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Wavelength dependence of stress-induced time of flight variations in graded-index multimode fibers

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ABSTRACT

We investigate the wavelength dependence of stress-induced time of flight variations in graded-index multimode fibers (GI-MMFs) for wavelength $\lambda = 1.26\ \mu m \sim 1.58\ \mu m$, theoretically and experimentally. Calculations were made based on simple equations using the refractive index of silica fibers. We measured the wavelength dependence of stress-induced time of flight variations by a newly proposed measurement method. We confirmed the similar wavelength dependence of GI-MMFs to that for standard single mode fibers (SSMF). However, the value of them is different. We compare the experimental and theoretical results for two types of fibers. The comparison indicates that the difference of stress-induced time of flight variations between two types of fibers is mainly due to the group velocity difference. We conclude that there is no significant difference of the photo-elastic constant between the measured SSMFs and GI-MMFs. Although many properties of GI-MMFs depended on the mode power distribution in general, we conclude the dependence of stress-induced time of flight variations on mode power distribution is small for the measured fibers.

1. Introduction

Increase of a widespread broadband internet services will be continued worldwide. High-speed optical transmission systems must fulfill a demand of broadband internet services. We have proposed SDM-WDM parallel transmission using a fiber ribbon to construct future ultra high-speed access network [1]. Parallel transmission systems using a fiber ribbon will be also used in local area networks (LANs). The important parameter for the optical parallel transmission is skew, which is defined as the maximum time of flight difference between fibers in a fiber ribbon. Fiber ribbons are usually used as an optical cable, which may be used in temperature change and under stress in an actual environment. The temperature dependence of skew has been investigated and we confirmed skew is temperature independent [2,3]. An optical cable under stress causes a fiber elongation, which changes both a fiber length and a refractive index. Both changes influence the time of flight. A fiber length change influences the time of flight through the group velocity of optical pulses. The refractive index change can be evaluated by the photo-elastic constant. The time of flight variations in a fiber ribbon due to the non-uniform stress cause a fiber skew and influence the transmission properties in optical parallel transmission systems. So far we have investigated stress-induced time of flight variations in both multimode fibers and single mode fibers (SMFs), including hole-assisted fibers [3–6]. However, the investigation in wavelength ranges of $\lambda = 1.3\ \mu m \sim 1.6\ \mu m$, which are used in ordinary optical transmission systems, was mainly for SSMFs in the previous paper [4]. GI-MMFs are used in short-reach transmission systems, such as LANs. And a few-mode fiber is recently intensively investigated and the fiber is not SMF. From this point of view, it is important to investigate the stress-induced time of flight variations in multimode fibers. Apart from the practical importance, it is interesting to know a fundamental skew property of two types of fibers (SSMFs and GI-MMFs). Is there a difference of stress-induced time of flight variations between them?

In this paper, we only investigate Ge-doped silica fibers, that is, Ge-doped core and pure-silica cladding. The fiber is a usual GI-fiber used for telecommunication, that is 50 μm core diameter and delta is 1% and the index profile is nearly optimized for longer wavelength. First of all, calculations of stress-induced time of flight variations were made using two assumptions. They are the small mode power distribution dependence and the same value of photo-elastic constant for two fiber types. Then, we measured the stress-induced time of flight of GI-MMFs for wavelength $\lambda = 1.26\ \mu m \sim 1.58\ \mu m$ by a newly proposed measurement method. We can measure the stress-induced time of flight variations for

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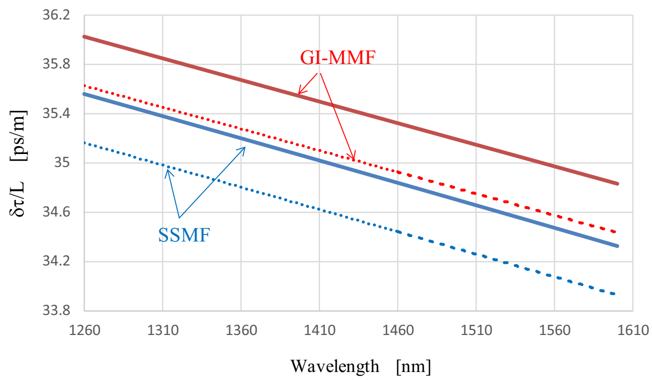

Fig. 1. Calculated wavelength dependence of $\delta\tau/L$ for the strain $\delta L/L = 1\%$ for both types of fibers using two values of C_g. Solid curve: C_g $C_g = -5.34 \times 10^{-12}$ [m^2/N], dotted curve: $= -5.49 \times 10^{-12}$ [m^2/N].

two wavelengths on the same condition. With this measurement method we can measure the wavelength dependence accurately. For comparison, we also measured the stress-induced time of flight of SSMFs by this method. The measured results show clearly that there is a difference of stress-induced time of flight variations between SSMFs and GI-MMFs. There are many modes in GI-MMFs and many properties are known to be mode-dependent. By a theoretical study, there is a negligibly small difference of stress-induced time of flight variations among modes in GI-MMFs. Although the measurement accuracy is not so good, this is confirmed by experiments. Therefore, we can conclude the dependence of stress-induced time of flight variations on mode power distribution is small for the measured GI-MMFs. We compare the experimental and theoretical results for two types of fibers. The comparison indicates that the difference of stress-induced time of flight variations between them is due to the group velocity difference and there are no significant difference of the photo-elastic constant between the measured SSMFs and GI-MMFs.

2. Theoretical study of stress-induced time of flight variations

Optical pulses or modulated signals propagating in a fiber are influenced when a fiber is pulled. The stress due to the pulling force changes the group velocity of signals and the fiber length L. The time of flight variation $\delta\tau$ due to the stress is expressed as the following equation [3–6].

$$\delta\tau = \frac{N}{c}\cdot\delta L + \frac{L}{c}\cdot\delta N = \frac{N}{c}\cdot\delta L + \frac{L}{c}\cdot\frac{C_g E\delta L}{L} = \left(\frac{N}{c}+\frac{C_g E}{c}\right)\delta L \tag{1}$$

Where, N and c are the group index of core and the speed of light ($c = 2.998\times10^8 [m/s]$). The symbols δL and δN represent the fiber length change and the group index change. E is the Young's modulus and C_g is defined as

$$C_g = C - \lambda\frac{dC}{d\lambda}. \tag{2}$$

The symbol C and λ represent the photo-elastic constant and the wavelength, respectively. When C is regarded as a constant for wavelength variations, C_g is equal to C. We previously measured the wavelength dependence of C for silica fibers [4,6]. The measurement indicates that C is a function of λ. The Eq. (1) is derived for a single mode fiber based on the approximation, that is, the group velocity V_g is approximately expressed by c/N. The value $V_g = c/N$ is uniquely determined in a single mode fiber. For the case of multimode fibers, $\delta\tau$ due to the stress for a mode with the group velocity V_g is as follows.

$$\delta\tau = \left(\frac{1}{V_g}+\frac{C_g E}{c}\right)\delta L \tag{3}$$

Here we use two assumptions, assumption-A, and -B. In assumption-A, the time of flight variation $\delta\tau$ due to the stress has very small mode dependence in GI-MMFs. Although each V_g takes different values, we assume $V_g = c/N_1$. Where, N_1 is the group index at the core center. In assumption-B, C_g of GI-MMFs takes the same value of SSMFs. We will discuss these two assumptions later. Based on the assumptions, we can use the same Eq. (3) for both types of fibers. Although we use the same equation for both fiber types, the refractive index difference takes a different value.

We can evaluate the wavelength dependence of $\delta\tau$ due to stress by using the following Sellmeier's equation.

$$n^2 = 1 + \sum_{i=1}^{3}\frac{a_i\lambda^2}{\lambda^2 - b_i} \tag{4}$$

Where, a_i and b_i are constants and we use the measured data in [7]. By differentiating Eq. (4), we obtain the group index N.

$$N = n - \lambda\frac{dn}{d\lambda} = n + \frac{\lambda^2}{n}\sum_{i=1}^{3}\frac{a_i b_i}{(\lambda^2 - b_i)^2} \tag{5}$$

Measured data of Ge = 3.2 mol% and Ge = 11.2 mol% are used for SSMF and GI-MMF, respectively [7]. The relative refractive index difference Δ is 0.323% for SSMF and 1.085% for GI-MMF at $\lambda = 1310$ nm. Here, Δ is defined by the following Eq. (6).

$$\Delta = \frac{n_1 - n_2}{n_1} \tag{6}$$

Where, n_1 is the refractive index of core and n_2 is that of cladding. The calculated wavelength dependence of $\delta\tau/L$ for the strain $\delta L/L = 1\%$ is shown in Fig. 1 using $E = 7.6\times10^{10}$ [N/m^2] and two values of C_g at $\lambda = 1310$ nm, $C_g = -5.34\times10^{-12}$ [m^2/N] and $C_g = -5.49\times10^{-12}$ [m^2/N]. The value of $C_g = -5.49\times10^{-12}$ is the previously measured value [4]. $C_g = -5.34\times10^{-12}$ is the result of this paper, which will be shown in Fig. 5. Although the values of $\delta\tau/L$ are different, the results indicate the similar wavelength dependence for both fiber types.

3. Experimental study of stress-induced time of flight variations

3.1. Experimental setup using two light waves

Here we propose a new measurement method to measure the wavelength dependence accurately. Before the proposal, we explain the previous measurement method by using Fig. 2.

The setup shown in Fig. 2 uses a pulling tool, which elongates a fiber length from L to $L + \delta L$. We used a tunable laser (T-LD) as a light source. The T-LD was intensity modulated by a sinusoidal wave from a signal generator (SG) with a $L_iN_bO_3$ (LN) modulator. An optical polarization controller (PC) was used between T-LD and LN. The modulated wave was detected by an optical receiver (O/E converter). Phase of the transmitted wave was compared with the original phase by a vector voltmeter. This method is the well-known phase method. The output of the vector voltmeter was connected to a personal computer thorough a data logger. The data were time-averaged to remove data fluctuation. A short part of the fiber (about 1.5 m) was set in the pulling tool and was pulled. The fiber length change δL was measured using a micrometer of the pulling tool. The change of the transmitted phase due to elongation was measured and it corresponds to a group delay variation. Intensity modulated optical power P is expressed as the following equation.