Single-photon optical-time-domain reflectometer at 1.3 μm with 5-cm resolution and high sensitivity

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We demonstrate an optical-time-domain reflectometer operating at λ = 1.3 μm. It features a spatial resolution of better than 5 cm and enough sensitivity to detect the Rayleigh scattering at the same resolution when operated with a low-power semiconductor laser. Field operation of the instrument is discussed.

Single-photon optical-time-domain reflectometry (OTDR) has proved to be a powerful tool for optical fiber diagnosis. With the use of silicon detectors and an excitation wavelength of 0.85 μm, centimeter resolution, the absence of dead space, and a sensitivity of 10⁻¹⁸ W at centimeter resolution were demonstrated.¹ Such instruments are commercially available both for fiber characterization and for applications in distributed optical fiber sensors. This performance is directly determined by the favorable characteristics of silicon avalanche photodiodes operated in the Geiger mode and by the photon-counting technique, which permit operation with zero dead space since they eliminate the need for high-speed, low-noise, extended dynamic preamplifiers.²³

Unfortunately, silicon is not sensitive at 1.3 and 1.5 μm; thus extension of single-photon OTDR to the second and third windows with similar performance is ruled out at present. Levine et al.⁴ demonstrated single-photon OTDR at 1.3 μm by employing a defect (a microplasma) in a separate absorption grating and multiplication photodiode operated in the Geiger mode. However, their results are affected by a severe limitation in the bias voltage that could be applied, so the spatial resolution of the measurement was not satisfactory, at least when compared with that obtained by use of a silicon detector. Also, the detector was in fact a defective avalanche photodiode, so the production of such devices is at least questionable with regard to yield and uniformity of performance. Last, the active area of the microplasma was very small; therefore optical alignment was critical.

Recently we demonstrated⁷ that a commercially available germanium avalanche photodiode can be operated as a single-photon detector if properly selected and cooled at liquid-nitrogen temperature. The quantum efficiency of such detectors at 1.3 μm is close to that of high-speed silicon detectors (≈6% at 0.85 μm), and the temporal resolution (i.e., the equivalent of the rise time in a single-photon environment) is better than 300 ps. The diameter of the active area is relatively large, 30 μm. Only the noise of the germanium samples is significantly higher than that of the silicon devices, and it is also dependent on the detector count rate. Nevertheless, we predicted that it should be possible to employ these devices in a single-photon OTDR setup. In this Letter we report what are to our knowledge the first results of OTDR measurements performed with cooled germanium photodiodes operated as single-photon detectors.

The optical part of the experimental setup is a conventional OTDR apparatus. The laser (Optoelectronics PPL30K) emitted 75-ps pulses with a peak energy of 30 mJ into a 50-μm-core/125-μm-cladding communication-grade fiber. The laser repetition rate was 5 kHz. The light was coupled to the fiber under test through a Y coupler (Canstar TC3-B). At the other arm of the coupler a suitable optic collected the backscattered light onto the Geiger-mode avalanche photodiode (Fujitsu FPD-13R31). The photodiode was mounted in a cryostat and cooled to 77 K. The electronic part of the setup consisted of a timing apparatus. An electric pulse synchronous with the laser pulse starts the voltage ramp of a time-to-pulse-height converter. The detector is operated by an active quenching circuit, which emits a pulse of standard amplitude and shape synchronously with the detection of a photon. This pulse stops the ramp generator of the time-to-pulse-height converter. The final amplitude of the time-to-pulse-height converter output pulse is thus proportional to the time between the laser shot and the backscattered photon detection. One measures the OTDR trace by collecting the histogram of the photon-arrival times.

It is worth noting that the setup is able to measure the arrival time of only the first detected photon for each laser pulse, therefore the OTDR trace suffers a distortion each time the probability of detecting more than one backscattered photon per laser pulse is not negligible. Since the sensitivity of the detector is high, this is the case in our measurements. We have
shown in Fig. 1 for the detector operating at the count rate employed in our experiments.

Figure 2 shows an OTDR measurement on a 170-m fiber before and after background subtraction. The measurement time is 3 min, and the spatial resolution is limited to 2.5 m owing to the choice of the time duration of the single histogram channel. In fact, the laser pulse duration is still 75 ps, and the bias voltage is 0.2 V above breakdown, which corresponds to a detector resolution of 800 ps. Notice from curve a that the ratio between the Rayleigh scattering and the device background, which is visible both before and after the fiber, is greater than 10, so that in this case the noise added by the Poissonian distribution of the dark counts is almost negligible. In fact, we get

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S/N = \frac{n_l}{\sqrt{n_d + n_l}} = \frac{1}{\sqrt{1 + n_d/n_l}} \cdot \frac{n_l}{\sqrt{n_l}} = 0.95(S/N)_{q}\, ,
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where \(n_l\) is the number of the detected photons at a given position, \(n_d\) is the number of dark counts at the same position, and \((S/N)_{q} = n_l/\sqrt{n_l}\) is the theoretical limit of the signal-to-noise ratio (quantum-limited detection). From this result we concluded that the dark count rate of the detector is compatible with the requirement of the present measurement. It is also clear that the signal-to-noise ratio in the measurement is limited by fundamental constraints.

By choosing a different duration of the histogram channel, we obtained the enlargement of the Fresnel reflection shown in the inset of Fig. 2. It is worth stressing that no other change of the setup was made here and that the measurement time was still 3 min. The spatial resolution appears to be better than 10 cm, which is now limited by the temporal resolution of the detector at this voltage.

In order to test further the spatial resolution achievable with our setup, we made other measurements on three fiber samples of lengths of 31, 22, and 13 cm. These fiber sections were connected through plastic biconic connectors. The OTDR trace thus employed suitable data-correction procedures\(^7\) to obtain a true OTDR trace from the raw data. In particular, we have adjusted the launched optical power so that the probability of detecting a backscattered photon was 63% for each laser pulse. It can be demonstrated that this percentage maximizes the signal-to-noise ratio at the fiber end. In our experiments, it was necessary to attenuate the laser pulse by a factor of \(~3\) to obtain this 63% probability; thus we estimated that the optical peak power launched into the fiber was \(~10\, mW\). Once data correction is performed, there is still a need for operating the subtraction of the count-rate-dependent background. It is important to note that there is a trade-off between the dark count rate and the time resolution in these devices: by increasing the bias voltage above the breakdown, one gets a better time resolution but also a higher dark count rate, i.e., a worse signal-to-noise ratio. This is quantitatively

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**Fig. 1.** Dependence of the dark count rate and the spatial resolution of the detector used on the bias voltage. For each point of the curve the bias voltage above the breakdown and the resulting quantum efficiency at 1.3 \(\mu m\) (in percent) are indicated.

**Fig. 2.** OTDR measurement of a 172-m 50-\(\mu m/125-\mu m\) graded-index fiber obtained with the present technique. The curves before (trace a) and after (curve b) background subtraction are shown. The inset shows a closeup of the final Fresnel reflection. Notice the achieved spatial resolution. The measurement time is 3 min.

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**Fig. 3.** OTDR measurement of three fiber samples of lengths 31, 22, and 13 cm connected through plastic biconic connectors. The OTDR trace...
as obtained with our instrument is shown in Fig. 3. Notice that the two Fresnel reflections 13 cm apart are well resolved; thus it is clear that the instrument has the ability to resolve two Fresnel reflections at a distance of less than 10 cm without data deconvolution. It is also apparent that the device has a sharp response and that the recovery from a Fresnel reflection down to the Rayleigh scattering level occurs in ≈20 cm of fiber. The bias voltage in this case was increased to 0.5 V above breakdown, for us to obtain 350-ps resolution.

We made a further test by measuring a fusion splice at a 20-m distance in a 30-m fiber. The splice was made deliberately lossy. The results are shown in the inset of Fig. 3. Notice that the splice is resolved with better than 5-cm resolution and that the loss is easily determined in 3 dB. In other tests, we detected a 0.3-dB splice with the same spatial accuracy in a 15-min measurement.

All the measurements were made on a multimode fiber, although there is a general trend to use monomode fibers at this wavelength. Unfortunately our laser was not able to provide an efficient coupling on monomode fibers, since it was already pigtailed on a multimode 50-μm/125-μm fiber. However, our results show that similar performance can be achieved with a single-mode fiber. The following points should be noted:

(i) The laser pulse duration in our experiments is only 75 ps, while the detector performance is 300 ps. Therefore one can achieve a fourfold increase in the laser pulse energy with no loss in spatial resolution by simply increasing the laser pulse duration to 300 ps. (ii) Even with the present 75-ps laser pulse, we had to reduce the laser peak power by a factor of 3 in order to obtain the 63% probability of a photon detection for each laser pulse. Thus there is room for an increase of a factor of 12 in the light energy that could be launched into the fiber. Since the ratio of Rayleigh backscattering between a multimode fiber and a monomode fiber is not far from 10, we conclude that the present technique certainly will be able to measure the Rayleigh scattering of even a monomode fiber at 1.3 μm with 10-cm resolution in a 3-min measurement.

In conclusion, we have shown for what is to our knowledge the first time that a single-photon OTDR employing a germanium detector is able to reach better than 5-cm spatial resolution at 1.3 μm, has an almost quantum-limited sensitivity, and can be operated with a simple diode laser. The instrument is thus compatible with field operation. The only drawback is the liquid-nitrogen operation of the detector; however, portable nuclear radiation detection systems operating at the same temperature are commercially available; thus field operation problems have been solved in similar instruments. It is also important to note that the low power of the excitation laser enables one to perform the OTDR measurement without disconnecting optical receivers from the fiber under test.

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References