FAULT LOCATION IN FULL-DUPLEX PLASTIC OPTICAL FIBER LINKS USING SYNCHRONIZED DECAY TIME DETECTION

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Abstract: In this work, a low cost fiber-fault location technique in full-duplex plastic optical fiber links is reported. The employed method consists of using real time measurements of overlaid optical supervision signals employed simultaneously at both ends of the plastic fiber link during operation, comparing the decay time detection at both ends of the link when a fiber fault occurs. The proposed technique is successfully demonstrated over Graded Index (GI) Plastic Optical Fiber (POF) links.

Key words: Fault location, graded-index POF, Optical Time Domain Reflectometer, Optical Frequency Domain Reflectometer, time-of-flight.

1. Introduction

Current deployments of Fiber to the Home (FTTH) are paving the way to 1 Gb/s and beyond broadband communication services for residential and business customers; nevertheless, in building legacy wiring based on coaxial cables, twisted pair cables and electrical Ethernet cables are not suitable for guaranteeing the required aggregated capacity and Quality of Experience (QoE) offer. Point to point POF technology has been demonstrated to be a cost-saving solution for office building networks with regards to Ethernet cables and Single/Multi Mode fibers [1] due to low cost of material and flexibility of installation. Triple-play services have already been trialed with passive point to multipoint topology using protocols such as G.hn over POF [2], being this approach even a more cost-effective promising approach for the future in-building wiring using POF.

On the other hand, plastic optical fibers are also a very interesting transmission media for sensing applications, due to their inherent advantages of safety in chemical and biological environments, as well as to their robustness against Electro-Magnetic-Interferences (EMI). Several remote measurement interrogation techniques and applications such as structural health monitoring and biomedicine based on plastic fibers have been reported [3].

In both data communication and sensor networks built with POF, it is desirable to provide cost-effective means for detecting and locating physical layer faults in order to achieve a quick repair and restoration of the data communication or sensor measurements in case of a fiber link failure. Optical Reflectometers are widely used to characterize fiber links and optical components. Reflectometric supervision is a well-known technique which exploits the measurement of the Rayleigh backscattering in optical fibers following the transmission of a high-power short optical pulse at one end of the fiber. The fiber path characterization is obtained by recording the backscattered light as a function of time and then translating it into distance measurement.

POF Optical Time Domain Reflectometers (OTDR) and Optical Frequency Domain Reflectometers (OFDR) have been reported for distributed strain measurements [4, 5] and can also be utilized for physical layer monitoring in POF data communication and sensor networks.

Nevertheless, the backscattering coefficient in optical fibers is very low (around -80dB in single-mode fiber for 1ns pulses) and in case of remote measurements, the measured signal suffers a two way attenuation, thus OTDR/OFDR receivers require a very high performance with very low Noise Equivalent Power (NEP). A more challenging situation appears when a point to multipoint topology is under test, because the reflections from different remote fiber branches are overlapped in time at the OTDR/OFDR equipment.

On the other hand, POF OTDR/OFDR equipment may be prohibitively expensive in most situations and therefore restricted to niche areas where a high initial investment is justified due to special requirements.

In this paper, we report a low cost alternative to OTDR/OFDR measurements in POF links using embedded transceivers for real time permanent physical layer supervision, thus allowing a quick location and a reduced repair time of a plastic fiber fault in a cost efficient way.

The paper is organized as follows: first, the fault location method is explained in detail and analytically described in Section 2; next, an experimental test-bed demonstrating the principle of operation of the proposed technique is reported in Section 3; finally, the measurement results are discussed and the conclusions are provided in Section 4.

2. Description of the fault location method

Fig. 1 shows a block diagram of the proposed method for fiber break location.

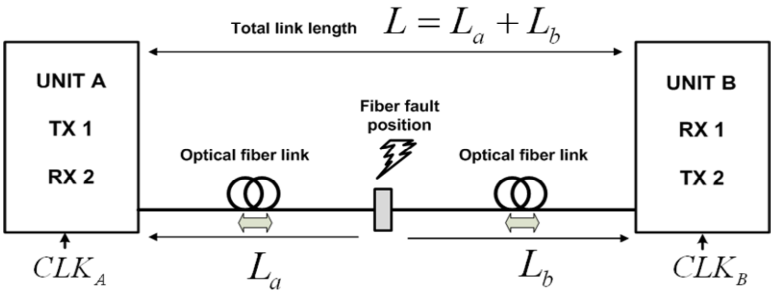

Fig.1. Duplex fiber fault detection scheme.

From the above figure, which depicts a fiber-based optical link between two optical devices (units A and B, respectively), and with synchronized clock timing, the following parameters can be defined:

- $\lambda_a =$ uplink monitoring wavelength, from unit A to unit B.
- N_{g_a} = POF effective refractive index, at a wavelength λ_a.
- $\lambda_b =$ downlink monitoring wavelength, from unit B to unit A.
- N_{g_a} = POF effective refractive index, at a wavelength λ_b.
- L = POF fiber length from unit A to unit B.
- L_a = link distance from break location to unit A.
- L_b = link distance from break location to unit B.

Let's now assume a hypothetical fiber break or fiber disconnection at a distance L that would cause an attenuation, and no light detection, at a time T_0, which propagates to both end terminal equipments (which can be referred as uplink and downlink, respectively). At a certain time depending on the operating wavelength and the fault location, the photodetectors located at units A and B, respectively, will detect an optical power decay and finally signal ceasing. At this point, any optical power attenuation threshold could be implemented thus providing a warning at the POF-fiber link monitoring system. Moreover, assuming that the clocking times at both terminals are synchronized, each unit will generate such a warning signal at the following time, respectively:

$$T_a = T_0 + \frac{L_a}{c} \cdot N_{g\_a}(\lambda_a) \quad (1)$$

$$T_b = T_0 + \frac{L_b}{c} \cdot N_{g\_b}(\lambda_b) \quad (2)$$

being *c* the speed of light in vacuum. The $(L_i/c) \cdot N_{g\_i}(\lambda_i)$ terms are thus the 'time-of-flight' values of the signal from the fault location to each end terminal, and where their respective propagation velocities directly depend on the different fiber effective refractive index considered as a function of the operating wavelength. A comparison of the timing values gives the position of the fiber break as follows:

$$L = L_a + L_b \quad (3)$$

$$|T_a - T_b| = \left| \frac{L_a}{c} \cdot N_{g\_a}(\lambda_a) - \frac{L_b}{c} \cdot N_{g\_b}(\lambda_b) \right| \quad (4)$$

being possible to determine the values of L_a and L_b and then solving the location uncertainty.

3. Experimental demonstration

To demonstrate the feasibility of the proposed fault location method, the setup shown in Fig. 2 has been implemented.

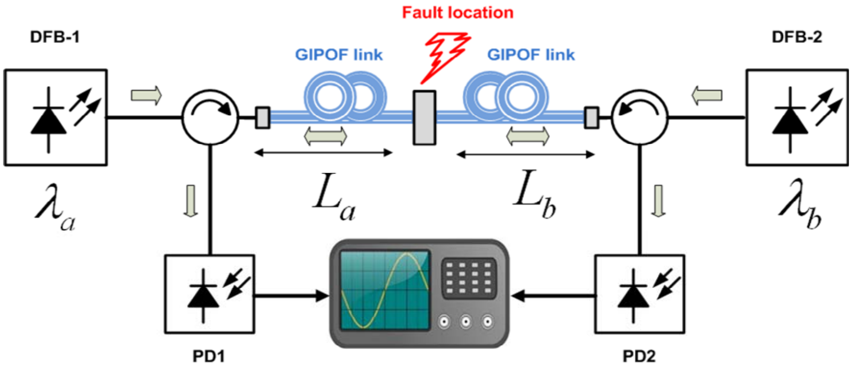

Fig.2. Experimental test-bed.

Two Distributed Feedback lasers (DFB) have been used to launch CW optical power into the system, at different pairs of operating wavelengths: 1) $\lambda_a =$ 1310 nm, λ_b = 1552.80nm ; 2) $\lambda_a =$ 1310 nm, λ_b = 1532,68 nm ; and 3) $\lambda_a =$ 1552.80 nm, λ_b = 1532,68nm. A 62.5µm-core diameter Graded-Index (GI) Plastic Optical Fiber (POF) has been used to perform the POF-link. The optical signals are redirected to two high-speed lightwave converters (model Agilent 83440C, 0-20GHz), with response time of less than 22ps, by means of two optical circulators. Consequently, a fiber break results in a simultaneous loss of light transmission for both directions. Finally, the output signal from the lightwave converters is then captured with appropriately time- scaling by a digital oscilloscope. A 6.25GS/s of sampling rate was selected to display simultaneously both electrical signals.

It is worth mentioning that mode scrambling techniques have been used to couple light into the fiber in order to assure the more uniform as possible power distribution of the light inside the POF as well as to avoid mode filtering effects which can lead to optical power fluctuations that can distort the final measurement. Special care has also been taken when connecting the optical circulators to the different GIPOF spools in order to minimize reflections that could distort the signals measured in the oscilloscope. For the sake of simplicity, these latter solutions to optimize the experimental test-bed have not been included within Fig. 2.

The following figures show the different signal transients detected at reception when a fiber disconnection occurs, and for different operating conditions. All figures have been normalized in terms of received voltage and are given in arbitrary units.

(a) (b)

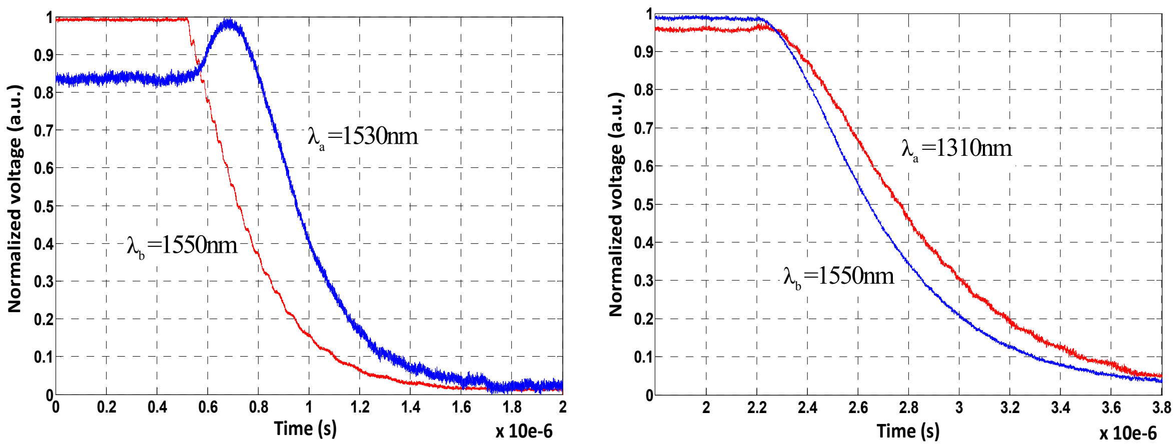

Fig.3. Examples of measured fiber break transients. (a) La=50m, Lb=0m, λa=1.53µm, λb=1.55µm ; (b) La=75m, Lb=50m, λa=1.31µm, λb=1.55µm.

(a) (b)

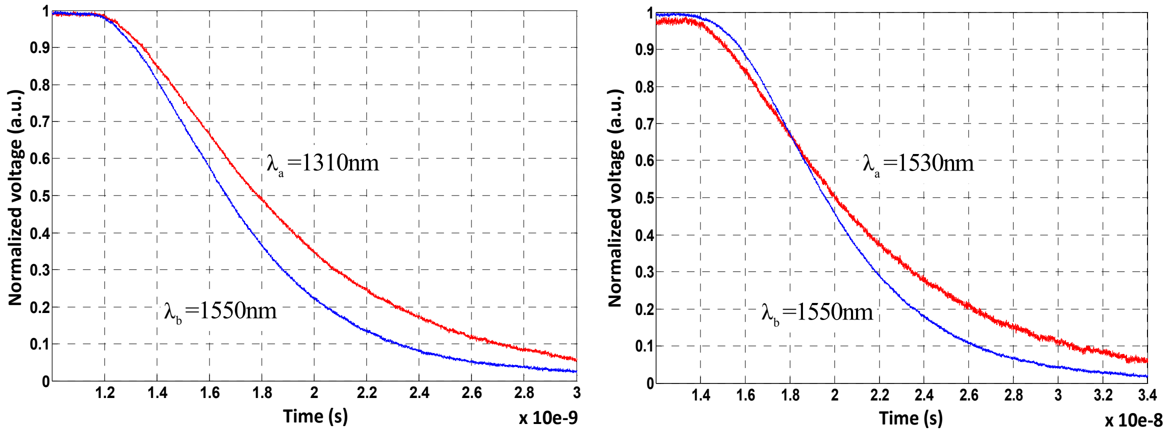

Fig.4. Examples of measured fiber break transients .(a) La=Lb=25m, λa=1.31µm, λb=1.55µm ; (b) La=110m, Lb=100m, λa=1.53µm, λb=1.55µm.

In order to calculate the fiber fault location from the measurements using Eq. (3)-(4), the PF-GIPOF core refractive indexes for the different operating wavelengths, N_{g_i}, were calculated using a three-term Sellmeier function with coefficients reported in [6]. Results of the PF GIPOF core/cladding refractive index dependency with the operating wavelength are given in Fig. 5. At the wavelengths of interest, they were found to be: $N_{g\_1.3\mu m}$=1.3485, $N_{g\_1.53\mu m}$=1.3468 and $N_{g\_1.55\mu m}$=1.3462, respectively.

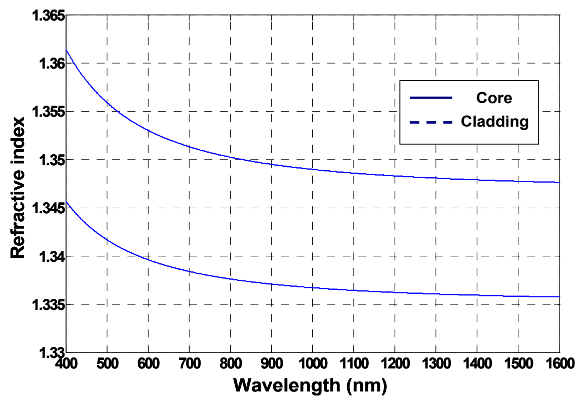

Fig.5. PF GIPOF core/cladding refractive index versus wavelength.

Table 1 gives the experimental results of different fiber breaks induced at different points within the GIPOF-based fiber link. In each case, a high level of agreement is noticed, with an actual worst-case of less than 1 meter deviation in fault location estimation, when comparing with theory. Theoretical results were obtained computing Eq. (4) from the aforementioned refractive index values depending on wavelength, and using the values of La and Lb measured with an OTDR. Time-of-flight difference between transients was evaluated at half the amplitude drop of the received signal from each transient. From the data shown in Table 1 resolutions of less than a meter when evaluating the fiber break location can be obtained. However, discrepancies are assumed to mainly be due to the theoretical estimation of the core refractive indices dependency with the operating wavelength, as well as the arbitrary nature of the induced fiber break [7]. As a matter of fact, the effective fiber break duration, i.e. the decay time of the transmitted light during fiber failure, will present a significant contribution to the location uncertainty.

On the other hand, optical path failures in real situation can be due to patch cord disconnections, fiber breaks due to, for instance, a back-hoe digger, strain, or even torsion. In the lab trials our path failure was artificially induced by different mechanisms: 1) simple fiber disconnection, 2) optical air-guided stage in which the light between the emitter and receiver fiber was cut off, 3) "hot-knife" cutting technique. These different mechanisms imply different transient timings (ranging from µs to ns) which are directly related to the system's resolution.

Operating conditions (experiment) Fiber disconnection	|Ta-Tb| measured	|Ta-Tb| theoretical	Deviation in fault location
La=50m, Lb=0m λa=1.53μm, λb=1.55μm	0.2227 μs	0.22447 μs	|0.394| m
La=50m, Lb=0m λa=1.31μm, λb=1.55μm	0.2286	0.22475 μs	|0.858| m
La=75m, Lb=50m λa=1.31μm, λb=1.55μm	0.1141 μs	0.1128 μs	|0.299| m
La=75m, Lb=50m λa=1.53μm, λb=1.55μm	0.1115	0.1123 μs	|0.186| m
La=Lb=25m λa=1.53μm, λb=1.55μm	0.015 ns	0.050 ns	|0.008| m
La=Lb=25m λa=1.31μm, λb=1.55μm	0.124 ns	0.192 ns	|0.015| m
La=110m, Lb=100m λa=1.31μm, λb=1.55μm	41.54 ns	45.717 ns	|0.931| m
La=110m, Lb=100m λa=1.53μm, λb=1.55μm	42.83 ns	45.093 ns	|0.504| m

Table 1. Summary of measured time-of-flights for different fiber disconnection trials and. comparison with theoretical results.

4. Conclusions

In this work, we report the results obtained during the experimental evaluation of a fiber-fault location technique in full-duplex plastic optical fiber links, employing an alternative method to Optical Reflectometer (OTDR/OFDR) measurements. These latter methods generally rely on a large number of measurements and a time consuming averaging process, not being efficient for the supervision of point-to-multipoint fiber topologies due to overlapping traces coming from different fiber branches. In contrast, the proposed method consists of a permanent monitoring system which employs two optical supervision signals in a fiber link, each optical signal being permanently transmitted from one fiber end to the other end. At the fiber link end terminals, two permanent monitoring receivers are measuring the received optical monitoring signal coming from the other end of the fiber link in real time. When a fiber break or a link interruption occurs, it causes a simultaneous loss of light transmission which is detected in both optical receivers. By comparing the delay between the two decay times which are detected by the monitoring receivers at both ends of the fiber link, the method allows a quick calculation of the fiber fault location. The utilized solution overcomes the sensitivity limitations imposed by Optical Reflectometer equipment to be used in plastic optical fiber (POF) links due to both POFs large backscattering coefficients as well as the different link topologies such as branched fiber topologies. Additionally, this fault location technique can be embedded within a transmission system thus offering significant operational advantages. The proposed technique has been successfully demonstrated over Graded Index (GI) Plastic Optical Fiber (POF) links.

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