Photon counts modulation in optical time domain reflectometry*

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The quantum fluctuation of photon counting limits the field application of optical time domain reflection. A method of photon counts modulation optics time domain reflection with single photon detection at 1.55 μm is presented. The influence of quantum fluctuation can be effectively controlled by demodulation technology since quantum fluctuation shows a uniform distribution in the frequency domain. Combined with the changing of the integration time of the lock-in amplifier, the signal to noise ratio is significantly enhanced. Accordingly the signal to noise improvement ratio reaches 31.7 dB compared with the direct photon counting measurement.

Keywords: single photon detection, optical time domain reflection, modulation, quantum fluctuation

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1. Introduction

Optical time domain reflectometry (OTDR) is the most common distributed measurement technique in fibre network characterization. It has become a universal diagnostic tool widely used not only for attenuation measurements but also for the general monitoring of the homogeneity of optical fibre systems and components. The traditional OTDR directly detects light pulse by a photoelectric device and the response relaxation properties of the photoelectric device lead to the testing dead zone of OTDR.[1−3] The real-time photon detection by the single photon detector (SPD) has the advantages of broad dynamic range, fast response time, high spatial resolution and the removement of the testing dead zone of other photoelectric devices.[4] Photon counting method measures the photon probability distribution of optical field by photoelectric counting. Lacaita *et al.* demonstrated a photon counting OTDR operating at $\lambda = 1.3$ μm in 44-dB dynamic range,[5] showing 6.5-dB higher than that using traditional methods. However, the quantum fluctuation (QF),[6,7] which may limit the signal to noise ratio (SNR) $R_{\rm SNR}$ of photon counting measurement, has not been considered.[3,8]

In this paper, we perform an OTDR measurement of standard telecom fibres by single photon detection, using photon counts modulation and lock-in technology to eliminate the influence of QF and thus improve the SNR of OTDR.

2. Theoretical analysis for photon counting modulation techniques

The SPD records the incident photons during a sampling time τ. Supposing the average photon number is α, the QF of the photon counting distribution can be expressed as[9,10]

$$I_{\rm QF} = \sqrt{\sum\nolimits_n P(n)(n-\alpha)^2}, \tag{1}$$

where n is the actual photon numbers measured during the experiment.

For coherent light field, the photon count distri-

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bution obeys Poisson's distribution

$$P_{\rm c}(n) = \alpha^n {\rm e}^{-\alpha}/n!. \quad (2)$$

The QF of coherent light field can be calculated by inserting Eq. (2) in Eq. (1)

$$I_{\rm QF} = \sqrt{\alpha}. \quad (3)$$

The SNR $R_{\rm SNR}$ of photon counting then can be expressed as

$$R_{\rm SNR} = \frac{\alpha\tau}{\sqrt{(\alpha+B+D)\tau}} = \frac{\alpha}{\sqrt{(\alpha+B+D)}}\sqrt{\tau}, \quad (4)$$

where B is the photon count rate caused by stray light, D is the photon count rate induced by the dark counts of the detector. In a low-temperature environment, the photon counts of background stray light and dark current of detector can be ignored compared to the signal counts. As a result the maximum value of $R_{\rm SNR}$ in Eq. (4) of $(\alpha\tau)^{1/2}$ can be obtained. Increasing τ could obtain a higher $R_{\rm SNR}$, but the temporal resolution is decreased in this way.

Lock-in amplifier[11,12] uses a technique known as phase-sensitive detection to single out the component of the signal at a specific reference frequency and phase. Noise signals at frequencies other than the reference frequency are rejected and do not affect the measurement. It is equivalent to a very narrow bandwidth band-pass filter and it is necessary to compress the filter bandwidth as much as possible in order to suppress noise. When the incident photons were intensity modulated by the sine-wave of frequency f, the instantaneous photon counts at time t is expressed as $r_0 + m\cos(2\pi ft)$, where r_0 is the average photon counts, m is the depth of modulation. Then within the sampling time τ the valid photon counts can be expressed as[3,13]

$$r_{\rm t}(\tau) = r_0 + m\left[\frac{\sin(\pi f\tau)}{\pi f\tau}\right]\cos(2\pi ft + \pi f\tau). \quad (5)$$

The probability of n photons being detected during the sampling time τ is

$$p(n) = \frac{{\rm e}^{-r_t(\tau)}(r_t(\tau))^n}{n!}. \quad (6)$$

The photon counts should first be converted to analog signal to fulfill the input demand of lock-in amplifier. In the demodulation process of lock-in amplifier, only the frequency components corresponding to the demodulation filter bandwidth will be retained. The $R_{\rm SNR}$ of demodulated signal is

$$R_{\rm SNR} = \frac{S_{\rm N}}{(I_{\rm QF}+I_{\rm ex})(\Delta f/f_n)}, \quad (7)$$

where $S_{\rm N}$ is the analog signal of photon counting, $I_{\rm ex}$ is excess noise. f_n is the noise distribution bandwidth. Compressing the filter bandwidth Δf will decrease the corresponding noise signal, and then enhance the SNR of OTDR measurement.

3. Experiment

The diagram of the OTDR system is shown in Fig. 1. A pulse laser diode (id300, 1550 nm, ID Quantique) externally triggered by a pulse generator (SRS DG645) was used to generate 300-ps laser pulses at a wavelength of 1550 nm and a repetition rate of 4 MHz. After passing through an isolator and an attenuator, the weak pulses were modulated by an acousto-optic modulator (AOM, GOOCH & HOUSEGO M200-2J-F2S). A sine-wave signal, with the frequency $F_{\rm rep}$ = 10 Hz, peak-to-peak voltage $V_{\rm pp}$ = 300 mV and offset voltage $V_{\rm offset}$ = 370 mV, works as the modulation signal and is added onto the AOM's driver. Rayleigh scatter and Fresnel reflection existing inside the fibre (3-m length) will be detected with an InGaAs SPD (Princeton Lightwave Inc.) through an optical circulator. The time jitter of the SPD is 300 ps. Meanwhile, the synchronizing transistor–transistor logic (TTL) pulses from DG645 are used to trigger the SPD. The reflection peak of OTDR is obtained by regulating the delay time between the trigger signals of laser and SPD.

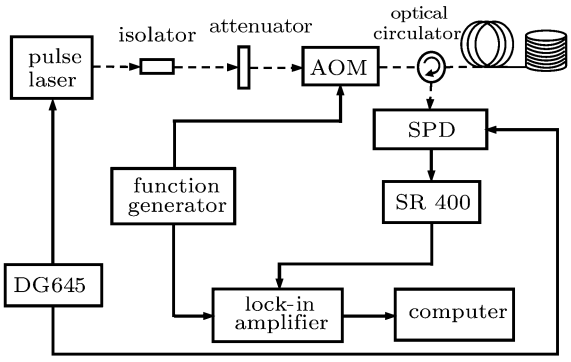


Fig. 1. The simplified block diagram of the OTDR system.

The digital outputs for the single photon detection from the SPD are 50-ns TTL pulses. We use a

photon counter (SRS SR400) to convert the photon counts to an analog signal, the digital-analog conversion factor is $g = 0.1$ mV/count. The analog signal is demodulated by a lock-in amplifier (SRS SR830). The experiment control and the data collection are completed by a computer.

4. Results and discussion

The OTDR measurement with photon counting is shown in Fig. 2(a), the average photon number $\alpha = 50$ kcps, sampling time $\tau = 1$ ms. It is found obviously about the quantum fluctuation of photon counting. Figure 2(b) reflects statistical characteristics of photon counting in Fig. 2(a). The solid line is the fitted curve of Poisson's distribution. As can be found from Fig. 2(b), the photon counting of coherent light field obeys Poisson distribution.

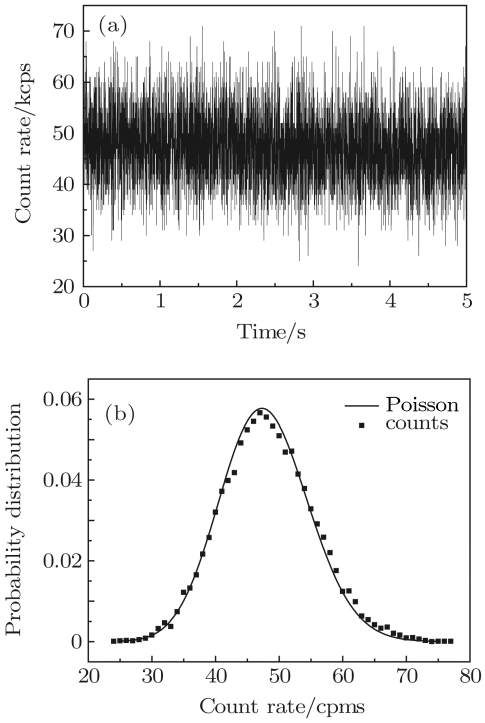


Fig. 2. Quantum fluctuation of photons counting (a) and its statistical characteristics (b) at $\alpha = 50$ kcps.

Figure 3 (a) depicts an analog signal of the photon counts after the digital-analog converted in photon counting OTDR from the end of the fibre. Figure 3(b) shows the Fourier transforms (FFT) results of the analog signal in Fig. 3(a). We found that the noise amplitude distribution of the photon counting quantum fluctuations is a uniform distribution in the frequency domain. The lock-in method here will not be affected by the low-frequency $1/f$ noise. The magnitude of the carrier signal is about –8 dB at the location of 10-Hz modulation frequency, two orders of magnitude higher than the corresponding noise amplitude. Figure 3(c) shows the linear relationship between noise power and the mean photon number. The slope is 7.2×10^{-8} V^2/Hz·photon.

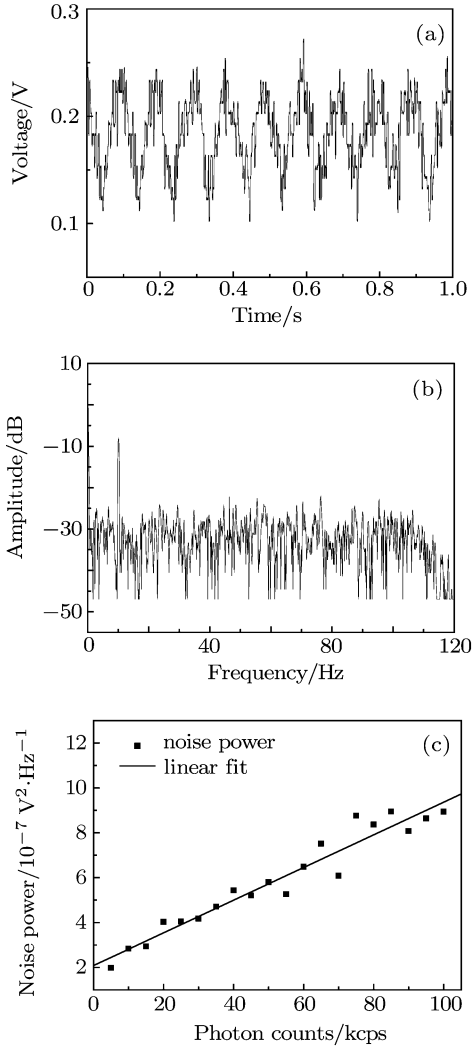


Fig. 3. The digital-to-analog signal for photon counting (a) and its noise amplitude spectral characteristics (b); panel (c) shows the linear relationship between noise power and the mean photon number.

However, the choice of modulation frequency also affected the measurement results. As shown in Fig. 4, the output signal value of the lock-in amplifier will gradually decrease as the modulation frequency increases. If the modulation frequency is lower, the data processing will need a longer time, which limits the measurement speed. Increasing the modulation frequency would increase the speed of data processing,

but reduce the average photon number and reduce the measurement sensitivity. In practical applications, we need to select an appropriate modulation frequency according to the average photon number.

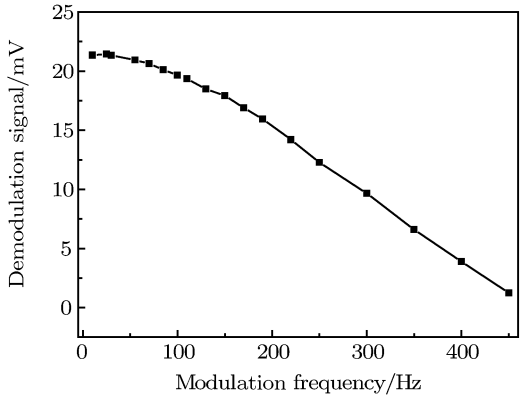


Fig. 4. The demodulation output from the lock-in amplifier versus modulation frequency.

Figure 5 shows the measurement results of the optical pulse OTDR at the end of the optical fibre. The x axis is the delay time between the trigger signals for laser and SPD. The reflection peak was obtained by regulating the delay time. The dashed line represents the time distribution characteristics of OTDR using photon counting methods directly. The counting time is $\tau = 10$ ms and the step of time delay is 5 ps. We found that bigger counts induce greater fluctuation. This is determined by the quantum fluctuations $(\alpha\tau)^{1/2}$ in photon counting. The solid line represents the photon count modulation OTDR results measured by the lock-in amplifier, where the quantum fluctuations are eliminated effectively.

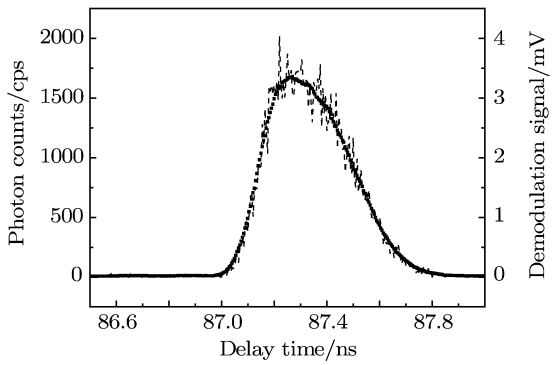


Fig. 5. The OTDR results from direct measurement of photon counting (dashed line) and photon counts modulation (dots).

Table 1 is the relationship between the slope of the low-pass filter and equivalent noise bandwidth (ENBW), where T is the integration time constant of lock-in amplifier. The filter slope determines the extent of the noise filter. The greater slope results in the smaller noise equivalent bandwidth and the ability to filter out the noise will be stronger. Improving the SNR could be achieved by selecting the integration time of the lock-in amplifier and then changing the filter bandwidth.

Table 1. The relationship between the slope of the low-pass filter and equivalent noise bandwidth (ENB) $W_{\rm ENB}$.

Slope	$W_{\rm ENB}$
6 dB/oct	$1/(4T)$
12 dB/oct	$1/(8T)$
18 dB/oct	$3/(32T)$
24 dB/oct	$5/(64T)$

Here, the slope of the filter used in our experiments is 18 dB, integraltion time is $T = 100$ ms. The filter bandwidth of lock-in amplifier, which means the noise equivalent bandwidth can be calculated $W_{\rm ENB} = 3/32T = 0.94$ Hz. For the 10-Hz modulation frequency in Fig. 3(b), the corresponding voltage noise spectral density is 10^{-3} V/Hz. Then the $R_{\rm SNR}$ of photon counts modulated OTDR is

$$R^{\rm M}_{\rm SNR} = 0.15\ {\rm V}/(10^{-3}\ {\rm V/Hz} \times 0.94\ {\rm Hz}) = 159. \quad (8)$$

With the average photon number at the peak $\alpha = 1700$ cps, maximum $R_{\rm SNR}$ of photon counting can be obtained from Eq. (3)

$$R^{\rm PC}_{\rm SNR} = \sqrt{\alpha\tau} = 4.12. \quad (9)$$

The signal-to-noise improvement ratio (SNIR) $R^{\rm I}_{\rm SNR}$ corresponding to the photon counts modulation is

$$\begin{aligned} R^{\rm I}_{\rm SNR} &= 20\log(R^{\rm M}_{\rm SNR}/R^{\rm PC}_{\rm SNR}) = 20\log(159/4.12) \\ &= 31.7\ {\rm dB}. \end{aligned} \quad (10)$$

5. Conclusion

In summary, a photon counts modulation method was presented to improve the SNR of OTDR. It is shown that, to our knowledge for the first time, the effects of quantum fluctuation can be effectively controlled and the SNIR was increased to 31.7 dB. The high SNR OTDR measurement can improve the dynamic range and time resolution effectively and has the possibility to be applied in single-photon sensing, quantum imaging and time of flight.

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