Characterizing nonlocal dispersion compensation in deployed telecommunications fiber

Cite as: Appl. Phys. Lett. 114, 131106 (2019); https://doi.org/10.1063/1.5088830
Submitted: 14 January 2019 . Accepted: 27 February 2019 . Published Online: 04 April 2019

James A. Grieve, Yicheng Shi, Hou Shun Poh, Christian Kurtsiefer, and Alexander Ling

ARTICLES YOU MAY BE INTERESTED IN

Symmetrical clock synchronization with time-correlated photon pairs
Applied Physics Letters 114, 101102 (2019); https://doi.org/10.1063/1.5086493

Cavity-enhanced harmonic generation in silicon rich nitride photonic crystal microresonators
Applied Physics Letters 114, 131103 (2019); https://doi.org/10.1063/1.5066996

Spatial modulation of heat source for highly sensitive photothermal detection
Applied Physics Letters 114, 131902 (2019); https://doi.org/10.1063/1.5080163
Characterizing nonlocal dispersion compensation in deployed telecommunications fiber

Cite as: Appl. Phys. Lett. 114, 131106 (2019); doi: 10.1063/1.5088830
Submitted: 14 January 2019 · Accepted: 27 February 2019 · Published Online: 4 April 2019

James A. Grieve,1,a) Yicheng Shi,1 Hou Shun Poh,1 Christian Kurtsiefer,1,2 and Alexander Ling1,2

AFFILIATIONS
1Centre for Quantum Technologies, 3 Science Drive 2, National University of Singapore, 117543 Singapore
2Department of Physics, National University of Singapore, Blk S12, 2 Science Drive 3, 117551 Singapore

a)Electronic mail: james.grieve@nus.edu.sg

ABSTRACT
Propagation of broadband photon pairs over deployed telecommunication fibers is used to achieve nonlocal dispersion compensation without the deliberate introduction of negative dispersion. This is made possible by exploiting time-energy entanglement and the positive and negative dispersive properties of the fiber. We demonstrate the preservation of photon timing correlations after transmission over two multi-segment 10 km spans of deployed fiber and up to 80 km of laboratory-based fiber.

© 2019 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5088830

Correlated photon pairs created via spontaneous parametric downconversion (SPDC) are a core component in entanglement based quantum key distribution (QKD)1–10 and may also be used as a resource for clock synchronization.11,12 Photon pairs produced by this mechanism are created within a short time window [typically 10 fs to 100 fs (Ref. 13)] and so share a high degree of temporal correlation. As the SPDC process is inherently broadband, fiber chromatic dispersion can obscure these timing correlations. In practical terms, this reduces the precision with which remotely detected photon pairs can be identified, increasing the rate of spurious “background” events. This may negatively impact QKD error rates14 and reduce the performance of clock synchronization protocols. For this reason, photon pair sources are often filtered spectrally prior to use in optical fiber links, reducing the throughput of the entire system.15,16

Management and engineering of dispersion are routine tasks in fiber optic communications.17,18 In 1992, Franson7 showed that photon pairs entangled in the time-energy basis could experience nonlocal compensation of chromatic dispersion, provided that the photons propagate through media with opposite dispersion coefficients. This is a direct consequence of quantum correlations and therefore impossible to replicate with classical light—a concept later expanded by Wasak et al.,20 who proposed the preservation of tight timing correlations in the presence of dispersive transmission as an entanglement witness. Beyond chromatic dispersion, related mechanisms such as polarization mode dispersion21 have also been studied in the context of nonlocal compensation effects.22

The nonlocal compensation of chromatic dispersion has been observed in the visible and near-infrared spectral range by using dispersive elements such as prisms and gratings.13,23–25 However, both negative and positive dispersion regions are available in all single-mode optical fibers.26 Most deployed telecommunication fibers exhibit this behaviour around the zero dispersion wavelength close to the 1310 nm “O-band,” with the location of this region specified by International Telecommunications Union standards (ITU-T G.65227).

Nonlocal dispersion compensation using the properties of a single optical fiber was first observed in measurements of fiber dispersion using SPDC photons28 and was applied to QKD field tests29 and entanglement distribution.30 These experiments utilized a tunable source of SPDC photons to generate wavelengths that would experience dispersion compensation in two continuous spans of deployed telecommunications fiber with lengths up to 9.3 km. These early experiments illustrate the potential for nonlocal dispersion compensation to increase the signal-to-noise ratio of a quantum channel, with a recent theoretical treatment14 also finding merit in this approach.

In this paper, we show that photon pairs which broadly degenerate at the approximate location of the zero dispersion wavelength can exhibit nonlocal dispersion compensation in standard, multi-segment telecommunication fiber. This scheme does not require specialized dispersive elements, measurement of the precise fiber characteristics, or tuning of the emission spectrum.
Nonlocal dispersion compensation can be understood by considering the energy anticorrelation of an entangled photon pair and dispersion on the individual photon wavepackets. For positive dispersion, higher energy (shorter wavelength) components of a light pulse travel faster, while lower energy components lag behind. 

This leads to a "chirp." The minimum and maximum delay \( t_{\text{min}} \) and \( t_{\text{max}} \) between the detection of the two photons from a pair determine the spread in propagation times.

The width \( \sigma \) of the timing distribution is related to the sum of the dispersion along the two paths \( (\beta_1 x_1 + \beta_2 x_2) \) for photons 1 and 2, respectively \(^{19} \)

\[
\sigma^2 = \frac{\left(\beta_1 x_1 + \beta_2 x_2\right)^2}{2\sigma_0^2},
\]

where \( \sigma_0 \) is the coherence time of the photons, and \( x_1 \) and \( x_2 \) are the propagation distances. If the dispersion coefficients \( \beta_1 \) and \( \beta_2 \) have the opposite sign, dispersion can be at least partially compensated. For \( \beta_1 x_1 = -\beta_2 x_2 \), the compensation is perfect. \(^{19} \)

Figure 2 shows a schematic of the experimental setup. A photon pair source is connected to two remote nodes by optical fiber. At the nodes, arrival times of single photons are recorded with respect to a local clock. To probe the interaction of photon pairs with the dispersive properties of optical fiber, we transmit photons through several lengths of fiber from 1 km to 10 km, cut from the same piece in order to maintain similar zero dispersion wavelengths. Figure 4 shows the width of \( \sigma(\tau) \) for the asymmetric case of one photon detected directly, while the other is first dispersed through an optical fiber. An approximately linear relationship is observed between the propagation distance and the correlation width, with a gradient of 167 ps km\(^{-1} \). We also investigate the symmetric case where both photons are transmitted over the same fiber, before being separated and detected. In the symmetric case, dispersion is reduced to 18 ps km\(^{-1} \). This reduction is in agreement with Eq. (1), consistent with \( \beta_1 \sim -\beta_2 \). While perfect compensation could be achieved by tailoring the degenerate wavelength \( \lambda_d \) to \( \lambda_0 \) of the
specific fiber, this is impractical in deployed networks comprising fibers with different $k_0$.

We carry out the symmetric measurement for longer fibers, with correlation signals shown in Fig. 5. These fibers are composed of several segments connected in series, with the longest (80 km) made up of three segments (10, 20, and 50 km). We no longer observe the linear increase in dispersion with the fiber length (Fig. 4). However, tight timing correlations are preserved ($<0.503(9)$ ns). We attribute small differences in the degree of dispersion compensation to variation in the exact position of the zero dispersion wavelength, which by specification may lie in a relatively wide range of 1302 nm to 1322 nm.36

It is interesting to note that the degree of compensation seen in these series of shorter fibers is less than for the longer spools. For example, the observed FWHM after 10 km of symmetric propagation is 0.506(7) ns, compared with 0.381(14) ns (Fig. 5). This observation again implies variation in the location of $k_0$ and suggests that with a sufficiently broadband source, significant compensation is possible without tuning $k_d$.

To test this mechanism in an operationally useful context, we transmit photons through two separate 10 km spans of deployed telecommunication fiber. An optical time domain reflectometer (OTDR) measurement for one fiber is shown in Fig. 6(a), revealing at least five segments. From our previous observations, we do not expect these segments to exhibit identical zero dispersion wavelengths. Measured $c(t)$ histograms for one photon transmitted and one detected locally and for both photons transmitted are shown in Figs. 6(b) and 6(c). With only one photon transmitted, chromatic dispersion results in a coincidence distribution with a FWHM of 1.938(47) ns. When both photons are transmitted over separate fibers, we observe a distribution with a FWHM of 0.258(7) ns. Laboratory and field test measurements unambiguously demonstrate that photon pairs with appropriately engineered spectral properties can experience self-compensation of dispersion in conventional telecommunication fiber networks. This is despite the presence of a range of zero dispersion wavelengths and accomplished without the requirement of source tuning. This capability paves the way for the use of broad spectrum entangled light sources for quantum key distribution and other forms of quantum communication. The use of the intrinsic anomalous dispersion available in standard telecommunication fiber can minimize or even remove the need for specialized dispersion-compensating apparatus. The trade-off of operating in the O-band (where attenuation losses are higher than in the more commonly used C-band) will be acceptable for many use cases, particularly for metropolitan areas with the substantial existing fiber infrastructure.
This research was supported by the National Research Foundation, Prime Minister’s Office, Singapore under its Corporate Laboratory@University Scheme, National University of Singapore, and Singapore Telecommunications Ltd.

The authors thank Amelia Tan Peiyu and the Singtel fiber team for facilitating our deployed fiber tests.

REFERENCES

1. T. Jennewein, C. Simon, G. Weihs, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. 84, 4729 (2000); e-print arXiv:9912117 [quant-ph].

2. G. Ribordy, I. Brendel, J. D. Gautier, N. Gisin, and H. Zbinden, Phys. Rev. A 63, 012309 (2001); e-print arXiv:0008039v2 [quant-ph].

3. A. Poppe, A. Fedrizzi, T. Loruenser, O. Maurhardt, R. Ursin, H. R. Boehm, M. Pev, M. Suda, C. Kurtsiefer, H. Weinfurter, T. Jennewein, and A. Zeilinger, Quantum Opt. 12, 3865 (2004); e-print arXiv:0404115v1 [quant-ph].

4. R. Ursin, F. Tiefenbacher, T. Schmitt-Manderbach, H. Weier, T. Scheidl, M. Lindenthal, B. Blauensteiner, T. Jennewein, J. Perdigues, P. Trojek, B. Omer, M. Först, M. Meyenburg, J. Rarity, Z. Sodnik, C. Barbieri, H. Weinfurter, and A. Zeilinger, Nat. Phys. 3, 481 (2007); e-print arXiv:1203.0980.

5. H. Hübner, M. R. Vanner, T. Lederer, B. Blauensteiner, T. Loruenser, A. Poppe, and A. Zeilinger, Opt. Express 15, 7853 (2007); e-print arXiv:0801.3620.

6. I. Marcikic, A. Lamas-Linares, and C. Kurtsiefer, Appl. Phys. Lett. 89, 101122 (2006); e-print arXiv:0606072 [quant-ph].

7. T. Honjo, S. W. Nam, H. Takesue, Q. Zhang, H. Kamada, Y. Nishida, O. Tadanaga, M. Asobe, B. Baek, R. Hadfield, S. Miki, M. Fujimura, M. Sasaki, Z. Wang, K. Inoue, and Y. Yamamoto, Opt. Express 16, 19118 (2008).

8. M. P. Peloso, I. Gerhardt, C. Ho, A. Lamas-Linares, and C. Kurtsiefer, New J. Phys. 11, 045007 (2009); e-print arXiv:0812.1880.

9. T. Inagaki, N. Matsuda, O. Tadanaga, M. Asobe, and H. Takesue, Opt. Express 21, 23243 (2013); e-print arXiv:1310.5473.

10. Y. Yin, Y. Cao, Y.-H. Li, J.-G. Ren, S.-K. Liao, L. Zhang, W.-Q. Cai, W.-Y. Liu, B. Li, H. Dai, M. Li, Y.-M. Huang, L. Deng, L. Qi, Q. Zhang, N.-L. Liu, Y.-A. Chen, C.-Y. Lu, R. Shu, C.-Z. Peng, J.-Y. Wang, and J.-W. Pan, Phys. Rev. Lett. 119(20), 200501 (2017).

11. A. Valencia, G. Scarcelli, and Y. Shih, Appl. Phys. Lett. 85, 2655 (2004); e-print arXiv:0407204v1 [quant-ph].

12. C. Ho, A. Lamas-Linares, and C. Kurtsiefer, New J. Phys. 11, 045011 (2009); e-print arXiv:0901.3203.

13. K. A. O’Donnell, Phys. Rev. Lett. 106, 063601 (2011); e-print arXiv:1103.0532.

14. K. Sedzicki, M. Lasota, and P. Kolenderski, Optica 4(1), 84–89 (2017); e-print arXiv:1607.01783.

15. S. Fasel, N. Gisin, G. Ribordy, and H. Zbinden, Eur. Phys. J. D 30, 143 (2004); e-print arXiv:0403144v1 [arXiv:quant-ph].

16. S. Wengerowsky, S. K. Joshi, F. Steinlechner, J. R. Zichis, S. Dobrovolskiy, R. van der Molen, J. W. Los, V. Zwiller, M. A. Versteegh, A. Mura et al., preprint arXiv:1803.00583 (2018).

17. G. Keizer, “Optical fiber communications,” in Wiley Encyclopedia of Telecommunications, Wiley Encyclopedia of Telecommunications (Wiley, 2003).

18. B. J. Ainslie and C. R. Day, J. Lightwave Technol. LT-4, 967–979 (1986).

19. D. Franson, Phys. Rev. A 45, 3126 (1992).

20. T. Asak, P. Szankowski, W. Wadlewski, and K. Banaszek, Phys. Rev. A 82, 052120 (2010); e-print arXiv:1006.5853.

21. M. Brodszky, E. C. George, C. Antonelli, and M. Shtaif, Opt. Lett. 36, 43 (2011).

22. M. Shtaif, C. Antonelli, and M. Brodszky, Opt. Express 19, 1728 (2011).

23. A. M. Steinberg, P. G. Kwiat, and R. Y. Chiao, Phys. Rev. Lett. 68, 2421 (1992); e-print arXiv:000815489.

24. S. Y. Baek, Y. W. Cho, and Y. H. Kim, in 2011 IEEE Photonics Society Summer Topical Meeting Series 17 (2011), p. 35; e-print arXiv:0811.2035.

25. J. P. W. Maclean, J. M. Donohue, and K. J. Resch, Phys. Rev. Lett. 120, 053601 (2018); e-print arXiv:1710.11541.

26. L. G. Cohen and C. Lin, Appl. Opt. 16, 3136 (1977).

27. Characteristics of a Single-Mode Optical Fibre and Cable, ITU-T G.652 Version 9.0 (International Telecommunications Union, Geneva, CH, 2016).

28. I. Brendel, H. Zbinden, and N. Gisin, Opt. Commun. 151, 35 (1998).

29. W. Tittel, J. Brendel, H. Zbinden, and N. Gisin, Phys. Rev. Lett. 81, 3563 (1998).

30. W. Tittel, J. Brendel, N. Gisin, and H. Zbinden, Phys. Rev. A 59, 4150 (1999); e-print arXiv:9809025 [quant-ph].

31. B. E. Saleh, M. C. Teich, and B. E. Saleh, Fundamentals of Photonics (Wiley, New York, 1991), Vol. 22.

32. E. Diamanti, H.-K. Lo, B. Qi, and Z. Yuan, NPJ Quantum Inf. 2, 16025 (2016); e-print arXiv:1606.05885.

33. T. Lunghi, C. Barreiro, O. Guinnard, R. Houlmann, X. Jiang, M. A. Itzler, and T. Schmitt-Manderbach, Phys. Rev. A 80, 053601 (2009); e-print arXiv:1607.01783.

34. M. Stipcevic, D. Wang, and R. Ursin, J. Lightwave Technol. 31, 1591 (2013).

35. C. M. Natarajan, M. G. Tanner, and R. H. Hadfield, Supercond. Sci. Technol. 25, 063001 (2012).

36. Corning SMF-28 Optical Fiber Product Information (Corning, Inc., 2005).