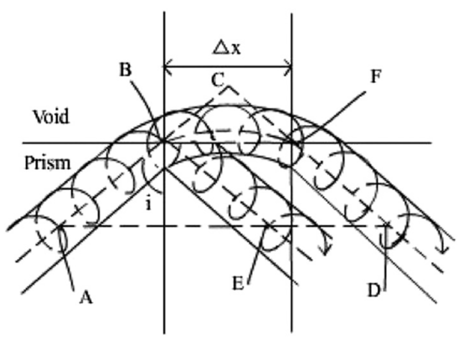

Fig. 12 The different trajectories of one photon with different cases.

Here, we can get three mean velocities of light. The first one is $\upsilon_1 = \mathrm{BF}/2t = \Delta x/2t$ which is the forward velocity along the surface of the denser medium. The second one is $\upsilon_2 = B\frown F/2t$, where $B\frown F$ stands for the arc from point B to point F. The third one is $\upsilon_3 = (\mathrm{BC} + \mathrm{CF})/2t$ which is the velocity without refraction of the photon at point B. Since υ_3 is equal to c, we obtain $\upsilon_3 > \upsilon_2 > \upsilon_1$, where υ_1 is the slowest velocity in this case. It is also the experimentally measured velocity of the evanescent wave along the x direction. That is why the evanescent wave is called a slow wave.

8 Comparison with the Electromagnetic Theory of Light

According to the phenomenon of the evanescent wave of a single photon shown in Fig. 5, when the total reflection occurs, part of the trajectory of the photon must be in the denser medium and part of it in the rarer medium. For many photons with the same frequency and the same incident angle ($i \geq i_c$), the situation of total reflection is like the case shown in Fig. 13. The main points of this evanescent wave are: (a) The greatest depth that the evanescent wave penetrates into the rarer medium is finite and less than the diameter of the spiral motion of the photon if the spiral plane of the photon is not changed. The intensity of the evanescent wave I equals 0 if z is greater than $2r$. (b) The distribution of I along the z direction, i.e., the I–z curve, is not exponential decay. (c) During total reflection, each photon only moves one Goos-Hanchen shift Δx in the x direction. It does not move in the x direction infinitely. (d) The boundary of the evanescent wave is clear. According to the electromagnetic theory of the light, the vector of the electric field of the evanescent wave is:[9]

$$E_2 = E_{20} \exp[-K_1 z\sqrt{(\sin^2 i - n^2)}] \times \exp[-i(\omega t - K_1 x \sin i)]. \tag{6}$$

Here, $K_1 = 2\pi/\lambda_1$, $n = n_2/n_1$, and i is the incident angle.

$$I = |E_2|^2 = |E_{20}|^2 \exp[-2K_1 z\sqrt{(\sin^2 i - n^2)}]. \tag{7}$$

From Eq. (7), we have that I of the evanescent wave is exponential decay along the z direction. If we let $i = 50$ deg, $n_1 = 1.4$, $n_2 = 1$, $\lambda_0 = 632.8$ nm, using Eq. (7), we can obtain the I–z curve showed in Fig. 14. That is the exponential decay curve. From this curve, we obtain: (a) When z approaches to 0, I decays sharply. The decay of I becomes slow when z becomes great. (b) When z becomes infinite, $z \to \infty$, I is equal to 0. This means that I is not equal to 0 forever within a finite z. From Eq. (6), E_2 also shows exponential decay along the z direction, and moves along the x direction infinitely not just one Goos-Hanchen shift Δx.

The experimental I–z curve was published in Ref. 9. Figure 15 is a copy of experimental I–z curve published

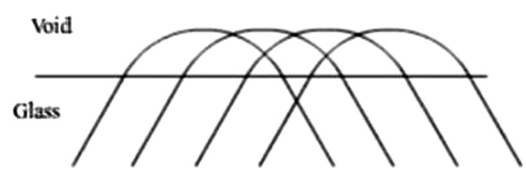

Fig. 13 The evanescent wave of many photons.

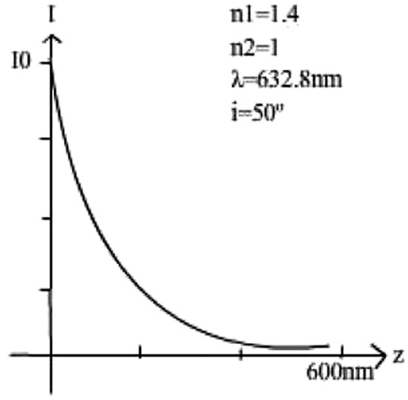

Fig. 14 The $I-z$ curve based on Eq. (7).

in Ref. 9 (Fig. 8 in Ref. 9). It also used the parameters of $i = 50$ deg, $n_1 = 1.4$, $n_2 = 1$, $\lambda_0 = 632.8$ nm. From this curve, we can see that I almost does not decay within 0 to 50 nm of z. It decays faster when z is between 100 and 250 nm. After that, I decays more slowly. The curve definitely does not decay exponentially. It is very different from the curve in Fig. 14. And I almost becomes 0 within the distance of one wavelength λ along the z direction. It is not that the I of the evanescent wave is not equal to 0 within the finite z, and the evanescent wave only moves one Goos-Hanchen shift Δx along the x direction. Therefore, the evanescent wave does not decay exponentially along the z direction and does not move along the x direction infinitely. The greatest depth of penetration into the rarer medium is less than $2r$ if the spiral plane of the photon does not change and each photon moves only one Δx along the x direction.

Goos-Hanchen shift Δx along the x direction is based on the photon's spiral motion. Neither the known particle property nor the wave property of light can explain the phenomenon of the evanescent wave satisfactorily. It is the nature of the spiral motion of the photon, or it is determined by the spiral motion of the photon.

Figure 16 shows the light in a single-mode optical fiber (a) and a multiple-mode optical fiber (b). From these figures, we can see that the boundary of the evanescent wave is clear. It does not decay exponentially along the z direction. It is very hard to imagine that the boundary of the electromagnetic wave is so clear in the case of an evanescent wave.

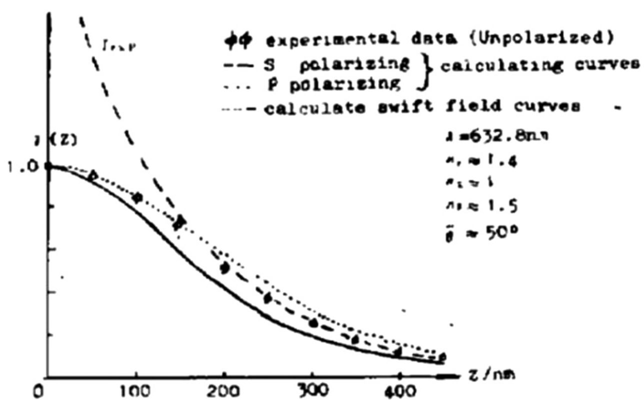

Fig. 15 The experimental $I-z$ curve copied from Ref. 9.

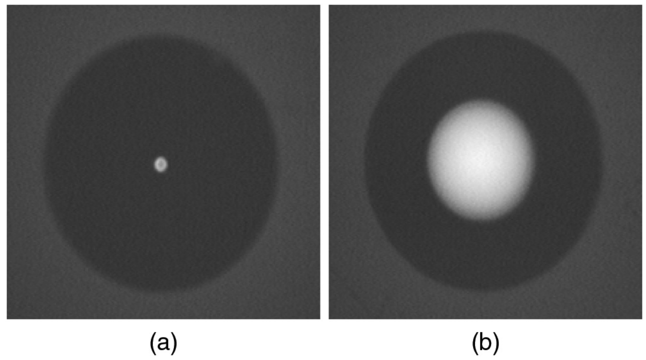

Fig. 16 The light in optical fiber. (These figures were provided by Dr. Peng Song, School of Physics and Technology, University of Jinan, Jinan, China.) (a) Single-mode optical fiber and (b) multiple-mode optical fiber.

9 Polarization of the Photon

There are only two spiral directions for moving photons in a beam of unpolarized light, clockwise and counterclockwise. The number of the photons in one spiral direction should be equal to the other. There is no reason for us to consider that the light source can produce more photons in one spiral direction than the other; it should be 50% for each. When this unpolarized light beam passes through one anisotropic medium (such as a crystal of calcite or quartz) in the direction normal to the section containing the optic axis, the two different kind of photons will be separated from each other by the medium because they experience different resistances resulting from their different spiral directions. They become two beams of moving photons, each with only one spiral direction. These two beams have different velocities in the anisotropic media and have different refractive indices. This is the double refraction of light. If we allow one unpolarized light beam to be incident on a polarizer, one of the two separated beams of photons is reflected or absorbed, the other beam of photons with only one spiral direction passing through the polarizer is polarized light. The spiral direction of these photons is either clockwise or counterclockwise. A perfect polarizer would transmit 50% of the incident unpolarized light. Now we can say that the polarization is an intrinsic property of a photon. For one photon, there is no unpolarized light at all. Every photon is polarized. If the polarizer cannot reflect or absorb photons with one spiral direction completely from the incident monochromatic light, the beam coming out from the polarizer should be partially polarized light. The number of photons in the two spiral directions is not equal.

Some crystals or substances that have optical activity have their enantiomers. The enantiomers can rotate the plane of polarized light in the opposite direction. They have the same molecular formulas, but they cannot be superimposed upon each other. They have a chiral structure and are just the mirror-image isomers. Fortunately, the trajectories of the two photons with the same frequency but opposite spiral directions are also mirror-image isomers. They cannot be superimposed upon each other either (Fig. 1).

10 Conclusion

Generally, a monochromatic light beam consists of clockwise spiralling photons and anticlockwise spiralling motion photons in equal numbers. Polarized light consists of photons with only one spiral direction. Partially polarized light consists of an unequal number of photons of clockwise and counterclockwise spiral motions. Polarization is the intrinsic nature of the photon. It is not caused by a polarizer. The trajectories of the two photons with equal energy but different spiral directions are mirror-image isomers. They cannot be superimposed upon each other. When one forward spiralling photon is obliquely incident onto the surface of a denser medium, the photon is reflected in an elastic collision reflection where the angle of reflection is equal to the angle of incidence. The photon cannot enter into the denser medium; there are no evanescent waves and lateral beam shift in this case. Because of the different resistance of the different mediums to the spiralling photon, when the photon is obliquely incident into the denser medium from the rarer medium, refraction occurs. The propagation direction of the photon bends toward the normal line in the denser medium. However, when the photon is obliquely incident into the rarer medium from the denser medium, the propagation direction of the photon bends away from the normal line in the rarer medium. When the angle of incidence is outside the critical angle, total reflection occurs. It seems that the resistance of the denser medium draws the photon back into the denser medium. The photon must sometimes move in the rarer medium and sometimes move in the denser medium. The part of the trajectory of the photon in the rarer medium is the so-called evanescent wave. If the incident light is white light, the evanescent waves become a band of colors, and the beam of incident light is dispersed. If we draw the photon away from the rarer medium (Newton's experiment), we cannot obtain total reflection in the denser medium. If we reflect the photon away from the interface in an elastic collision reflection (colliding with a silvered surface) we cannot obtain an evanescent wave in the rarer medium. If the photon is absorbed by a photosensitive material on the interface, there are no evanescent waves and no total reflection. Meanwhile, the formation of the evanescent wave requires that the photon sometimes moves in the rarer medium and sometimes moves in the denser medium. The distance the photon moves when being totally reflected is longer than the distance the photon moves when it is reflected by the silvering. This results in a lateral beam shift called the Goos-Hanchen effect. The evanescent wave does not decay exponentially along the z direction and does not move along the x direction infinitely. The boundary of the evanescent wave is very clear. It is very hard to imagine that the boundary of the electromagnetic wave is clear in the case of an evanescent wave.

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Hongrui Li: biography and photograph is not available.