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# Catastrophic and Parametric Fault Modelling for Photonic Systems

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## Abstract

*In this paper we investigate the impact of the most common catastrophic and parametric faults in photonic systems. We demonstrate, using the example of a photonic correlator, the effectiveness of testing techniques for fault detection in photonic systems. To the best of our knowledge, this constitutes the first attempt to define a fault model and to develop a test methodology for photonic systems.*

**Keywords:** photonic, fault modelling, fault simulation, photonic testing, catastrophic faults, parametric faults.

## 1. Introduction

Photonics is regarded as one of the most pervasive and enabling technology of the 21st century. Optoelectronic devices, including televisions, compact disc players, fibre optic communication systems, barcode scanners and mobile telephones have become a staple of everyday life. Photonics is catching on because of the advantages of optical fibre over copper cable for data transmission, and the use of optoelectronic techniques for sensing and instrumentation. Optical fibres capable of carrying data at rates exceeding a terabit per second and also spanning distances of tens of thousands of kilometres without electronic signal regeneration is impossible with copper and microwave systems [1].

Photonic circuits and systems generally have far fewer components than electronic circuits because the bandwidths of typical photonic components can reach terahertz, compared to tens of gigahertz for electronic components. However, the interactions of the components can be complex, being akin to analogue electronics where inter-modulation, feedback, reflections, resonances, and nonlinearities are important. As a result of these interactions, the design of a photonic system can be a truly daunting task [1]. However, integrated photonic circuit designs have been proposed with different approaches [2]-[5], and for different applications [6]-[8].

The rapidly evolving role of photonic RF signal processing has spawned off a variety of mixed-signal circuit applications. The integration of the optical and digital circuits has created a lot of concerns in testing these devices. This paper presents a hierarchical fault modelling approach for catastrophic as well as out-of-specification (parametric) faults in photonic circuits. These include both passive as well as active components. A case study based on photonic correlator has been used in this paper. The purpose of using a photonic correlator is mainly because it is composed of components used in most photonic systems. These are the transmitter, optical amplifier, optical channel and optical receiver. We have simulated large numbers of possible faults and tested the resulting behaviour against the design specification.

This paper is organized as follows: the most common photonic faults are illustrated in section 2. Section 3 demonstrates the photonics case study and the simulation results. Finally, the paper is concluded in section 4.

## 2. Photonic System Level Common Faults

With the emergence of high-performance Photonic systems, it has become crucial to test their reliability and lifetime. The list of possible faults for a Photonic system is in fact extensive; however by considering only the most likely faults, the development of a practical finite fault set becomes possible. There are many sources of faults in photonic systems depending on the nature of the components used. The component fault sources can be classified into two categories, namely, (i) hard or catastrophic faults and (ii) soft or parametric faults [9]. Hard faults are mainly due to component permanent failure, such as the break of a fibre connection, and the damage of a laser source or a photodetector. These defects cause hard faults that can easily be isolated. Soft faults are caused by variations in component characteristics, which are greater than the tolerance limits. Examples include faults caused by the manufacturing process, the deterioration of a polarizer due to manufacturing defects, the increase in coupling loss due to slight misalignment, and the reduction in amplification due to gain fluctuations. The first step in developing a realistic fault model is to review the variation types of defects and their causes and effects.

Fibre optic cables were until not long time ago reserved for high-performance applications, but today it is present in network applications. Fibre optic cables are very different from copper cables, not only in the installation process, but also for troubleshooting. Fibre optic cables are also far more fragile than copper cables, which make them more subject to defects than copper cables. The following defects are some of the most common fibre optic cable problems with their possible causes:

- Broken fibres due to physical stress or excessive bending.
- Insufficient transmitting power.
- Disproportionate signal loss due to excessively long cable span.
- Excessive signal loss due to a contaminated connector.
- Excessive signal loss due to faulty splices or connectors.
- Excessive signal loss due to high number of splices or connectors.

Typically, if a connection is defective, it is most likely due to a break in the cable. However, if the connection is intermittent, there are several possible causes:

- The cable's attenuation may be too high because of poor quality splices or too many splices.
- Dust, fingerprints, scratches, and humidity are among the reasons of connector contamination.
- Low transmitter strength.
- Bad connections in the wiring closet.
- Faulty connection of fibre to the patch panel or in the splice tray.

Testing the optical properties of fibre optic cable involves measuring two characteristics. These are attenuation and bandwidth.

Attenuation is the measure of signal loss during its progress through the cable, from the transmitter to the receiver. A small amount of loss is unavoidable, often acceptable, and generally do not affect the data. But because the number of splices/connections can have an effect (more interruptions = more likelihood of loss), and handling being another contributing factor on performance, it is important to measure attenuation after installation to ensure the cabling system is performing to specification.

Bandwidth is a measure of the information-carrying capacity of the cable. The quality and length of the fibre determine bandwidth. Installer handling has no effect on bandwidth. However, it is important that a cable system's bandwidth provide the information-carrying capacity required by the end-user. Bandwidth can be verified by simply stating the documented specifications of the installed cable type. An actual field test is only necessary if this is not sufficient to determine bandwidth, or if the installer's practice is to run a field test anyway, or else if the end-user requires a field test.

## 3. Case study of photonics correlator

The case study of optical correlator circuit is shown in Figure 1. A 4-bit bit-pattern is generated by a pattern generator and modulated with 1550nm optical signal generated by a laser source. The modulated optical signal splits into 4 output fibre ports whose lengths are chosen to delay the modulated optical signals by $T_0$, $T_0$+T, $T_0$+2T, and $T_0$+3T, where $T_0$ is an arbitrary delay, which is the bit time of the input pattern. The photoreceiver array, which integrates 4 discrete photodetectors, 4 variable-gain amplifiers and an RF combiner, with the amplifier gain are configured to match the input bit pattern. For example, for a bit pattern 1011 we set the gain of the second amplifier to a low value which corresponds to a "0" state, while the gains of the other amplifiers are set to high values, which correspond to "1" states. The output electrical signal from the RF combiner is monitored by a digital oscilloscope.

When the bit sequence of the header matches the gain of the photoreceivers the sum of the output signals from the photoreceivers produces the autocorrelation of the header bit sequence with a central lobe at N·T where N is the number of bits in the pattern and T is the bit time. The ideal circuit process parameters used in this example are shown in Table 1. Single or multiple faults may occur in either the active or passive components of the circuit. Note that the noise effect is not considered in this study.

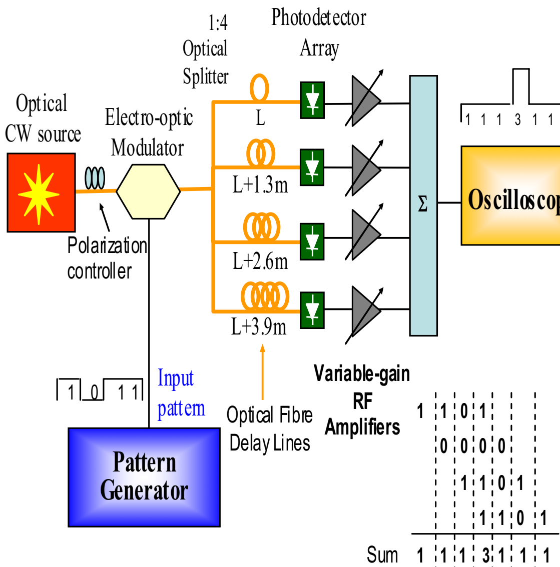


**Figure 1.** Photonics correlator circuit

| Process Parameter | Specification |
|---|---|
| Laser wavelength | 1550nm |
| Laser power | 1 mW |
| PD Responsivity | 0.95 A/W |
| Amplifier output | 2 mV |
| Pattern input | 1101000 |

**Table1**. Process parameters

Sufficient number of measured output parameters is required for the computation of deviation of many defective components in the circuit. Therefore, simulation studies have been carried out to evaluate the effects of the injected faults on the behaviour of the circuit through observing the output waveform. Figure 2 shows the simulation results of catastrophic faults in the photoreceiver. It shows that each photoreceiver's fault can affect the output waveform in a different way that can be easily recognised. Figure 3 shows some parametric faults on the variable gain amplifier. It shows the effect of changing the gain of the amplifier on the output waveform; it shows also that each amplifier can affect different parts of the output waveform when it changes.

From Figure 2 and Figure 3 it is noticeable that faults in each branch can be easily detected from the output waveform as shown in Fig. 4, where each branch has different contribution on the output waveform

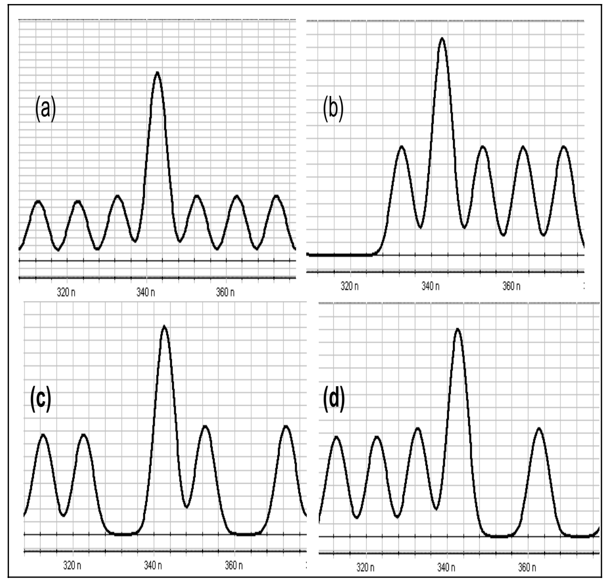


**Figure 2.** Catastrophic faults in the photoreceivers, (a) Process parameters are within the limit; no fault detected. (b) The first photodetector responsivity is zero; fault detected. (c) The third photodetector responsivity is zero; fault detected. (d) The fourth photodetector responsivity is zero; fault detected.

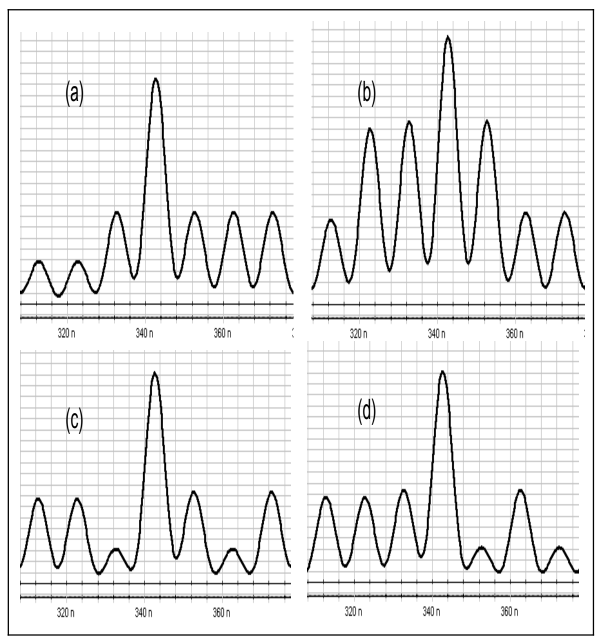


**Figure 3.** Parametric faults of the variable gain amplifier, (a) The first Amplifier output voltage < 1.2mV; fault detected. (b) The second Amplifier output voltage equal 2mV, fault detected. (c) The third Amplifier output voltage < 1.2mV; fault detected. (d) The fourth Amplifier output voltage < 1.2mV; fault detected.

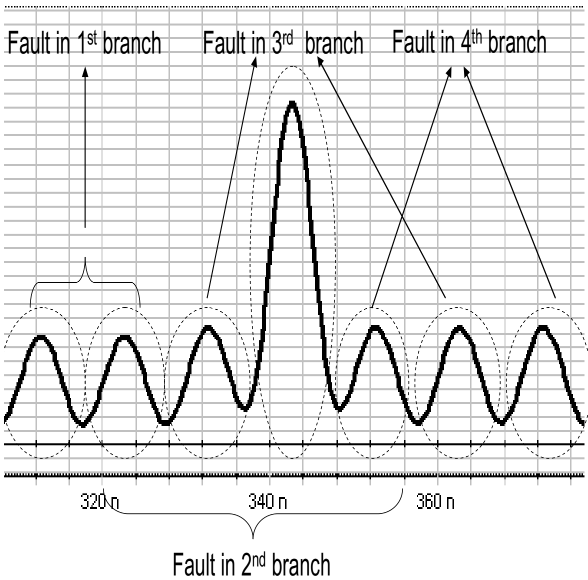


**Figure 4.** Optical correlator output signature

## 4. Conclusion

We have addressed some of the general defects that commonly happen in photonic systems. Break or open fibre typically occur more frequently than parametric faults and have great consequences, but these are detectable. However, more research needs to be done in this area to cover testing of the larger integrated photonics system.

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