Impact of spontaneous Raman scattering on quantum channel wavelength-multiplexed with classical channel in time domain

Ningna Yu (于宁娜), Zhaoyue Dong (董照月), Jindong Wang (王金东)*, Zhengjun Wei (魏正军), and Zhiming Zhang (张智明)

Laboratory of Nanophotonic Functional Materials and Devices (SIPSE) and Laboratory of Quantum Engineering and Quantum Materials, South China Normal University, Guangzhou 510006, China

**Corresponding author: wangjd@scnu.edu.cn*

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In the quantum key distribution system, quantum channel is always affected by spontaneous Raman scattering noise when it transmits with classical channels that act as synchronization and data channels on a shared fiber. To study the effect of the noise exactly, the temporal distribution characteristics of the Raman scattering noise are analyzed theoretically and measured by a single-photon detector. On the basis of this, a scheme to decrease the noise is proposed.

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Since the first experimental implementation of the quantum key distribution (QKD) in 1992, the key generation rate and transmission distance have been improved significantly[1–7]. However, the compatibility of QKD with existing dense wavelength division multiplexing (DWDM) network has not been resolved so far, because DWDM network usually multiplexes up to dozens of different wavelength channels on a shared fiber. If the quantum channel coexists with other classical channels on a single fiber, several effects, such as spontaneous Raman scattering and four-wave mixing, can degrade QKD system performance severely[8,9].

To quantitatively study the effect of the noises, a spectrograph is always used to measure the power of the noises at different wavelengths[9–12]. However, the sensitivity of the spectrograph decreases the accuracy of the noise measurement. And the result measured by the spectrograph is different from that by the single-photon detector (SPD), because when two or more photons reach the SPD through one gate, the SPD records only one photon. Therefore, using a spectrograph to measure noises and calculate the quantum bit error rate (QBER) is not accurate, so we adopt a method in which the SPD is used to measure the time distribution characteristics of spontaneous Raman scattering noise. Then we can know the number of the noises per second recorded by the SPD, based on which the QBER is more accurate.

This letter evaluates the effect of the spontaneous Raman scattering noise on the quantum channel wavelength-multiplexed with classical channels. We theoretically analyze and experimentally measure the time distribution characteristics of the spontaneous Raman scattering noise from a classical channel. Then based on the experimental results, we proposed a scheme to decrease the spontaneous Raman scattering noise.

When the classical signal is propagating in the fiber, it will produce Stokes and anti-Stokes Raman scattering noises. To study the effect of the noise on the quantum signal when the classical signal propagates with the quantum signal in the same fiber, we model the time distribution characteristics of Stokes and anti-Stokes Raman scattering noise power. Suppose the power of the pump light (classical signal) is not high enough to induce stimulated Raman and Brillouin scatterings, and the time of the pump light arriving at the SPD is 0. Then the arriving time t of Stokes Raman scattering noise produced at z is written as

$$t = \frac{l-z}{u_i} - \frac{l-z}{u_c},\ n_g = \frac{c}{u}, \tag{1}$$

where z is the transmission distance of the pump light in the fiber; t is the arriving time of Stokes Raman scattering light when the arriving time of the classical light is 0, and here $t>0$; l is the fiber length; c is the speed of light in vacuum; u_i is the group velocity of Stokes Raman scattering light at λ_i (i is a variable); u_c is the group velocity of the classical signal; n_{gi} is the group refractive index of Stokes Raman scattering light; n_{gc} is the group refractive index of the classical light.

The power of Stokes Raman scattering light produced at z is written as

$$p_{iz} = p_0 \rho_i \exp(-\alpha_c z), \tag{2}$$

where p_0 is the input pump light power, ρ_i the Raman efficiency of Stokes Raman scattering light, and α_c the loss coefficient for the classical light.

Then Stokes Raman scattering light power at l is written as

$$p_i = p_0 \rho_i \exp(-\alpha_c z) \exp[-\alpha_i (l-z)], \tag{3}$$

where p_i is Stokes Raman scattering light power at λ_i (i is a variable) and α_i the loss coefficient for Stokes Raman scattering light.

Substituting Eq. (1) into Eq. (3), we have

$$p_i = p_0\rho_i \exp\left[-\alpha_c l + \left(\alpha_c - \alpha_i\right)\left(\frac{ct}{n_{gi} - n_{gc}}\right)\right]. \quad (4)$$

Similarly, the power of anti-Stokes Raman scattering light at l is written as

$$p_j = p_0\rho_j \exp\left[-\alpha_c l + (\alpha_c - \alpha_j)\left(\frac{ct}{n_{gj} - n_{gc}}\right)\right], \quad (5)$$

where p_j is anti-Stokes Raman scattering power at λ_j (j is a variable), ρ_j is the Raman efficiency of anti-Stokes Raman scattering light, α_j is the loss coefficient for anti-Stokes Raman scattering light, n_{gj} is the group refractive index of anti-Stokes Raman scattering light, and t is the arriving time of anti-Stokes Raman scattering light when the arriving time of the classical light is 0, and here $t<0$.

Let us assume that the bandwidth of the filter is given, then the total power of Stokes and anti-Stokes Raman scattering noises at l is

$$p = \sum_{\lambda_i=\lambda_L}^{\lambda_i=\lambda_U} p_i + \sum_{\lambda_j=\lambda_L}^{\lambda_j=\lambda_U} p_j, \quad (6)$$

where λ_U and λ_L are, respectively, the upper and lower bound wavelengths of the filter bandwidth. The first item on the right-hand side of Eq. (6) is the power of Stokes Raman scattering noise and the second item is the power of anti-Stokes Raman scattering noise.

According to the filter bandwidth and the Raman efficiencies of Stokes and anti-Stokes Raman scattering light, we can calculate the time distribution characteristics of Stokes and anti-Stokes Raman scattering noise power by Eq. (6). And then based on the characteristics of the SPD, we can know the number of the noise light at different times recorded by the SPD per second, which is the expectant experiment result.

The experimental setup, as shown in Fig. 1, is used to study the time distribution characteristics of Stokes Raman scattering noise from a classical channel with different repetition frequencies and in different fiber lengths. To accurately measure the scattering noise, the quantum channel (1550 nm) is not added in the experiment. In the transmitter, a sequence of optical pulses (1309 nm) is generated by a pulsed laser (PDL808; PicoQuant), and the average transmitting power is 36 μW when pulse repetition frequency is 80 MHz. An optical filter centered at 1309-nm (bandwidth 12-nm) is installed to suppress the side mode of the laser. Extra 1310/1550 nm multiplexer and demultiplexer are used to get the same spontaneous Raman scattering noise in this experiment as that in the experiment of multiplexing a quantum channel with a classical channel, because 1310/1550 nm multiplexer can further filter noises. In the receiver, an optical 1550-nm filter (bandwidth 14 nm) is installed to suppress the cross talk from classical signal and the spontaneous Raman scattering noise around the wavelength of the quantum signal. The SPD in the setup is produced by Auréa Technology, of which the quantum efficiency, the dark count rate, and the duration of the gate are set to 10%, 8×10^{-6} count/ns· gate, and 2.5 ns, respectively. The output clock signal of the laser is transformed to 1.25 MHz by an electrical level translator and a frequency divider, and then fed to the SPD as the clock, which can reduce noises from after-pulse in the SPD. Then, we can obtain the time distribution characteristics of Stokes Raman scattering noise centered at a wavelength of 1550 nm by adjusting gate delay of the SPD.

The temporal distribution characteristics of Stokes Raman scattering noise (wavelength 1443–1557-nm) from the classical channel through different fiber lengths (i.e., 25 and 50 km) are shown in Fig. 2. The noises are recorded under four pulse repetition frequencies: 10, 20, 40, and 80 MHz. In all the cases, peak pulse power remains unchanged. When two or more photons arrive at same gate of the SPD simultaneously, only one noise photon is recorded by the SPD. Then we can know that when some noise photons and the quantum signal reach the same gate of the SPD, only one photon is counted. Here we assume that the recorded photon is the noise photon.

As shown in Fig. 2(a), the highest number of noises (1443–1557 nm) from a single classical signal (pulse repetition frequency of 10 MHz) through 25-km single-mode fiber (SMF) is about 850/s, which means noises exist 850 times/s or more when the number of the classical signal pulses is 10×10^6/s. On the basis of the experimental data, we can calculate the QBER more accurately when quantum channel exists in the experimental setup and the pulse repetition frequencies of the quantum signal and the classical signal are the same. As we can see from Fig. 2(a), there is no noise for some time (about 40 ns) when the pulse repetition frequency is 10 MHz, and the area no longer exists when the pulse repetition frequency is ≥20 MHz, which means the noise distribution time range increases as the pulse repetition frequency

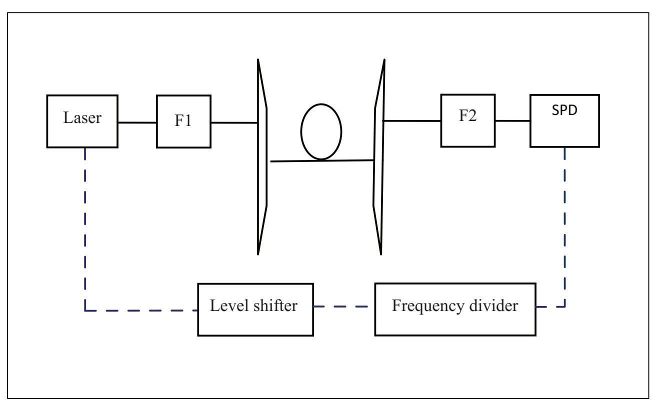

Fig. 1. Stokes Raman scattering noise test setup. Solid lines indicate the route of optical signal and dotted lines indicate the route of electrical signal. F1, 1310-nm filter; F2, 1550-nm filter.

increases, and then the noise is distributed throughout the time domain. In this situation, we cannot extract the keys accurately. By comparing Figs. 2(a) and (b), we can see that the noise distribution time increases as the fiber length increases, and the number of the noise increase as the pulse repetition frequency increases. We cannot distinguish the quantum signal from the noise when their wavelengths are the same or similar, then the effect of the noise on the distillation of secret key increases as the pulse repetition frequency or the fiber length increases.

The experimental system, as shown in Fig. 1, can also used to study the time distribution characteristics of anti-Stokes Raman scattering noise produced by classical pulse with different repetition frequencies propagating through different fiber lengths. To accurately measure the scattering noise, the quantum channel (1310 nm) is not added in the experiment. A sequence of classical optical pulses (1550 nm) is generated by a pulsed laser (PDL808; PicoQuant), and the average transmitting power is 36-μW when their pulse repetition frequency is 80 MHz. The classical signals (1550 nm) pass through an optical 1550 nm filter in the transmitter and through an optical 1310 nm filter in the receiver. Then, we can obtain the time distribution characteristics of anti-Stokes Raman scattering noise centered at a wavelength of 1310 nm by adjusting gate delay of the SPD.

As shown earlier, the noises are measured under the same four conditions.

Figure 3 shows the photon counting of anti-Stokes Raman scattering noise (1304–1316 nm) from a classical pulse through different fiber lengths (i.e., 25 and 50 km). The number of the noises from a single classical signal (pulse repetition frequency of 10 MHz) through 25-km fiber is about 15/s, which means noises exist 15 times/s or more when the number of the classical signal pulses is 10×10^6/s. On the basis of the experimental data, we can calculate the QBER more accurately when there exists quantum channel in the experimental setup, and the pulse repetition frequencies of the quantum signal and the classical signal are the same.

The distribution of noise in Fig. 3 is similar to that in Fig. 2. According to Figs. 2 and 3, we can see that the spontaneous Raman scattering noises are distributed all over the time domain when the pulse repetition frequency of the classical signal is high. Although the number of anti-Stokes Raman scattering noise is less than that of Stokes Raman scattering noise when their pulse repetition frequencies and fiber lengths are the same, anti-Stokes noises still have an influence on the quantum channel when the pulse repetition frequency of

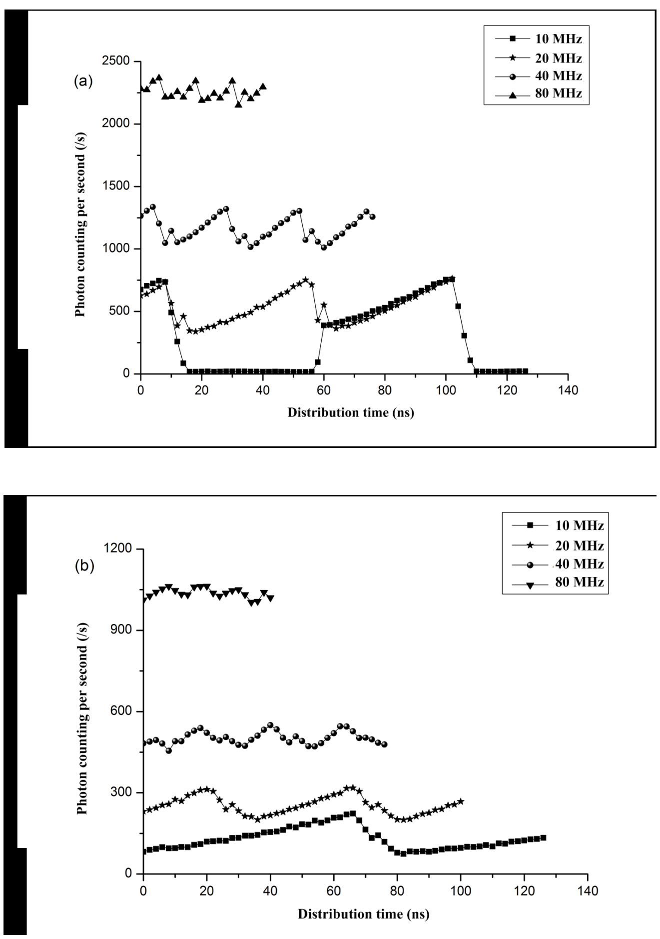

Fig. 2. Experimental data of photon counting of Stokes Raman scattering noise when the SMF length is (a) 25 and (b) 50 km.

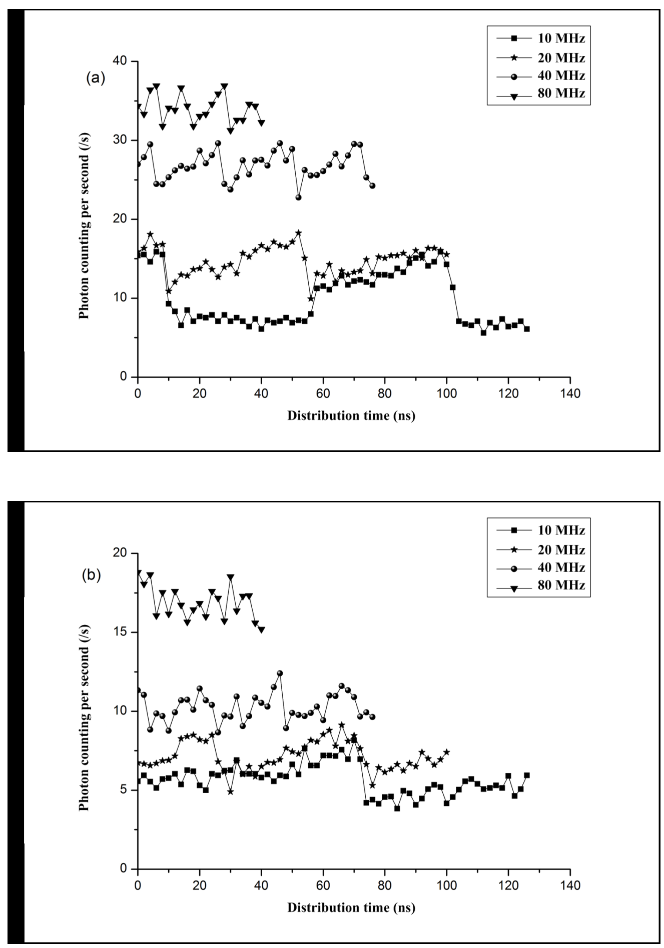

Fig. 3. Experimental data of photon counting of anti-Stokes Raman scattering noise when the SMF length is (a) 25 and (b) 50 km.

the classical signal is high. Therefore, quantum channel wavelength-multiplexed with classical channel cannot filter noise completely no matter the wavelength of the quantum channel is larger or smaller than that of the classical channel.

To solve this problem, we can use a synchronization time-division multiplexing (STDM) scheme. In this scheme, quantum signal and classical signal both have same wavelength and fixed time slice that includes a lot of pulse signals. At this point, only a few quantum signals that are near to the classical signal are covered by the noises, because the noises are distributed around the classical signals. In addition, the wavelengths of the noises are different from the wavelength of the quantum signal, and the distribute time of the noise passed through a narrow band filter is reduced compared with the wavelength division multiplexing technology. We need only discard a few quantum signals that are covered by noise, then theoretically we can obtain the quantum signals without noises.

In conclusion, we theoretically and experimentally investigate the effect of the spontaneous Raman scattering noise on the quantum channel when the quantum channel is wavelength-multiplexed with a classical channel. First of all, we theoretically analyze the power distribution of Stokes Raman and anti-Stokes Raman scattering noise. Then the number of the spontaneous Raman scattering light is measured at different fiber lengths, pulse repetition frequencies, and wavelengths of the classical signal using a new method. On the basis of the experimental results, we propose STDM scheme to decrease the noises, and theoretically the noise can be removed completely.

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References

1. F. Z. Guo, S. J. Qin, Q. Y. Wen, and F. C. Zhu, Chin. Phys. Lett. **27**, 090307 (2010).
2. Z. Zhao, Y. Luo, Z. Zhao, and H. Long, Chin. Opt. Lett. **9**, 032702 (2011).
3. R. Z. Jiao, C. Zhang, and H. Q. Ma, Acta Phys. Sin. **60**, 110303 (2011).
4. G. Xin, L. Shen, H. Pi, D. Chen, H. Cai, H. Feng, J. Geng, R. Qu, G. Chen, Z. Fang, and W. Chen, Chin. Opt. Lett. **10**, 101403 (2012).
5. L. H. Gong, N. R. Zhou, L. Y. Hu, and H. Y. Fan, Chin. Phys. B **21**, 080302 (2012).
6. F. Tang and B. Zhu, Chin. Opt. Lett. **11**, 090101 (2013).
7. L. Liu, M. Zhang, M. Liu, and X. Zhang, Chin. Opt. Lett. **10**, 070608 (2012).
8. T. E. Chapuran, P. Toliver, N. A. Peters, J. Jacke, M. S. Goodman, R. J. Runser, S. R. McNown, N. Dallmann, R. J. Hughes, K. P. McCabe, J. E. Nordholt, C. G. Peterson, K. T. Tyagi, L. Mercer, and H. Dardy, New J. Phys. **11**, 105001 (2009).
9. N. A. Peters, P. Toliver, T. E. Chapuran, R. J. Runser, S. R. McNown, C. G. Peterson, D. Rosenberg, N. Dallmann, R. J. Hughes, K. P. McCabe, J. E. Nordholt, and K. T. Tyagi, New J. Phys. **11,** 045012 (2009).
10. H. Kawahara, A. Medhipour, and K. Inoue, Opt. Commun. **28,** 4691 (2011).
11. I. Choi, R. J. Young, and P. D. Townsend, New J. Phys. **13,** 063039 (2011).
12. K. A. Patel, J. F. Dynes, I. Choi, A. W. Sharpe, A. R. Dixon, Z. L. Yuan, R. V. Penty, and A. J. Shields, Phys. Rev. X **2,** 041010 (2012).