Tutorial – 10

Exam Text of 07/02/2005 (Problem 3)

A faulty joint in optic fibers reflects about 1% of the power coming from a laser pulse. This can be used to locate faulty joints in fibers. Rectangular laser pulses with a duration T_P=100ns and power P=1mW generated by a diode laser emitting light at 800nm are exploited. Reflections are observed using a silicon p-i-n photodiode (reflective coefficient at surface of 0.2; surface neutral region thickness 0.5μm, depleted region thickness around 10μm). The photodetector is connected to a current preamplifier featuring a wide bandwidth (limited by a single pole at f_{PA}=100MHz) and input-referred current noise with wideband unilateral spectral density Si=$(1pA)^2$/Hz. Speed propagation of pulses in fiber is 20cm/ns and the attenuation is 2dB/km.

a) Evaluate the minimum optical power of a pulse that can measured, assuming a minimum acceptable SNR=5.
b) Evaluate consequently the maximum distance in fiber at which it is possible to locate a faulty joint (hint: please note that the pulse has to travel forward and come back).
c) What is the spatial resolution, i.e. the minimum distance between two faulty joints that allows you to locate them both individually?
d) You are now asked to increase the maximum distance at which you can locate a faulty joint without impairing the spatial resolution. Discuss if and how it is possible to achieve this goal. Then, select a filter and evaluate the improvement factor that you can obtain with it.

A) Given that we are working with a sensor whose output is a current signal, it's better to work directly with current signals, let's assume the shot noise introduced by the signal is negligible the noise introduced by the pre-amplifier is equal to:

$$\sigma_i = \sqrt{S_I \cdot \frac{\pi}{2} f_p} \cong 12.5\, nA$$

Obtaining an SNR of:

$$SNR = \frac{I_P}{\sigma_i}$$

To satisfy the requirement on the SNR, the minimum measurable signal is:

$$I_{P,min} = 5\sigma_I \cong 62.5\, nA$$

Let's now check if the shot noise is effectively negligible:

$$\sqrt{S_{IP}} = \sqrt{2q_e I_{P,min}} \cong 141 \frac{fA}{\sqrt{Hz}}$$

The noise introduced by the signal is effectively negligible.
The quantum efficiency of the detector is the product of the probabilities of the photon of not being reflected at the surface, not being absorbed in the neutral region, and being absorbed in the depleted region:

$$P = 1 - e^{-\frac{W_D}{L_\alpha}}$$

Combining the three probabilities, we obtain:

$$\eta_D = (1-R) \cdot e^{-\frac{W_n}{L_\alpha}} \cdot \left(1 - e^{-\frac{W_D}{L_\alpha}}\right) \cong 0.48$$

From the quantum efficiency, we obtain the radiant sensitivity of the detector:

$$S_D = \eta_D \cdot \frac{\lambda[\mu m]}{1.24} \cong 0.31$$

From the radiant sensitivity we can derive the minimum optical power measurable:

$$P_{P,min} = \frac{I_{P,min}}{S_D} \cong 202\, nW$$

B) Given a faulty connection reflects only $\mathbf{1}\%$ of the input power we have that for a $\mathbf{0}$ length fibre, the power reflected is:

$$\boldsymbol{P_{R,0} = \frac{P}{100} = 10\ \mu W}$$

From the minimum measurable optical power calculated at point A, we obtain a factor:

$$\boldsymbol{K = \frac{P_{R,0}}{P_{P,min}} \cong 50}$$

To have an attenuation of $\mathbf{50}$ (considering both travel direction) the fibre has to have a length of:

$$\boldsymbol{L[Km] = \frac{10\log(K)}{4\ db\ /\ Km} = 4.27\ Km}$$

C) To properly detect two different faulty joints, the pulse reflected by the two joints must be distinct, thus, a distance strictly greater than $T_P = 100\ ns$ is needed.

Considering both travel direction, and a time distance between two pulses of $\boldsymbol{2T_P}$ the minimum distance between two joints is:

$$\boldsymbol{D_{min} = \frac{1}{2}(2T_P \cdot v_P) \cong 20\ m}$$

D) To improve the maximum detectable distance, we have to lower the minimum measurable power, given we have no information on the arrival time of the reflection pulse, a switching parameter LP (like a GI) has a non-trivial implementation, thus we can consider a simple low-pass RC filter.

To limit the effect of the filter on the signal we can chose a time constant shorter than the duration of the pulse, for example $\boldsymbol{\tau_{LPF} = 10\ ns}$, in this case we obtain for the noise:

$$\boldsymbol{\sigma_i = \sqrt{S_I \cdot \frac{1}{4\tau_{LPF}}} \cong 5\ nA}$$

To satisfy the requirement on the SNR, the minimum measurable signal is:

$$\boldsymbol{I_{P,min} = 5\sigma_I \cong 25\ nA}$$

That is equivalent to a minimum optical power measurable of:

$$\boldsymbol{P_{P,min} = \frac{I_{P,min}}{S_D} \cong 80.6\ nW}$$

This corresponds to an improvement on the measurable distance of:

$$\boldsymbol{L = \frac{10\log\left(\frac{P}{100 \cdot P_{Pmin}}\right)}{4\ db\ /\ Km} = 5.23\ Km}$$

We could also have used a mobile mean filter, implementing an optimum filter, for the noise we have:

$$\boldsymbol{\sigma_i = \sqrt{S_I \cdot \frac{1}{2T_P}} \cong 2.24\ nA}$$

To satisfy the requirement on the SNR, the minimum measurable signal is:

$$\boldsymbol{I_{P,min} = 5\sigma_I \cong 11.2\ nA}$$

That is equivalent to a minimum optical power measurable of:

$$\boldsymbol{P_{P,min} = \frac{I_{P,min}}{S_D} \cong 36\ nW}$$

This corresponds to an improvement on the measurable distance of:

$$\boldsymbol{L = \frac{10\log\left(\frac{P}{100 \cdot P_{Pmin}}\right)}{4\ db\ /\ Km} = 6.1\ Km}$$