

Here, t_{jH} (t_{jV}) and r_{jH} (r_{jV}) correspond to the transmission and reflection coefficients of the PDBS for an incident horizontal (vertical) photon, respectively, and the index j indicates the input port of the BS. Usually, we use a notation in which this index is dropped, and this is followed in the remaining part. Further, as before, a phase change of $\frac{\pi}{2}$ would be associated with the reflected mode. PDBS is frequently used in implementing schemes of quantum communication and it may be viewed as the most general type of BS. The reason for referring it as the most general type of BS can be visualized easily by considering its special cases. For example, if we consider the polarization-independent case, i.e., $r_H = r_V = r$ and $t_H = t_V = t$, then we obtain the BS described in Section 2.1.2. Further, if we consider a special case of PDBS with $|t_H| = 1$ and $|r_V| = 1$, then the PDBS reduces to a PBS, one of the most important optical components that is characterized by its ability to completely transmit (reflect) all the H - (V -) polarized photons. Although a PBS is just a special type of PDBS, keeping its importance in mind, we briefly describe PBSs in Section 2.1.3.

2.1.3 Polarizing beamsplitter

We have already mentioned that a PBS is a special case of PDBS, where for a horizontally polarized photon $R_H = 0$, $T_H = 1$ (i.e., $|r_H| = 0$, $|t_H| = 1$) and for a vertically polarized photon $R_V = 1$, $T_V = 0$ (i.e., $|r_V| = 1$, $|t_V| = 0$). Thus, a PBS always transmits a horizontally polarized photon and reflects a vertically polarized photon. The input–output relation for a PBS is illustrated via a few examples in Fig. 2.

In the schematic diagrams shown so far, a PBS and a BS look quite different. However, the actual optical components that are used in the laboratories look quite similar. Just to emphasize this point, look at Fig. 3, where we show some simple optical components on their mounts. You may especially compare Fig. 3(a) (which shows a BS) and Fig. 3(b) (which shows a PBS) to visualize that in an actual laboratory a BS and a PBS look quite similar.

There are a few other optical components that can also be viewed as BSs. Here, we describe a particularly interesting example of such a component, known as a beam displacer (BD).

A BD is a simple optical device (prism) that can separate an input beam into two orthogonally polarized output beams (as shown in Fig. 4). Clearly, a PBS also does the same, but the output beams of a conventional PBS are 90 deg apart from each other. Thus, we can use a BD as a PBS in situations where we do not want to separate the output beams by 90 deg. A BD is usually fabricated using a single piece of optical grade calcite crystal of the best quality. Thorlabs and other companies commercially produce BDs. In Ref. 8, two BDs and a few other linear-optical elements described in this Spotlight are used in a very interesting scheme, which was designed for the storage of polarization qubits (cf. Ref. 8). Further, in Ref. 9, four BDs along with a few HWPs, QWPs, detectors, and PBSs are used to demonstrate the experimental implementation of a linear-optical controlled phase gate.

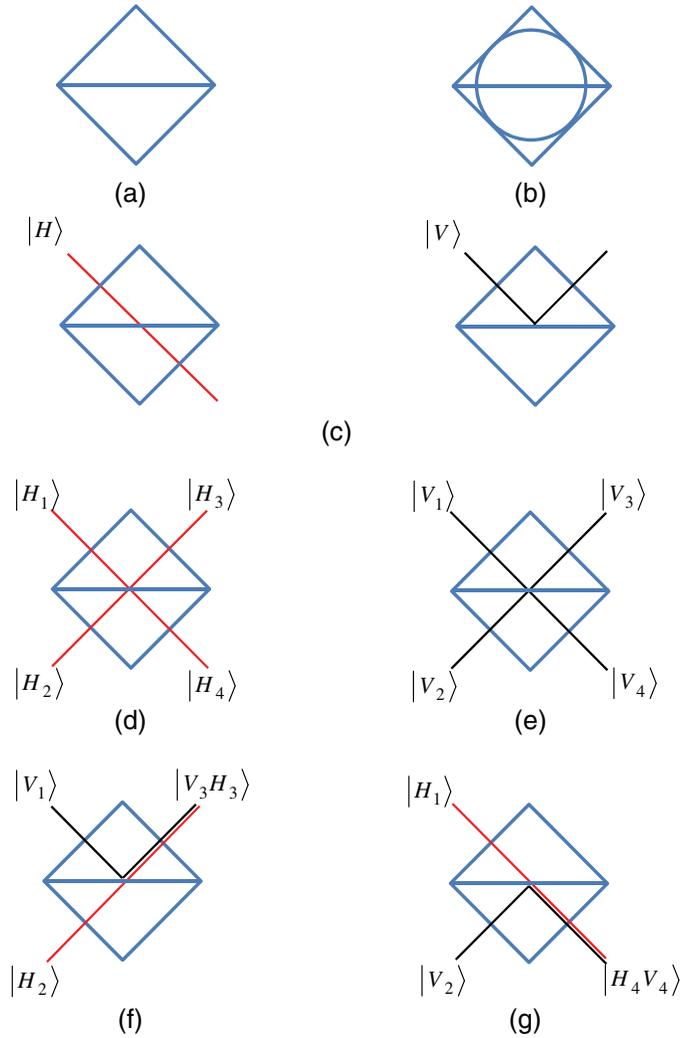


Figure 2 Input–output relations for a PBS for various possible input states: (a) and (b) PBS for horizontal–vertical polarization and diagonal polarization (i.e., at ± 45 deg) of photons. Here, we only discuss input–output relation of the PBS shown in (a), but similarly it can be shown for (b), as well. (c) It is shown that a PBS always transmits (reflects) a horizontally (vertically) polarized photon. In (d)–(g), input and output ports of a PBS are marked with the subscripts 1, 2, 3, and 4, and it is considered that two photons are incident simultaneously in two input ports (1, 2) of the PBS (one in each input port). If the incident photons have the same polarization [as shown in (d) and (e)], we will have one photon in each of the two output ports (3, 4). However, if the incident photons have opposite polarizations [as shown in (f) and (g)], we will obtain both of the photons in one of the two output ports and no photon in the other output port. This is very useful when designing ECPs.

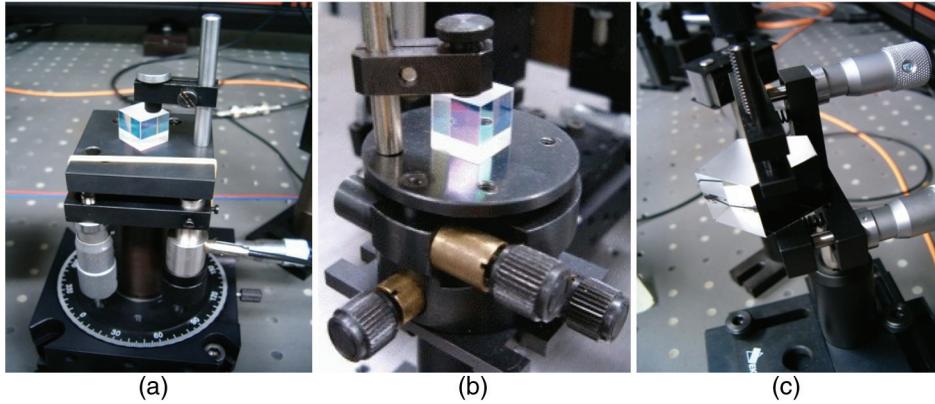


Figure 3 Some optical components mounted on an optical bench: (a) a BS, (b) a PBS, and (c) a pentaprism. Photo courtesy Professor Jan Soubusta.

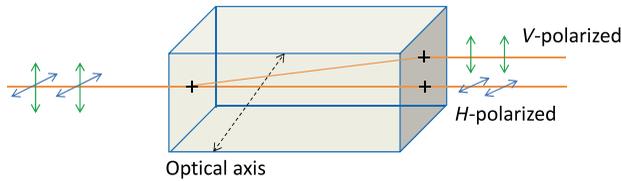


Figure 4 Beam displacer.

2.2 Optical delay

In Figs. 5(a) and 5(b), we show how an optical delay (OD) may be introduced into the path of a ray using four mirrors. At the top of Fig. 5(b), two mirrors are joined perpendicularly to form a corner mirror, which is used here to reflect the incident ray in a direction parallel and opposite to the incident ray. Clearly, the 5-m path shown in Fig. 5(a) is increased to 15 m in Fig. 5(b), without changing the final direction of the ray. This is how the four mirror arrangement shown in Fig. 5(b) can be used to introduce a delay in open air, but, in practice, in place of the corner mirror we usually use a retroreflector. The retroreflector or corner cubes are commonly used to produce a delay in the style shown in Fig. 5(b); it reflects back any incident ray from the source along a path that is parallel to the incident ray but opposite in direction. This is why an equivalence of a corner mirror and retroreflector is shown in Fig. 5(c). In fiber optic implementations, the introduction of a delay is much easier, as we just need to add a few loops of fiber, as shown in Fig. 5(d). Often in schematic diagrams of free space Mach–Zehnder-interferometer (MZI)-based realizations of schemes for quantum communications (cf. schematic diagram of Goldenberg–Vaidman (GV) protocol shown in Fig. 1 of Ref. 10), the delay is shown using loops of optical fibers [as

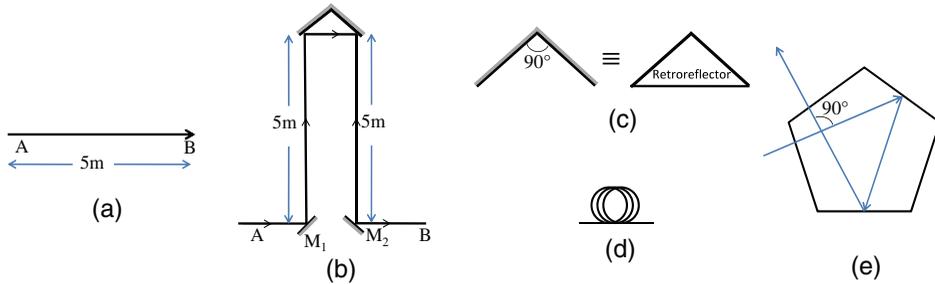


Figure 5 (a) Consider that light was propagating from points A to B, which are 5 m apart. (b) Delay can be introduced using two mirrors and a corner mirror (which can also be viewed as a combination of two mirrors). Sizes of the mirrors in the diagrams are not scaled. Clearly, in (b) light travels additional 10 m. (c) Usually corner mirror used in (b) is shown as a triangle as shown in (c), and it actually represents a retroreflector. (d) Similarly, a delay in an optical fiber-based system can be introduced simply by using a long coil of fiber as shown in (d). Often in open-air implementations also, delay is shown in this manner. In those cases, it is to be considered as a symbol of OD. Further, mirrors M_1 and M_2 shown in (b) can be replaced by pentaprisms [shown in (e)]. Thus two pentaprisms and one retroreflector can also be used to introduce OD.

shown in Fig. 5(d)]. This representation of delay in the schematic diagrams has to be viewed as a symbol only and not as a prescription for practical implementation. In the experimental realization of the schemes in open air, delay is introduced using a setup as in Fig. 5(b) (cf. construction of OD1 and OD2 in Fig. 1 of Ref. 11 and Figs. 1.10 and 1.14 of Ref. 12). Further, in Fig. 5(b), the mirrors along the original path of the ray may be replaced by another optical component which is known as a pentaprism. A pentaprism, which is shown with its mount in Fig. 5(c), is a five sided reflecting prism that can deviate a beam of light by 90 deg and this amount of the deviation is independent of the incident angle. An actual pentaprism with its mount is shown in Fig. 3(c). As the deviation caused by a pentaprism is independent of the incident angle, it is often convenient to use a pentaprism compared to a mirror (cf. Ref. 13, where pentaprisms are used to replace mirrors of an MZI in a successful effort for experimental implementation of linear-optical partial SWAP gates, see Fig. 17(a) for the experimental setup). There are merits and demerits of using mirrors and prisms in an optical experiment, and these are nicely summarized in Ref. 14. Further, a reasonable amount of delay can be produced in this way, even in the open air implementations of the schemes for quantum information. For example, in Fig. 1 of Ref. 15, a setup for Bell state analysis is shown, where a delay of 3 ns is used. Now, if we note that light travels 90 cm in 3 ns, we can easily understand that if we use the delay shown in Fig. 5(b), then each arm of the delay [i.e., distance between the mirror and the corner mirror in Fig. 5(b)] should be 45 cm, which can be easily achieved in an optical bench.