Optical Frequency Domain Reflectometry with a Narrow Linewidth Fiber Laser

P. Oberson, B. Huttner, O. Guinnard, L. Guinnard, G. Ribordy, and N. Gisin

Abstract—We present a new optical frequency domain reflectometer based on a tunable fiber laser with a very narrow linewidth (about 10 kHz). This instrument performs reflectivity measurements with about 110 dB sensitivity and 80 dB dynamic range. The narrow linewidth allows long-range measurements, at 150 m, with a spatial resolution of 16 cm. At short range, about 5 m, the resolution increases to subcentimeter.

Index Terms—Frequency modulation, OFDR, tunable laser.

I. INTRODUCTION

OPTICAL reflectometry is a powerful technique for the characterization of optical fibers and components. Different techniques have been developed, depending on the desired spatial range, resolution, dynamic range, and sensitivity. Time domain techniques, using an optical time domain reflectometer (OTDR) are generally used for a measurement range of several kilometers, with resolutions of a few meters. The typical dynamic range is about 40–50 dB, while the sensitivity (lowest measurable reflection) is limited to about 60 dB. At the other end of the scale, submillimeter resolutions are usually obtained with optical low coherence reflectometers (OLCR’s). In this case, because of the coherent detection system, sensitivities down to about 160 dB have been achieved [1]. However, the spatial range is generally lower than about one meter, owing to the need to scan an optical delay line.

Between these two extremes, coherent optical frequency domain reflectometry is a useful technique for measurements of intermediate range and resolution. Like the OLCR, the optical frequency domain reflectometer (OFDR) has a high sensitivity and dynamic range because of the coherent detection principle. In addition, in contrast to the OLCR, the time required for measurement is very short, from a fraction of a second up to a minute if averages of many measurements are required. To date, however, the spatial range of the OFDR, based on available semiconductor lasers, has been limited to tens of meters, because of the limited coherence length. Note that it is possible to extend the range to a few hundred meters by using a DFB laser coupled to an external cavity [2], but this technique cannot be used for shorter spatial range and resolution.

In this paper, we describe a new OFDR prototype based on a tunable fiber laser [3]. This laser is built from a commercially available single-mode erbium-doped fiber laser and a piezoelectric component that stretches the fiber to change its frequency. It has a very narrow bandwidth of about 10 kHz, corresponding to a coherence length of about 3.3 km within a fiber. Since this is approximately two orders of magnitude higher than multisection semiconductor DFB tunable lasers [6], the spatial range of the OFDR technique is drastically increased with this new kind of laser. Moreover, we found that this type of laser can be continuously tuned over more than 1 nm, given a sufficient spatial resolution at short range.

II. PRINCIPLE

The principle of our OFDR has been extensively described in previous works [4]–[6]. The heart of the instrument is a Michelson interferometer. During the measurement, the frequency ν of the narrow linewidth laser is continuously scanned and the reflections from the device under test (DUT) interfere at the detector with a fixed reflection, the local oscillator (LO) (see Fig. 1). Let us consider a single reflection, R(l) coming from the fiber under test at a distance l from the LO. The ac current at the photodetectors is given by the interference between the reflection and the LO, in the following way:

\[ I(\nu) = \frac{I_0}{2} \sqrt{R_{LO} R(l)} \exp\left(-2 \frac{l}{L_c}\right) \cos\left(\frac{4\pi n\nu}{c} l - \phi\right) \]

(1)

where n is the effective index of refraction of the fiber, R_{LO} and R(l) are the reflection coefficient of the LO and the measured reflection, respectively, I_0 is the amplitude of the laser, and \( \phi \) a phase. The exponential decay \( \exp(-2l/L_c) \) is due to the finite coherence length of the laser, \( L_c \). Equation (1) shows that, for a reflection at a given distance l, the intensity of the photocurrent is a sinusoidal function of \( \nu \). The frequency \( 2\pi l/c \) of this function is given by the distance between the reflection and the LO. Therefore, each reflection from the fiber under test corresponding to different lengths can be distinguished by means of a Fourier transform.

In our previous works, we used a linear frequency ramp, which means that the photocurrent was also a sinusoidal function of time. A given reflection would thus appear as a peak in the temporal Fourier transform of the signal. In the present work, the frequency scan is obtained by mechanical means, an elongation of the fiber laser induced by the vibration of a piezoelectric. It is thus preferable to use a sinusoidal function to avoid harmonics. In this case, we need to measure the laser frequency \( \nu \) at each time and perform directly a Fourier transform of the intensity versus \( \nu \). This is achieved by
means of a reference Mach–Zehnder interferometer (not drawn in Fig. 1). Each peak in the Fourier spectrum thus corresponds to a reflection at a given length. An extra advantage of working directly with $\nu$ instead of time is that there is no need for calibration of the instrument. The length of the reference interferometer has only to be measured once and for all.

III. EXPERIMENTAL SETUP

The experimental setup is described in Fig. 1. The laser (IONAS) is made of an erbium-doped fiber imprinted with two gratings inscribed by UV radiation directly into the erbium fiber, forming the laser cavity. The emission wavelength corresponds to the pitch of the grating. It is pumped by a 980-nm pump, connected to the laser by a WDM coupler in the backward configuration. The long laser cavity (several centimeters compared to millimeters for a semiconductor) ensures a long coherence length of $L_c = 3.3$ km (within the fiber). The power of the laser is 6 mW with an 80-mW pump.

If the fiber is stretched by $\Delta x$ then, because of the change in the grating pitch, the frequency $\nu$ decreases according to $(\Delta \nu/\nu) = -\alpha (\Delta x/x)$ where $x$ is the fiber laser length and $\alpha$ is a coefficient taking into account the change in refractive index induced by the stress on the fiber. $\alpha = 1 + (x/n)(dn/dx)$, where $n$ is the effective index of refraction of the fiber. Experimentally, we measured the frequency scan as a function of $\Delta x$ to obtain $\alpha \approx 0.8$ and we found that this laser was adjustable with no loss of coherence over at least 1 nm (corresponding to an elongation of 0.09% and a frequency range of 125 GHz).

After Fourier transform, the distance between two points is $\Delta l = c/(2\Delta \nu)$ where $c$ is the frequency range. A Blackman–Harris (four terms) window with 92-dB dynamics is used [8]. With this measurement window the resolution at full width half maximum (FWHM) of a single reflection peak is close to $2\Delta l$. If $N$ is the number of acquisition points, the maximum visible distance is given by $l_{\text{max}} = (N/3)\Delta l$ (only the third of the Fourier transform is used, corresponding to the part between zero and $2/3$ of the Nyquist frequency).

The measurement is done with only $N = 8192$ acquisition points. For a given $l_{\text{max}}$ the FWHM resolution is $(6/N)l_{\text{max}}$ and the frequency range is $\delta \nu = (Nc/6n l_{\text{max}})$. Therefore, we used only a frequency range between 41 GHz and 1.3 GHz for a spatial range between 5 m and 200 m, respectively. The decay of the signal, due to the finite coherence length, by the factor $\exp(-4l/L_c) \approx -5$ dB/km is not critical for this range.

A general problem with coherent measurements is the polarization dependence. Indeed, the polarization of the reflected light with respect to the LO influences the intensity of the measured signal. In order to avoid this dependence, we added a polarization diversity receiver (see Fig. 1). The $R_{LO}$ polarization is adjusted so that the sum of the measurements from both detectors is independent of the polarization. We measure a dependence lower than 0.5 dB.

IV. RESULTS AND DISCUSSION

Fig. 2 shows an OFDR measurement over a 200-m range. The device under test was a series of pigtails measuring, respectively, 3.1 m, 100.2 m, 10.1 m, 3.2 m, 3.2 m, 30.1 m, and 0.4 m. All the connectors were APC’s except one, which is FC/PC and gives the highest backreflection ($\sim 40$ dB). All the reflection peaks are clearly seen above the Rayleigh backscattering (RBS). The RBS is smoothed by averaging about 20 single measurements (of 16 ms each), with different central frequencies. Note the connection loss of about 2 dB, given by half of the RBS difference level at the fourth connection (about 4 dB).

Fig. 3 is a zoom of the last 40-cm-long pigtail in Fig. 2. The FWHM resolution over this range is 16 cm. The points represent the acquisition points after Fourier transform.

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Fig. 4 presents results at short range. As mentioned above, we now use the largest spectral range. At zero, the APC connector between the OFDR prototype and the system under test can be seen. The device under test is a fiber with one thermal splice at 63 cm and one at 147 cm, an FC/PC connector at 167.7 cm, and an APC connector at the end of the fiber at 270.6 cm. The first thermal splice is not seen in Fig. 4, as is usually the case for good splices. The second one is clearly identified, by a ~70-dB backreflection. This means that the splice is faulty, not so much in transmission (no loss can be detected), but in reflection. This may be due to insufficient heating of the splice, leading to a small remaining air gap between the cores of the two fibers. We also see that, in addition to the real peaks, we have three ghost peaks, which do not correspond to physical reflections in the fiber. These ghost peaks are created by the beating between two reflections inside the fiber under test. They only appear when at least one reflection in the fiber under test is comparable to the LO. Here the strong reflection is the FC/PC connector. In order to identify these ghost peaks, the simplest way is to reduce the LO reflection, by adding some attenuation in front of the Fresnel reflection, and perform a new scan. The intensity of the real peaks decreases according to the attenuation, while the ghost peaks, which are not created by a reflection from the LO side, remain unchanged. Comparing the two traces enables us to identify the real peaks and the ghost peaks. Note that this problem may arise for all types of reflectometers in the presence of strong reflections. It is more apparent in this OFDR because of the very large dynamic range. Indeed, in Fig. 4, we see a dynamic range of 80 dB between the highest peak and the noise floor. The high spatial resolution at this range is emphasized in the inset of Fig. 4, to give 5-mm FWHM. This higher resolution corresponds also to a lowering of the RBS, at about ~95 dB, also in good agreement with [9]. The rather large fluctuations in the RBS are not due to an instrumental problem, but to the intrinsically random behavior of RBS for a given central frequency of laser.

V. CONCLUSION

We have presented a polarization-independent OFDR prototype with a new tunable laser source design, whose coherence length (3.3 km) is two orders of magnitude greater than the previous semiconductor DFB laser [6]. Its measurement range easily bridges the gap between OLCR and OTDR measurements. Moreover, the instrument requires only a short acquisition time (less than a minute) and has a sensitivity of $-110$ dB with a dynamic range of 80 dB. At present, the spatial range of the prototype extends from 5 m to 200 m, but there is nothing to prevent the range from being increased up to lengths typical of OTDR, e.g., about 2 km, since losses due to the decoherence, a factor $\exp(-4l/\lambda)$, would be only $-10$ dB at this distance. In contrast, for short distances, a 0.8% elongation of the fiber laser (the breaking limit is about 2%) would give a spectral range of 10 nm and a theoretical resolution of 0.16 mm (FWHM). This corresponds, with our present 8192 point numerical processing, to a range of 20 cm. This is a typical OLCR value. To obtain a better range/resolution ratio, it will only be necessary to increase the number of acquisition points of the present prototype. It might also be possible to further improve the sensitivity of the prototype using the method described in [7].

All the above shows that the tunable fiber laser design already leads to a high-performance instrument, well adapted to the intermediate range of measurement, between OLCR and OTDR. Moreover, it has a very promising potential for future improvements in OFDR measurements.

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REFERENCES


