Section 3.3, Chapter 3

From

“Causal Physics: Photon Model by Non-Interaction of Waves”

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3.3 Critical Role Played by a Beam Combiner; Collinear versus Non-Collinear Beam Superposition

In Section 2.5.1 (see Figure 2.3) we briefly described the role of a beam combiner in a two-beam interferometer when the two beams to be combined are incident on it from the opposite sides. The incident Poynting vectors of the two beams can have two different alignments. In one case, the Poynting vectors for the two pairs of transmitted and reflected beams are non-collinear, which produces spatially varying fringes on a detector array. Under this condition, intensities of both pairs of emergent beams follow the reflectance R and transmittance T and the energy conservation is given by $R + T = 1$, with the assumption that the reflection coating is lossless. In the second case, the emergent Poynting vectors in both the output ports are collinear and emerge as indistinguishable single beams. The output energy, of course, is still conserved, but only when one accounts for the energy in both the output ports. Under such collinearity condition, a 50% beam splitter ($R = 0.5$) can functionally become 100% transmitter for one port and a 0% transmitter for the other port, and vice versa, depending upon the total relative phase delays experienced by the two incident beams together with the relative π -phase shift between the external and internal reflections. This subtle point does not automatically emerge out of the straightforward mathematical formulation since it basically predicts the same correct observable data. Let us view this analytically [3.8, 3.9] as shown in Figure 3.5). When the two incident amplitudes from the bottom and left directions are a_1 and a_2, then the two pairs of emergent beam amplitudes out of the beam combiner in the right and up directions are (we have suppressed χ for the boundary dipole materials just for convenience):

$$d_{right}(\tau) = a_1 r e^{i2\pi\nu(t+\tau)} + a_2 t e^{i2\pi\nu t} \tag{3.27}$$

$$d_{up}(\tau) = a_1 t e^{i2\pi\nu(t+\tau)} + a_2 r e^{i2\pi\nu t} \tag{3.28}$$

The relative temporal delay is τ, whether it is introduced by tilt for spatial fringe or by displacing one of the interferometer mirror in the scanning fringe mode. The corresponding two separate irradiances are:

$$D_{\mathrm{right}}(\tau) = \left|d_{\mathrm{right}}\right|^2 = a_1^2 r^2 + a_2^2 t^2 + 2a_1 a_2 tr \cos 2\pi\nu\tau \tag{3.29}$$

$$D_{\mathrm{up}}(\tau) = \left|d_{up}\right|^2 = a_1^2 t^2 + a_2^2 r^2 + 2a_1 a_2 tr \cos 2\pi\nu\tau \tag{3.30}$$

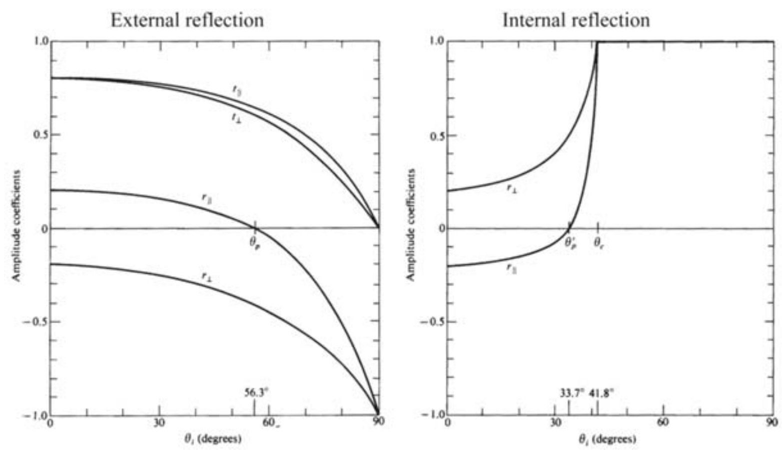

Figure 3.5 Change in reflection coefficients with angle of incidence for orthogonal and vertical polarizations for a glass surface. There is always a relative π-phase shift in reflection between external and internal reflections, irrespective of the state of polarization of the incident beam below Brewster angle [from ref. 2.10].

To simplify modeling, let us assume that *r* and *t* represent amplitude reflectance and transmittance such that $|r|^2 + |t|^2 = 1$, or $R + T = 1$. Then the sum total irradiances in the two directions are

$$D_{total}(\tau) = D_{\text{right}}(\tau) + D_{\text{up}}(\tau) = a_1^2 + a_2^2 + 4a_1a_2rt\cos 2\pi\nu\tau \tag{3.31}$$

However, the sum total energy from the two ports, irrespective of whether the Poynting vectors are collinear, should be the sum of the two incident irradiances:

$$D_{total}^{actual}(\tau) = D_{\text{right}}(\tau) + D_{\text{up}}(\tau) = a_1^2 + a_2^2 = 2a^2 \ \ (\text{for } a_1 = a_2 = a) \tag{3.32}$$

One can recognize that the third term in Equation 3.31 should vanish when we sum Equations 3.29 and 3.30. This would be possible only if the superposition cross terms are of opposite signs to cancel each other. This requires that either *t* or *r* should assume a negative value, *exp*($i\pi$), or a relative π-phase jump between the external and internal reflections. And classical electrodynamics tells us that it is the *external* reflection that undergoes the π-phase jump for vertically polarized light, as in Figure 3.5 [2.10]. In our case (Figure 3.6b), the "right" going reflection suffers the *exp*($i\pi$) phase jump (assuming vertical polarization). Hence, let us rewrite the "right" going amplitude and irradiance:

$$d_{right}(\tau) = a_1(re^{i\pi})e^{i2\pi\nu(t+\tau)} + a_2te^{i2\pi\nu t} \tag{3.33}$$

$$D_{\text{right}}(\tau) = \left|d_{\text{right}}\right|^2 = a_1^2r^2 + a_2^2t^2 - 2a_1a_2tr\cos 2\pi\nu\tau \tag{3.34}$$

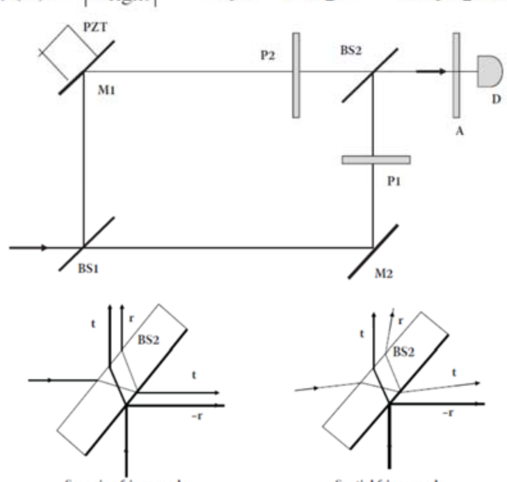

Figure 3.6 Collinear superposition of two beams in Mach–Zehnder output beam combiner facilitates the redirection of energy from one output to other, depending upon relative phase delays brought on by the two beams on the dielectric boundary from the opposite

sides. The presence of wave energy from both sides is a physical condition by classical electromagnetism. So, single indivisible photons from one side alone cannot create the superposition effect.

So, under the condition of $\tau = 0$, the right-going energy would be zero whenever $a_1/a_2 = t/r$, since:

$$D_{\text{right}}(\tau = 0) = (a_1 r - a_2 t)^2 \;\; [= 0,\; a_1/a_2 = t/r] \qquad (3.35)$$

All the energy will be redirected along the upper port under this condition. One can easily see, under the simplifying conditions of $R = T = 0.5$ (a 50% beam splitter), and $a_1 = a_2 = a$, the sum total energy of both the beams, $2a_2$, will go in the upper port. Such behavior will be true also for all $\nu\tau$ = integer.

$$D_{up}(\tau = 0) = 2a^2 \;\; [R = T = 0.5;\, a_1 = a_2 = a] \qquad (3.36)$$

We are underscoring this *trivial* undergraduate classical electromagnetism to make the point that an *indivisible photon* cannot be redirected along one port or the other out of a two-beam interferometer, even if there is success in creating and sending only one photon in the interferometer at a time. All the energy can be redirected in one preferred direction because of the negative sign before the superposition cross term (Equation 3.34). Thus, the boundary molecules, receiving simultaneous stimulations from both sides with appropriate phases, facilitate the redirection of energy out of the interferometer. Without the presence of waves from both sides on the beam combiner, the energy redirection cannot conform to the basic superposition equation. Thus, classical electromagnetism dictates that under Poynting vector collinearity condition, a beam combiner in a two-beam interferometer cannot redirect energy in one direction or other unless the beam-combining boundary molecules experience properly phased EM waves from both the directions simultaneously. So, even if indivisible single photons exist, but sending them one at a time in an interferometer can never generate a measurable superposition effect. Note, further, that for an incident beam of polarization parallel to the plane of incidence, the reflected energy becomes zero at the Brewster angle $\_{B}$ because at this angle, the light beam, after entering *inside the boundary layer* due to refraction, becomes orthogonal to the direction of the would-be reflected beam. Classical physics explains this by showing that an oscillatory dipole cannot emit any energy along its axis, which is also valid in quantum mechanics. Again, we are raising this elementary result of classical electromagnetism to underscore that the molecules of an isotropic boundary surface play active roles, which should be taken into account before accepting the unnecessary ad hoc interpretation that an indivisible single photon can decide on its own regarding which way it should propagate when incident on a beam combiner.

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