

Optical Fiber Cables for Synchronous Remoting of Numerous Transmitters/Receivers

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Abstract—The relative fiber-to-fiber microwave phase changes induced in optical fiber cables by interfiber thermal and strain (bending-induced) gradients are reported. It is found that these changes are effectively minimized in cables where the fibers spin around the center member at a fast rate. Commercial “loose-tube” cables are found to preserve the fiber-to-fiber phases within 1° at modulation frequencies as high as 18 GHz. These cables appear well suited for fiber-optic remoting of numerous phase-matched transmitters and receivers.

Index Terms—Fiber-optic remoting, optical fiber cables, time-steered antenna arrays.

I. INTRODUCTION

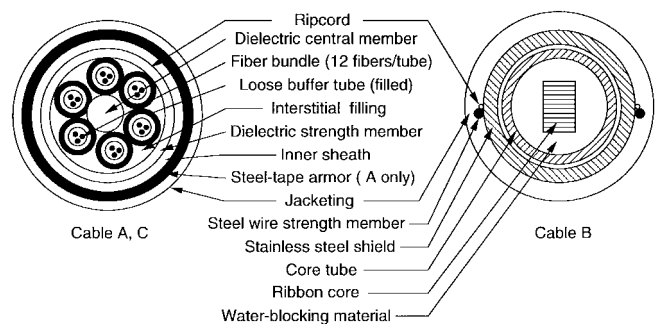
PHOTONIC remoting of systems containing numerous phase-matched transmitters and receivers requires optical fiber cable to distribute the relative time or phase information. An example of such a system is a time-steered antenna array [1]. For these systems to operate reliably at high-modulation rates and under realistic operating conditions, the fiber cable must preserve the relative timing of the transmitters and receivers even in the presence of interfiber temperature and strain gradients. By an “interfiber gradient,” it is meant that the temperature and strain vary from fiber to fiber across the cable. These fiber-to-fiber variations result in strain and temperature differentials which, through thermooptic and elasto-optic effects, change the relative delay between the fibers and disrupt the synchronization of the system. In principle, even a small strain or temperature differential between two fibers can add up over several meters to a significant relative phase error. Interfiber temperature and strain gradients can be created by laying a cable on a hot/cold surface and by bending the cable, respectively.

Previously, we presented the first measurements on the relative microwave phase changes induced by interfiber thermal and strain gradients on optical fiber cables [2]. In that work, we tested several cables and found that some cables preserve the relative phase better than others. In this letter, we show that cable geometry plays an important role in the cable's immunity to interfiber gradients. The geometry is important because inside the cable, the fibers spin around the center axis with a nominal *spiral period*. We show that cables having short spiral periods are most effective in preserving the relative timing of the fibers.

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Cable	Diameter (cm)	Minimum Bend Radius (cm)	Spiral Period (cm)	Fiber Count
A	1.4	15	10	6 tubes (12 SMFs/tube)
B	1.8	18	90	18 ribbons (12 SMFs/ribbon)
C	1.2	15	10	6 tubes (12 SMFs/tube)

Fig. 1. Specifications of fiber cables tested.

II. EXPERIMENT

Fig. 1 shows the cross sections of the three commercially available single-mode fiber (SMF) cables (labeled A, B, and C) used in our tests. Cables A and C are “loose-tube” technology, consisting of individual gel-filled tubes twisting around a dielectric center member with a spiral period of 10 cm, with each tube containing 12 SMF's. Cable A is armored, whereas cable C is not armored. Cable B is “ribbon” technology, consisting of 18 stacked ribbons immersed in a gel compound, with each ribbon containing 12 fibers. Unlike cables A and C, cable B has no dielectric center member, and the ribbon spiral period is 90 cm.

The relative microwave phase between two fibers in the cable was measured with a microwave Mach-Zehnder interferometer (Fig. 2). An 18-GHz RF signal was fed to a LiNbO₃ Mach-Zehnder modulator (MZM) to amplitude modulate a 1550-nm distributed-feedback (DFB) laser diode. The two complementary modulated outputs of the MZM were spliced to two radially opposite fibers within the test cable. The two fiber outputs were demodulated with separate high-speed photodetectors (PD's) and amplified. The relative phase difference, $\phi_1 - \phi_2$, between the RF outputs generated by the two photodetectors was measured using a doubled-balanced microwave mixer and a voltmeter. A microwave trombone was placed in one of the RF arms to calibrate the system and to bias the mixer output at 0 V (i.e., quadrature phase) before any temperature or strain gradients were applied. For all tests, the mixer input signal amplitudes remained constant, resulting in measured amplitude variations at the mixer output

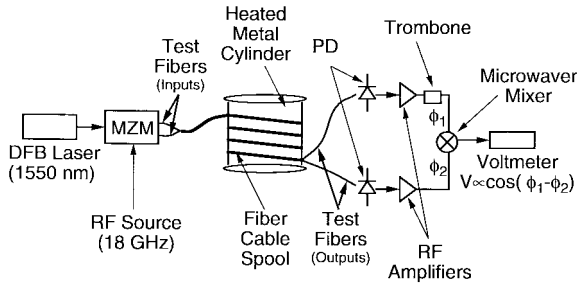


Fig. 2. Experimental apparatus used to measure microwave phase changes.

being phase-induced. At 18 GHz, the phase resolution of this system was $\pm 0.1^\circ$, as limited by the voltmeter.

To create a temperature differential across the fiber cable, the cable was wound around an aluminum cylinder with an attached heating pad. The cylinder temperature was monitored with a thermocouple and ramped from 25 °C to 80 °C in 30-min intervals by 5 °C. For all three cables tested, we measured relative phase changes of 1° or less at 18 GHz for temperature differentials as high as 40 °C. Here, the temperature differential was taken as the difference between the temperature of the metal cylinder and that of the outer cable surface. The measurement was repeated for different heated lengths by winding/unwinding additional turns around the cylinder. For heated lengths between 1 and 5 m, the temperature-induced phase deviations were 1° or less for all three cables. No proportionality between heated length and measured phase shift was observed.

The strain differential test consisted of uncoiling (or coiling) the cable from the cylinder and monitoring the relative phase change between the two fibers. During these tests, we observed both transient and steady-state phase changes. Fig. 3(a) shows a typical measured transient response to a sudden stress. In general, the transient phase variations lasted 100 to 500 ms and settled at a steady-state value close to (but not necessarily) zero. Cable B showed higher peak transient phase deviations than cables A and C. Fig. 3(b) shows the steady-state phase change measured as each cable was uncoiled from the cylinder. The measured peak phase shift was independent of the cable length. For cables A and C, the relative phase did not change by more than 1° at 18 GHz after fully uncoiling five meters of cable. For cable B, however, we measured phase deviations as high as 7° at 18 GHz.

III. DISCUSSION

The above results show that the cables tested were virtually immune to temperature differentials, but sensitive to strain differentials. The fact that the measured relative phase change was independent of fiber length suggests that cable geometry plays a role in averaging out strain differentials. Furthermore, the fact that the “ribbon” cable was more susceptible to strain differentials than the “loose-tube” cables suggests that proper cable design is important.

We can understand the role of cable geometry in averaging out interfiber gradients by modeling the microwave Mach-Zehnder experiment of Fig. 2. In the presence of thermal and strain differentials between two similar fibers, the

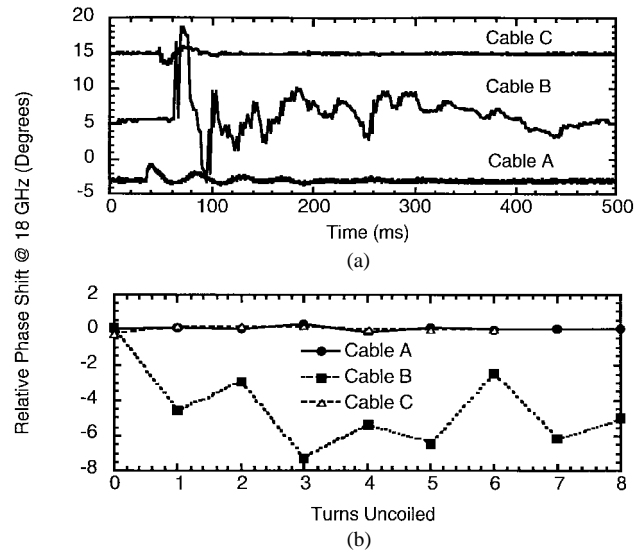


Fig. 3. (a) Measured strain-induced transient and (b) steady-state phase changes at 18 GHz. Cable length and bend radius are 5 m and 14 cm, respectively.

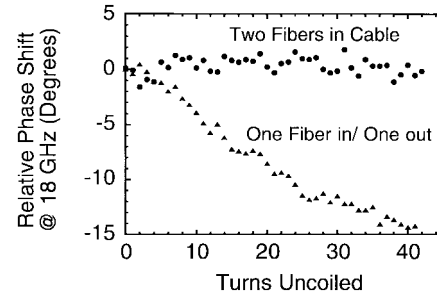


Fig. 4. Effect of spiral geometry in averaging out strain-induced effects. Cable length and bend radius are 50 m and 14 cm, respectively.

measured relative phase difference, $\phi_1 - \phi_2$, at the output of the balanced mixer is

$$\phi_1 - \phi_2 = \frac{2\pi f n_o}{c} \left[\left(\frac{1}{n} \frac{dn}{dT} + \frac{1}{l} \frac{dl}{dT} \right) \int_0^{l'} \Delta T_{12}(z) dz + \left(\frac{1}{n} \frac{dn}{dS} + \frac{1}{l} \frac{dl}{dS} \right) \frac{1}{A} \int_0^{l'} \Delta F_{12}(z) dz \right] \quad (1)$$

where f is the frequency of the microwave signal (18 GHz in this case), n_o is the effective index of the fiber, and l' is the fiber length over which the differential is established. The terms $(1/n)dn/dT$, $(1/l)dl/dT$, $(1/n)dn/dS$, and ldS/dl represent the refractive index thermal coefficient ($8 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$) [3], the thermal expansion coefficient ($8 \times 10^{-7} \text{ }^\circ\text{C}^{-1}$) [3], the refractive index strain coefficient ($-2.3 \times 10^{-12} \text{ m}^2/\text{N}$) [3], and the Young's modulus ($7.2 \times 10^{10} \text{ N/m}^2$) [4] of the fiber, respectively. ΔT_{12} and ΔF_{12} are the applied temperature and force (load) differentials, respectively, between fibers 1 and 2, and A is the fiber cross-sectional area. Notice that we have allowed the differentials to vary along the fiber length.

In order to simplify the analysis, we model the spiral arrangement of the fibers as a sinusoid with spiral period

L_s , and assume that the spiral orientation does not change. Under these assumptions, a constant temperature or strain differential across two spiraling fibers is equivalent to a sinusoidal differential across two straight fibers. Therefore, we can write

$$\Delta T_{12}(z) = \Delta T_o \sin\left(\frac{2\pi}{L_s} z\right) \quad \Delta F_{12}(z) = \Delta F_o \sin\left(\frac{2\pi}{L_s} z\right) \quad (2)$$

where ΔT_o and ΔF_o are the maximum temperature and force (load) differentials between fibers. Substituting (2) into (1) and integrating yields the maximum relative phase shift between two fibers

$$(\phi_1 - \phi_2)_{\max} = \frac{fn_o L_s}{c} \left[\left(\frac{1}{n} \frac{dn}{dT} + \frac{1}{l} \frac{dl}{dT} \right) \Delta T_o + \left(\frac{1}{n} \frac{dn}{dS} + \frac{1}{l} \frac{dl}{dS} \right) \frac{\Delta F_o}{A} \right]. \quad (3)$$

Thus, spiraling the fibers around the center axis averages out the thermo-optic and elasto-optic effects induced by temperature and strain differentials. From (3), the maximum induced phase shift depends not on the cable length but on the spiral period, L_s . Consequently, cables with short spiral periods will show less phase deviation. Cables A and C have a shorter spiral period than cable B (see specifications in Fig. 1), and thus show smaller phase deviations, as evidenced in Fig. 3.

In order to verify the model described above, (3) was used to estimate the temperature and load differentials required to create temperature and strain-induced phase shifts of 0.1° and 1° at 18 GHz, respectively, in cable A. Assuming SMF-28 fibers (250- μm coating diameter) and $L_s = 10$ cm, (3) yields $\Delta T_o = 20^\circ\text{C}$ and $\Delta F_o = 8.9$ N. Such differentials are representative of those established in our heating and coiling/uncoiling experiments.

As final proof of the above observations, the coiling/uncoiling experiment was repeated on a 50-m-long cable similar to type A. Two measurements were performed. In the first measurement, both fibers in the interferometer of Fig. 2 were inside the cable. In the second measurement, one fiber was inside the cable and the other one was outside. The results, shown in Fig. 4, show that when both fibers were inside the cable, the induced phaseshift was independent of cable length. When only one fiber was inside the cable, the phase shift increased proportionally with the number of turns coiled or uncoiled. These results clearly illustrate how the spiral arrangement of the fibers inside the cable averages out strain differentials.

IV. CONCLUSION

We have measured the fiber-to-fiber phase changes induced by interfiber temperature and strain gradients on optical fiber cables. Cables having short spiral periods were found more immune to interfiber gradients. Commercial “loose-tube” cables appear well suited for photonic applications involving synchronous remoting of multiple transmitters and receivers.

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