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CURRENT DEVELOPMENTS IN PHASE SHIFT TECHNIQUES APPLIED TO FIBER MEASUREMENTS

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3.2 Current Developments in Phase Shift Techniques applied to Fiber measurements

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ABSTRACT

We review current developments in phase shift technology applied to fiber measurements. Reviewed will be the different types of fiber measurements which are possible (such as chromatic dispersion and stretching measurements) using phase shift technology.

INTRODUCTION

Time-based measurements of fiber characteristics are important in fiber optic testing technology. These measurements, based on time-of-flight values or phase shifts are used in the characterization of different fiber parameters, especially when long fibers are being measured. Some of the fiber parameters which can be measured using these methods are: group delay as a function of wavelength (i.e. the chromatic dispersion), fiber length measurement, and fiber strain measurements (elongation of the fiber under stress).

Different methods have been proposed for the measurement of the propagation time of light through a length of optical fiber. The two most important methods are the direct measurement of time-of-flight of a light pulse (time domain) and the phase measurement of the radio frequency modulation of a laser diode or LED source (frequency domain).

Even though it is easier to produce intense light impulses than it is to carry out RF modulation, sophisticated instrumentation is needed to measure the time delay with the necessary precision when carrying out time-domain measurements. The results are often affected by such problems as jitter, pulse width and time resolution.

The phase shift technique however, allows attaining better than picosecond resolution (depending on the modulation frequency and response characteristics of the detectors used). In addition, this method uses classical instrumentation (oscillators, vector voltmeters) already widely used in radio frequency applications. Using such well-known radio frequency techniques for fiber optic metrology confirms the phase shift method as the method of choice for industrial fiber measurement.

RF MODULATION PHASE MEASUREMENT

Time resolution

Knowing the modulation frequency f, it is possible to calculate the incremental group delay T using the formula

$$T = \frac{\Delta\phi}{360^\circ} \cdot \frac{1}{f}$$

where $\Delta\phi$ is the measured modulation phase variation due to any effect on the time of propagation through the fiber. Given a phase accuracy of say 0.1°, it can be seen that a modulation frequency of 100 MHz will give a time accuracy of better than 3 picoseconds. Doubling this frequency will halve the time accuracy to bettter than 1.5 picoseconds. It is obvious that phase measurements should be conducted at a relatively high modulation frequency.

Classic phase measurement

The basic principle of phase measurement is shown in figure 1. A frequency generator is used to modulate a suitable optical source such as a LED or laser diode. After propagation through the fiber, the signal is detected and its phase is compared to a reference phase obtained from the modulating generator. The actual phase detection can be carried out using a purpose-built detector (mixer), or classical vector voltmeter.

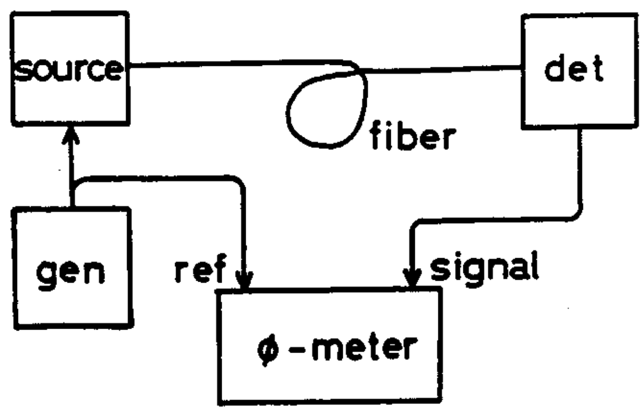

Fig. 1. Simple fiber optic phase measurement setup.

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Frequency down-shifting

In some cases measurement at a high frequency (necessary to insure picosecond resolution of the group delay) causes problems. This is because a fast detector with a consequently high noise level is required. Furthermore, radio frequency interference from the strong drive current gives biased results. For these reasons, it is possible to use a frequency conversion technique to down-shift the RF modulation frequency to a low audio frequency where highly sensitive amplifiers can be used. Thus it is possible to accurately measure the phase of the high frequency signal using a low frequency lock-in amplifier.

For the detection, a local signal generator operating at a frequency w_2 modulates the arriving optical signal w_1 in the fiber using an optical electrooptic modulator to down-convert w_1 to the difference frequency $w_2 - w_1$ (see figure 2). This low frequency signal is then amplified and phase analyzed using lock-in techniques. Even though the signal is converted to a low frequency, the phase information is preserved.

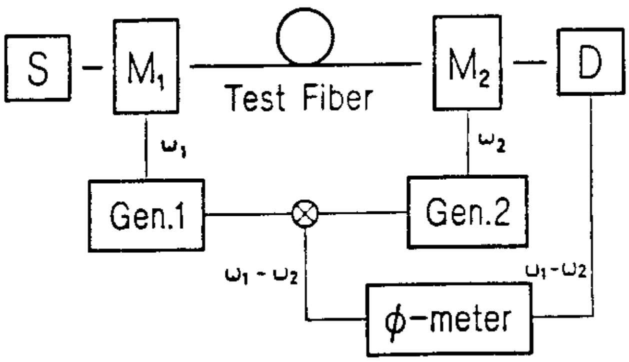

Fig. 2. Phase shift measurement technique using frequency down-shifting.

The situation can be expressed mathematically as follows. When the intensity of the optical source is sinusoidally modulated the instantaneous intensity at the other end of the fiber is expressed as

$$I(t) = I_0(\lambda)\cos(w_1 t + \phi_1 + \bar{t}(\lambda)w_1 L)$$

where $I_0(\lambda)$ is the output modulation amplitude, w_1 the modulation frequency, ϕ_1 an arbitrary constant phase, $\bar{t}(\lambda)$ the group delay per unit length at the emission wavelength λ, and L the fiber length.

When a second intensity modulation at frequency w_2 is optically performed between the fiber output and the detector, the detected intensity becomes

$$I(t) = I_0(\lambda)m_2\cos(w_1 t + \phi_1 + \bar{t}(\lambda)w_1 L) \cdot\cos(w_2 t + \phi_2)$$

$$= \frac{1}{2}I_0(\lambda)m_2 \cdot\{\cos[(w_1 - w_2)t + \phi_1 - \phi_2 + \bar{t}(\lambda)w_1 L] + \cos[(w_1 + w_2)t + \phi_1 + \phi_2 + \bar{t}(\lambda)w_1 L]\}$$

where m_2 is the second modulation depth and ϕ_2 is another arbitrary constant phase. This second modulation generates sum and difference frequency signals, each conserving the phase information of the primary signal. The second modulation frequency w_2 is chosen to be very close to w_1 so that the difference-frequency component $(w_1 - w_2)$ is about 5 kHz, where ultrasensitive optical detection, signal amplification and high-resolution phase measurements can be performed. Therefore this frequency transformation allows the low-frequency measurement of the phase shift while at the same time using a high frequency for the transmitted signal.

Multiplication of the two high-frequency sine waves results in a low-frequency sine wave which preserves the phase information of the high-frequency signal.

THE PARAMETERS INVOLVED

Source parameters

The source can be varied either with respect to its modulation frequency (fiber length and fiber bandwidth measurements) or its wavelength (chromatic scan). When wavelength variations are involved, it is also possible to use a broadband source and use a wavelength selective element (monochromator) in front of the detector.

Fiber parameters

The fiber parameters involved during a phase shift measurement are: the group delay time variation as a function of wavelength (i.e. the chromatic dispersion); the phase variation as function of the RF frequency (used for total fiber length determination); the group delay time variation as a function of stress (i.e. stretching measurements) and the attenuation as a function of the RF modulation frequency (i.e. the bandwidth). Any or all of these parameters can be measured and modified as desired and the effects observed by studying the phase shift.

MEASUREMENT OF THE GROUP DELAY AS A FUNCTION OF WAVELENGTH

The measurement of the chromatic dispersion in long fibers is becoming more and more important as transmission volumes are pushed to higher and higher values. For these needs, phase shift chromatic dispersion measuring equipment has become available which allows the measurement of lengths from 1 to 50 km of fiber without necessarily having the two ends available at the same place.

Principle of operation

A broad wavelength source (LED) is modulated at an RF frequency w_1 of say 100 MHz and launched into the fiber. The relative phase of this signal is measured at the other end of the fiber. In the receiver, the arriving optical signal is split into the phase reference channel and the monochromator channel. The relative phase between these two signals is then measured to within 0.1 degree using precise phase measuring equipment and a scan is made of the incremental propagation delay as a function of wavelength. Knowing the fiber length allows calculation of the group delay per unit length using a least squares method to calculate the parameters of the so-called Sellmeier equation. Taking the mathematical derivative of this equation gives the values for the chromatic dispersion at the different wavelengths, the zero dispersion wavelength (λ_0) and the slope.

Chromatic dispersion instrument

The essential elements of the chromatic dispersion instrument are shown in figure 3. The transmitter consists of one or several broad-band sources modulated at an RF frequency w_1. The receiver is attached to the other end of the fiber and consists of an optical modulator operated at a slightly different frequency w_2 in order to down-convert the optical signal to a low frequency while at the same time preserving the phase information. The optical signal is divided into two parts. One constitutes the reference phase and the other goes through the monochromator necessary for the optical spectral analysis. The two electrical signals are brought to the phase meter for signal recording and analysis.

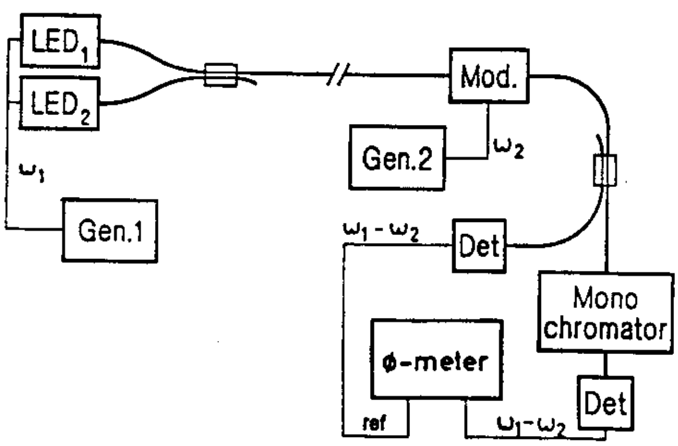

Fig. 3. Long fiber chromatic dispersion measurement equipment.

Reference phase

A phase measurement always requires a reference signal of the same frequency. This signal must be at a wavelength for which the LED emission is strong (1300 nm). The other detector however, receives the signal after wavelength selection has taken place by means of the monochromator. The measured phase difference is therefore the difference between a constant phase at 1300 nm and the variable phase due to the chromatic dispersion.

In this way, the optical signal propagating through the fiber under test is used as the reference phase. It is however, also at the low down-shifted frequency of 5 kHz since the optical demodulation described above has already occured. By this means, all perturbing effects (temperature variation, fiber movement, modulation frequency variation, etc.) which can occur during the measurement are eliminated.

Phase calibration

The modulated sources used show some variation in phase as a function of wavelength. In order to eliminate the effect of this "zero phase" or "phase offset", an apparatus calibration is necessary. This is accomplished by simply coupling the transmitter to the receiver through a short length of fiber (a few meters), doing a spectral scan and recording the phase values with respect to the reference. These values are then stored in memory and when actual measurements on long fibers are carried out, the calibration phase values are simply subtracted from the newly measured values, giving the actual phase retardation due to the long fiber itself.

Group delay curve fitting

Having obtained several measured values for the incremental group delay as a function of wavelength, it is now possible to fit a mathematical function to this data using the least squares method. Several different equations are currently used for this least squares fit depending on the number of measured points, the spectral range covered and the type of fiber being measured. The usual equation is the so-called Sellmeier three-term expression:

$$\tau(\lambda) = c_1\lambda^{-2} + c_2 + c_3\lambda^2$$

which gives reasonable fits for a small number of delay measurements around the minimum dispersion wavelength. When the spectral range of the measurement is large covering both the 1300 and 1550 nm windows, a better fit is obtained wth the five-term Sellmeier expression:

$$\tau(\lambda) = c_1\lambda^{-4} + c_2\lambda^{-2} + c_3 + c_4\lambda^2 + c_5\lambda^4$$

which can describe both normal and dispersion-shifted fibers. Dispersion flattened or more complicated fibers can also be described by a polynomial expression:

$$\tau(\lambda) = c_0 + c_1\lambda + c_2\lambda^2 + \ldots + c_n\lambda^n$$

Dispersion Calculation

Once the incremental group delay has been determined, the dispersion values can be found by taking the derivative, either mathematically or directly from the least squares fit. In the case of the three-term Sellmeier expression, the equation for the dispersion is:

$$D(\lambda) = 2(c_3\lambda - c_1\lambda^{-3})$$

Lambda zero and slope

The value for the zero dispersion wavelength, represented as λ_o, is found by setting the dispersion equation to zero (when using the three-term Sellmeier group delay equation):

$$\lambda_o = (c_1/c_3)^{\frac{1}{4}}$$

The slope of the dispersion at this wavelength, represented as S_o, is the derivative of the dispersion equation and is found to be:

$$S_o = 8c_3$$

For the higher order equations, it is easier to find these values by numerical analysis.

Some typical results of chromatic dispersion measurements are shown below.

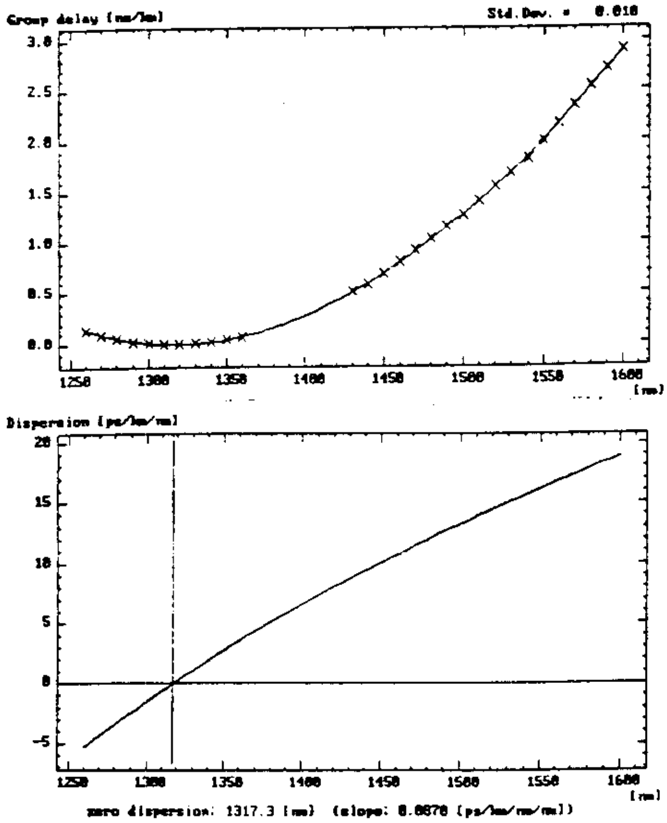

Fig. 4. Chromatic dispersion results.

STRAIN MEASUREMENTS

When fiber optic cables are constructed, it is very important that the individual fibers inside the cable not be under tension. They must be loose and free to move slightly when the cable is wound and unwound from drums, installed and pulled through conduits, etc. In order to test a section of cable for the correct fiber conditions, it is necessary to stretch it using a special test bench and to simultaneously monitor each fiber inside for possible abnormal tension and stretch. For this purpose, stretch monitoring equipment exists which can check each fiber during the test.

The procedure consists essentially of monitoring the phase of the transmitted signal in each fiber during the test. Using a modulation frequency of 100 MHz it is possible to detect an elongation as small as 0.5 mm.

In order to monitor several fibers at once, rapid switching between fibers is necessary. This can be carried out by using a 1 to N fiber optic multiplexer.

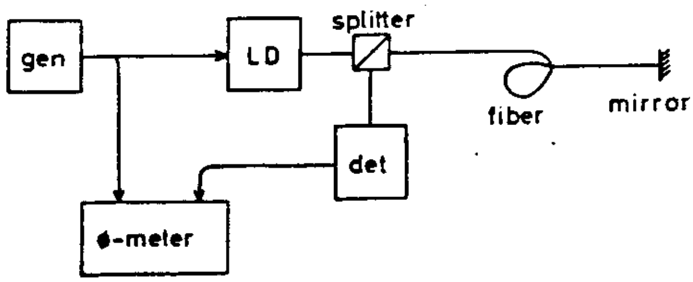

Fig. 5. Fiber stretching measurement setup.

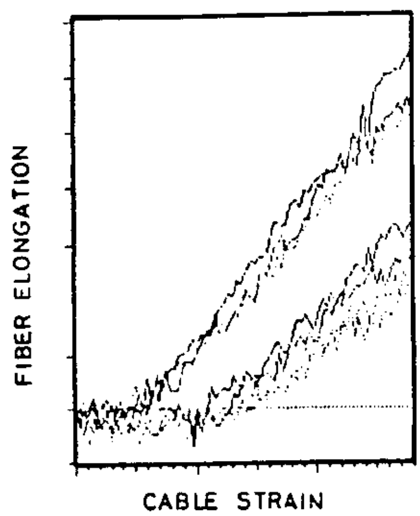

Fig. 6. Typical results of fiber stretching measurements.

the fiber is possible. In this case it is necessary to monitor the signal on a go-and-return path rendered possible by suitably reflectorizing the other end of the fiber. A typical diagram is shown in figure 5.

Typical results

Typical results of elongation measurements on seven fibers in a loose-tube type cable being stretched are shown in figure 6. It can be seen that the results differ accrording to the relative positions of the fibers within the cable structure. The results are divided into two groups which differ according to where elongation of the individual fibers begins to occur and the rate at which they are stretched (slope). This type of result shows the importance of simultaneous measurement of the several fibers within a cable during mechanical testing.

CONCLUSIONS

We have presented here practical applications of phase shift measurement technology applied to fiber optic measurements. Chromatic dispersion measurements: important in fiber design for high-volume telecommunications and fiber stretching measurements: important in cable design and manufacture. We mention in passing other applications of similar technology: fiber length determination, bandwidth measurements obtained by measuring the attenunation as a function of modulation frequency and phase measurements of retro-reflected light: OFDR (optical frequency domain reflectometry).

-- Marcuse, Dietrich. Principles of Optical Fiber Measurements. Academic Press 1981.

-- Katsuyama, Y. et ali. "Study on mechanical and transmission charactersitics of optical fiber cable during installation". Journal of Optical Communications. 3, No. 1, pp. 1-7. 1982.

-- Noda, K. (ed.) Optical Fiber Transmission. North-Holland 1986.

-- Geckeler, Siegfried. Optical Fiber Transmission systems. Artech House 1987.

-- EIA standard. "Chromatic dispersion measurement of multimode graded-index and single-mode optical fibers by spectral group delay measurement in the time domain". FOTP-168. EIA-455-168. July 1987.

-- Von der Weid, J.-P. "Chromatic dispersion in single mode fibres". Groupe de Physique Appliquée, Geneva 1986.

-- Thévenaz, L. and J.-P. Pellaux. "Modulation frequency-shift technique for dispersion measurements in optical fibres using LEDs". Electronics Letters. 23, No. 20, pp. 1078-1079 (24 Sept. 1987).

-- Thévenaz, L. and J.-P. Pellaux. "Group delay measurement in single-mode fibers with true picosecond resolution using double optical modulation". Presented at OFC/OFS '88, New Orleans 27-29 Jan. 1988.

-- Thévenaz, L. "Effets et measure de la dispersion dans les guides d'ondes optiques". Thesis, University of Geneva, Switzerland. 1988.