217 km long distance photon-counting optical time-domain reflectometry based on ultra-low noise up-conversion single photon detector

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Abstract: We demonstrate a photon-counting optical time-domain reflectometry with 42.19 dB dynamic range using an ultra-low noise up-conversion single photon detector. By employing the long-wave pump technique and a volume Bragg grating, we achieve a noise equivalent power of $-139.7\ \mathrm{dBm}/\sqrt{\mathrm{Hz}}$ for our detector. We perform the OTDR experiments using a fiber of length approximate 217 km, and show that our system can identify defects along the entire fiber length in a measurement time of 13 minutes.

OCIS codes: (190.7220) Upconversion; (120.4825) Optical time domain reflectometry; (270.5570) Quantum detectors.

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1. Introduction

Optical time-domain reflectometry (OTDR) is a commonly used measurement technique for fiber network diagnosis. By detecting the Rayleigh backscattered light of a pulse launched into fiber under test (FUT), one can get information about the attenuation properties, loss and refractive index changes in the FUT [1, 2]. Conventional OTDRs using linear photodetectors are widely used, but their performance is limited by the high noise equivalent power (NEP) of the p-i-n or avalanche photodiodes used in these systems. Photon-counting OTDRs (ν-OTDR), which employ single photon detectors instead, have been the subject of increased attention, becauase they offer better sensitivity, superior spatial resolution, an inherent flexibility in the trade-off between acquisition time and spatial precision, and the absence of the dead zones.

Several ν-OTDR systems have been demonstrated with InGaAs/InP avalanche photodiode (APD) operated in Geiger-mode [3, 4]. But in these demonstrations, the InGaAS/InP APDs used suffer from noise issues caused by large dark current and after pulsing [5]. Time gated operation of the detectors is used in these ν-OTDR measurements to reduce the noise. However, a consequence of time gated operation is that it only allows part of the fiber to be measured at a time, so the measurement time is longer than that using free running detectors by almost 3-order of magnitude [6]. Recently, ν-OTDRs based on free running superconducting single photon detectors (SSPD) have been reported [7, 8]. Thanks to the low NEP of SSPD, which is about $-140.97\ \mathrm{dBm}/\sqrt{\mathrm{Hz}}$, a dynamic range of 37.4 dB is achieved in a total measurement time of about 10 minutes [8]. However, the superconducting nanowire is operated in a bulky liquid helium cryostat to reduce the thermal noise. Up-conversion single photon detectors that consist of a frequency upconversion stage in a nonlinear crystal followed by detection using a silicon APD (SAPD), provide an elegant room-temperature free-running single-photon detection technology, and have been successfully applied in ν-OTDR systems [6, 9]. Recent results include a two-point resolution of 1 cm [9] and a measurement time more than 600 times shorter [6]. But these systems are not appropriate for long-distance fiber measurements, for the NEP of these up-conversion single photon detectors is about 2-order of magnitude larger than that of the SSPD. The high NEP means that much longer measurement times are required to obtain the same signal-to-noise (SNR) ratio at the end of the ν-OTDR trace.

In a recent paper, we demonstrated an ultra-low noise up-conversion single photon detector by using long-wavelength pump technology, and a volume Bragg grating (VBG) as a narrow band filter to suppress the noise[10]. The up-conversion single photon detector we used in the experiment has a NEP of about $-139.7\ \mathrm{dBm}/\sqrt{\mathrm{Hz}}$. Here, we employ the ultra-low noise up-conversion single photon detector and a high peak power pulsed laser, and present a ν-OTDR over fiber of 217 km length. With measurement time of 13 minutes, we achieve a dynamic range of 42.19 dB. The distance resolution of our system is about 10 cm; while the two-point resolution is about 100 m.

2. Experimental Setup

The experimental setup is shown in Fig. 1. Laser pulses with central wavelength of 1549.87 nm are launched into the FUT through an optical circulator. The peak power can be adjusted using

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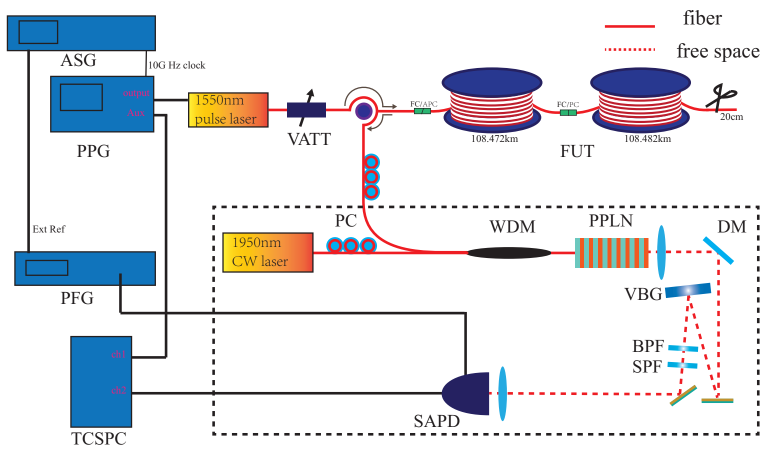

Fig. 1. Schematic of the experimental setup. ASG: analog signal generator, PPG: pulse pattern generator, PFG: pulse function arbitrary noise generator, TCSPC: time correlated single-photon counting system, VATT: variable optical attenuator, Circ: optical circulator, FUT: fiber under test, DM: dichroic mirror, PC: polarization controller, SPF: 945 nm short pass filter, BPF: 857 nm band pass filter, VBG: volume Bragg grating.

a variable optical attenuator (VATT). The FUT consists of two fiber spools of length 108.47 km and 108.48 km sequentially. The back scattered light is coupled into the third port of the circulator, and then detected by the ultra-low noise up-conversion single photon detector. The output of SAPD is fed into a time correlated single-photon counting system (TCSPC), which is operated in time-tagged time-resolved (TTTR) mode.

An analog signal generator acts as a clock of the whole ν-OTDR system by feeding a 10 GHz signal into "clock in" plug of a pulse pattern generator (PPG), and a 10 MHz signal as external reference of a pulse function arbitrary noise generator (PFG). The PPG's output is used to control the pulse laser, while its auxiliary output connected with TCSPC module to provide a 20 MHz synchronized clock. The output of PFG is used to switch the SAPD off temporarily during a repetition period of laser pulse, when we need to measure the FUT by sections.

The up-conversion single photon detector we used for this experiment, shown in the dash box of Fig. 1, is fully described in [10]. The signal light and 1952.39 nm pump laser are combined by a 1950 nm/1550 nm WDM and coupled into the z-cut PPLN waveguide through the fiber pigtail. A polarization controller is used to adjust the pump laser to the TM mode, for the PPLN waveguide only supports Type-0 (ee $\rightarrow$ e) phase matching. A Peltier temperature controller is used to keep the waveguide's temperature at 60.8 °C to maintain the phase-matching of the sum frequency generation (SFG) process. The generated SFG photons are collected by an AR-coated objective lens, and separated from the pump by a dichroic mirror (DM). A VBG, a 945 nm short pass filter (SPF) and a 857 nm band pass filter (BPF) are used to suppress the noise. Finally, the SFG photons are collected and detected by a SAPD. The dark count rate of the SAPD we used is about 60 Hz. Thanks to the long-wavelength pump and the narrow band VBG filter, we can suppress the dark count rate of the up-conversion single photon detector to 80 Hz while the detection efficiency is 15%, which corresponds to an NEP of about -139.7 dBm/$\sqrt{\text{Hz}}$. This condition is set as the operation point in our experiment.

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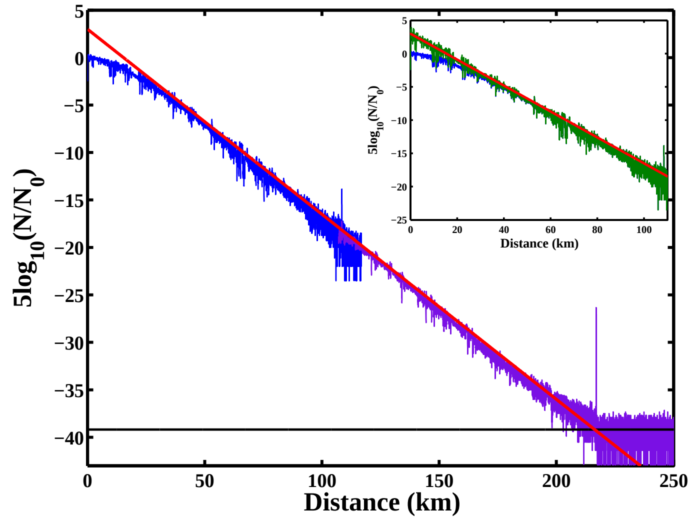

Fig. 2. Measurement of optical fiber of 217 km length performed by our ν-OTDR system. The pulse width is 1 μs. N is the counts of back scattered photons, N_0 is the count at the the initial point of the trace. The blue trace and violet trace are obtained in the first step and the second step of measurement, respectively. The position of the two peaks, 108.47203 km and 216.95422 km, coincides with the length of the two fiber spools. The black horizontal line shows the RMS noise level of the trace,which is about -39.19 dB. The intersection and slope of the extrapolated trace (red line) are 3 dB and 0.195 dB/km, respectively. The inset shows the comparison between the corrected trace (green) and the trace measured directly (blue).

3. Long distance ν-OTDR Application

In long distance ν-OTDR applications, if the pulse extinction ratio is poor and there is still light in the pulse interval, the back scattered photons of the light will cause non-negligible noise. Therefore the laser pulse extinction ratio is also crucial for a good signal noise ratio. To take advantage of the our low NEP of up-conversion detector, we expect the noise to be below the noise level of the detector. This requires a extremely high pulse extinction ratio of more than 100 dB. This is achieved by providing a small reversed bias voltage to the laser diode; we have confirmed that the emission between laser pulses is below our detection limit . The maximum peak power of our laser pulse is about 23 dBm. The repetition frequency is chosen according to the length of FUT. For a 217 km-long fiber, the round trip time of laser pulses in it is 2.14 ms. So the repetition frequency of the laser pulse must be lower than 452 Hz and in our experiment, we set the laser pulse repetition frequency at 400 Hz. The pulse width of the laser is set at 1 μs.

The measurement is divided into two steps. The repetition frequency and pulse width are unchanged in the two steps. In the first step, we attenuated the peak power to about 5 dBm and perform a 3minute ν-OTDR measurement. Due to the fiber loss, the counts of back scattered photons become smaller than the detector noise at about 120 km of the FUT. We only record the $0-120$ km ν-OTDR trace of FUT in the first step. And then, we manually adjust the laser peak power to 23 dBm, and perform a 10 minutes measurement of the remaining fiber. Because the peak power is high, there will be a great amount of photons reflected by the input surface and backscattered by the initial several kilometers of the FUT. To protect the SAPD, we apply a TTL signal to the SAPD gate input. The frequency of the signal is 400 Hz and the duty cycle

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of the signal is 60%. The low TTL level is applied to the SAPD gate input to switch it off after the pulses are launched into the FUT. Thus, we only get the ν-OTDR trace from 100 km to the end of FUT in the second step. The two sections are jointed into one according to their time delays, as shown in Fig. 2.

The up-conversion single photon detector in the experiment is polarization dependent. The strong fluctuation of the ν-OTDR trace in Fig. 2 corresponds to the polarization state revolution when the light propagates through the fiber, and can be used to study the polarization properties of fiber. The polarization induced fluctuation can be eliminated by using a polarization scrambler [9] or a polarization independent up-conversion single photon detector [11]. The cross talk and Fresnel reflection of the optical circulator will induce a very high peak in the ν-OTDR trace, which is not useful for diagnosing the FUT. Furthermore, the high peak will induce a following dip in the ν-OTDR trace due to the dead time of SAPD and TCSPC. In order to avoid this, we adjust the high peak's polarization so that it has a very low probability to be recorded by our polarization dependent OTDR.

In Fig. 2, N is the counts of back scattered photons, N_0 is the count at the the initial point of the trace. Thus $10\log_{10}(N/N_0)$ represents the total loss in the round trip of the fiber. As is common in OTDR experiments, we plot $5\log_{10}(N/N_0)$, which represent single-pass loss through the fiber. The dead time of the SAPD used in the experiment is about $T_d = 60$ ns,during which, the photons will not be recorded successfully. So the measured counting rate is smaller than the actual one. Here we utilize a standard way to make the correction [12]. So when the measurement time $T \gg T_d$, the counting rate registered per time bin reduces to $C_r(t)T = C_{act}(t)T - C_{act}(t)T\sum C_r(t^{'})$, where $C_r(t)$ is the registered counting rate per time bin, $C_{act}(t)$ is the actual counting rate without dead time effect and the summation means the total counting rate of time bins of time interval $[t - T_d, t]$. The actual counts can be corrected as $C_{act}(t)T = \frac{C_r(t)T}{1-\sum C_r(t^{'})}$. It is obvious that the difference between measured and true actual counting rate is small when the counting rate is very low. In the first step of our experiment, the count rate is more than 7×10^5 Hz for the beginning of the ν-OTDR trace. As shown in inset of Fig. 2, we correct the measurement trace (with a color of blue) with the above formula and the achieved trace (with a color of green) coincidences with the extrapolated trace (with a color of red) obtained by a linear fit of measured trace. The slope of the extrapolated trace indicates the attenuation of fiber of 0.195 dB/km. The intersection of the extrapolated trace is the actual value of the trace at the initial point, which is about 3 dB. The trace of experiment can be distinguished from the noise obviously at the end of the fiber. The root mean square (RMS) noise level is calculated from the data at the tails of the trace. The dynamic range is about 42.19 dB, which is determined by the difference between the intersection of the extrapolated trace and the RMS noise level.

One important parameter of OTDR is the distance resolution. It is the ability of the OTDR to locate a defect along the FUT, especially, the ability to locate the end of the FUT. The timing jitter of the detector Δt determines the distance resolution ΔL. The distance resolution can be estimated as $\Delta L = v_g \Delta t/2$, where v_g is the group velocity of light in fiber. From our detector timing jitter of 500 ps we compute a distance resolution of approximately 5 cm. In order to demonstrate the spatial resolution experimentally, we cut 20 cm fiber off at the end of the second fiber spool, and perform the experiment again as described above. The last reflection peaks of the two ν-OTDR traces are shown in Fig. 3. As shown in the Fig., the laser pulse is not broadened after transmitting through 217 km fiber. The leading edges of the two peaks, as shown in inset of Fig. 3, are separated with a 20 cm distance which coincides with the length of the cutting off fiber. According to the Fig., the experimental distance resolution is about 10 cm, which is larger than the expected resolution of 5 cm. The difference is caused by the fluctuation of the counts, which can be improved by extending the measurement time. Note that

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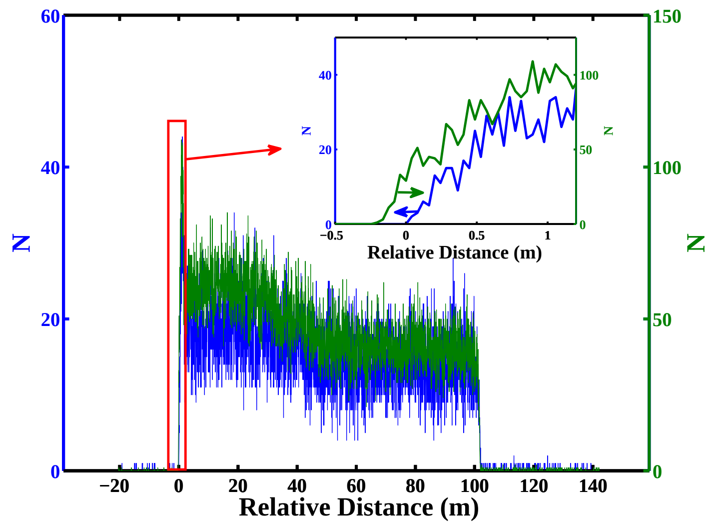

Fig. 3. Counts of last reflection peaks of ν-OTDR trace of the 217 km fiber (blue line) and after the 20 cm fiber is cut off at the end (green line), which are represented by the right y-axis and left y-axis, respectively. The amplitude of the two peaks are different because the cutting surfaces of fiber end are not identical. The inset shows the enlarged view of the leading edge of the two peaks.

the distance resolution is different than the two-point resolution, which is minimum distance between the defects that can be discriminated. The two-point resolution we can achieve is about 100 m, which is determined by the 1 μs pulse width we used in our experiment. Using shorter pulses will improve two-point resolution. But meanwhile, shorter pulses with a constant peak power means less photons in the pulse, which will decrease the measuring range and resolution.

4. Conclusion

In conclusion, we have presented the implementation of a ν-OTDR over 217 km-long optical fiber. It is based on an ultra-low noise up-conversion single photon detector, and the NEP of the detector is suppressed to -139.7 dBm/$\sqrt{\mathrm{Hz}}$ by using long-wavelength pump technology and a VBG as a narrow band filter. We also use laser pulses of 23 dBm peak power to reduce the measurement time. This apparatus can achieve a dynamic range of 42.19 dB and distance resolution of about 10 cm at the distance of 217 km in measurement time of 13 minutes.

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