

Twin-photon techniques for fiber measurements

N. Gisin J. Brendel and H. Zbinden

Group of Applied Physics, University of Geneva, 1211 Geneva 4, Switzerland

A. Sergienko and A. Muller

Dept. of Electrical and Computer Engineering, Boston University

November 9, 1998

1 Introduction

Characterization of single-mode optical fibers requires a basis for time, wavelength and polarization. Parametric downconversion in non-linear crystals naturally provide pairs of photons extremely highly correlated in time, energy (thus wavelength) and polarization. It is thus tempting to explore such photon pairs for fiber and fiber device characterization. Historically, entangled photon pairs were first used in delicate tests of quantum mechanics [1]. Indeed, their correlation is higher than classically possible! However, nowadays photon pair sources can be made cheap and compact enough to offer practical alternatives for many of the traditional measurement schemes. In addition photon pairs provide entirely new possibilities and open the door to new developments in metrology. The purpose of this contribution is first to present some concrete proposals and results along the above lines, and next to draw the attention of the audience to these rather revolutionary new combinations of quantum optics and communication.

2 A photon pair source

Figure 1 presents an example of a photon pair source. A non-linear crystal, like BBO, $KNbO_3$, $LiIO_3$, is pumped by a 15 mW laser diode, at 660 nm in the present example. The prism between the laser diode and the crystal removes all extra infra-red light. The crystals are well known for frequency doubling, as in doubled Nd-YAG lasers. Here we use the time reversed process: wavelength doubling, better known as downconversion (recall that all elementary quantum processes are time symmetric). Since initially the infrared modes are empty (ie are in their quantum vacuum state and the power of pump radiation is not very strong), this downconversion process is spontaneous: a photon from the pump spontaneously splits into two infrared photons. Energy and momentum conservation forces these two photons to be highly correlated: they are created exactly at the same time and the sum of their energy (optical frequency) equals the energy of the pump photon. Note that the latter is defined within the spectral width of the laser, typically expressed in MHz, hence the sum of the two downconverted photon is well defined. But the spectral width of each downconverted photon can be quite large, up to tens of nm, or even hundreds of nm. Following the optical path on Fig. 1, the photon pairs are then injected into a single mode fiber, with standard techniques (microscope objective in the shown example). Next, a directional coupler separates both photons and guides them to two optical connectors.

Figure 1 presents one possible implementation. Other examples are discussed in the next sections. For instance, it might be useful to replace the directional coupler by a wavelength demulti-



Figure 1: Example of a compact twin-photon source.

plexer: the two photon are still quantum correlated (ie extremely highly correlated) in time and energy, but the photon at one output is in the short wavelength end of the spectrum, while the companion photon is in the complementary long wavelength range. In fig. 1 a collinear configuration is present: the pump and both downconverted photons follow parallel trajectories. Another possibility exploits momentum conservation: if one photon emerges at an angle with respect to the pump beam, the companion photon emerges on the opposite angle (the detail depend on the exact phase matching conditions, wavelength filters, etc). This will be illustrated in the next section for various dispersion measurements.

So far we did not mention polarization, but since the crystals are anisotropic, polarization is important (actually birefringence is required for the phase matching condition). There are two kinds of downconversion processes. In type I both infrared photons have identical polarization, both orthogonal to the pump laser's polarization. In type II downconversion, on the contrary, the two infrared photons can be totally unpolarized, however their polarization states are quantum correlated: if one passes through a polarizer, the other one is immediately polarized in the orthogonal direction. This will be illustrated in subsection 4.3 for polarization mode dispersion measurement.

Other examples of interesting configurations for 2-photon sources are described in [2, 3].

3 Photon counters

Photomultipliers exist for years, but are not effective at telecom wavelengths (1.3 and 1.55 μ). Photon counting devices based on silicon Avalanche Photo-Diodes (APD) are commercially available, but also limited to wavelengths below 1 μ . However, a few groups around the world have demonstrated that germanium and InGaAs APD are suitable for photon counting at telecom wavelengths [4]. Admittedly, this is still the weak point of "quantum optics at telecom wavelengths", because most of the demonstrations used liquid nitrogen cooled APD. Actually, very recently we have demonstrated that InGaAs APDs Peltier cooled are suitable for metrology applications where noise requirement is not as severe as for quantum communication applications. Anyway, progress in this field is fast. The fact that until now not much efforts have been put into these developments, allows one to be optimistic about a possible breakthrough in the near future.

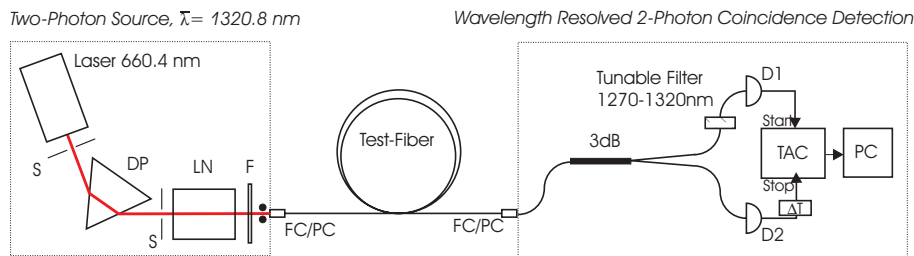


Figure 2: Setup for chromatic dispersion measurements.

4 Dispersion measurements

The intrinsic time-energy-polarization correlation of the downconverted photons make them natural candidates for dispersion measurements, as illustrated in the next 3 subsections.

4.1 Chromatic dispersion measurements on long fibers

This is possibly the simplest example. It exploits only the time and energy correlations of the photons: the difference in detection times provides the information on the time of flight and the measurement of the wavelength of one photon is enough to obtain the necessary information on the wavelength of the companion photon. Therefore we have direct access to the group delay between complementary wavelengths. Choosing moreover the central wavelength near the zero chromatic dispersion, these delays will be small, thus not necessitating any long electronic delay lines. In short, this technique makes use of the photon pairs as a broadband lightsource, comparable to a LED, with sub-picosecond pulsewidth.

A possible implementation is presented in Fig. 2. For technical details we refer the interested reader to [5]. In our first experiment we could determine the zero chromatic dispersion wavelength with a precision of ± 0.5 nm [5]. In a forthcoming experiment, we expect to achieve higher resolution, larger spectral width (up to 300 nm) and measurement times of minutes.

4.2 Chromatic dispersion measurements on short fibers

The spectra of the downconverted photons are large, like LEDs or even broader. However, the photon pairs, considered as a whole, still enjoy the high coherence of the pump laser. Hence, using 2-photon interferometry, the chromatic dispersion of meters long samples of fiber can be determined. This is similar to the well-known white light interferometric measurement technique [6], but with the advantage that the fiber sample length does not need to be adjusted with millimeters accuracy. Thanks to the meter long coherence of the pump laser, the sample length needs only to be adjusted within cm or meter precision. The proposed setup is presented in Fig. 3. Admittedly, this example is more complex than the previous one. Depending on the temperature of the crystal the wavelengths of the collinearly emitted photons vary between 1250 and 1350 nm for one photon and between 1450 and 1600 nm for the other, the central wavelength being at 1400 nm. The interferometer is unbalanced, having the test-fiber in the long arm and a wavelength division multiplexer (WDM) and a moveable mirror in the short arm. The two photon have four choices: The first one can either take the long arm and the other one the short one or vice versa, or both photons take either the short or the long arm. The first two cases are distinguishable due to the time difference between

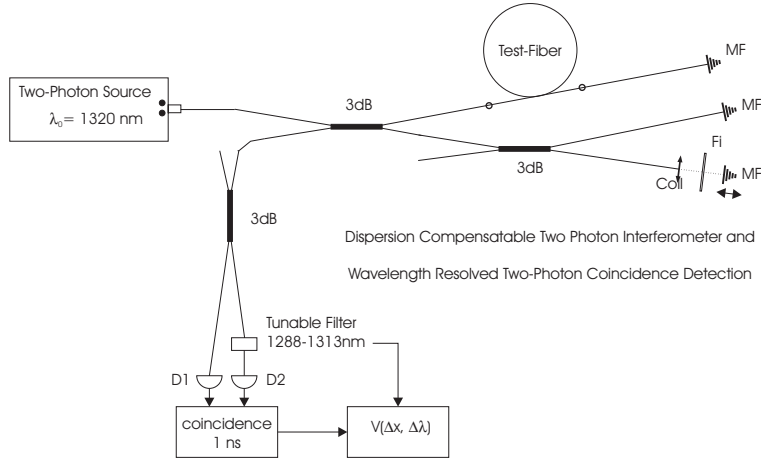


Figure 3: Setup 2-photon interferometric measurements.

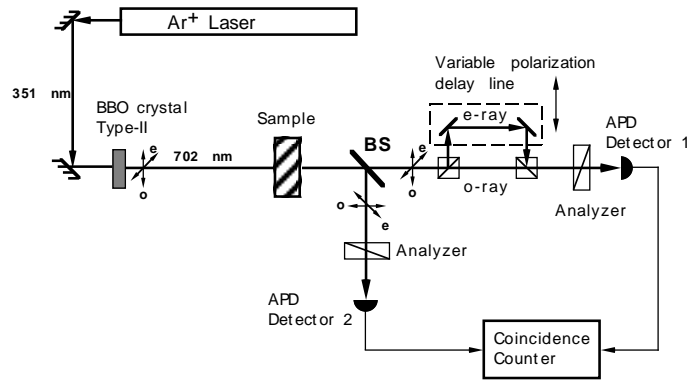


Figure 4: Setup for PMD measurements.

the arrival times of the two photons. The latter two possibilities are indistinguishable, hence lead to two photon interference. The visibility of the interference pattern is reduced, if the dispersion is not identical in the two arms of the interferometer. We can compensate for the difference in the group velocities in test fiber between the photon around 1300 nm and the photon around 1500 nm by separating them with the WDM in the short arm and by introducing an adjustable delay for one of them by a moveable mirror. The position of this mirror for optimal interference visibility is a measure for the time delay between the two wavelengths introduced by the dispersion in the test fiber. We can now scan over the whole wavelength range by tuning the temperature of the nonlinear crystal and obtain the dispersion between 1250 and 1600 nm, thus obtain the group delay as function of wavelength.

4.3 Polarization mode dispersion measurements

In this example, the photon pairs are produced by type II parametric downconversion. Hence, in addition to their time and energy correlations, they are also entangled in polarization, thus suitable

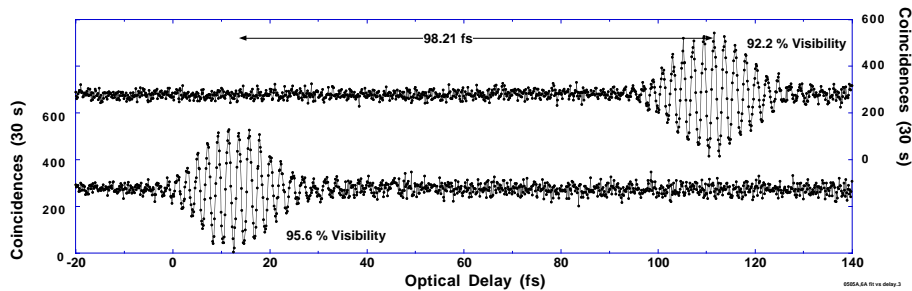


Figure 5: Result of the PMD measurement with sub-femtosecond resolution.

for Polarization Mode Dispersion (PMD) measurements. A possible implementation is presented in Fig. 4, for details see ref. [7]. In this experiment, birefringent plates were actually measured, not fibers, and the source was an Argon laser. However, the results clearly demonstrate the potential of the method, see Fig. 5. Essentially the method is similar to the white light interferometric technique, but thanks to the wide spectrum of the downconverted photons (about 300 nm in this experiment), a resolution of 0.01 fs was achieved. This should be contrasted with the 50 to 100 fs resolution of the standard interferometric technique based on LEDs [8].

5 Absolute calibration of sources and detectors without black-body radiation

As a last example, we present the use of photon pairs for the determination of the absolute efficiency of detectors. Let us emphasize that this technique, contrary to all other techniques we are aware of, is not based on a light source calibrated with black body radiation. Hence, this new technique allows to determine detector efficiencies independently of temperature. The basic idea is simple [9]. Since the downconverted photons are always produced by pairs, the number N_{AB} of coincidence detections with two detectors A and B equals:

$$N_{AB} = N\eta_A\eta_B \quad (1)$$

where N is the total number of photon pairs, and η_A and η_B are the efficiencies of detectors A and B, respectively. Moreover the single counts at detector B equals $N_B = N\eta_B$. Consequently, the efficiency of detector A is given by the simple relation:

$$\eta_A = \frac{N_{AB}}{N_B} \quad (2)$$

This elegant idea has now been tested in several labs [9], in particular at the NIST-Washington, and the accuracy limitations due to the statistics of photon counting have been estimated [10]. A trial to extend this technique to analog detectors is presented in [11].

Analogously, a calibrated source can be devised.

6 Conclusion

The potential of highly correlated photon pairs produced in parametric downconversion for optical fiber and devices has been emphasized. The huge technological progress in simple and efficient

photon pair sources and the ongoing progress in photon counting techniques at telecom wavelengths open new possibilities for the fiber optic community. The intrinsic correlations of the photon pairs offer advantages such as automatic determination of a common time basis, complementary wavelengths and polarization. Thus all the degrees of freedom of photons in single-mode fibers are entangled in these photon pairs. Each photon may be totally depolarized and cover a bandwidth of tens or even hundreds of nanometers. Now, at the same time the two photons form a single quantum object (a bi-photon) with large coherence lengths, up to meters. This offers the possibility to combine advantages of low and high coherence interferometry.

The examples presented in this contribution are but a few ones, more should be expected. Finally, let us briefly mention that quantum optics has also interesting potentials for communication. As examples we mention quantum cryptography [12] and noiseless amplifiers that beat the 3dB "quantum limit" [13].

Acknowledgments

This work profited from support by the Swiss Priority Program in Optics and by the European TMR network on "The physics of quantum information".

References

- [1] see e.g. J. Freedman, and J. F. Clauser, Phys. Rev. Lett., **28**,938-941, (1972); A. Aspect, P. Grangier, and G. Roger, Phys. Rev. Lett., **47**, 460-463, (1981); Z. Y. Ou and L. Mandel, Phys. Rev. Lett., **61**, 50-53, (1988); Shih and Alley, Phys. Rev. Lett. **61**, 2921, (1988); P. R. Tapster, J. G. Rarity, and P. C. M. Owens, Phys. Rev. Lett., **73**, 1923-1926, (1994). W. Tittel et al., Phys. Rev. A **57**, 3229, 1998.
- [2] P. G. Kwiat et al., Phys. Rev. Lett., **75**, 4337, (1995). ??? nb400
- [3] P. Kwiat, CLEO/IQEC, pp, San-Fransisco, 1998.
- [4] F. Zappa et al, Optics Lett. **19**,846-848,1994; P.C.M. Owens et al, Applied Optics **33**,6895-01,1994; G.L. Morgan et al, Los Alamos National Laboratoty report LA-UR-97-4375, 1997; G. Ribordy et al, Applied Optics, in press, 1998.
- [5] J. Brendel, H. Zbinden and N. Gisin, Optics Commun., in press, 1998.
- [6] L. Thvenaz et al, J. Lightwave Tech. **6**, 1-7, 1988.
- [7] A.V. Sergienko et al., preprint, Boston University, 1998.
- [8] N. Gisin et al, JEOS Pure & Applied Optics **4**, 511, 1995.
- [9] see e.g. A.V.Sergienko and A. N. Penin, Applied Optics, **30**, 3582, 1991; A.L. Migdall et al., Metrologia **32**, 479-483, 1995; G. Brida et al, preprint, Istituto Electrotecnico Nazionale G. Ferraris, Torino, Italy, 1998.
- [10] P. Kwiat et al, Applied Optics **33**, 1844, 1994; N. Gisin, J. Brendel and A. Stefanov, preprint, Geneva University, 1998.
- [11] A. Sergienko and A.N. Penin, Sov. Tech. Phys. Lett. **12**, 328, 1986.
- [12] W. Tittel, G. Ribordy and N. Gisin, Phys. World, March 1998.
- [13] D.J. Loring et al, Optics Lett. **21**, 1439, 1996.