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CORRECTION OF OTDR DATA FOR PHOTODETECTOR TRAPPING PHENOMENA

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Single-photon detectors used in OTDR suffer from carrier trapping phenomena, resulting in severe OTDR trace distortion. We introduce a simple data correction procedure which enables to evaluate the effects of such traps, thereby allowing an almost complete cancellation of their effects.

1. INTRODUCTION

With their extreme sensitivity, semiconductor single-photon detectors SSPDs are well suited to optical time domain reflectometry OTDR measurements. They are reverse-biased junctions operated above the breakdown. The absorption of a single photon in the active region causes the entire junction to break down, thus allowing the flow of large currents, which are easily detected. The rising edge of the current pulse is synchronous to the photon absorption with very small jitter, down to 20ps. Spatial resolution in OTDR measurements employing such detectors can be thus much better than a centimetre.

Various techniques for data acquisition with SSPDS have been proposed. All of them send a narrow light pulse into the fibre, time the arrival of the backscattered photons and accumulate an histogram of the photon arrival times by repeating this experiment many times. Unfortunately, the avalanche pulses cannot be assured only to impinging photons: thermal generation and trapping phenomena will also contribute avalanches. If the correct informations on the fibre under test are to be extracted, the latter contributions should be eliminated. Thermally-generated avalanches are easy to subtract, since they give rise to a continuous background which can be separately measured and then subtracted from the OTDR trace. On the contrary, the trap contribution is more difficult to evaluate and has been so far neglected.

Aim of this paper is to show that the effects of traps will significantly distort the OTDR trace in a complex way, and to introduce a fairly simple method to virtually eliminate the distortion.

2. AFTERPULSES FROM TRAPS

In a SSPD, a significant charge crosses a p-n junction any time a photon is detected. Free carriers can be trapped in so-called trap centres. These carriers will be subsequently released with exponentially decaying probability, thus triggering correlated afterpulses.

The physics of these states has been thoroughly investigated. It is here worth mentioning only that a SSPD can be used in operating conditions to characterize its own trap centres. Fig. 1 shows the results of one such experiment.

Accuracy of these data is very high: this opens the way for evaluating trap effects in OTDR data and for designing data correction routines. Data correction is necessary any times the probability of an
avalanche trigger due to traps is not negligible in comparison to light-triggered avalanches. This happens, for instance, when the detector is enabled to trigger again a few hundreds of nanoseconds after the preceding avalanche has been quenched. This is required in order to reduce measurement time.

3. DATA CORRECTION

Let us consider the ideal situation of a pure detector dead-time after an avalanche. This means that all photogenerated carriers and trap releases will generate an avalanche. Thermally generated carriers are not considered, since their effects can be easily taken into account.

Consider light-generated avalanches: each of them will be followed by trap-generated afterpulses. Since the process is linear, if the experiment is repeated many times, the trap contribution $H(t)$ will be the convolution integral of the backscattered light $L(t)$ with the trap decay curve $T(t)$, that is,

$$H(t) = \int_0^\infty L(t-r)T(r)dr = L(t) * T(t) \quad (1)$$

Trap-generated avalanches will themselves populate trap centres, therefore a "second generation" of trap releases will be present, which will give rise to a third generation and so on.

![Graph](image)

**Fig. 1.** Measurement of trap emission. Four trap levels are present in the trap, each of them contributing an exponential term to the curve.

The measured trace will be:

$$M(t) = L(t) + \sum_{k=1}^{\infty} L(t) * T(t) * k \quad (2)$$

where we have indicated with $T(t) * k$ the convolution of $T(t)$ with itself for $k$ times.

It is possible to obtain the function $L(t)$ from the knowledge of $T(t)$; let us convolve $M(t)$ with $T(t)$. We obtain:

$$M(t) * T(t) = \sum_{k=1}^{\infty} L(t) * T(t) * k \quad (3)$$

which is the total contribution of the traps to the OTDR trace. Therefore $L(t)$ will be given by:

$$L(t) = M(t) - M(t) * T(t) \quad (4)$$

This correction procedure is easy to implement and does not give mathematical instability problems.

4. DETECTOR DEAD-TIME

The presence of a dead time introduces problems in the correction procedure. Let us first consider trap effects as negligible. Not all of the photons will be observed. It is however possible to extend a known procedure for correction of an infinite dead-time to the present case.

We obtain:

$$L(t) = \left[ \frac{N \cdot M(t)}{N - \int_t^{T_d} M(\theta) \, d\theta} \right] \quad (5)$$

where $N$ is the number of laser pulses; $T_d$ is the dead time and $M(t)$ is the measured trace at time $t$. The procedure is easily interpreted as follows. The number of laser pulses that can result in an observed backscattered photon at time $t$ is not $N$, but $N$ reduced by the number of avalanches occurred in a dead time preceding $t$.

If traps are present in $M(t)$, correction for their effects is very complicated. Here we present an heuristic method to evaluate their contribution. First note that only
avalanches can populate traps. It follows that the trap contribution should be evaluated on the measured trace $M(t)$. We convolve $M(t)$ with $T(t)$ to get $C(t)$, the total trap contribution. In doing this, we remember that no trap release within a dead time after the filling avalanche can result in an avalanche. Therefore, $T(t)$ will be zero for $t < T_d$. Eq. (5) is then used to correct $M(t)$ for dead-time effects. Only at this point $C(t)$ is subtracted from the corrected trace.

Since this correction procedure is not mathematically founded, we have tested its ability to correct OTDR data by using a Monte Carlo simulation of an OTDR measurement with SSPD.

5. RESULTS

OTDR trace simulations were performed by considering a 2.5dB/km fibre, and a laser emitting 100ps pulses at 980nm with a peak power of 100mW. It follows that the average number of backscattered photons from a fibre of infinite length is $N = 1100$ per laser pulse.

The photodetector data are a quantum efficiency of 1%, a dark count rate of $10^4$ s$^{-1}$, and an average trap level with a time constant of $4\mu s$. To evaluate the importance of the various trap parameters, various simulations were performed, with number of trap-initiated avalanches from 0.2 to 0.5 per filling pulse, and detector dead times from 0.2 to 4.5. All these values are consistent with real SSPDs.

The simulated data acquisition technique was to measure the leading edge of each avalanche pulse, to impose the given dead time and to wait for the next avalanche pulse. Other acquisition techniques can anyway be simulated, yielding similar results.

Fig. 2 shows the results of the simulation for a 2km fibre. The dead-time is 0.5$\mu$s and the number of trap-initiated avalanches is 0.5 per filling pulse. The plotted curves refer to the impinged photons, to the OTDR trace as measured by the SSPD, and to the measured trace as corrected with the present procedure. Note that there is an evident discrepancy between the slopes of the photon and measured traces. This is due to the trap effects and can be verified by switching off the trap pulses in the simulation. The time constant of the photon trace is $4.6\mu$s in agreement with the 2.5dB/km assumption for the fibre. If no correction for trap effects were considered, the measured fibre attenuation would have been evaluated only 1.6dB/km. Note that this distortion of the data happens notwithstanding a trap time constant of less than a half of the photon trace time constant.

It should also be noted from the measurement that the trap correction procedure has restored the correct background level after the fibre end. The dynamic range of the measurement has improved of $= 25$dB.

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![Fig. 2 Monte Carlo simulation of an OTDR measurement on a 2km fibre. A thermal generation of 10$^{14}$s$^{-1}$ was considered and can be seen after the fibre end. The curves represent the backscattered photons (a), the measured trace (b), the trace corrected for dead-time (c). The final trace with subtracted trap effects (d) is undistinguishable from trace (a).](image-url)
Fig. 3 shows the simulation of a Fresnel reflection due to a connector. The duration of the dead-time is evident in the plot, by looking after the reflection. Also in this case the correction procedure is accurate, with the only exception of the dead-time following the reflection. This is due to the incorrect evaluation of traps in this region and can be confirmed by switching off the trap effects in the simulation. The correct OTDR trace after a Fresnel reflection can be however obtained by proper gating of the detector, as already shown by us.

6. COMMENTS AND CONCLUSIONS
We have introduced the first method to correct OTDR data for SSPD trap effects. The method is fairly simple and is able to accurately recover the data.

The use of such correction routine opens the way for a further reduction of measurement time in single photon OTDR.

For instance, the trace in Fig. 2 was obtained by simulating $10^6$ laser pulses. The number of detected photons was $7.2 \times 10^5$, that is, 64% of the total number of photons absorbed by the SSPD. If no correction routine for trap effects were available, a correct OTDR trace would be obtained only if the detector dead time were set to allow only one avalanche to be generated for each laser pulse. In this case, the number of detected photons would have been only $10^6$.

In conclusion, the reduction of the SSPD dead time yields a much faster acquisition of OTDR data, and the unavoidable effects of trapping can be almost eliminated by proper data correction procedures.

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