Dynamic Birefringence Induced Extensional Stress in Curled Hole-Assisted Fiber

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Abstract: This paper describes the dynamic birefringence induced by the extension of a curled optical hole-assisted fiber, which increases linearly under high tension. This technique can be a used for monitoring premises wiring.

OCIS codes: (060.2300) Fiber measurements; (260.1440) Birefringence

1. Introduction

Hole-assisted fiber (HAF), which has a hole structure, has an extremely low bending loss characteristic [1] that makes it attractive for flexible optical wiring with the potential for easy and economical domestic installation. An optical-fiber curl cord consists of a HAF with a spiral cord structure and small diameter that makes it easy to stretch to a considerable degree. This means we can use it to wire an optical home network without adjusting the cord length or attaching a connector. To consider the optical characteristics of the wired curl cord, we should take account of the effects induced in the cord by the bending and dynamic stretching of the curl cord. The dynamic loss in HAF and the static birefringence in curled single-mode fiber have been reported [2, 3]. However, the dynamic birefringence induced when a curl cord is stretched remains unclear. In this paper, we investigate the dynamic birefringence in a stretched optical-fiber curl cord and confirm its characteristics experimentally to identify the loading state of optical-fiber curl cord when used for premises wiring.

2. Birefringence in stretched curl cord

Fig. 1 shows an image of an optical-fiber curl cord and the cross-sectional structure of the HAF used for the curl cord. HAF has a low bending loss property as the result of several holes being arranged around its core. Birefringence, which determines the polarization state of the curl cord, is essentially a stress effect. Fig. 2 shows the stress induced by stretching the curl cord. There is the bending stress τ_{bend} in the direction away from the center of the curl, shear stress τ_{shear} in the tension direction and a torsion moment $\tau_{torsion}$ in the rotation direction. The shear stress in silica is generally negligible compared with $\tau_{torsion}$. Thus, the total stress τ_{total} can be expressed as follows

$$\tau_{total} = \sqrt{\tau_{bend}^2 + \tau_{torsion}^2 + 2|\tau_{bend}||\tau_{torsion}|\cos\theta} \,. \quad (1)$$

These stresses generate a birefringence β_{total} in the curled fiber. The birefringence is calculated by using Brewster's law;

$$\beta_{total} = \frac{2\pi}{\lambda} \cdot C_b \cdot \tau_{total} \,. \quad (2)$$

where λ and C_b are the measurement wavelength and the Brewster constant, respectively.

The static birefringence per cord length is calculated as a function of cladding diameter d and curl diameter D. The birefringence is caused by the bending stress, $\tau_{bend}=Ed^2/(2D^2)$ [4]. E is Young's modulus [7.2 x 10^{10} N/m^2].

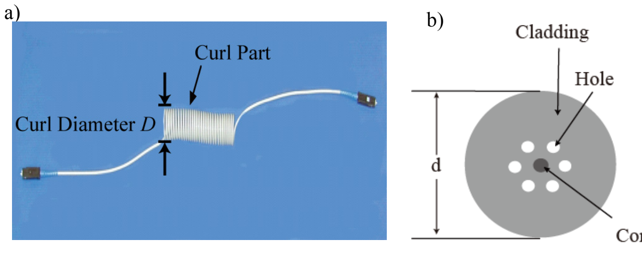

Fig. 1a) Image of optical-fiber curl cord and b) cross-sectional structure of HAF.

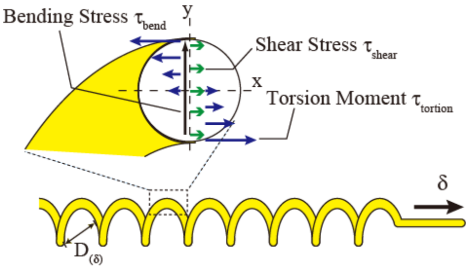

Fig. 2 Bending stress, shear stress and torsion moment in stretched optical-fiber curl cord.

When the curl cord is stretched, curl diameter D increases to $D_{(\delta)}$ for stretching δ. The $D_{(\delta)}$ can be calculated using the relation of a circular arc;

$$D_{(\delta)} = A \cdot Sin \frac{45 \cdot D_{(0)}\pi}{A}, \quad A = \sqrt{D^2 \cdot \cos\left(\sin^{-1} \frac{\delta}{D_{(0)}\pi}\right)^2 + \left(\frac{\delta}{2}\right)^2} \; . \tag{3}$$

Here, $0 < \delta < N \cdot D_{(0)}\pi$, N is the number of turns on a spiral and δ is stretching length. The β_{bend} is decreased by decreasing the stress in the curl cord because curled bending decreases with the stretching.

The tension related to the spring shape is accrued as $\tau_{torsion}$. The torsion moment $\tau_{torsion}$ varies with the ellipticity of the core diameter in the curl cord, because there is a difference between the stresses of the major and minor axes in elliptical core section. Therefore $\tau_{torsion}$ are calculated as follows,

$$\tau_{torsion} = \frac{16k\delta \cdot d_c}{\pi d^4} \cdot \frac{n_e}{(1-n_e)^2}, \tag{4}$$

$$k = \frac{Gd^4}{8ND_{(0)}^{\;3}}, \tag{5}$$

where n_e, k and G are the non-circularity, the spring constant and the modulus of rigidity, respectively.

This dynamic birefringence β_{total} calculated by eq. (2) is shown as a function of the stretching length in Fig. 3, where G is 3 x 10^{10} [N/m^2], C_b is 3.5 x 10^{-12} [m^2/N], λ is 1.55 x 10^{-6} [m], $D_{(0)}$ is 0.012 [m] and n_e is 0.2 [%]. Additionally the birefringence that originated from τ_{bend} and $\tau_{torsion}$ is shown in Fig. 3. As a result, the bending birefringence per cord length β_{bend} decreased gradually and the torsion birefringence per cord length $\beta_{torsion}$ increased linearly with the stretching length. β_{total} decreased by the initial torsion moment countered the effects of τ_{bend}. The $\beta_{torsion}$ is the dominant birefringence when δ is large. Therefore, we found that the β_{total} was highly dependent on the torsion birefringence.

Monitoring the birefringence in the curl cord is suitable for the beat-length measurement method performed in the longitudinal direction of the HAF. The polarization power I is calculated as follows [5, 6]:

$$|I_p| = I_0 \sin^2(2\theta) \cdot \sin^2(\beta_{total} \cdot l), \tag{6}$$

where p is the axis of the component, I_0 is the input power, θ is the input angle and l is the longitudinal length of the optical fiber. I_0 and θ are determined by the parameters of the input light. Then, the polarization beat-length is given as follows:

$$l_{beatlength} = \frac{\pi}{\beta_{total}} \; . \tag{7}$$

3. Measurement Results and Discussion

On the basis of the above theory, we measured the beat length of the curl cord using an optical frequency domain reflectometer (OFDR). Our experimental setup technique is shown in Fig. 4. The measurement signal from the tunable laser source (TLS) in the OFDR was input into the curl cord and backscatter light. The backscatter light was split by a polarization beam splitter (PBS) into x- and y-axis signal power components, and then transferred to photo detectors. The transferred optical signals were converted to electrical signals with an analog-digital converter (ADC). Fig. 5 shows the OFDR traces of the curl cord with and without stretching. The beat lengths were 0.0659 m and 0.0299 m at $\delta = 0$ and 2.4 m, respectively. The calculated and measured values of $b_{eat\ length}$ from $\delta = 0$ to $\delta = 3.6$ are plotted in Fig. 6. Fig. 6 shows the beat length l for the stretching curl cord per turn. l was calculated by (7). The measured results agree with the calculated values when δ is large. With a small δ, the measured result is slightly larger than the calculated l because there is an initial stress in the curl cord. Thus, we confirmed that the dynamic birefringence is dominated by the torsion moment when the stretching length is long. With a short stretching length, the birefringence is dominated by the bending stress. Thus, we can identify the state of the optical-fiber curl cord in premises wiring using the technique for measuring the polarization beat length.

We also measured the continuous status of the phase at the end of the stretched curl cord. Fig. 7 shows the experimental setup. A light launched from the polarization analyzer was linearly polarized by the polarization controller and passed through the stretched curl cord. Then, the light signals were linearly polarized at angles of 0°, that of 45° and that of 0° and passed through a quarter-wavelength plate and detected by the PD to be analyzed for the state of polarization. Fig. 8 shows the trajectory for the polarization state in the stretched curl cord from $\delta = 0$ to 6.3 cm. 45-degree linear polarization was converted into circular polarization on a Poincaré sphere. Then, the polarization state was returned to 45-degree linear polarization at δ = 6.3 cm. These results clearly show the dynamic birefringence as the described in eq. (1). The end-to-end measurement enables to monitor the detailed stretching.

4. Conclusion

We investigated the dynamic birefringence in a stretched optical-fiber curl cord. We described three stress factors, and showed that the dynamic birefringence is dominated by the torsion moment when the stretching length is long. We also showed the trajectory for the polarization state in the stretched curl cord. By measuring the beat length of the curl cord, we can detect the state of the optical-fiber curl cord in premises wiring.

5. References

[1] T. Kurashima, K. Hiramatsu, H. Aoyama, K. Nakajima and S. Tomita, ECOC 2007, (2007).
[2] Y. Yen and R. Ulrich, Appl. Opt. Vol. **19**, No. 15, 2721-2725 (1981).
[3] R. Ulrich and A. Simon, Appl. Opt. Vol. **18**, No. 13, 2241-2251 (1979).
[4] R. Ulrich, S. C. Rashleigh and W. Eickhoff, Opt. Lett. Vol. **5**, 273-275 (1980).
[5] A. M. Smith, Appl. Opt. Vol. **17**, No. 1, 52-56 (1978).
[6] W. J. Tabor, A. W. Anderson and L. G. Van Uitert, J. Appl. Phys. **41**, 3019-3021 (1970).

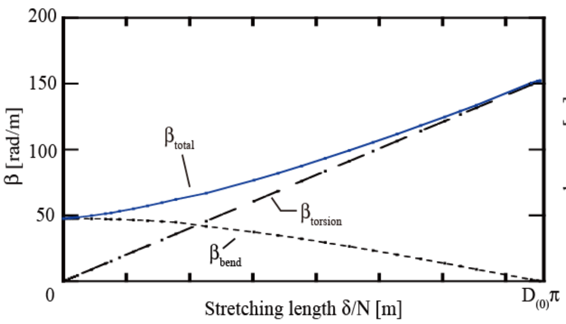

Fig. 3 Calculated birefringence β with stretch length.

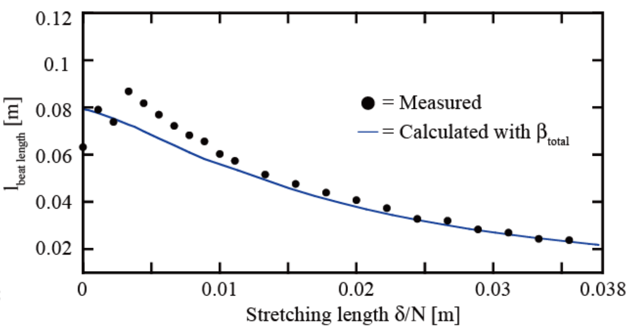

Fig. 6 Beat length l of the curl cord with a stretch length δ per turn.

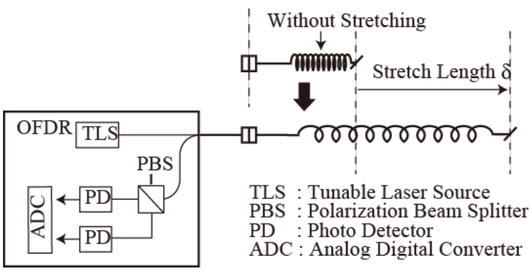

Fig. 4 Experimental setup for polarization beat-length measurement in optical-fiber curl cord.

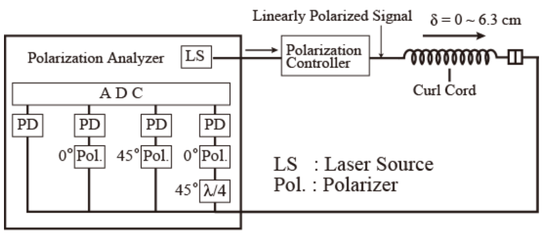

Fig. 7 Experiment setup for polarization-state trajectory measurement.

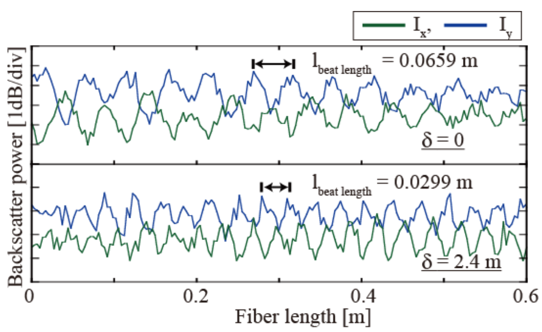

Fig. 5 Polarization power in optical-fiber curl cord with and without stretching.

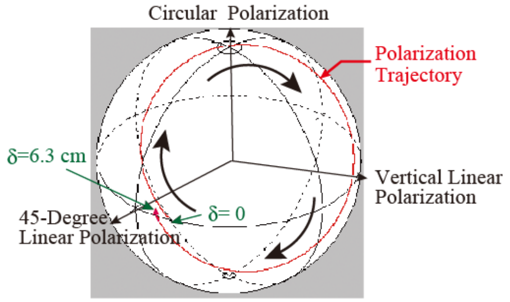

Fig. 8 Trajectory of a polarization state in curl cord for stretching.