OPTICAL FREQUENCY DOMAIN REFLECTOMETER FOR CHARACTERIZATION OF OPTICAL NETWORKS AND DEVICES

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Abstract: We have developed a first prototype of an optical frequency domain reflectometer. This instrument is designed to measure backreflections from optical networks with great precision and sensitivity. We present the principle of the instrument and some applications.

1. Introduction

Optical Frequency Domain Reflectometry is a new technique, designed to measure backreflections from optical fiber networks and components [1]. Within the framework of the European ACTS project BLISS (Broadband Lightwave Sources and Systems), a first prototype of an Optical Frequency Domain Reflectometer (OFDR) has been developed. The main advantages of the OFDR with respect to the more standard Optical Time Domain Reflectometer (OTDR) are the higher spatial resolution and sensitivity. The spatial range is however limited to about 80 meters. In this work, we first present the principle of the technique, and give the properties of our prototype. We then turn to potential applications of the technique for characterization of optical fiber networks and devices.

2. Principle of the OFDR

The principle of the OFDR, as implemented in the GAP-Optique prototype, is shown in Fig. 1. Backreflections from the Device Under Test (DUT) beat with a fixed Fresnel reflection, the Local Oscillator (LO), and are detected on the photodiode. The laser optical frequency is swept, as shown in Fig. 1, so that reflections from points at different distances in the DUT correspond to different beat frequencies on the detector. The signal is Fourier transformed, and analyzed in the frequency domain. Each frequency thus corresponds to a distance (in contrast to the OTDR, where the time when the signal is detected corresponds to a distance).

Our prototype is presented in Fig. 2. The OFDR box proper comprises a DFB laser, the optical system (coupler and detector), and all the driving electronics. It is connected to a PC, which performs the Fourier Transform and signal processing. The characteristics of the prototype are as follows:

1. Range
   Since the signal is obtained from an interference between the DUT and the LO, the range is limited by the coherence of the laser. The present DFB laser has a linewidth of about 1MHz over the whole tuning range, which gives a spatial range of about 80 m (depending on the strength of the reflections). Increasing the range is possible, but would require a tunable laser with smaller linewidth.
2. Sensitivity
   Due to the coherent detection (interference between a fixed LO and the reflection from the DUT), the sensitivity is very high, above 100 dB in principle [2]. However, strong reflections, even when they are from far away (i.e. further than the coherence length of the laser) generate a large background noise, which limits the sensitivity. The OFDR is thus better suited to the measurement of optical networks and devices with low backreflection levels, below –30 dB. This is not a major limitation anymore, since all recent systems have such a low backreflection.

3 Resolution
Here, the limiting factor is the tunability of the laser. The present one is limited to a continuous tuning of about 20 GHz, which gives a resolution of about 1 cm at close range (a few meters), and increasing at longer range. We plan to increase the resolution by increasing the tuning range.

3. Applications of the OFDR

The initial applications were essentially in the detection of discrete reflections, such as the ones created by splices, connections or defects in the fibers (see Fig. 3). The OFDR can also measure the reflections from optical elements. We present here, as an example, a wavelength-division multiplexed (WDM) filter (see Fig. 4) [3]. In addition, we discovered that the instrument is also very good at detecting distributed reflections. For example, we measured the distributed loss and gain in Erbium-doped fibers (see Fig. 5) [4], and the distributed birefringence in optical fibers (see Fig. 6) [5]. We now believe that this type of distributed measurements may become the main application of our instrument.

To exemplify the potential of the OFDR for measuring backreflections, we show in Fig. 3 the trace obtained with a single mechanical splice connecting two pieces of fibers. We clearly see the reflection from the splice, followed by the one created by the end of the fiber. The flat sections correspond to the Rayleigh backscattering of the fiber. The slope is not due to the attenuation in the fiber, but rather to the finite coherence length of the laser. The step created in the splice corresponds to coupling loss of 0.6 dB (seen as a 1.2 step, due to the double pass of the light).

Another interesting possibility is to measure optical devices inserted in a network. We give the example of a WDM filter (Bragg grating) in Fig. 4 [3]. In dense WDM optical networks, where channel separation may be smaller than 200 GHz, it is desired to have narrow flat-top filters, with sidelobes as small as possible, in order to minimize the crosstalk between neighboring channels. Therefore, acurate characterization of the device reflectivity as a function of the wavelength is required. The OFDR is well suited to this type of measurement, since it has both spatial and frequency resolution. Spatial resolution is obtained with a standard configuration as in Fig. 3. It enables to measure the backreflection coming from the filter itself, even if it is preceded or followed by other optical elements. The frequency resolution is obtained by scanning the central frequency of the laser by temperature tuning. We managed to get an excursion of 2.5 nm, which is sufficient to see both the flat top of the filter (Fig. 4 a), and the reflectivity at the first neighboring channel (Fig. 4 b).

In addition to these discrete reflections, we also used the OFDR to measure distributed reflections from optical fibers. The first example, shown in Fig. 5, measures the distributed gain of an Erbium-doped fiber [4]. This fiber is coupled to a pump at 980 nm through a WDM coupler. The various curves represent the backreflection for different values of the pump power. We see clearly the initial absorption, for zero pump power, which is replaced by gain as the pump power increases. The most valuable information that can be extracted from these curves is the optimal length of the Erbium-doped fiber, after which the gain levels off. Here we see that, for the highest pump power, the gain flatens at about 4 meters, and then starts to decrease. This shows that the optimal length for an optical amplifier with this particular fiber and pump power is about 4 meters. Let us emphasize that, in conventional time domain reflectometry, measurements of Er-doped fibers with the pump on is impossible, due to the strong Amplified Spontaneous Emission (ASE) noise. Here, since we are using a coherent detection, the ASE noise, which is not coherent with the signal, is simply not seen, except as an increase in the background noise, as seen clearly in Fig. 5. The only alternative to measure the distributed gain in Er-doped fibers is to use the cutback method, which is a destructive measurement.

As a final example, we present in Fig. 6 a measurement of the distributed birefringence in a singlemode fiber [5]. Since the OFDR signal is created by an interference between the backreflected signal and the LO, it is naturally sensitive to their relative polarization. For most applications, this sensitivity is a nuisance, and has to be removed. In our instrument, we use a polarisation scrambler to average out the polarization [6]. However, in some cases, this polarization sensitivity can be of use. In a birefringent fiber, the polarization of the light rotates around the birefringence axis as the light propagates down the fiber. The periodicity of the rotation is known as the beat length, and is an important parameter for characterizing the fiber. In an OFDR trace, as shown in Fig.6, this rotation of the polarization is translated as oscillations in the detected Rayleigh backscattering. The period of these oscillations gives the polarization beat length of the fiber under test.

4. Conclusion

The participation of GAP-Optique in the ACTS project BLISS was quite successful. With the help of the BLISS partners, we built a prototype of the OFDR, fulfilling the expected specifications. During the work, we also discovered new interesting applications, especially in the important field of distributed measurements. GAP-Optique is now considering building a second prototype, with improved specifications. This should lead to future commercialization of this instrument.

Acknowledgements

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Figures

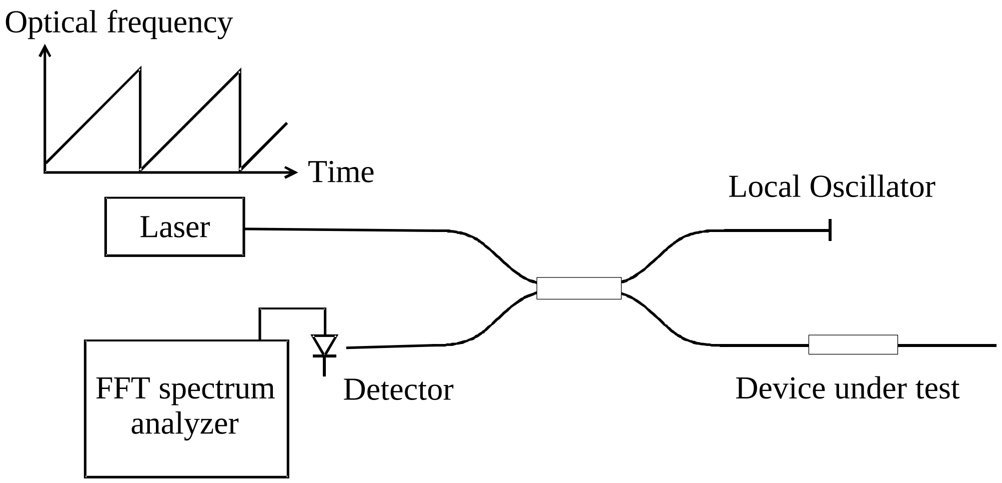

Figure 1: Principle of the OFDR

The OFDR is based on coherent detection of the signal reflected from the Device Under Test interfering with a fixed reflection, the Local Oscillator. The laser frequency is swept linearly in time, so that the beat frequency between the two reflections is proportional to the distance between the LO and the reflection point. The Fourier Transform of the detected signal thus allows visualization of multiple reflections.

Figure 2: The prototype.

The OFDR box contains all the optical system and the control electronics. It is linked to a PC, which performs the FFTs and the signal processing.

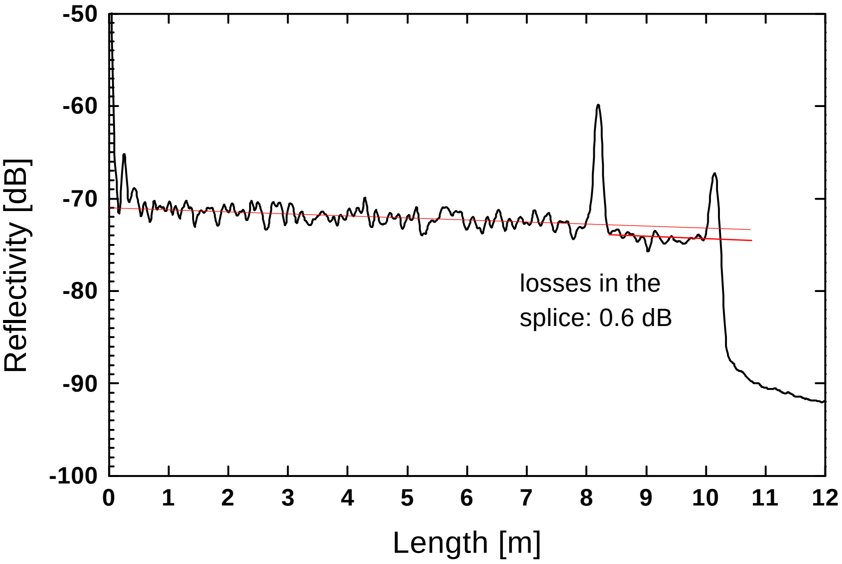

Figure 3: Measurement of a mechanical splice.

This trace shows the signal coming from two fiber trunks, connected by a mechanical splice. We see clearly the two discrete reflections coming from the splice and the end of the fiber, and separated by the Rayleigh backscattering. The jump in the Rayleigh backscattering is caused by the coupling loss in the splice: 0.6 dB (translated into 1.2 dB in the trace, due to the double passage of the reflected light through the splice).

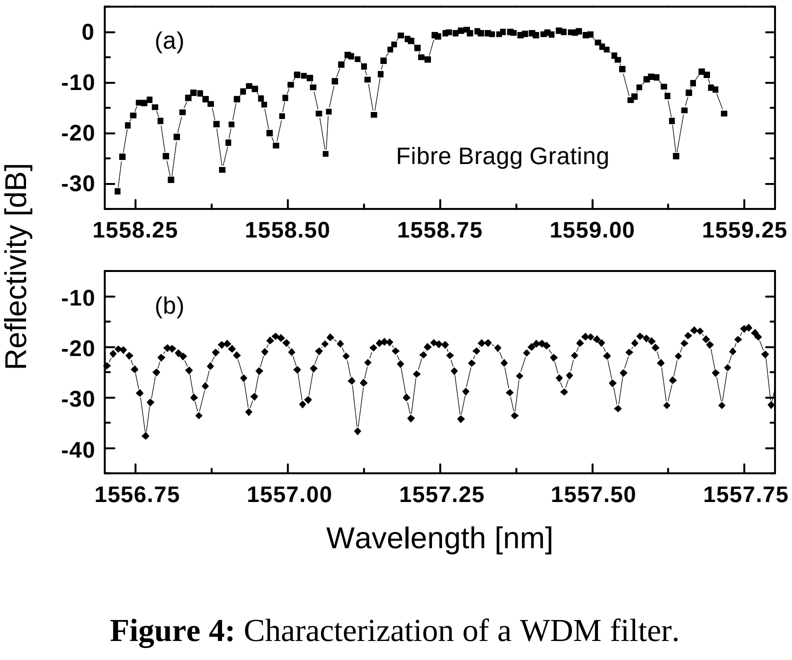

Figure 4: Characterization of a WDM filter.

These two graphs give the reflectivity of a WDM add/drop filter, built from a fibre Bragg grating: (a) shows the in-channel reflectivity, which has a flat-top and low side lobes; (b) represent the first neighboring channel, with a crosstalk below 20 dB. Each square and each diamond on these curves represent one OFDR scan. Points corresponding to the various frequencies were obtained by tuning the laser temperature between each scan.

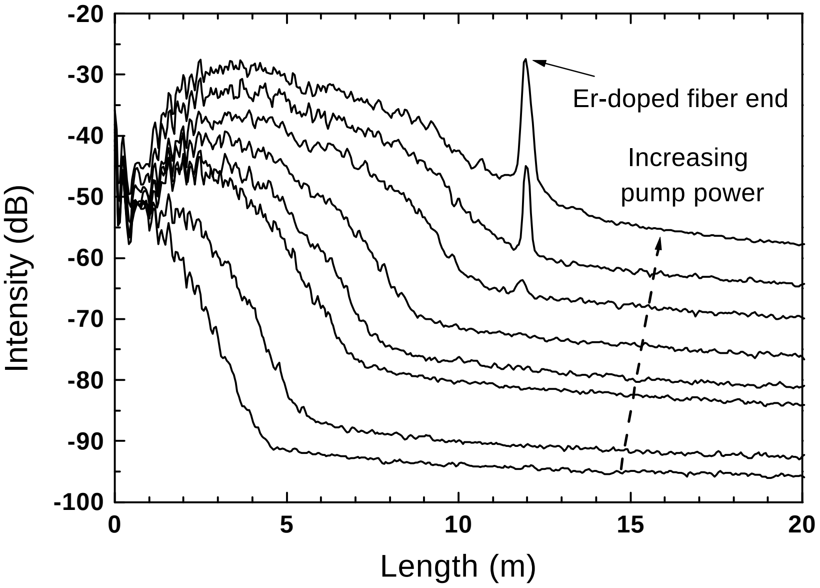

Figure 5: Distributed gain of an Erbium-doped fiber.

A pump laser at 980 nm is coupled to the Erbium-doped fiber through a WDM coupler. The various curves represent different pump powers. We see clearly the attenuation of the Er fiber at low pump powers, and the gain at higher powers. Moreover, we also see gain saturation after about 4 m of Er fiber, due to the pump absorption. The final reflection is created by the endface of the fiber.

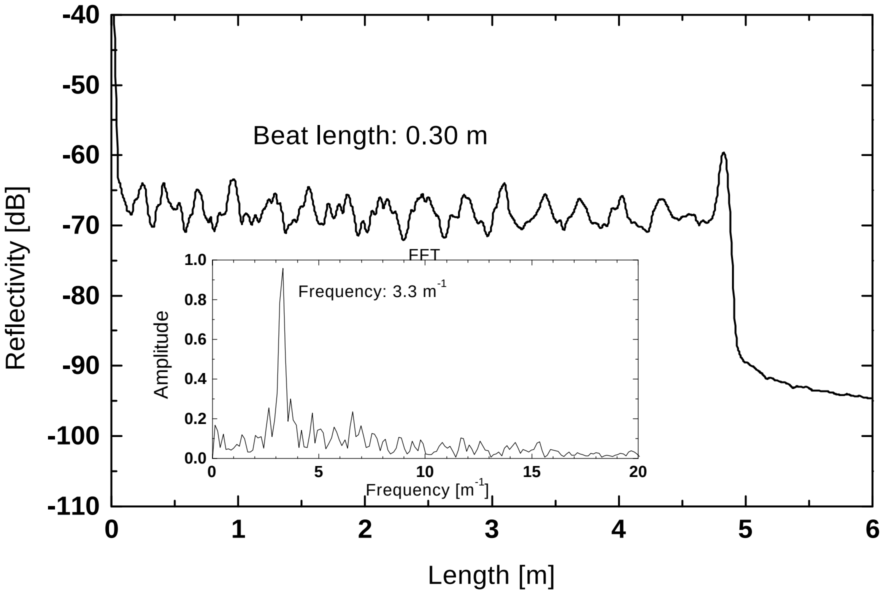

Figure 6: Local birefringence of a single-mode fiber.

The OFDR is naturally sensitive to polarization. Here we see the polarization rotating along the birefringence axis of the fiber. The period of the rotation, known as the beat length, is obtained by a Fourier Transform of the main curve (inset).