Optimization of Classical Light Wavelengths Coexisting with C-band Quantum Networks for Minimal Noise Impact

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Abstract: We investigate the optimal coexisting classical light wavelengths to use alongside C-band quantum networks to minimize noise from spontaneous Raman scattering and discuss techniques for optimizing coexisting time synchronization systems for teleportation and entanglement swapping.

Quantum networks (QNs) based on fiber optics can benefit from coexistence with classical light for the purposes of classical light-based control plane functions such as time synchronization [1-4]. This becomes critical for applications such as quantum teleportation or entanglement swapping which require independent photons to arrive at the exact same time at a network node. The issue that arises when weak quantum signals are multiplexed into the same fibers as much higher-power classical light is the introduction of noise photons, mainly due to spontaneous Raman scattering (SRS). A common approach for mitigating SRS noise is to place the quantum and classical signals in different telecom bands. This usually corresponds to placing the classical signal in the O-band (1260 nm-1360 nm) for C-band (1530 nm -1565 nm) QCs [1-5] or using the O-band for QCs when C-band classical communications coexist in the same fibers [6]. As quantum functions such as teleportation and swapping are susceptible to any extraneous noise, an analysis of SRS to find the classical wavelengths which introduce the least possible noise allowed by SRS would be beneficial. To our knowledge, the spectral distribution of Stokes SRS has been characterized across the C-band only for O-band classical light sources near 1310 nm [5], and some analysis of the benefits of different O-band wavelengths have been studied for quantum signals near 1550 nm in [4]. However, a full analysis of the SRS spectrum across the C-band for classical light between 1260 nm and 1360 nm can greatly benefit the engineering of quantum networks to design the most noise robust quantum-classical coexisting networks that is allowed by SRS.

In this paper we measure the C-band SRS spectrum induced by O-band classical light to find the optimal classical wavelength to use for classical channels coexisting with C-band quantum networks. Our analysis includes the limitations of clock signal receiver power sensitivity to adjust the initial launch power based on the loss spectrum and length of the fiber. We find that shifting the classical wavelength from ~1310 nm to the 1260-1300 nm range provides significant reduction in SRS noise depending on the C-band quantum wavelengths. We then analyze the impact on multi-photon coincidence detection in entanglement distribution, teleportation, and entanglement swapping, showing multiple orders of magnitude improvements in the noise impact on these QN applications.

To characterize the coexistence of C-band QNs with O-band classical light, we measure the SRS spectrum across the C- and L-bands for classical light at wavelengths λ_{cl} ranging from λ_{cl} =1260 nm to λ_{cl} =1360 nm. We use an O-band tunable CW laser to pump 25 km of spooled SMF-28 fiber at a fixed launch power of 1.00 mW. A band pass filter is used to remove amplified spontaneous emission and the launch power is monitored using a 90:10 splitter. At the end of the spool, a cascade of DEMUX filters isolate the C- and L-bands to ensure the O-band is not detected. We use a tunable grating filter with a 0.55 nm bandwidth to scan the spectrum from 1530 to 1625 nm and detect SRS using superconducting nanowire single photon detectors. Fig.1(a) shows the resulting SRS singles count spectrum for different λ_{cl}. For λ_{cl} =1310 nm, the amount of SRS begins to decrease significantly at quantum wavelengths λ_{qu} around 1560 nm, the edge of C-band, decreasing by nearly order of magnitude from 1550 nm to 1580 nm. Reducing λ_{cl} below 1310 nm shifts the SRS spectrum such that the minimum occurs at lower C-band wavelengths. For λ_{cl} between 1260 nm-1280 nm, the entire C- and L- bands is significantly reduced compared to λ_{cl} >1290 nm. Next, using the same experimental design we fix the tunable filter at λ_{qu} =1536 nm, 1550 nm, and 1566 nm while tuning λ_{cl} from 1260 nm

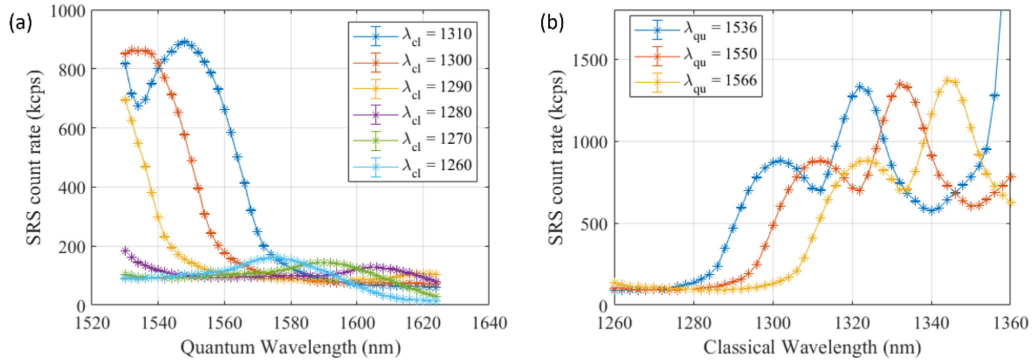

Fig. 1 (a) SRS photon count spectrum across the C- and L-bands over 25 km from O-band classical light sources in kilo-counts per second (kcps). (b) SRS photon count rate (kcps) at quantum wavelengths of 1536 nm, 1550 nm, and 1566 nm for O-band classical wavelengths between 1260 nm and 1360 nm.

to 1360 nm. The results are shown in Fig. 1(b). We see that for λ_{qu} =1550 nm and λ_{qu} =1566 nm, the amount of noise is minimized at around λ_{cl} =1280 nm and λ_{cl} =1290 nm, respectively. However, the λ_{qu} = 1536 nm spectrum indicates that one needs to shift λ_{cl} to the 1260 nm-1280 nm region to minimize the SRS across the entire C-band, which is within the standard 1270 nm CWDM grid. It is interesting to consider whether λ_{cl} <1260 nm can further improve coexistence. The λ_{cl} = 1260 nm and 1270 nm spectra show an increase in the SRS between 1560 nm to 1600 nm where it then begins to decrease to more than 50 times weaker at 1610 nm compared to 1550 nm. However, we would need to shift λ_{cl} ~1210 nm to see any improvements at λ_{qu} ~1550 nm and even further to cover the full C-band. In future studies it could be worthwhile to examine the loss spectrum for various fiber types in this regime to see whether these improvements can be achieved in the C-band despite the higher losses, however L-band QNs could benefit from this dramatic reduction in noise using O-band classical channels. Thus, we conclude that the 1260-1280 nm band is most optimal for minimizing SRS across the entire 1533 nm-1566 nm C-band using telecom band classical light.

We now use these results to simulate the coexistence of time synchronization channels using a technique of controlling the launch power of the classical clock based upon the minimum power sensitivity of the clock receiver and wavelength dependent fiber losses. We can predict the amount of forward scattered SRS power from a copropagating classical signal based on a particular fiber link of length L, launch power P_0, and quantum filter bandwidth $\Delta\lambda$ via [7]

$$P_{\text{Raman}}(\lambda_{\text{cl}}, \lambda_{\text{qu}}) = \beta(\lambda_{\text{cl}}, \lambda_{\text{qu}}) P_0 \, \Delta\lambda \, \frac{e^{-\alpha_{cl}L} - e^{-\alpha_{qu}L}}{\alpha_{cl} - \alpha_{qu}} \quad (1)$$

where α_{cl} and α_{qu} are the classical and quantum transmission loss coefficients in SMF-28 fiber and β is the Raman scattering coefficient between the classical and quantum wavelengths. In the time synchronization experiments in [2,3], the photon pairs were generated at λ_{qu} =1536 nm with a coexisting clock at λ_{cl} =1310 nm. For these wavelengths, β was determined to be β (1310 nm, 1536 nm) = 4.6×10^{-10} nm^{-1}km^{-1} for the 57 km fiber link between Argonne National Laboratory and Fermilab National Laboratory. Using our results in Fig. 1(b) and eq. (1), we use this value for β at λ_{cl} =1310 nm to scale the spectrum of β (λ_{cl}, λ_{qu} =1536 nm) for λ_{cl} =1260-1360 nm. Fig. 2 (a) shows the spectrum of the SRS coefficient as a function of classical wavelength for λ_{qu} =1536 nm. From this plot, we can see that the SRS coefficient near 1260 nm is >7 times smaller compared to 1310 nm, indicating this can significantly improve coexistence with C-band QNs. To further minimize noise, we can optimize coexistence by using launch powers based upon the minimum power sensitivity of the time synchronization detectors. To analyze the minimum possible noise impact of a coexisting clock, we set P_0 based upon the loss spectrum of SMF-28 for each clock wavelength. We use a minimum received power of -30 dBm as was required to achieve picosecond level time synchronization in [2,3]. Fig. 2(b) shows the simulated launch powers versus fiber link length adjusted for the ideal loss spectrum across the O-band. Fig. 2(c) shows the predicted SRS count rates for each classical O-band wavelength as the length of the fiber is increased using the minimum launch powers shown in fig. 2(b). We can see that the lower wavelengths will require higher powers to overcome loss and as a result the improvements will decrease as a function of fiber length. For λ_{qu} =1536 nm, we estimate improvements compared to λ_{cl} =1310 nm for L= {10, 25, 50, and 100} km by factors of approximately {5.5, 4.7, 3.4, 1.6} for λ_{cl} =1260 nm, {6.2, 5.6, 4.6, 2.7}for λ_{cl} =1266 nm, {5.9, 5.3, 4.3, 3.7, 2.7} for λ_{cl} =1270 nm, and {4.5, 4.2, 3.7, 2.7} for λ_{cl} =1280 nm, whereas λ_{cl} = 1290 nm and greater improve by less than 1.3 over all lengths. Although we analyzed λ_{qu} = 1536 nm to compare with [2,3], λ_{qu} =1550 nm has even greater

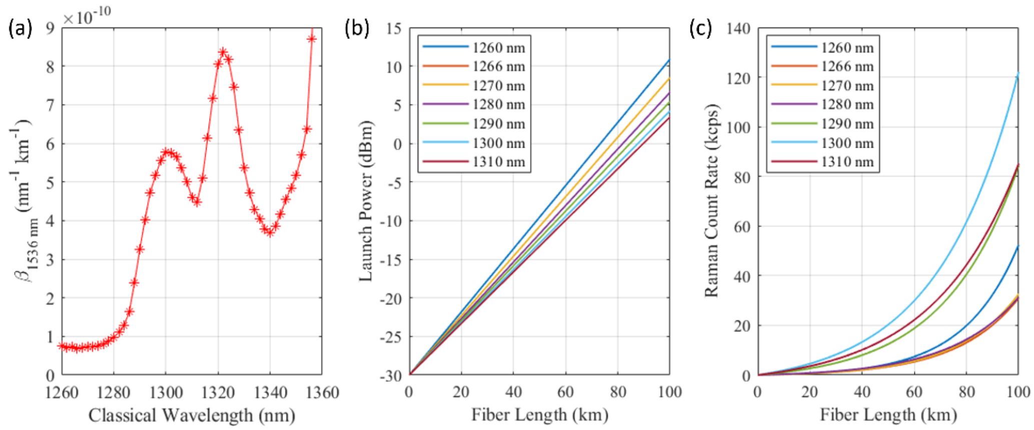

Figure 2 (a) Raman scattering coefficient at λ_{qu} =1536 nm used for simulating SRS. (b) Launch power to receive -30 dBm based on the ideal loss spectrum of SMF-28. (c) Predicted SRS count rate (kcps) at 1536 nm using the launch powers in (b).

improvements due to it being near a local maximum of the λ_{cl} = 1310 nm SRS spectrum compared to λ_{qu} =1536 nm being near a local minimum. We estimate the optimal for λ_{qu} =1550 nm to be λ_{cl} ~1276 nm with improvements of roughly {8.2, 7.7, 6.7, 5.0}, respectively.

We then estimate the impact of our analysis on quantum network functions that will benefit from time synchronization. For applications that require the detection of n photons between nodes using n-fold coincidence detection, such as entanglement distribution (n=2), teleportation (n=3), and entanglement swapping (n=4), one can quantify the impact of noise using the number of accidental coincidences (AC) between channels. For example, an increase in AC will result in a reduced Hong-Ou-Mandel interference visibility and as a result the visibility of a teleported qubit or swapped entangled state. The n-fold AC rate is $\propto R_1 \ldots R_n$ [8], where R_j are the single photon count rates in each channel including quantum signals S_j and SRS noise N_{Rj} such that $R_j = S_j + N_{Rj}$. Thus, we can estimate the AC rates including SRS as $AC_{n\text{-fold}} \propto (S_1 + N_{R1})(S_2 + N_{R2}) \ldots (S_n + N_{Rn})$. A reduction in the Raman counts by a factor of m will result in terms that are reduced by m^{-1}, m^{-2}, …, and m^{-n}. For teleportation (n=3) and entanglement swapping (n=4) with n coexisting classical channels, the expansion of the AC rate will result in terms that are proportional to m^{-1}, m^{-2}, m^{-3}, and m^{-4}. As an example, for n 25 km links with λ_{qu} =1550 nm, our results in fig.2 (c) predict that λ_{cl} =1276 nm will reduce AC rates by ~7.7 for n=1 terms, ~60 for n=2 terms, ~456 for n=3 terms, ~3515 for n=4 terms compared to λ_{cl} =1310 nm. Thus, the impact of optimizing the choice of classical wavelengths using the analysis in this paper will have orders of magnitude differences in the impact of noise on quantum network applications benefiting from the inclusion of classical time synchronization systems.

In conclusion, we analyzed the optimal wavelengths to choose for classical light coexisting within C-band QNs. By using a model for SRS and considering the loss spectrum of standard fiber, we analyzed the technique of minimizing launch powers based on the minimum power sensitivity of the classical receiver to achieve the least possible noise introduced into the quantum bands. We found that λ_{cl} within the 1270 nm CWDM grid are optimal for minimizing SRS across the entirety of the C-band. We analyzed the impact on quantum network functions requiring multi-photon detection by estimating improvements in AC rates compared to a 1310 nm clock signal. These results will be valuable for designing C-band quantum networks coexisting with classical light to have the least possible noise dictated by the SRS spectrum, wavelength dependent fiber loss, and power sensitivity of the classical receiver.

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