

Fiber Bragg Gratings: Applications for Quantum Optics

White Paper

Abstract

This white paper shows how dispersion-engineered FBG technology from Proximion can materially improve QKD performance. FBG-based dispersion management suppresses timing errors that raise QBER and erode SKR. Low-loss dispersion compensation recompresses photon wave packets, extending reach, increasing repetition rates, and supporting broader bandwidths.

The same dispersive platform enables fast spectral characterization and precise quantum state control for scalable next-generation networks.

Dispersion compensation for QKD

Chromatic group dispersion is the variation of the propagation speed of a light pulse as a function of the wavelength. For the propagation of optical pulses in optical fibers, dispersion causes broadening of the pulse in time as each frequency component of the pulse travels at different speeds. If the length of the fiber or the repetition rate is large enough, it might result in consecutive optical pulses overlapping, causing lower Signal to Noise Ratio (SNR) or disrupting the communication altogether.

The same effect affects QKD systems. Whether the system is based on attenuated photons or entangled photons to generate the quantum keys, dispersion will negatively impact the performance at higher repetition rates and for longer fiber length. Additionally, the broader the bandwidth of the spectrum of the source, the more problematic dispersion becomes. In QKD, the qubits are encoded in polarization, frequency, phase or time and a temporal spread due to chromatic dispersion will negatively impact those qubits. It will cause different wave packets to overlap, increasing the error rate and degrading the QBER, possibly giving additional information to an attacker.

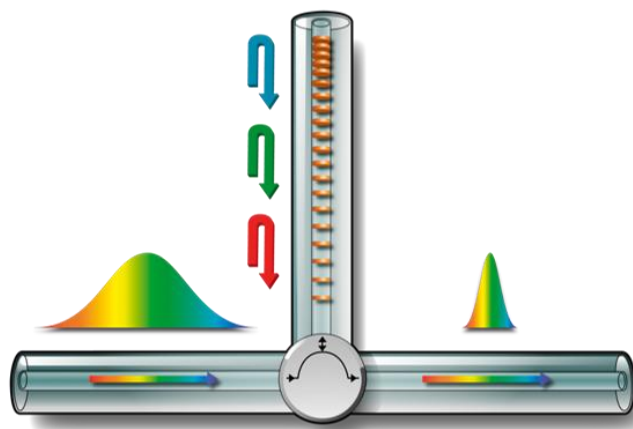


Figure 1: FBG based dispersion compensation principal.

In those instances, dispersion compensation can be used to compensate for the chromatic dispersion experienced by the photons and compress the wave packet to its original temporal width. This step maintains the temporal and spectral fidelity of quantum signals, ensuring secure and reliable key exchange in practical fiber-based QKD networks.

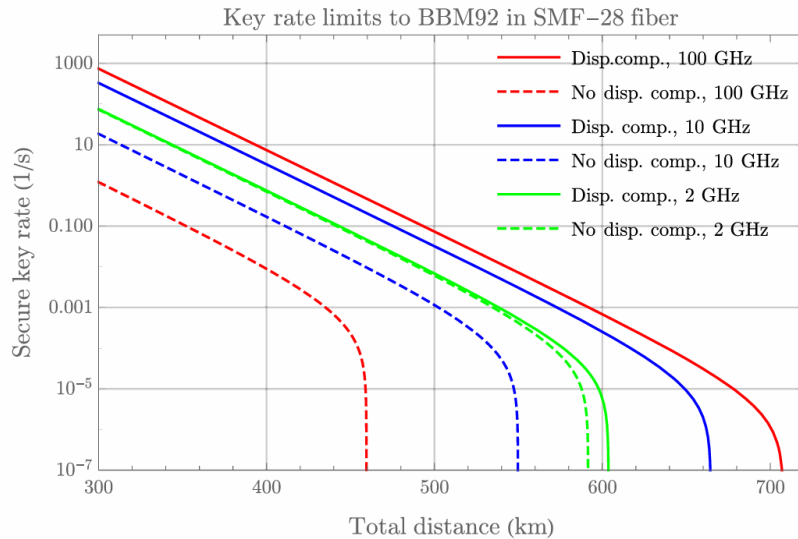


Figure 2: Secure Key Rate as a function of propagation distance for different bandwidth with and without dispersion compensation (Neumann, 2021).

SKR is the number of encryption keys generated by a QKD system per second and is one metric used to measure the performance of the system. Figure 2 shows the SKR as a function of the propagation distance through a fiber link and for different bandwidth of the photon source. For each value of bandwidth, two cases are displayed, with or without dispersion compensation. Those results are a simulation for the BBM92 QKD protocol using non-local dispersion compensation. The figure shows a dramatic improvement of the SKR as the bandwidth increases.

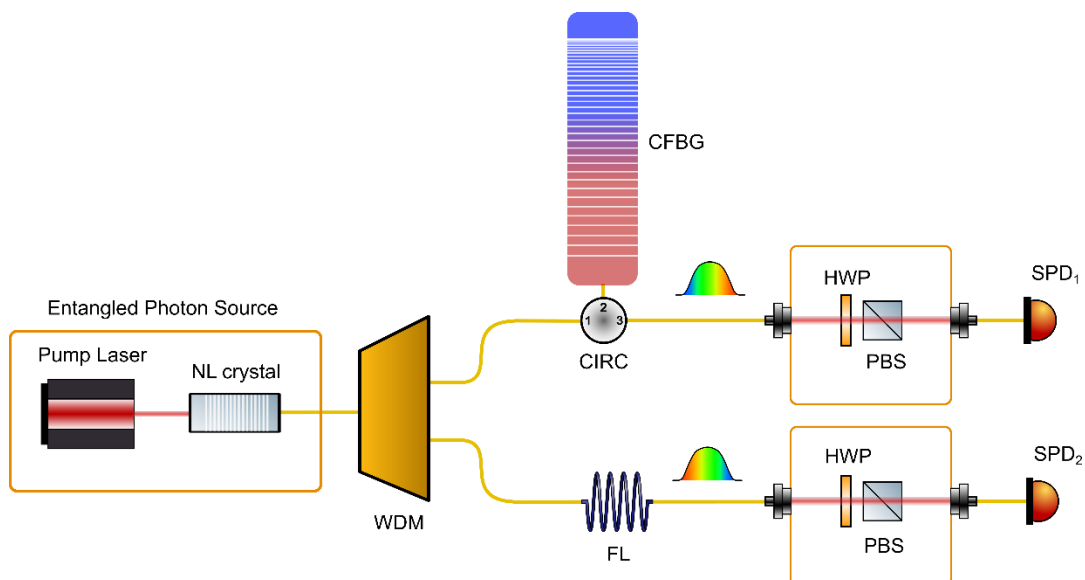


Figure 3: Experimental implementation of the BBM92 QKD protocol. Entangled photon pairs are generated by driving a nonlinear crystal (NL crystal). One output of the wavelength division multiplexing (WDM) is sent to a Chirped Fiber Bragg Grating (CFBG) via a circulator (CIRC) and the photons are spread temporally as a function of their wavelength. The other output of the WDM is sent to a fiber link (FL). The value of the dispersion of the CFBG is opposite to the FL. The photons in each arm are then sent to a polarization analyser composed of a half-wave plate (HWP) and a polarizing beam splitter (PBS) and then to a single photon detector (SPD).

The BBM92 Protocol is an entanglement-based QKD protocol proposed by Charles Bennett, Gilles Brassard, and N. David Mermin in 1992 as an extension of the BB84 Protocol. In this protocol, a source generates pairs of entangled photons and distributes one photon to Alice and the other to Bob. Both users independently measure the polarization of their photons using randomly chosen measurement bases and later compare their chosen bases over a public classical channel while keeping the actual measurement outcomes secret. When compatible bases are used, the measurement results exhibit strong quantum correlations that allow Alice and Bob to establish identical secret cryptographic keys. BBM92 is widely used in experimental QKD systems employing entangled-photon sources such as spontaneous parametric down-conversion (SPDC) and is particularly well suited for long-distance fiber-optic and free-space quantum communication.

In the case of QKD with entangled photons, dispersion doesn't need to be compensated for both photons. Instead, one can take advantage of the nonlocal behavior of entangled photons and compensate twice the dispersion for one photon, effectively compensating in time for the whole pair and recompressing the coincidence window. This effect is used in this instance to both increase the SKR and limit the losses on the fiber link and has been implemented experimentally as seen in Figure 3.

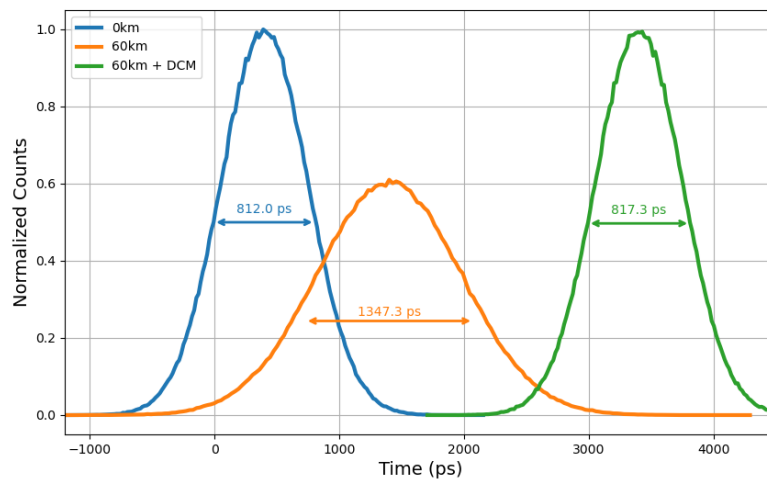


Figure 4: Coincidence peaks measured by single photon detectors after 0km of propagation (blue), 60km of propagation (orange) and 60km of propagation and compensated for dispersion with a Proximion DCM (green). This data is simulated and depicts realistic effects of dispersion and dispersion compensation on coincidence histograms.

Figure 4 shows the arrival time for photons measured by a single photon detector and a time tagger. The blue curve shows the photons arriving within an 812 ps coincidence window due to the inherent jitter of the single photon detection system. As the photons propagate through 60 km of fiber, they will spread temporally as a function of their color. This will lead to a widening of the coincidence peak to 1347.3 ps, consistent with a bandwidth of 1 nm. This widening has adverse effects on communication systems as

previously discussed. The green curve shows the coincidence peak after the photons have propagated through 60 km of fiber and a Proximion's DCM with 1 ns/nm dispersion value, corresponding to 60 km. The width of the peak is now 817.3 ps, which shows that DCMs can be used to compensate for the dispersion caused by a fiber link.

Dispersion compensation is necessary to preserve the integrity of Quantum signals. Dispersion increases the broadening of the coincidence peak and the timing uncertainty. The coincidence units in QKD system define precise time windows to detect correlated photons and when the photons fall outside of the coincidence window, the information is lost increasing detection error and lowering the noise to signal ratio. Dispersion compensation recompresses the photon wave packet in time as shown in Figure 5.

Additionally, QKD systems typically use small spectral bandwidth of their entangled or single photon sources. As for telecommunication, wavelength multiplexing is a natural step to take to increase the number of Qubits generated per second and the SKR as seen in Figure 2, where it is shown that between a 2 GHz, a 10 GHz and a 100 GHz bandwidth, the higher bandwidth yields the highest SKR. However, larger bandwidth or multiple channels combined with dispersion and higher repetition rate will lead to the channels overlapping with each other in the time domain. This in turn will increase the QBER as uncorrelated photons will be detected and generate coincidences.

We recommend using our DCM as they will compensate for dispersion with the lowest amount of loss and can be customized to very specific dispersion values. For reference, DCM can provide the dispersion equivalent to between 10 to 600 km of SMF-28 optical fiber for between 2.5 and 3.5 dB of loss respectively, which is much lower than alternatives such as DCF fibers. Furthermore, we design our DCM to compensate the dispersion slope of standard fibers very precisely, resulting in very small residual dispersion across the C band. As seen in Figure 5, the dispersion profile of DCF fiber does not perfectly match that of standard fibers, resulting in residual dispersion reaching more than 10%.

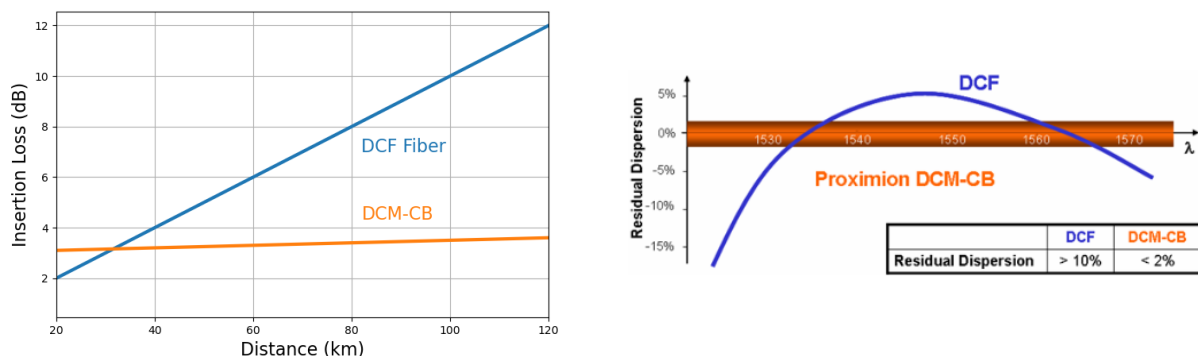


Figure 5: Insertion losses (left) for SMF-28 equivalent length and residual dispersion (right) for DCM and DCF.

Additionally, Proximion provides Dispersion Emulation Modules (DEM) to test communication systems by evaluating the effect of dispersion with a minimum amount of

loss. Those DEM are designed to match the dispersion profile of standard telecom fibers and can be customized to ranges similar to our DCM range.

Dispersive Fourier Transform applied to quantum signals

Spectral measurements are necessary in quantum optics to determine the quality of photon source. In QKD, precise spectral filtering is required to process quantum states correctly, to ensure that unwanted photons, background noise and neighboring wavelength channels are rejected and optimize SKR as well as decrease QBER. Spectral properties critically impact photon indistinguishability, which underpins interference effects such as Hong–Ou–Mandel interference, where even small spectral mismatches degrade visibility. Spectral characterization enables the precise engineering and optimization of sources by tailoring phase-matching conditions and filtering strategies to produce desired quantum states.

Dispersive Fourier Transform (DFT) was originally developed to observe the spectral component of optical pulses in the time domain, allowing fast and single-shot spectral measurement. When an optical pulse travels through a dispersive element, each frequency component travels at different speed and is therefore mapped to the time domain. A device that resolves signals relative to time such as an oscilloscope or a time-tagging unit will be able to record the spectrum of the optical pulse.

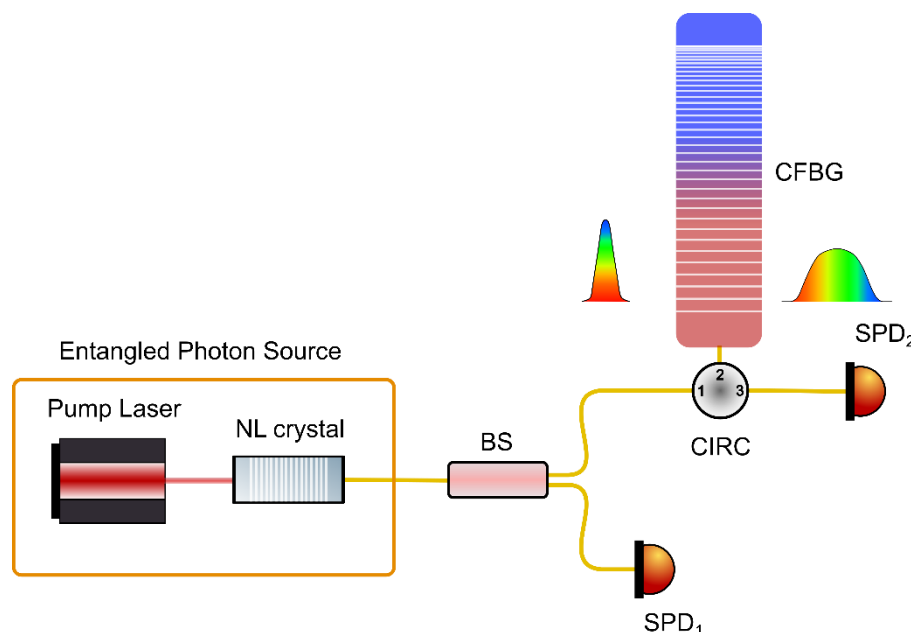


Figure 6: Example of an experimental setup to perform spectral analysis of an entangled photon source. Entangled photon pairs are generated by driving a nonlinear crystal (NL crystal), split with a Beam Splitter (BS). One output of the BS is sent to a Chirped Fiber Bragg Grating (CFBG) via a circulator (CIRC) and the photons are spread temporally as a function of their wavelength. The photons in each arm are then sent to two Single Photon Detectors (SPD).

The same principle can be applied to entangled or single photons. In the case of entangled photon sources (EPS), one can use dispersive elements to translate a wavelength

difference between two photons into a time difference. The photons are split, and one photon is sent into the dispersive element while the other is sent directly to the single photon detector (SPD_1) and used as a trigger for the detection of the second photon on SPD_2 . The time difference between the two photons is directly related to the wavelength of the photon propagating in the dispersive element.

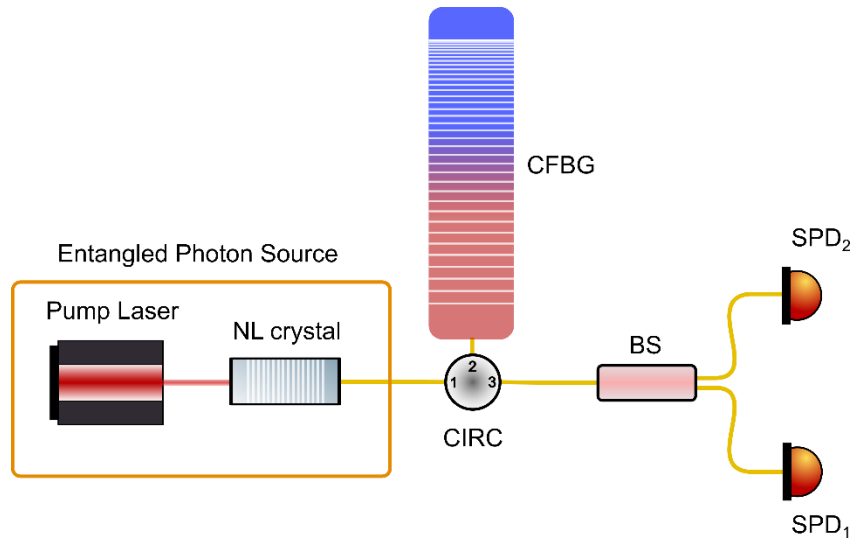


Figure 7: Example of an experimental setup to perform spectral analysis of an entangled photon source.

Alternatively, both photons can be propagated through the same dispersion medium and split into two different SPDs. The arrival time of the photons can be measured and from that measurement, the Joint Spectral Intensity (JSI) is post-processed. These measurements are relevant to the characterization of entangled photon sources and the optimization of their emission. The JSI is an important measurement for quantum photons sources as it clearly reveals spectral correlations between photons, the bandwidth and symmetry of the photon pair as well as the degree of spectral entanglement.

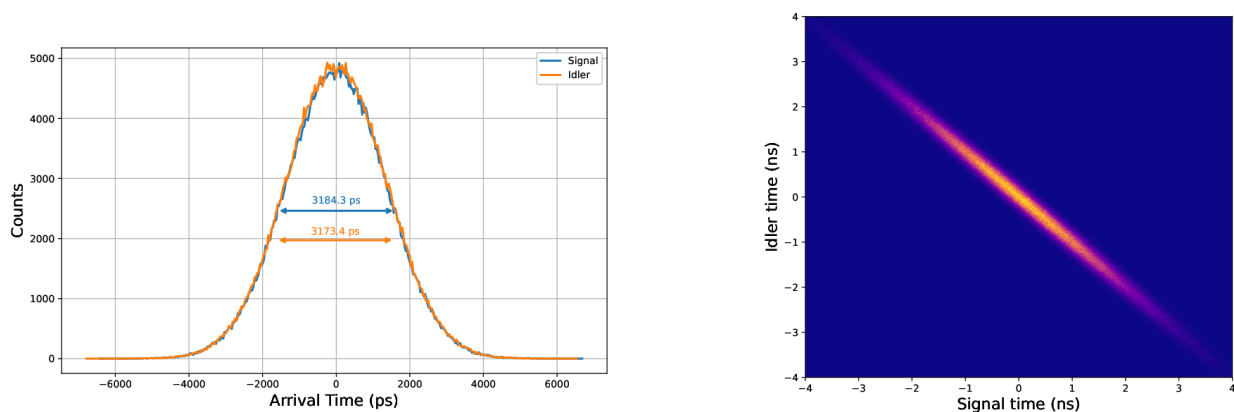


Figure 8: Joint Temporal Intensity (JTI) of an Entangled Photon Source. The arrival time of the photon pairs generated of the entangled photon source (left) can be measured and the coincidence measurement in the time domain with dispersion of the photons is used to reconstitute the JTI (right).

DFT can also be used to measure the spectral properties of attenuated single photon sources used in QKD or the single photon emitters. Photons are sent through a dispersive medium and the time of arrival is compared to an electrical or optical signal synchronized to the signal used to trigger the attenuated pulsed laser or the single photon emitter.

DFT enabled spectral measurement comes with many advantages compared to traditional spectral characterization methods such as scanning monochromators. It performs parallel (single shot) measurement which is faster than a wavelength scanning element. It allows real time acquisition. Dispersion modules offer a very high temporal resolution which is limited only by the value of the dispersion module and the jitter of the detection system. For reference, a 2 ns/nm dispersion module (120 km SMF-28 fiber equivalent) with a detection system with a 90 ps jitter will yield a 45 pm resolution over the C band (1528 - 1565 nm). Proximion provides higher values of dispersion and single-photon detectors can reach lower values of jitter and even better spectral resolution can be reached.

CFBGs are loss efficient for quantum signals; they are passive components and can be easily integrated into existing quantum setups due to their plug-and-play nature and compatibility with standard telecom components.

Chirped Pulse Modulation

There is a need to generate complex multipartite quantum states. In the context of QKD complex and high-dimensional quantum states allow more information to be encoded onto each transmitted photon, increasing the SKR and improving the spectral efficiency. High-dimensional QKD protocols have been shown to achieve greater robustness against noise, losses and eavesdropping attacks, leading to improved security and higher tolerance to transmission errors. These advanced quantum states are therefore a promising pathway toward scalable, high-capacity and long-distance quantum communication networks.

Chirped pulse modulation (CPM) is a novel method used to generate complex quantum states. CPM consists of using DFT to map the spectral components of an input signal to the time domain. A modulation element is placed after the dispersive element to address the spectral components of the signal. This element can be an electro-optic phase modulator (EOPM) to address the spectral phase or an intensity modulator to shape the amplitude of the spectrum. An inverse DFT is performed to project the spectral components back into the time domain.

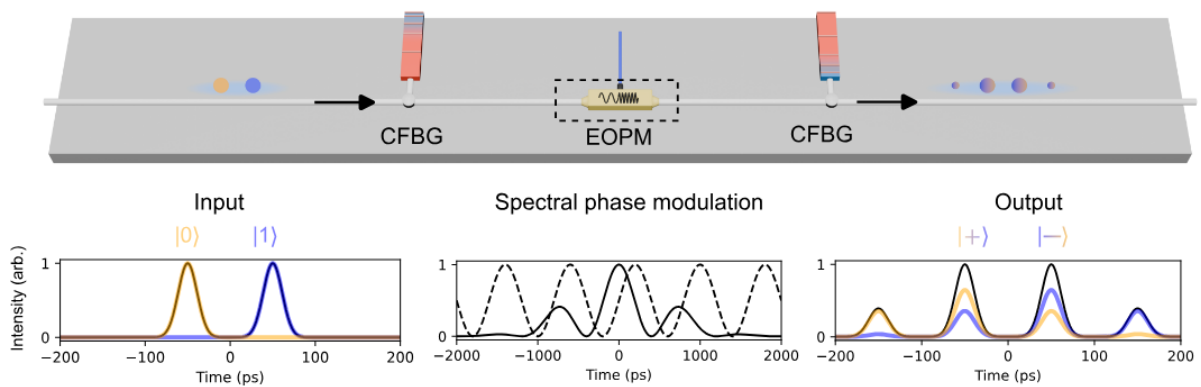


Figure 9: Implementation of the Chirped Pulse Modulation principle. A cluster state is sent to a first CFBG with a dispersion of $+10\text{ns/nm}$, then to an EOPM driven by a RF signal. After modulation, the cluster state is projected back into the time domain by using a second CFBG with a dispersion of $+10\text{ns/nm}$ (Rübeling, 2025)

CPM was used as a reconfigurable quantum pulse-shaping technique to manipulate ultrafast time-bin encoded cluster states after transmission through 25 km of optical fiber. The CPM method was implemented using two Proximion's CFBGs with opposite dispersion placed around an EOPM. The first CFBG performs a DFT, mapping the spectral components of the photons into the time domain, where radio-frequency modulation applied by the EOPM selectively controlled the spectral phase of the quantum states. A second CFBG with opposite dispersion then recompressed the photons through an inverse DFT. This process enabled the realization of a fully tunable time-bin beam splitter capable of coherently superimposing time bins separated by 100 ps and 300 ps, allowing the researchers to perform projective measurements, certify multipartite entanglement on the transmitted cluster states. CPM therefore replaced multiple stabilized interferometers with a compact, flexible, and scalable dispersion-engineered approach for quantum state processing in fiber-based quantum networks.

Conclusion

Dispersion is often seen as a fundamental limitation in fiber-based optical systems, but in the context of quantum optics it can be effectively transformed into a controllable and even enabling parameter with Fiber Bragg Grating technologies. As demonstrated, chromatic dispersion directly impacts the temporal integrity of quantum states, degrading system performance in QKD and increasing the QBER. Precise dispersion management is therefore beneficial to maintaining the fidelity and security of quantum communication links as well as improve the performances such as communication speeds.

CFBGs provide a compact, low-loss, and highly customizable solution to this challenge. Compared to conventional DCF, they offer significantly lower insertion loss while enabling precise matching of dispersion values across a wide range of link distances. This makes them particularly well suited for next-generation quantum networks, where minimizing loss and preserving quantum coherence are critical.

Beyond compensation, dispersion engineering using FBGs also unlocks advanced functionalities such as DFT techniques for real-time spectral characterization of photon sources or the CPM method used to generate complex quantum states. These capabilities highlight the dual role of dispersion as both a challenge and a powerful tool in quantum optics.

In summary, FBG-based solutions from Proximion AB enable both the mitigation of dispersion-induced impairments and the exploitation of dispersive effects for novel quantum measurement and control techniques. As quantum technologies continue to evolve toward higher rates, longer distances, and more complex architectures, such flexible and high-performance optical components will play a key role in ensuring robust, scalable, and secure quantum systems.

References

Neumann, S. P. (2021). Experimentally optimizing QKD rates via nonlocal dispersion compensation. *Quantum Science & Technology*.

Rübeling, P. J. (2025). Fiber transmission of cluster states via multi-level time-bin encoding. *arXiv preprint arXiv:2507.01497*.

About Proximion AB



Figure 10: Dispersion compensator and Wistom optical layer monitor.

Proximion AB is a world-class provider of optical modules and sub-system based on FBG technology. We provide custom solutions for many different applications in sensing and telecom and work in close collaboration with our customers. Throughout the years, innovation and quality have been the heart of our business