No Dead-Space Optical Time-Domain Reflectometer

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Abstract—An optical time-domain reflectometer operating at room temperature with the single-photon counting technique is described. It features subcentimeter resolution without data deconvolution, and the capability of observing Rayleigh scattering a few centimeters after a reflecting (Fresnel) discontinuity.

The key component for the instrument is a silicon single-photon detector of a new design. It is shown that the instrument limitations in the measurements depend mainly on the gain-switched laser diode, which is the laser of choice in portable instruments suitable for field measurements.

I. INTRODUCTION

OPTICAL time-domain reflectometry (OTDR) is a widely employed method for measuring the attenuation characteristics of optical fibers. Since its first demonstration [1], much effort has been spent in order to increase the performance of OTDR apparatus [2].

The OTDR technique consists of sending a light pulse into the fiber under test and measuring the waveform of the backscattered light. This backscattered light is due to essentially two physical mechanisms, i.e., total (Fresnel) reflection from fiber discontinuities, and Rayleigh scattering. Since the velocity of the light in the fiber is known, the optical backscattered power measured at a time T after the exciting light pulse gives information on the fiber attenuation characteristics at a distance L = TV/2 (the factor 2 is needed since the light travels for a distance 2L from the injection point to the backscattering position and then back to the detector). It follows that the duration of the light pulse and the impulse response of the photodetector (whose quadratic sum is, in practice, the instrument resolution) must be sufficiently short if a small portion of the fiber has to be characterized. For example, if a 1-cm resolution is required, the instrument resolution should be less than 100 ps. The equivalent bandwidth is high, and problems arise in the signal-to-noise due to the very low power of the backscattered light.

Furthermore, the Rayleigh scattering intensity is many orders of magnitude lower than the Fresnel reflection intensity when optical pulses of duration in the 10–100 ps range are used. If photodetectors operating in the analog regime are employed, the preamplifier placed at the photodetector output is likely to saturate when a Fresnel reflection is detected. The small Rayleigh scattering of the subsequent fiber (if any) is not detectable for a certain distance because the preamplifier has to recover from nonlinear behavior. This effect is well known in the literature, and is called dead space. Various techniques have been suggested to substantially reduce the dead space [2]-[4].

The new application of short-haul optical fiber connections, e.g., for local-area networks, requires improved OTDR instruments, possibly with subcentimeter resolution, enough sensitivity to detect Rayleigh scattering, and no dead space. Portability of the apparatus is also a must if the measurements have to be made on the field.

In this paper, we show that a time-correlated photon-counting apparatus that makes use of single-photon avalanche diode SPAD [5]-[7] can fulfill all of these requirements. Time resolution of these diodes is remarkably better than 50-ps FWHM, corresponding to the ability of spatially separate two Fresnel reflections placed 5 mm apart without requiring any mathematical treatment of the data. Sensitivity in the 10⁻¹⁵ W range at 1-cm resolution is obtained. There is no dead space since the digital detection process avoids problems related to the nonlinearity and saturation of analog amplifiers. We demonstrate that the Rayleigh scattering can be seen a few centimeters after a Fresnel reflection. This characteristic limit is related not to nonlinearities, but to the resolution function shape; in order to quantify it, we introduce the concept of hidden space.

II. DEAD SPACE AND HIDDEN SPACE IN OTDR MEASUREMENTS

Centimeter or even millimeter resolution is claimed by a number of manufacturers of portable OTDR apparatus [8], [9]. However, different definitions of resolution are used for the various instruments. Such definitions are compared in the following.

The word “resolution” is almost always used to define the precision with which a Fresnel reflection can be located along the fiber. The following definitions of “resolution” have indeed been employed:

1) The uncertainty in the location of the centroid of the Fresnel reflection peak [8].
2) The rms error in the position of the peak value of the Fresnel reflection.
3) The full-width at half-maximum (FWHM) value of the waveform corresponding to the reflection [6].

Definition 3) is indeed the most stringent. It is equiva-
lent to requiring that two Fresnel reflections having equal amplitude should give two different peaks in the raw data if their distance is greater than the resolution of the OTDR. In order to discriminate two different peaks separated by the nominal resolution distance, defined according to 1) or 2), one has to deconvolve the data. Such deconvolution consists of a) supposing that the observed peak in the OTDR trace is due to two (or more) different discontinuities, and b) fitting the actual shape of the observed OTDR trace with the two (or more) OTDR traces of a single discontinuity. The fitting parameters are the amplitudes of the single Fresnel reflections and the distances between them.

None of these resolution definitions is well suited to the case where the Rayleigh scattering after a large Fresnel reflection is to be measured. In fact, even in the case of absence of dead space, the trace corresponding to a Fresnel reflection normally exhibits a long tail. The low-amplitude Rayleigh scattering is therefore hidden for a long distance by the tail. In the following, this effect will be called hidden space. Note that this effect has nothing to share with the dead space, which depends on a saturation, i.e., a nonlinearity. In principle, hidden space can be eliminated with data deconvolution. In practice, however, we estimate that deconvolution is possible only when the tail of the Fresnel reflection is lower than 1/100 of its peak value. We define therefore (somewhat arbitrarily) the hidden space as the full-width at 1/100-maximum (FW100M) of the impulse response of the apparatus. This estimate is based on the results that can be achieved with sophisticated reconvolution programs that are currently in use for analyzing fluorescence decays [10]. If no deconvolution is available, the FW100M is not a good figure for defining the hidden space. Instead, one should use the time needed to attenuate the tail to the Rayleigh scattering level. In conclusion, the dead space plus the hidden space define the region after a Fresnel reflection in which Rayleigh scattering is not measurable in practice.

Photon-counting OTDR features no dead space. In fact, the information is not carried by the analog waveform of the detector pulse, and consequently, there is no problem of finite linear amplitude range. In photon-counting setups, the detector supplies standard pulses (that is, pulses having constant shape and amplitude), and the information consists of the time of occurrence of such pulses (see the next section). For this reason, the detection of Rayleigh scattering after a Fresnel reflection is limited in photon-counting OTDR only by the hidden space. This strongly suggests that photon-counting OTDR can be the ideal technique for characterizing local area networks of optical fibers.

Various single-photon detectors are available that have time resolution and sensitivity useful for the purpose, namely, microchannel-plate photomultipliers [11] and geiger-mode avalanche photodiodes [12], [5]. We have demonstrated a centimeter-resolution OTDR with SPAD’s, which are specially designed silicon avalanche photodiodes operating in the geiger mode [6], [7]. The new generation of such devices has led us to reduce the hidden space to a few centimeters.

III. MEASUREMENT TECHNIQUE AND COMPONENTS

In order to achieve a centimeter resolution with single-photon OTDR, a time-correlated single-photon counting setup is employed [11]. The measurement principle is shown in Fig. 1. An electronic chronometer (which is actually made of a time-to-amplitude converter and an analog-to-digital converter) accurately measures the time between the emission of the laser pulse and the detection of the backscattered photon. These events are marked by fast electrical pulses, which come respectively from the electric laser drive circuit and a custom active quenching circuit [14], [15] for the SPAD device (see later in this section). A multichannel analyzer records the time histogram of the backscattered photons. In this way, the rise-time requirements for the pulses in the chronometer are not stringent; instead, all jitters in the circuits of the setup should be minimized. Commercially available time-to-amplitude converters and multichannel analyzers can achieve an electronic resolution of 10-ps FWHM in the time measurement [5].

For the same reason, the single-photon detector should output an electrical pulse (which is fed to the chronometer) having the least possible jitter with respect to the backscattered photon absorption. The same holds for the jitter between the laser emission and the laser trigger pulse. A final requirement is the duration of the laser pulse: it must be as short as possible. The total time resolution can be estimated by quadratically summing all the mentioned jitters and the laser pulse width. The wide dynamic range of the backscattered light power implies further requirements in the laser pulse: first, its background CW luminescence emission should be kept to a minimum (otherwise, it may obscure the Rayleigh scattering). Second, the laser pulse should itself have an FW100M as small as possible for the reasons explained in the previous section. Third, the shape of the laser pulse should be as regular as possible because even small secondary peaks or irregularities are clearly visible. As we show in the following, these requirements are rather stringent, and it is often necessary to filter the laser light in order to improve the pulse shape.

It is important to note that in the time-correlated photon-counting technique, the information is processed in a digital way right from the beginning. Therefore, there is no problem of linearity. The technique is, in fact, being used in various fields, in particular, in time-resolved spectroscopy, for accurate measurements over many decades. The only limit in the linearity comes from the accuracy of the time sorter, that is, mainly from the differential linearity of the analog-to-digital converter. Typical values for this parameter are of the order of $10^{-3}$.

The single-photon detector is the key component of the apparatus. Specially designed avalanche photodiodes can be used above the breakdown as geiger-mode single-photon detectors. In this bias condition, a single carrier can
trigger a self-sustaining avalanche current. If the carrier is photogenerated, the leading edge of the avalanche pulse marks the arrival time of the detected photon. The current then continues to flow until the external circuit [14], [15] lowers the bias close to or below the breakdown voltage, thus quenching the avalanche. At the end of a short dead time (typically 500 ns), the bias is rapidly restored in order to make possible the detection and timing of another photon. The avalanche can also be triggered by carriers thermally generated and emitted from the trap levels [16] in the depletion layer of the active junction. This effect causes the inherent dark count rate of the device that sets the achievable sensitivity in OTDR measurements. The detector resolution is determined by the statistical distribution of the delay between the true arrival time of the photon at the detector and the actual detection time, as derived from the electrical output signal of the detector.

The most extensively employed commercial photodiode suited to be operated as a single-photon detector is the RCA C30921. The best reported values for the FWHM resolution of these devices are 400-ps FWHM resolution when cooled to −40°C and 460-ps FWHM resolution at room temperature [12]. The achieved FWHM is 2 ns (see Fig. 4), corresponding to a hidden space of 20 cm. However, this figure is not really significant since the detector noise is too high for measuring the Rayleigh scattering. In fact, at the above-mentioned detector temperatures, the dark count rate is in the range of $10^3$ pulses/s. It is possible to circumvent this limitation by reducing the photodiode bias voltage, but at the expense of a much worse resolution.

However, these results by no means represent the ultimate performance limit for solid-state detectors. Much higher resolution and a much lower dark count rate are obtained with special avalanche devices, single-photon avalanche diodes (SPAD’s), specifically designed to work in the geiger mode.

We have already demonstrated an OTDR with SPAD detectors of old design (which are referred to in the following as SPAD 3; see Fig. 5) [17]. The FWHM resolution attained 60 ps, and the Rayleigh scattering was clearly visible since the sensitivity was $10^{-15}$ W at that resolution. The structure of SPAD 3 is shown in Fig. 2. We have now designed and fabricated SPAD devices with a novel epitaxial structure [18], [19] for improved timing performance. A schematic diagram of the new structure is shown in Fig. 3. A complete description of the SPAD devices and of their performance is given in [5], [17]–[19]. Here, we briefly comment on their main features.

As previously observed, reducing the dark count rate is essential in order to achieve the sensitivity required to measure the Rayleigh scattering. This goal is obtained by reducing the generation centers and trap concentration in the depleted region of the diode by careful wafer processing, and by reducing the volume of the depleted region itself. In the commercial devices, the depleted region is a cylinder having 500-μm diameter and 35-μm thickness. We reduced the volume in our devices to 8–10-μm diameter and 3-μm thickness. Consequently, the dark count rate was reduced to $10^2$–$10^3$ pulses/s at room temperature. A much better time resolution, in the 20–60-ps FWHM range, was obtained by reducing the depleted region thickness (thereby reducing the transit time for the carriers) and by redesigning the high-field region of the device.

It might be objected that such a substantial reduction of the device dimensions, in particular of the depleted region thickness, may cause a serious drawback in OTDR measurements. Since at 850-nm wavelength the absorption length in silicon is around 15 μm, the quantum efficiency of the device is strongly reduced. It must, however, be noted that in the time-correlated photon-counting technique, the number of detected photons per excitation pulse has to be lower than one, typically about 0.05 [13]. The
peak power of commercially available gain-switched laser diodes is more than enough to attain such a detected intensity in OTDR measurements with SPAD’s. The reduction in the quantum efficiency of SPAD devices is therefore found to be acceptable in practice, and the time required to collect an acceptable number of photon counts is not adversely affected. At any rate, there is an obvious tradeoff between resolution and quantum efficiency since the transit time in the depleted region directly affects the resolution. In order to achieve a 100-ps FWHM resolution, the thickness of the depleted region of the device should be less than 10 μm. It should also be observed that increasing the depleted region thickness also increases the dark count rate, and therefore the detector noise.

The time-correlated photon-counting measurements of a picosecond gain-switched laser diode, obtained with the RCA C30921S photodiodes and SPAD’s of the old (3) and new (11) design, are shown in Figs. 4 and 5. Note that all the curves show a fast peak and a slower tail. The resolution in the peak (i.e., the FWHM) is clearly much better in both SPAD’s, but the tail in SPAD 3 is very long. This is confirmed by the FW100M value, which is 5.2 ns, much worse than the FW100M of the RCA device, which is only 1.7 ns. The effects of the long tail of SPAD 3 in OTDR measurements are clearly shown in [6, fig. 2] and in [7, fig. 3]. The best value for the FW100M is obtained in SPAD 11, only 570 ps, corresponding to a hidden space of 5.7 cm in OTDR measurements.

The physical effect underlying the tail is the diffusion of photogenerated carriers in the neutral region beneath the active junction [20]. The RCA devices exhibit a very short tail since the carriers are almost entirely photogenerated in a field region, the photodiode being an almost completely depleted structure. In the SPAD structures of Figs. 2 and 3, the dotted regions represent neutral regions where carriers can be photogenerated and successively diffuse to the active region. The generation region is side-limited by the diaphragm action of the aluminum metallizations. Note the different extension of such regions in the two structures.

Not all the carriers photogenerated in the dotted region will eventually reach the active region, thus giving rise to delayed avalanches, and therefore to the tail. In their random walk, the carriers can reach other depleted regions where the applied bias is lower than the breakdown voltage. Such carriers will thus be swept out of the diffusion region, without generating an avalanche. The absorbing interfaces are shown in the figures as bold lines. Note the larger extension of the absorbing interfaces in SPAD 11.

From this discussion, the reasons why SPAD 11 exhibits such a dramatic improvement with respect to the older (3) SPAD are evident: a lower number of carriers is photogenerated in the neutral region, and a higher percentage of them reaches an absorbing interface.

IV. Experimental Results

The experimental tests were carried out on a 65/125-μm graded-index fiber. One end of the fiber was terminated in a biconic connector; the other was cut 8 mm apart. The laser was a Hamamatsu C1308 emitting at 833 nm. The pulses have 45-ps FWHM duration, at a repetition rate of 10^9 pulses/s. The active quenching circuit for the SPAD [14], [15] was homemade. The time-to-amplitude converter was an ORTEC Model 566 and the multichannel analyzer was a Silena Model Cicero. A 10–90% three-port fiber-optic coupler (courtesy of SIRTI, Italy) conveyed the laser light pulse to the fiber under test and the backscattered light from the fiber to the SPAD.

Coupling the laser to the fiber was critical. In fact, we observed secondary peaks and irregular features in the waveform of the laser pulse coupled into the fiber. This
was true, in particular, when focusing the laser light at the fiber end. Curve $a$ in Fig. 6 shows a typical waveform of the laser in this situation. In particular, a secondary peak is observed after 160 ps, and a relatively long-lasting luminescent emission is found before the onset of the laser pulse. We found that the secondary peak can be almost eliminated by filtering the light with an interference filter, and by operating a sort of spatial filtering, namely, by coupling only the light coming from a small section of the laser beam (this obviously reduced the available peak power of the laser pulse). This scheme also succeeded in almost completely eliminating a CW broad-band light emission. Moreover, the luminescent emission before the main laser peak was attenuated only by about 3 dB (see Fig. 6, curve $b$). All of the gain switched laser sources available in our laboratory exhibit irregularities in the waveform observed over various decades. None was perfectly fit to the purpose. We concluded that the gain-switched laser at present is the most critical component in measurements with both high resolution and sensitivity.

A measure on the test fiber is shown in Fig. 7. The coupled intensity was attenuated, so that a backscattered photon was observed from the fiber every 20 laser pulses on the average [13]. The measurement time was 10 min. In Fig. 7, three peaks are observed among them. Peak $a$ is due to the (rather poor) biconic connector, and peak $b$ is attributed to the fiber end. We attributed peak $c$ (that seems to come from a point after the fiber end) to that light that is first reflected by the fiber end, then by the connector, then once again by the connector, then once again by the fiber end, therefore traveling two more times in the fiber section under test. This is confirmed by the observation that the distance $a$-$b$ is equal (within an experimental error of about 2 mm) to the distance $b$-$c$.

Note that the tail of the reflection $a$ is reduced below 1/100 of the peak value well before the onset of the fiber end reflection. Therefore, we estimate that the Rayleigh scattering should be visible for such a short fiber by making use of a suitable deconvolution program. This also would be true if the hidden space were defined by the full-width at one-thousand-maximum (FW1000M). After the fiber end, the dark level can be observed. This is significantly lower than the Rayleigh scattering level in the fiber (compare to the level before peak $a$), and confirms that scattering can be observed a few centimeters after a reflection.

V. CONCLUSIONS

We have shown that time-correlated photon-counting OTDR inherently features no dead space. The detrimental effects of a Fresnel reflection consist only of a tail that obscures the Rayleigh scattering for a distance that is called hidden space.

New silicon single-photon detectors, the SPAD's, combine a high resolution in positioning a reflection (5-mm FWHM) with a short hidden space (5.7-cm FW100M) and very high sensitivity ($10^{-15}$ W at 1-cm resolution), thus outperforming commercial devices. In fact, a commercial apparatus operating with the single-photon timing technique reaches millimeter resolution only after deconvolution. For these OTDR's, the resolution of the data before deconvolution is claimed to be about 5 cm [21], that is, almost the same as the FW100M of the present apparatus.

The gain-switched laser employed in the measurements does not need to produce a high power to be useful for the purpose. However, the shape of the pulse in the available lasers is frequently poor, and must be monitored and corrected by optical filtering. The low optical power required makes it possible to characterize local-area networks without causing problems for the safety of the optical receivers in the network.

The measurement time is not yet completely satisfactory. It is dependent on the fiber length, and ranges from some minutes to several tens of minutes. It is obvious that the measurement time can be reduced drastically if the resolution can be kept lower or if there is no interest in observing the Rayleigh scattering with centimeter resolution. A possible strategy is to measure a long fiber with lower resolution and to successively perform high-resolution measurements of the portions of interest. We are
now working to implement a new measurement strategy that should reduce the measurement time, while maintaining the centimeter resolution and Rayleigh scattering sensitivity.

In conclusion, the described instrument fulfills the requirements for the characterization of local-area networks of optical fibers operating in the first window (850 nm).

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REFERENCES


* G. Ripamonti, photograph and biography not available at the time of publication.

* M. Ghioni, photograph and biography not available at the time of publication.

* A. Lacaita, photograph and biography not available at the time of publication.