The Utility of Optical Frequency Combs in Modern Quantum Cryptography

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Abstract

This literature review seeks to evaluate what research has been done on the optical frequency comb. Through the comparison of several versions of the optical frequency comb, it shall be analyzed as to which best suits the needs modern quantum cryptography has for a successful data encryption process. In terms of electronic material that must be protected, it shall be defined as anything that an individual would consider private information, yet that could be transferred over the Internet (such as electronic bank account info, username logins and passwords, and personal records such as scanned family history records. Through proper utilization of the optical high frequency comb, data protection will become further possible. It can be concluded that, after comparing prior arts to modern modelocked frequency combs, they are of great potential in solving the current problem in quantum cryptography’s data encryption. Further research must be done to find which organic element best supports the modelocked frequency comb’s nonlinear functionality in terms of optical switching, electro-optic modulation, and two-photon absorption. Such will solve the problems found in the current state-of-the-art modelocked frequency comb. Further research in photon entanglement must also be done to improve the integration and manufacturing of the modelocked frequency comb if it is to be implemented in quantum cryptography.

*Keywords:* frequency comb, cryptography, photon

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The Utility of Optical Frequency Combs in Modern Quantum Cryptography

Modern quantum cryptography proves that previous models provide no effective implementation of encrypted verification; such is often called “eavesdropping” (Gisin, Ribordy, Tittel, & Zbinden, 2002). Therefore, users who transfer accounts and materials across bandwidths cannot differentiate whether their product has been manipulated with during this transfer. The results prove that criminals can access others’ personal information with little to no detection. On October 22 of 2017, a group of hackers refactored the Domain Name System (DNS) registration at a Brazilian bank, which allowed them to steal online account information from the bank’s clientele. Throughout the entire afternoon, members using ATM’s provided by this bank lost all their funds’ security through a simple swipe of their credit card. The thieves continued their charade with no detection until after the theft was complete six hours later (Greenberg, 2017). Expertise, money, power, such is regarded as naught when matched against quantum cryptography: once anyone breaches the security of any server, their once private information can be considered as good as public.

The answer to such a problem falls to an invention of the 21st century: the modelocked optical frequency comb. Originally meant for extreme precision measurement, electromagnetic energy becomes a valuable apparatus for cybersecurity. By utilizing equidistant lines of electromagnetic frequencies, ultrashort pulses of light create accurate measurements both visually as well as graphically. Therefore, it can hone the results of any measurement, from length, depth, frequency, and other variables to submillimeter accuracy. This invention has been improved for decades from its previous models. Due to its incredible measuring capabilities, it can be applied in a variety of fields, such as telecommunications, engineering, and even more advanced fields like astronomy or quantum cryptography (Delfyett et al., 2006).

After the analysis of several versions of the optical frequency comb, the utility of the modelocked optical frequency combs in modern quantum cryptography concludes the following: Though modelocked optical frequency combs have their disadvantages, further research of this product and photon entanglement can provide unfaltering protection for private electronic information. All this shall be analyzed by comparing previous models of the frequency comb and its current models, their applications to quantum cryptography, and future research that will be needed for the frequency comb to fulfill its purpose in solving the “eavesdropping” problem in quantum cryptography.

**The Previous and Current Model**

To provide a better understanding of frequency combs today, the following three paragraphs will include the origin of the frequency comb. Such shall provide both context and act as a guide for further understanding of problems found with the current model of the modelocked optical frequency comb. In the early ‘70s, scientists furthered their research in spectroscopy, with the help of monochromatic dye lasers. These microwaves were finely tunable, allowing researchers to have more control over the light emittance’s wavelength which they lacked in the ‘60s (Del’Haye et al., 2007). Scientists understood that it would be necessary to have finer measurements as neighboring technologies progressed. Though the finely-tuned waves of the ‘70s made excellent progress in the machine’s mechanics, the emittance of those waves proved to be inconsistent or sporadic, thus defeating the invention’s entire purpose (Del’Haye et al., 2007). Because of such inconsistencies, these apparatuses had little potential in providing consistent measurements. Also, because these waves were remotely impossible to increase in frequency, scientists further researched their potential for the enhancement of the device’s frequency.

After decades of studies, scientists reached a conclusion: Hänsch (2006) proved that lasers removed several complexities found in the frequency comb’s previous model. The mechanics’ upgraded systems provided ultrafine, consistent measurements as their wavelengths could be emitted constantly and with a higher frequency (Hänsch, 2006). Lasers provide optical wave frequencies instead of radio waves (such as the microwave). Hence, the invention of the optical frequency comb. Simply a year prior to reaching this conclusion, Hänsch received the Nobel Prize in Physics for his contribution to the quantum theory of optical coherence (“The Nobel Prize in Physics 2005”, 2014). In merely a decade since, the optical frequency comb has advanced dramatically through several physicists’ contributions, which have improved the device overall (along with increasing its potential applications).

Delfyett et al. (2006) concluded that through Fourier’s Theory, modelocked lasers provide the most beneficial measurement for the frequency comb’s intended purpose. The difference between these modelocked lasers to Hänsch’s original optical frequency comb is that with Hänsch’s model, merely one frequency emittance can be optically presented. The modelocked optical frequency comb model provides several laser grids to be emitted at once, allowing not only precise measurements, but also such measurements can be better analyzed on graphs and periodic grids (Delfyett et al., 2006). This has become crucial for its application in other fields, such as that of telecommunications, signal processing, and quantum cryptography (which shall be addressed later).

Air-silica microstructure optical fibers can be best explained as a necessary evil for the modelocked optical frequency comb. According to Ranka, J. K. and Windeler, R. S. and Stentz, A. J. (2000), the air-silica microstructure optical fibers of the comb broaden the specificity of its measurements, making them incredibly more accurate than without (Ranka, Windeler, & Stentz, 2000). These fibers are the most common fix to the problem explained above, for without these fibers, the lasers would not be emitted at a constant frequency. Diddams et al. (2000) concluded that these microstructures are generally intentional and resolve the issue of its laser-implementation instead of solely using microwaves. From several experiments, Diddams et al. explained that these fibers alone allow the comb to broaden its potential frequency a full octave than it was previously able. A normal modelocked frequency comb centered near 800 nm (which is its average frequency with the air-silica fibers) was compared to a local rubidium microwave standard frequency comb. After several controls were provided in said experiment, Diddams et al. concluded that a cesium microwave of near infrared standard allows better provision for balancing (Diddams et al., 2000). Mildner, J. and Meiners-Hagen, K. and Pollinger, F. (2016), however, poses issues found with this current model through their analysis of these fibers (Mildner, Meiners-Hagen, & Pollinger, 2016). Though Diddams et al. concluded that the modelocked frequency combs can be calibrated through cesium or rubidium microwave standards, Mildner et al. stated that these combs are ineligible for the calibration of astronomical spectrographs. They concluded that due to these fibers, frequency combs run short of the repetition rate by a couple hundred MHz, which provided problems persisting in several fields, even outside that of astronomy. Mildner et al. concluded that, due to such low repetition, it is difficult for the device to separate its own measurements made within adequate dimensions (Mildner et al., 2016). Therefore, because of these air-silica fibers, it can be concluded that the modelocked optical frequency comb cannot function at their fullest capacity.

Mildner et al. overcame this by running experiments that thin the modes set by the comb through a Fabry-Perot filtering cavity (Mildner et al., 2016). Willke et al. summarized that these filtering cavities act as a cleaner for most laser devices and concludes such through their experiments with a 10-W laser beam and its laser emittance before and after filtering (Willke et al., 1998). From the cleaning provided by the Fabry-Perot filtering cavity, the 10-W laser was able to reduce both the noise from the comb’s emittance and was also able to increase the overall measuring accuracy for these lasers. As a side note, realize that another issue found in frequency combs was the noise they emit while they are operating. Surprisingly enough, the soundwaves and vibration from the machine itself inhibit the results of the frequency comb’s accuracy in measurements (which is understandable, given that the machine is measuring at submillimeter distances, any bump or vibration could do nothing else than interfere). This noise problem shall be answered again later (with better results than Willke et al. provided), though is important to understand here for the sections that follow. Continuing forward, however, Mildner et al. concluded that a great deal of power is lost from such filtering that Willke et al. experimented with, regardless of it benefits (Mildner et al., 2016). In efforts to counteract this loss of power, Mildner et al. used optical laser amplifiers to increase the lasers’ emittance strength. Overall, it was concluded that due to such a trivial yet overly-complicated calibration process, even the slightest refraction from the comb’s results render them useless (Milder et al., 2016). Therefore, though the modelocked frequency comb is needed for several fields it cannot meet the expectations its users request, even with the noise reduction and improved results from filtering. Such cannot be resolved until the frequency comb is able to perform with a higher repetition rate and is separated under finer dimensions.

What follows is a more in-depth description as to how the most advanced modelocked frequency combs can be implemented into quantum cryptography. The modelocked optical frequency comb’s application in this field can also solve many of the problems found with them, and simultaneously, as stated, can resolve many issues found in quantum cryptography.

**Applications to Quantum Cryptography**

As initially concluded in the previous section from Mildner et al., which Diddams et al. ignored, air-silica fibers have provided a serious problem for modelocked frequency combs. Another problem previously mentioned by Mildner et al. is that the amount of power needed to operate the combs is too high, especially after calibration (Mildner et al., 2016). Both these problems were resolved recently by Shen, X. and Beltran, R. C. and Diep, V. M. and Soltani, S. and Armani, A. M. (2018), who concluded that it is not the fibers themselves that pose the problem, it is simply the matter with which they are coated (Shen, Beltran, Diep, Soltani, & Armani, 2018). Carbon-based fibers prove to be of much more promise than the current utilization of silicon-based microstructure optical fibers. Shen et al. concluded that by applying a twenty-five-atom layer to the surface of the laser itself, power efficiency has been reduced by one thousand times the silicon-based frequency comb (Shen et al., 2018), thus resolving the problem addressed by Mildner et al. Ergo, which such implementation of carbon fibers, modelocked frequency combs can now provide the connection between spectroscopy and quantum cryptography, as deducted by Hänsch (Hänsch, 2006). Shen et al. concluded that the potential for photon entanglement through the frequency comb will be its greatest potential for improving data encryption. Shen et al. also concluded that a great deal of research in integration and manufacturing must be done for such to be possible (Shen et al., 2018). To maintain the overall organization of this paper, it shall be later discussed in the following section what advances must be done and what research must be provided for photon entanglement to be successful.

Another problem not previously mentioned has been found in frequency combs today, though this problem can also be fairly resolved and can also be applied to quantum cryptography. In the realm of spectroscopy and physics, it is important to receive both a short-distance contribution as well as a long-distance contribution. Such is necessary to provide a fair comparison of data. According to Valencia (1998), long distance contribution is founded under the framework of the chiral perturbation theory (Valencia, (1998). This theory suggested a parameter by which two-photon contribution can produce constants necessary for making precise measurements. By implementing this theory, Valencia argues that long distance contribution is the only way to remove the uncertainty found from these unknown constants, which are unknown only to the short-distance contribution (Valencia, 1998). However, it was concluded that it is impossible to calculate these constants through this theory. Such a conclusion provides an important contribution to this paper in the following paragraphs and sections, so it shall be quoted directly here: “We believe that it will be impossible to extract any information on the short distance parameter . . . in the foreseeable future. This situation will change only when we are able to calculate reliably the long distance amplitude from QCD [quantum chromodynamics].” (Valencia, 1998). It can then be concluded that, because the short distance parameter cannot be calculated, frequency combs still are not accurate enough. Many know that such is a common problem found in spectroscopy as well, thus prohibiting the accuracy that these frequency combs provide.

Hosseini and Sparkes and Campbell and Lam and Buchler (2011) removed a significant portion of these concerns, though not completely Hosseini, Sparkes, Campbell, Lam, & Buchler, 2011). Hosseini et al held a study based on how quantum repeaters, which act to provide long distance quantum key distribution, require optical memory. Optical memory is a combination of both short-distance and long-distance contributions, and a comparison of the two. By using a rubidium vapour, optical memory can be provided with an accuracy of eighty-seven percent (Hosseini et al., 2011). This study took two-level atoms, switching its frequency gradient from positive to negative, thereby emitting a photon-echo. Such an echo is later set through several modulators and splitters, and ultimately a rubidium vapour. Hence the recall from the vapour proved a recall efficiency of optical memory up to eighty-seven percent than without (Hosseini et al., 2011). Also note that such results were given linearly, therefore reducing the noise issue to almost zero (for such, as previously stated on page seven, was yet another issue for frequency combs). Ergo, it can be concluded that through the study of Hosseini et al., rubidium vapour poses a fair solution to both the noise problem, as well as the lack of ability to find the short-distance contribution constants that Valencia (1998) deducted (Hosseini et al., 2011). The need for finding said constants has been resolved because, as mentioned in Valencia’s studies, the long-distance amplitude can now be found using quantum chromodynamics (as do the experiments of Hosseini et al.). Since such has been rendered successful, then it can be further concluded that photon entanglement is possible. Considering that quantum encryption functions based off the need for the recollection of optical memory, by having such an accuracy of recall eavesdropping can also be possible, as defined in the introduction. Or, by taking a separate approach and with further research, the photon-echoes that are recalled in the studies from Hosseini et al. could be implemented in photon entanglement directly (Hosseini et al., 2011). However, though the study provides yet another platform, having the average result only be of eighty-seven percent poses another issue: With an error of thirteen percent of photon echoes not being recalled, its reliability is to be still in question.

It shall be explained in the next section how the above conclusions can be corrected through future research.

**Needs for Further Research**

According to what has been previously mentioned in this paper, Shen et al. concluded that a great deal of research in integration and manufacturing must be done for photon entanglement to be successful (Shen et al., 2018). The studies Hosseini et al. performed concluded that a thirteen percent of recall for photon echoes cannot be provided, so there is yet another error of the current model. It shall be discussed what research is being/can be done regarding these subjects to enhance the current model of the modelocked frequency comb and how it can be implemented in modern quantum cryptography.

Rubidium is one of the most electropositive and alkaline elements. It is also the 22nd most common element, meaning that it is somewhat inexpensive (Ritter, 2003). Such was most likely the reason why Hosseini et al. used its vapour throughout his experiments. The only elements that are more reactive than rubidium is cesium and francium. Several researchers, such as Pang and Han and Zhao and Liu and Wei (2016), have focused on changing the vapours and coatings of materials over the fibers (Pang, Han, Zhao, Liu, & Wei, 2016). Pang et al. concluded in a recent study that by using ytterbium-doped fibers, optical frequency combs can reach their maximum stability (Pang et al., 2016). This conclusion might be important if researchers decide that a different vapour should be used. For example, though more expensive, a francium vapour could be of greater utility in terms of photon-echo recall. Francium is the most reactive element; however, it is the most unstable of the three elements rubidium, cesium, and francium (Ritter, 2003). Therefore, if physicists decide to switch vapours and coatings, it would be most viable to use ytterbium-doped fibers with a francium vapour to provide the best results (which can be concluded by that which has just been stated). Such would improve the frequency comb’s overall photon echo recall, though it would also require greater funds for research.

Regardless, the vapour isn’t necessarily what is in question, neither is the comb’s stability. As concluded by Mildner et al., regardless of cesium’s implementation the frequency comb would still run short of its needed repetition rate by several hundred MHz (Mildner et al., 2016). The most viable solution would be to focus not so much on switching vapours but switching the fiber-based material to a more compatible carbon-based/ organic coating. Shen et al. concluded that several organic materials are compatible with their model, which would prove that there can obviously be better materials than others for their current model (Shen et al. 2018). Shen et al. concluded that extensive research has been done on their part as to which organic elements would be of best utility, though to find a specific element that would best coat the fibers has been of little success. However, as specifically by Shen et al., their parameters of study include an element’s nonlinear applications, such as optical switching, electro-optic modulation, and two-photon absorption. We have already received Valencia’s input on two-photon contribution; yet, again, we receive their conclusions with little success (1998).

Therefore, it can be concluded that further research must be done in terms of finding which organic element best supports the modelocked frequency comb’s nonlinear functionality in terms of optical switching, electro-optic modulation, and two-photon absorption. Such must be done before any integration and manufacturing research be initiated for photon entanglement in quantum cryptography (Shen et al., 2018). It can also be concluded that, if funding provides, further research must be done in developing ytterbium-based combs with a francium vapour to see how improved the photon-eco recalls can be. The modelocked optical frequency comb can therefore provide maximum benefit to quantum cryptography’s “eavesdropping” problem if such is researched further. If the modelocked optical frequency comb can provide a clearer photon-echo recall than its original eighty-seven percent (again, through the possible methods just mentioned) then such a solution to this problem in quantum cryptography can be provided.

**Conclusion**

After comparing prior models to modern modelocked optical frequency combs, it can be concluded that they are of great potential in solving the current problem found in quantum cryptography’s data encryption/ “eavesdropping.” Though they serve of great potential in resolving this problem, a great deal of research has yet to be done. Such research must include finding which organic element best supports the modelocked frequency comb’s nonlinear functionality and can be found by emphasizing the element’s terms of optical switching, electro-optic modulation, and two-photon absorption. Such will solve the problems found in the current state-of-the-art modelocked optical frequency comb. Also, further research in photon entanglement must also be done to improve the integration and manufacturing of the modelocked frequency comb if it is to be implemented in quantum cryptography. Until such is accomplished, it can only be applied in the fields in which it currently does.

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