Optical Telecom Networks as weak quantum measurements with post-selection

Nicolas Brunner, Antonio Acín[†], Daniel Collins, Nicolas Gisin, Valerio Scarani
Group of Applied Physics, University of Geneva, 20,
rue de l'Ecole-de-Médecine, CH-1211 Geneva 4, Switzerland

(Dated: 13 June 2003)

We show that weak measurements with post-selection, proposed in the context of the quantum theory of measurement, naturally appear in the everyday physics of fiber optics telecom networks through polarization-mode dispersion (PMD) and polarization-dependent losses (PDL). Specifically, the PMD leads to a time-resolved discrimination of polarization; the post-selection is done in the most natural way: one post-selects those photons that have not been lost because of the PDL. The quantum formalism is shown to simplify the calculation of optical networks in the telecom limit of weak PMD.

Several times in the history of science, different people working on different fields and with different motivations happened to discover the same thing, or to introduce the same concepts. Think to the connection between differential geometry and general relativity: physics received a convenient mathematical tool for its predictions, mathematics gained in popularity and interest because, apart from its intrinsic beauty, it proved useful. In this work, we point out a connection which should help to bring together two very different communities: quantum theorists and telecom engineers. The physical degree of freedom that supports this connection is the *polarization* of light; we show that the quantum formalism of *weak measurements and post-selection* [1–3] applies to the description of polarization effects in optical networks [4]. We show how the connection holds down to the detailed formulae; in particular, the knowledge of the "quantum" formalism can simplify some "telecom" calculations.

A modern optical network is composed of different devices connected through optical fibers. With respect to polarization, two main physical effects are present. The first one is *polarization-mode dispersion* (PMD): due to birefringency, different polarization modes (*P-modes* in the following) propagate with different velocities; in particular, the fastest and the slowest polarization modes are orthogonal. PMD is the most important polarization effect in the fibers. The second effect is *polarization-dependent loss* (PDL), that is, different P-modes are differently attenuated. PDL is negligible in fibers, but is important in devices like amplifiers, wavelength-division multiplexing couplers, isolators, circulators etc. In particular, a perfect polarizer is an element with infinite PDL, since it attenuates completely a P-mode. Thus, an optical network can be described by a concatenation of trunks, alternating PMD and PDL elements. Combined effects of PMD and PDL elements have been studied in Ref. [5, 6]; in particular, interesting phenomena like anomalous dispersion have been shown to arise even in simple concatenations, namely a PDL element sandwiched between two PMD elements.

The first piece of the connection we want to point out is the following: *a PMD element performs a measurement of polarization on light pulses.* In fact, PMD leads to the separation of two orthogonal P-modes in time; this separation is called *differential group delay* (DGD), noted $\delta\tau$. If $\delta\tau$ is larger than the pulse width, the measurement of the time of arrival is equivalent to the measurement of polarization — PMD acts then as a "temporal polarizing beam-splitter". However, in the usual telecom regime $\delta\tau$ is much *smaller* than the pulse width. In this case, the time of arrival does not achieve a complete discrimination between two orthogonal P-modes anymore; but still, some information about the polarization of the input pulse is encoded in the modified temporal shape of the output pulse. We are in a regime of *weak measurement* of the polarization; we are going to show later that we recover indeed the notion of weak measurement of the quantum theorists, by measuring the *mean time of arrival* (that is, the "center of mass" of the output pulse).

The second piece of the connection defines the role of PDL: *a PDL element performs a post-selection of some polarization modes.* Far from being an artificial ingredient, post-selection of some modes is the most natural situation in the presence of losses: one does always post-select those photons that have not been lost! This would be trivial physics if the losses were independent of any degree of freedom, just like random scattering; but in the case of PDL, the amount of losses depends on the meaningful degree of freedom, polarization. An infinite PDL, as we said above, would correspond to the post-selection of a precise P-mode (a pure state, in the quantum language); a finite PDL corresponds to post-selecting different P-modes with different probabilities (a mixed quantum state).

In summary: by tuning the PMD, we can move from weak to strong measurements of polarization; by tuning the PDL, we can study the post-selection of a pure or of a mixed state of polarization. More usefully, the elegant formulae derived by physicists for the outcomes of weak measurements allow us to calculate the mean time of arrival of light pulses passing through networks with several sections of PMD and PDL. Previously such configurations had appeared to be analytically quite complex, even in the case with a single PMD and PDL. The weak measurement formalism is therefore useful for describing important effects in real telecom fibres.

[1] Y. Aharonov, D. Albert, L. Vaidman, Phys. Rev. Lett. **60**, 1351 (1988)
[2] Y. Aharonov, L. Vaidman, quant-ph/0105101 (2001); published in: J. G. Muga, R. Sala Mayato and I. L. Egusquiza (eds), *Time in Quantum Mechanics*, Lecture Notes in Physics, (Springer Verlag, 2002).
[3] A.M. Steinberg, quant-ph/0302003 (2003).
[4] The possibility of testing the theory of weak values with linear optics and polarization has been exploited in: N.W.M. Ritchie, J.G. Story, R.G. Hulet, Phys. Rev. Lett. **66**, 1107 (1991); D. Suter, Phys. Rev. A **51**, 45 (1995).
[5] B. Huttner, C. Geiser, N. Gisin, IEEE J. Sel. Top. Quant. Electron. **6**, 317 (2000)
[6] P. Lu, L. Chen, X.Y. Bao, J. Lightwave Technol. **19**, 856 (2001)