Analysis of the Polarization Evolution in a Ribbon Cable Using High-Resolution Coherent OFDR

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***Abstract*—Exploiting the inherent polarization dependence and good spatial resolution of optical frequency domain reflectometry (OFDR), the beatlength in a ribbon fiber can be straightforwardly measured. The results clearly show the different amount of polarization ordering for inner and outer ribbon fibers due to the stress-induced birefringence from the common outer coating.**

***Index Terms*—Birefringence, fiber metrology, optical fiber ribbons, optical reflectometry, polarization-mode coupling.**

I. Introduction

FIBER ribbons, where the individual fibers are densely arranged in a common outer coating, can present a popular low-cost solution—mainly for access networks—because of the possibility of mass splicing. With the bit rates ever increasing down to the end user, polarization-mode dispersion (PMD) of these fibers is becoming an issue. Several studies [1]–[4] address this topic, and often a different polarization evolution was found in the inner and outer fibers of the ribbon. For the four-fiber ribbon used in [4], e.g., the PMD was three times larger for the inner fibers than for the outer ones. A possible explanation is the birefringence induced by the stress of the ribbon itself. A finite element method was used in [4] to model the stress distribution within the ribbon, and the corresponding induced birefringence was found to be larger for the inner fibers by a factor of three as well.

The influence of a uniform external perturbation (usually of fiber twist) on the polarization evolution in an ideal fiber having a uniform, constant intrinsic birefringence and no polarization coupling has been investigated long ago [5]. In a real fiber, however, the intrinsic birefringence has random relative orientations of its (local) birefringent axes leading to polarization-mode coupling. In fiber ribbons, it is on such fibers that the external stress from the common coating is acting, and it is therefore not *a priori* clear to what extent the induced stress birefringence will change the polarization evolution (namely the polarization-coupling length). These points are clarified in this paper using high-resolution coherent optical frequency domain reflectometry (OFDR) measurements [6].

II. Experimental Setup

The OFDR technique (Fig. 1) is based on the detection of a beat signal between the distributed reflections from the fiber under test (Rayleigh backscatter, connectors, etc.) and a fixed Fresnel reflection (local oscillator). Using a linear frequency sweep of the laser, one can straightforwardly map the measured beat frequencies on a distance scale, whereas the normed square power for a given beat frequency gives the reflectivity at the corresponding distance. The polarization dependence of the coherent detection used in the OFDR can be exploited to get information about the evolution of the polarization state along the fiber [6], [7]. For a good general overview of the OFDR principles and limits, the reader is referred to [8], [9].

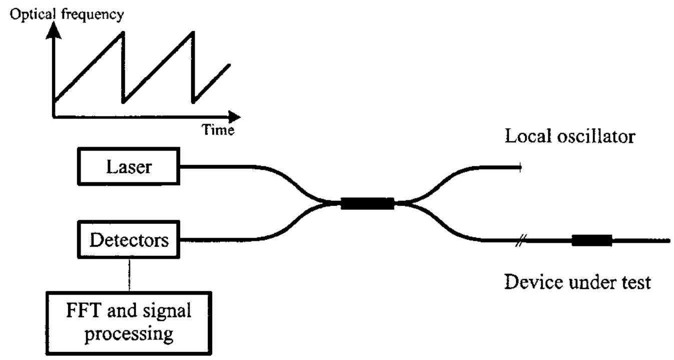

Fig. 1. Sketch of the OFDR setup.

In the device used for the measurements presented here, several important improvements have been implemented. A polarization-diversity detection allows to subtract the (polarization-independent) Rayleigh structure from the polarization-dependent channel, thereby removing the frequencies that are not related with the fiber birefringence. Along with the greatly enhanced range (2 km) and two-point resolution (0.08% of the range, i.e., 5 mm for a range of 6 m, 1.5 m for 2 km), this allows for precise measurements of the polarization evolution.

III. Results and Discussion

The fiber ribbon analyzed here consists of four fibers. Its length is 1.5 km, loosely spooled on a drum with a diameter of 35 cm.

First, PMD was measured both with the Jones matrix eigenanalysis (JME) and the interferometric method. The results are summarized in Table I. The inner fibers have a consistently larger PMD than the outer ones, the difference being as large as a factor of 3.6. As predicted by the model in [4], we found the DGD to vary more for the inner fibers between the measurement series done at different times during the day (different temperatures).

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TABLE I
PMD, BEATLENGTH, AND COUPLING LENGTH FOR INNER AND OUTER FIBERS

	inner fibers	outer fibers
JME	0.4 ± 0.2 ps/√km	0.13 ± 0.05 ps/√km
interferometric	0.4 ± 0.2 ps/√km	0.11 ± 0.05 ps/√km
beatlength L_b	2.4 m	4.2 m
coupling length h	36 m	9.5 m

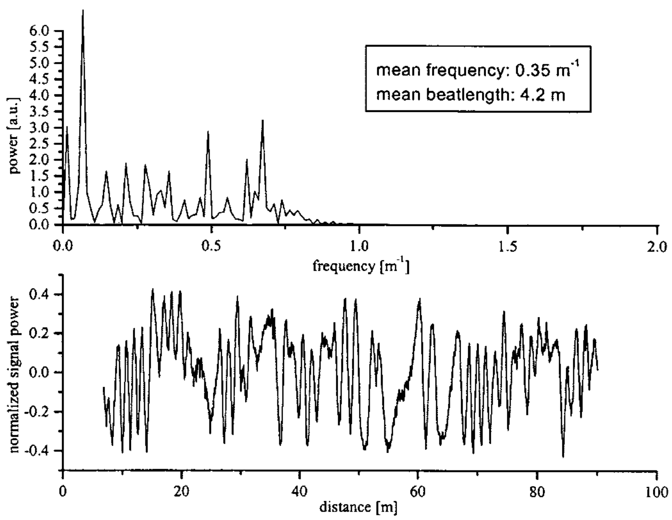

Fig. 2. Reflected signal and spectrum for an outer fiber.

We then used the OFDR to analyze the polarization evolution in the four different fibers. Fig. 2 shows the polarization-dependent reflections from an outer fiber, after removal of the Rayleigh noise and normalization-to-zero mean power. This curve is then Fourier transformed to get information about the rotation period of the polarization vector, i.e., the beatlength. The figure shows that there is not one specific, well-defined beatlength period, but a distribution of such values. While the structure of the peaks changes somewhat for different launch polarizations, the mean value of the distribution is fairly constant, giving a mean beatlength of about 4 m. The uneven structure of the signal is typical for a low PMD, standard fiber with a relatively short coupling length. The influence of the ribbon stress is small, but still induces some ordering (e.g., at distances around 10 m and 70 m in Fig. 2).

On the other hand, the situation is drastically changed for the inner ribbon fibers. As is shown in Fig. 3, the backreflected signal is now very regular, indicating a long coupling length and well-defined birefringent axes induced by the larger external ribbon stress. Accordingly, the Fourier transform now shows a distinctive peak corresponding to $L_b/2$ [7], giving a beatlength value of $L_b = 2.4$ m. Consequently, the external stress both enhanced the coupling length *and* the local birefringence. It is interesting to note that when the fibers are torn out of the ribbon, inner and outer fibers show the same characteristics. A typical example is shown in Fig. 4. Comparing the spectrum of the "free fiber" (Fig. 4) and the outer ribbon fiber (Fig. 2), one observes that the two strong low-frequency components, corresponding to an intrinsic beatlength of about 55 m, are present

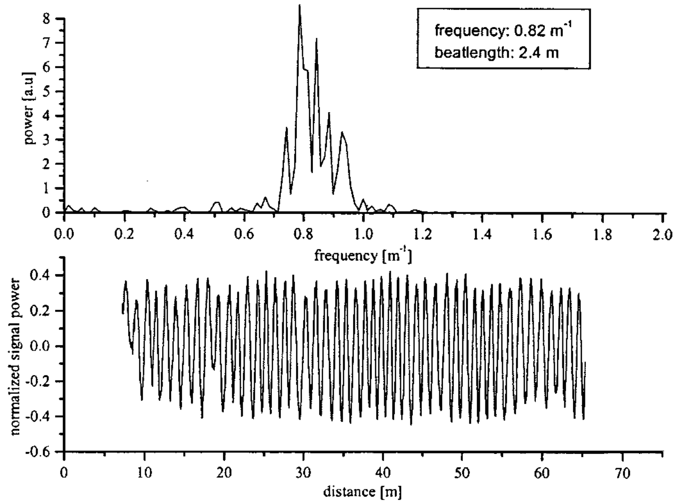

Fig. 3. Reflected signal and spectrum for an inner fiber.

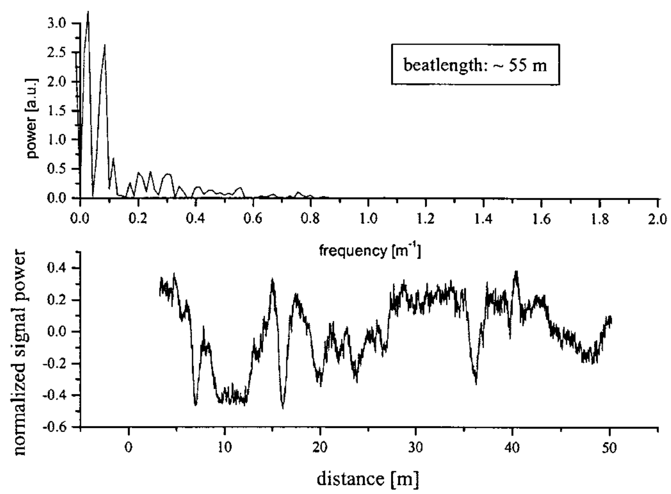

Fig. 4. Reflected signal and spectrum from a "deribbonized" fiber.

in both cases. For the outer ribbon fiber, there are, however, additional peaks due to the stress-induced birefringence, demonstrating that in that fiber intrinsic and induced birefringence are of similar magnitudes.

The coupling lengths h for inner and outer fibers can be determined more precisely by using the measured PMD (Table I) and beatlength values and applying the well-known relation $\mathrm{PMD} = (\lambda/cL_b)\sqrt{hL}$, valid for fibers where the fiber length $L \gg (h, L_b)$. The obtained coupling lengths are 36 m for the inner, and 9.5 m for the outer fiber (see, also, Table I), confirming the qualitative observations given above. These findings are also in good qualitative agreement with those reported in [1].

IV. CONCLUSION

Using high-resolution coherent optical frequency domain reflectometry, the polarization evolution in fibers of a ribbon cable have been straightforwardly measured. The reflected signal for inner ribbon fibers shows a well-defined, regularly varying structure. This demonstrates that the ordering from the external stress, induced by the common ribbon coating, is important. Consequently, a small beatlength and a large coupling length were obtained. For the outer ribbon fibers, the signal variations were more random, indicating that the externally induced stress birefringence is of the same order than the intrinsic one.

The measurements further point out that for long-range applications of fiber ribbons, a careful design of the common coating is important, as PMD values as large as 0.4 ps/$\sqrt{\text{km}}$ are otherwise experienced.

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