The Nonlocal Creation of an Element of Reality

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Abstract

A gedanken experiment is described in which an element of reality (in the EPR sense) is created by nonlocal means.

1. Introduction

The famous 1935 paper of Einstein, Podolsky, and Rosen (EPR) contains the following statement [1]:

"If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exits an element of reality corresponding to that quantity."

This paper describes a gedanken experiment in which an EPR element of reality is created nonlocally. The experiment employs nonlocal, two-photon interference like that described in [2].

A representation of the experimental setup is shown in Figure 1. The system is composed of a Source (Src) and two remote locations (RL1 and RL2).

The optical path length from the Source to RL1 is adjusted to be somewhat less than the optical path length from the Source to RL2. The separation between RL1 and RL2 may be very large.

To simplify the description of this experiment, the effects of optical filters, detector quantum efficiency and dark counts, and most other potential losses are not included in the following discussion.

2. Notation

In the following discussion, both probability amplitude and probability will be calculated. As an example:

$$P[D1;D3;(\Delta)] = \left|pa[D1;D3;(\Delta)]\right|^2$$

In the above, pa[D1;D3;(Δ)] is the probability amplitude for the detection of a photon in detector D1 at RL1 followed by the detection of an associated photon in detector D3 at RL2.

The time parameter (Δ) is the time between the detection in D1 and the detection in D3. P[D1;D3;(Δ)] is the probability for the same detection events.

The variable designation "pa" is used, rather than "Ψ", to emphasize that the probability amplitude is a mathematical function (only).

Both intensity and amplitude variables are used in the following. As an example, for amplitude beam splitter ABS1:

$R_1 = |r_1|^2$, $T_1 = |t_1|^2$ and $R_1 + T_1 = 1$

In the above, R_1 is the intensity reflectance, T_1 is the intensity transmittance, r_1 is the amplitude reflection coefficient, and t_1 is the amplitude transmission coefficient of ABS1.

3a. Source

The Source (Src) contains a single-mode, continuous wave (cw) pump laser (LSR), a periodically-poled lithium niobate crystal (PPLN), a dichroic mirror (DM), a polarizing beam splitter (PBS1), four amplitude beam splitters (ABS1, ABS2, ABS3a, and ABS3b), five mirrors, two detectors (DA and DD), and a beam stop (Stp). The detectors along with their associated electronics are capable of photon counting.

Pump laser LSR has a stable output, and the coherence length of the photons from LSR is greater than 100 meters.

The PPLN crystal is temperature-controlled, and is set to allow collinear, degenerate, type II spontaneous parametric down-conversion (SPDC) in which a photon from pump laser LSR is annihilated and a signal and idler pair of photons is created. The signal photon is horizontally (H) polarized, and the idler photon is vertically (V) polarized.

Short wavelength pump photons from laser LSR that are not down-converted in the PPLN are reflected at long pass dichroic mirror DM and are incident on the beam stop.

The long wavelength signal and idler photons exit from the PPLN and are transmitted through DM to PBS1. The H polarized signal photons are transmitted through PBS1 and the V polarized idler photons are reflected by PBS1.

Two of the amplitude beam splitters (ABS1 and ABS2) along with two mirrors form an unbalanced Mach-Zehnder interferometer (MZ). The unbalanced MZ provides a short path and a long path between ABS1 and ABS2. Amplitude beam splitters ABS1 and ABS2 may be partially-silvered plate beam splitters.

The path lengths through the MZ are adjusted so that the net phase difference from input to output for a given path depends on the reflections at the mirrors and the reflections (or transmissions) at the beam splitters [3].

The time difference between the time a photon may be incident on ABS2 via the short path, and the time the photon may be incident on ABS2 via the long path through the MZ is equal to X.

The fixed time X should be of sufficient duration to allow the short path and the long path to be temporally distinct. Time X should be much longer than the coherence time of an idler (or signal) photon but should also be much shorter than the coherence time of a pump photon from laser LSR.

An idler photon travels from PBS1 to ABS1. The photon then travels by either the short path or the long path through the MZ to ABS2. If the idler photon exits the MZ from output B, it travels to RL1.

If the idler photon exits the MZ from output A, it is incident on detector DA. If an idler photon is detected in DA, then that particular idler/signal photon pair is ignored with respect to the experiment. The probabilities associated with the detection of an idler photon in detector DA are given in the Appendix.

Two of the amplitude beam splitters (ABS3a and ABS3b) along with two mirrors form an optical circulator (OC1). The amplitude beam splitters may be partially-silvered plate beam splitters.

Amplitude beam splitters ABS3a and ABS3b are identical. The characteristics of ABS3a and ABS3b are:

$r_{3a} = r_{3b} = r_3$

$R_3 = |r_3|^2$; $T_3 = |t_3|^2$ and $R_3 + T_3 = 1$

The path lengths through OC1 are adjusted so that the net phase difference for one complete pass through OC1 depends on the reflections at the mirrors and the transmission (or reflection) at the beam splitters [3].

The time required for a signal photon to make one complete pass through OC1 is equal to X. This is the same as the time difference between the short path and the long path through the MZ.

A signal photon travels from PBS1 to ABS3a. The photon may reflect at ABS3a or it may enter OC1 and travel one or more times around through OC1. If the signal photon exits OC1 at output D, it is incident on detector DD. If a signal photon is detected in DD, then that particular signal/idler photon pair is ignored with respect to the experiment. The probabilities associated with the detection of a signal photon in detector DD are given in the Appendix.

The signal photon may enter OC1 and then exit immediately from output F, or it may travel one or more times around through OC1 before exiting from output F. If the signal photon exits OC1 from output F, it travels to RL2.

3b. Remote Locations

Remote location 1 (RL1) contains a Pockels cell (PC), a polarizing beam splitter (PBS2), an amplitude beam splitter (ABS4), three mirrors, and two detectors (D1 and D2). The detectors along with their associated electronics are capable of photon counting.

Pockels cell PC may be used to rotate the polarization direction of an idler photon from the Source. If the PC is turned off, a V polarized idler photon will remain V polarized when it exits from the PC. If the PC is turned on, the idler photon will be H polarized when it exits from the PC.

Amplitude beam splitter ABS4 may be a partially-silvered plate beam splitter. Amplitude beam splitter ABS4 and three mirrors are set to form an optical circulator (OC2).

The path lengths through OC2 are adjusted so that the net phase difference for one complete pass through OC2 depends on the reflections at the mirrors and the transmission (or reflection) at beam splitter ABS4 [3].

The time required for an idler photon to make one complete pass through OC2 is equal to X. This is the same as the time difference between the short path and the long path through the MZ in the Source.

Polarizing beam splitter PBS2 is set to reflect incident V polarized idler photons to detector D1 and to transmit incident H polarized photons to OC2.

Remote Location 2 consists of a single optical detector D3. Detector D3 along with its associated electronics is capable of photon counting.

4a. Experiment: Part 1

The experiment involves those pairs of signal and idler photons in which the signal photon exits OC1 from output F and the idler photon exits the MZ from output B in the Source.

Initially, the Pockels cell PC at remote location RL1 is turned off. A V polarized idler photon of a down-converted pair that exits from output B of the MZ in the Source travels to RL1. The V polarized idler photon passes through the PC unchanged, is reflected by PBS2, and is incident on detector D1. In part 1 of this experiment, the idler photon does not reach OC2 in RL1.

The idler photon may have taken either the short path or the long path through the MZ in the Source.

The H polarized signal photon of the pair exits from output F of OC1 in the Source and travels to RL2. The signal photon may have travelled multiple times around through OC1 before exiting from output F.

If the idler photon travels from PBS1 directly through the MZ via the short path, reflects from PBS2 and is detected in detector D1 at RL1, and the signal photon of the pair travels from PBS1 directly through OC1 being transmitted through both ABS3a and ABS3b without reflection and is subsequently detected in detector D3 at RL2, then the time between the detection of the idler photon in detector D1 and the detection of the signal photon in detector D3 is equal to τ.

If the time difference between the detection of the idler photon in detector D1 at RL1, and the detection of the signal photon in detector D3 at RL2 is equal to τ, then there is an ambiguity as to which path was followed by the idler photon in the MZ and the signal photon in OC1 at the Source.

The idler photon may have taken the short path through the MZ, and the signal photon may have travelled directly through OC1 without reflection at either ABS3a or ABS3b. Alternately, the idler photon may have taken the long path through the MZ, and the signal photon may have travelled via one cycle through OC1 from ABS3a, reflection at ABS3b, reflection at two mirrors, reflection at ABS3a, and then transmission through ABS3b.

These two different, indistinguishable path combinations cause nonlocal, two-photon interference to occur between the idler photon at RL1 and the signal photon at RL2. The probability amplitude and probability in this case are:

$pa[D1;D3;(\tau)] =$

$$\{[(t_1)(ir_2)][(t_3)(t_3)]\} + \{[(ir_1)(-t_2)][i^4(t_3)(r_3)^2(t_3)]\} =$$

$$[i\ t_1\ r_2\ t_3^2] - [i\ r_1\ t_2\ t_3^2\ r_3^2]$$

With: $r_1 = (t_1 \bullet r_3^2)$ and $r_2 = t_2 = 1/\sqrt{(2)}$

$$pa[D1;D3;(\tau)] = [(i\ t_1\ t_3^2)(1 - r_3^4)]/\sqrt{(2)}$$

$$P[D1;D3;(\tau)] = \left|pa[D1;D3;(\tau)]\right|^2 = [(t_1^2\ t_3^4)(1 - r_3^4)^2]/2$$

The variable assignments: $r_1 = (t_1 \bullet r_3^2)$ and $r_2 = t_2 = 1/\sqrt{(2)}$ will be used in all of the following.

If the time difference between the detection of the idler photon in detector D1 at RL1, and the detection of the signal photon in detector D3 at RL2 is equal to (τ+X), then there is an ambiguity as to which path was followed by the idler photon in the MZ and the signal photon in OC1 at the Source.

The idler photon may have taken the short path through the MZ, and the signal photon may have travelled via one cycle through OC1 from ABS3a, reflection at ABS3b, reflection at two mirrors, reflection at ABS3a, and then transmission through ABS3b. Alternately, the idler photon may have taken the long path through the MZ, and the signal photon may have travelled via two cycles through OC1 before transmission through ABS3b.

These two different, indistinguishable path combinations cause nonlocal interference to occur. The probability amplitude and probability in this case are:

{Note: τ > X}

$$pa[D1;D3;(\tau+X)] =$$

$$\{[(t_1)(ir_2)][i^4(t_3)(r_3)^2(t_3)]\} + \{[(ir_1)(-t_2)][i^8(t_3)(r_3)^4(t_3)]\} =$$

$$[i\ t_1\ r_2\ t_3^2\ r_3^2] - [i\ r_1\ t_2\ t_3^2\ r_3^4] =$$

$$[(i\ t_1\ t_3^2\ r_3^2)(1 - r_3^4)]/\sqrt{(2)}$$

$$P[D1;D3;(\tau+X)] = \left|pa[D1;D3;(\tau+X)]\right|^2 = [(t_1^2\ t_3^4\ r_3^4)(1 - r_3^4)^2]/2$$

In the general case, if the time difference between the detection of the idler photon in detector D1 at RL1, and the detection of the signal photon in detector D3 at RL2 is equal to (τ+nX), then the probability amplitude and probability are:

$$pa[D1;D3;(\tau+nX)] = [(i\ t_1\ t_3^2\ r_3^{2n})(1 - r_3^4)]/\sqrt{(2)}$$

$$P[D1;D3;(\tau+nX)] = \left|pa[D1;D3;(\tau+nX)]\right|^2 = [(t_1^2\ t_3^4\ r_3^{4n})(1 - r_3^4)^2]/2$$

There is one additional case in which the time difference between the detection of the idler photon in detector D1 at RL1, and the detection of the signal photon in detector D3 at RL2 is equal to (τ-X). This can only happen in one way. The idler photon must have taken the long path through the MZ, and the signal photon must have travelled directly through OC1 without reflection at either ABS3a or ABS3b.

Since this can happen in only one way, there is no ambiguity as to which path was followed by the idler photon or the signal photon at the Source, so nonlocal interference does not occur. The probability amplitude and probability in this case are:

$$pa[D1;D3;(\tau\text{-}X)] = \{[(ir_1)(-t_2)][(t_3)(t_3)]\} =$$

$$-[i\ r_1\ t_2\ t_3^2] = -[i\ t_1\ t_3^2\ r_3^2]/\surd(2)$$

$$P[D1;D3;(\tau\text{-}X)] = \left|pa[D1;D3;(\tau\text{-}X)]\right|^2 = (t_1^2\ t_3^4\ r_3^4)/2$$

In part 1 of this experiment, after the detection of the idler photon of a down-converted pair in detector D1 at RL1, the location of the signal photon of the pair is not an element of reality. The location of the signal photon exists as a superposition of many possibilities.

Consequently, we cannot predict with certainty (with probability equal to unity) a singular location for the signal photon. Thus, the EPR requirement for a physical quantity to be an element of reality is not met [1].

{Note: This should <u>not</u> be construed to mean that the photon (energy or momenta) is in any way “spread out”.}

The total probability for the detection of an idler photon in detector D1 at RL1 and its associated signal photon in detector D3 at RL2 in part 1 of this experiment is:

$$P_1[D1;D3] = \{[(t_1^2\ t_3^4)(1 - r_3^4)^2]/[2\bullet(1 - r_3^4)]\}+\{(t_1^2\ t_3^4\ r_3^4)/2\} =$$

$$(t_1^2\ t_3^4)/2$$

4b. Experiment: Part 2

Again, the experiment involves those pairs of signal and idler photons in which the signal photon exits OC1 from output F and the idler photon exits the MZ from output B in the Source.

In part 2 of the experiment, the Pockels cell PC at remote location RL1 is turned on. A V polarized idler photon of a down-converted pair that exits from output B of the MZ in the Source travels to RL1. The polarization direction of the idler photon is rotated as it passes through the PC, and it exits from the PC H polarized. The idler photon is transmitted through PBS2 and travels to OC2.

The idler photon may have taken either the short path or the long path through the MZ in the Source.

The H polarized signal photon of the pair exits from output F of OC1 in the Source and travels to RL2. The signal photon may have travelled multiple times around through OC1 before exiting from output F.

The probability amplitude component for the case in which the idler photon travels via the short path through the MZ and subsequently reflects from ABS4 without entering OC2 and travels to detector D2 at RL1 is:

$pa_{1r} = (t_1)(ir_2)(ir_4) = - [t_1\ r_2\ r_4]$

In this case, there is also a component of probability amplitude that enters OC2:

$pa_{1t} = (t_1)(ir_2)(t_4) = [it_1\ r_2\ t_4]$

This probability amplitude component travels one time around through OC2 (via three reflections) and undergoes one-photon interference at ABS4 with the probability amplitude component due to the possibility of the (same) idler photon having taken the long path through the MZ in the Source. This results in two possibilities at ABS4:

The “reflected” component that travels to detector D2:

$pa_{2r} = i^3[it_1\ r_2\ t_4^2]+[(ir_1)(-t_2)(ir_4)] = +[(t_1\ r_2\ t_4^2)+(r_1\ t_2\ r_4)]$

The “transmitted” component that may remain in OC2:

$pa_{2t} = i^4[it_1\ r_2\ t_4\ r_4]+[(ir_1)(-t_2)(t_4)]=[(it_1\ r_2\ t_4\ r_4)-(ir_1\ t_2\ t_4)]$

With: $r_1 = (t_1 \bullet r_4)$ and $r_2 = t_2 = 1/\sqrt{(2)}$

$pa_{2t} = 0$ (due to one-photon “destructive” interference)

Therefore, there are two probability amplitude components that may be incident on detector D2. These components are separated by a time equal to X.

$pa_{1r} = - [t_1\ r_2\ r_4] = -r_1/\sqrt{(2)}$

$pa_{2r} = + [(t_1\ r_2\ t_4^2) + (r_1\ t_2\ r_4)] = +t_1/\sqrt{(2)}$

If the idler photon travels from PBS1 directly through the MZ via the short path, passes through PBS2, is immediately reflected at ABS4 of OC2, and is detected in detector D2 at RL1, and the signal photon of the pair travels from PBS1 directly through OC1 being transmitted through both ABS3a and ABS3b without reflection and is subsequently detected in detector D3 at RL2, then the time between the detection of the idler photon in detector D2 and the detection of the signal photon in detector D3 is equal to Λ. {Note that Λ is slightly less than τ}.

If the time difference between the detection of the idler photon in detector D2 at RL1, and the detection of the signal photon in detector D3 at RL2 is equal to Λ, then there is an ambiguity as to which path was followed by the idler photon in the MZ and at OC2, and the signal photon in OC1 at the Source.

The idler photon may have taken the short path through the MZ and reached detector D2 as component pa_{1r}, and the signal photon may have travelled directly through OC1 without reflection at either ABS3a or ABS3b. Alternately, the idler photon may have reached detector D2 as component pa_{2r}, and the signal photon may have travelled via one cycle through OC1 from ABS3a, reflection at ABS3b, reflection at two mirrors, reflection at ABS3a, and then transmission through ABS3b.

These two different, indistinguishable path combinations cause nonlocal interference to occur. The probability amplitude and probability in this case are:

$pa[D2;D3;(\Lambda)] =$

$$\{[-r_1/\surd(2)][(t_3)(t_3)]\} + \{[t_1/\surd(2)][i^4(t_3)(r_3)^2(t_3)]\} =$$

$$[(-r_1\ t_3^2) + (t_1\ t_3^2\ r_3^2)]/\surd(2)$$

From part 1: $r_1 = (t_1 \bullet r_3^2)$; {Note: $r_3^2 = r_4$}

$pa[D2;D3;(\Lambda)] = 0$

$P[D2;D3;(\Lambda)] = \left|pa[D2;D3;(\Lambda)]\right|^2 = 0$

If the time difference between the detection of the idler photon in detector D2 at RL1, and the detection of the signal photon in detector D3 at RL2 is equal to $(\Lambda+X)$, then there is an ambiguity as to which path was followed by the idler photon and the signal photon.

The idler photon may have taken the short path through the MZ and reached detector D2 as component pa_{1r}, and the signal photon may have travelled via one cycle through OC1 from ABS3a, reflection at ABS3b, reflection at two mirrors, reflection at ABS3a, and then transmission through ABS3b. Alternately, the idler photon may have reached detector D2 as component pa_{2r}, and the signal photon may have travelled via two cycles through OC1 before transmission through ABS3b.

These two different, indistinguishable path combinations cause nonlocal interference to occur. The probability amplitude and probability in this case are:

{Note: $\Lambda > X$}

$pa[D2;D3;(\Lambda+X)] =$

$$\{[-r_1/\sqrt{(2)}][i^4(t_3)(r_3)^2(t_3)]\} + \{[t_1/\sqrt{(2)}][i^8(t_3)(r_3)^4(t_3)]\} =$$

$$pa[D2;D3;(\Lambda)] \bullet r_3^2 = 0$$

$$P[D2;D3;(\Lambda+X)] = |pa[D2;D3;(\Lambda+X)]|^2 = 0$$

In the general case, if the time difference between the detection of the idler photon in detector D2 at RL1, and the detection of the signal photon in detector D3 at RL2 is equal to $(\Lambda+nX)$, then the probability amplitude and probability are:

$$pa[D2;D3;(\Lambda+nX)] = pa[D2;D3;(\Lambda)] \bullet r_3^{2n} = 0$$

$$P[D2;D3;(\Lambda+nX)] = |pa[D2;D3;(\Lambda+nX)]|^2 = 0$$

The only non-zero probability in part 2 of the experiment occurs when the time difference between the detection of the idler photon in detector D2 at RL1, and the detection of the signal photon in detector D3 at RL2 is equal to $(\Lambda-X)$. This can only happen in one way. The idler photon must have reached detector D2 as probability amplitude component pa_{2r}, and the signal photon must have travelled directly through OC1 without reflection at either ABS3a or ABS3b.

Since this can happen in only one way, there is no ambiguity as to how the idler photon reached detector D2 at RL1 or the signal photon reached detector D3 at RL2, so nonlocal interference does not occur. The probability amplitude and probability in this case are:

$$pa[D2;D3;(\Lambda-X)] = \{[t_1/\sqrt{(2)}][(t_3)(t_3)]\} = [t_1\ t_3^2]/\sqrt{(2)}$$

$$P[D2;D3;(\Lambda-X)] = |pa[D2;D3;(\Lambda-X)]|^2 = (t_1^2\ t_3^4)/2$$

In part 2 of this experiment, after the detection of the idler photon of a down-converted pair in detector D2 at RL1, the location of the signal photon of the pair is an element of reality. The signal photon has a real trajectory: it exists at a single location at any given time after the detection of the idler photon, until the signal photon is annihilated in detector D3.

Once the idler photon is detected in detector D2, the location of the signal photon can be predicted with certainty (with probability equal to unity), which is the EPR requirement for a physical quantity to be an element of reality [1].

The total probability for the detection of an idler photon in detector D2 at RL1 and its associated signal photon in detector D3 at RL2 in part 2 of this experiment is the same as P_1[D1;D3] from part 1 of the experiment:

$$P_2[D2;D3] = (t_1^2\ t_3^4)/2$$

5. Conclusion

This paper describes a gedanken experiment in which an EPR element of reality is created nonlocally.

The experiment employs nonlocal, two-photon interference between the idler photon of a down-converted pair at remote location RL1 and the signal photon of the pair at remote location RL2.

Whether or not the location of the signal photon at RL2 is an "element of reality" is determined by the method that is used to detect the idler photon of the down-converted pair at RL1. This is independent of the separation between RL1 and RL2. The distance between RL1 and RL2 may be so large that the detection of the idler photon at RL1 and the detection of the signal photon at RL2 may be space-like separated events.

Due to the constraint of special relativity, EPR considered the nonlocal control of the value of a physical quantity to be an impossibility. This was the crux of EPR's objection to quantum mechanics.

This gedanken experiment is another example of the inherent nonlocality exhibited by Nature.

Appendix

Probabilities associated with part 1 of the experiment:

{Note: $t_1^2 = [1/(1+r_3^4)]$}

$P_1[DA;DD] = \{[t_1^2\ r_3^2\ ((1-(t_3^2\ r_3^2))^2)]/2\}$

$+ \{[t_1^2\ t_3^4\ r_3^2\ ((1+r_3^4)^2)]/[2(1-r_3^4)]\} + \{[t_1^2\ r_3^6]/2\}$

$P_1[DA;D3] = \{[t_1^2\ t_3^4\ ((1+r_3^4)^2)]/[2(1-r_3^4)]\} + \{[t_1^2\ t_3^4\ r_3^4]/2\}$

$P_1[D1;DD] = \{[t_1^2\ r_3^2\ ((1+(t_3^2\ r_3^2))^2)]/2\}$

$+ \{[t_1^2\ t_3^4\ r_3^2\ ((1-r_3^4)^2)]/[2(1-r_3^4)]\} + \{[t_1^2\ r_3^6]/2\}$

$P_1[D1;D3] = \{(t_1^2\ t_3^4)/2\}$

$P_1 = P_1[DA;DD] + P_1[DA;D3] + P_1[D1;DD] + P_1[D1;D3] = 1$

Probabilities associated with part 2 of the experiment:

$P_2[DA;DD] = P_1[DA;DD]$

$P_2[DA;D3] = P_1[DA;D3]$

$P_2[D2;DD] = \{[t_1^2\ r_3^2]/2\} + \{[t_1^2\ r_3^2]/2\}$

$P_2[D2;D3] = \{(t_1^2\ t_3^4)/2\}$

$P_2 = P_2[DA;DD] + P_2[DA;D3] + P_2[D2;DD] + P_2[D2;D3] = 1$

References

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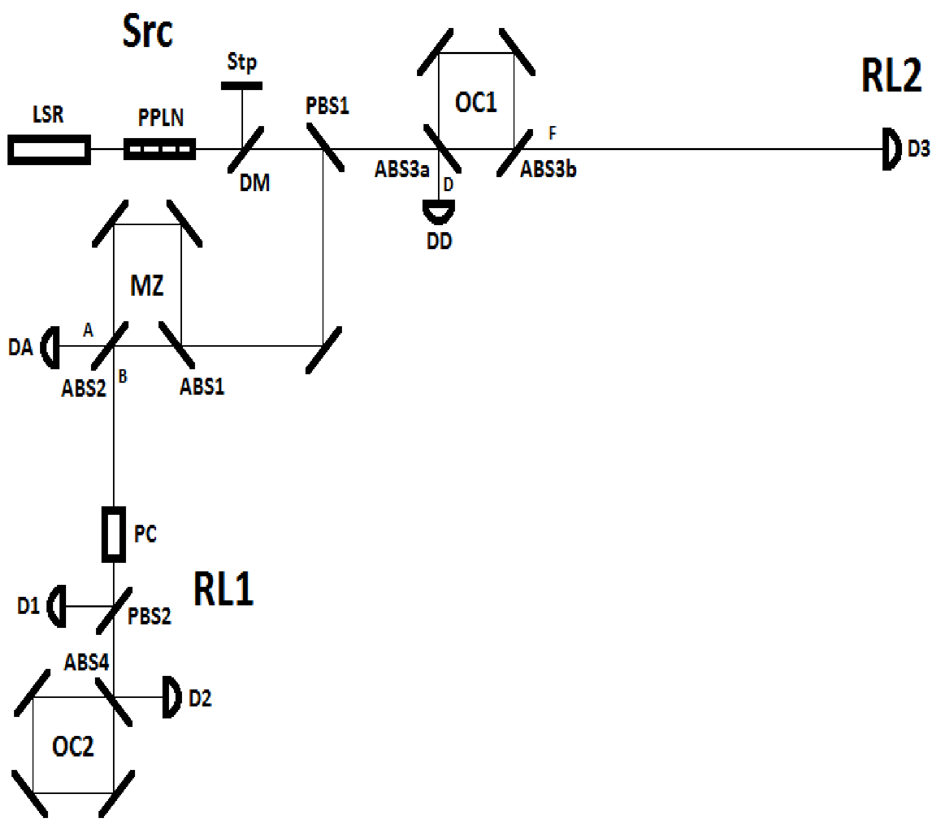

Figure 1: Experimental Setup