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Wavelength and Temporal Dependency of Polarization Mode Dispersion based on 150,000 Continuous Measurements over Buried Field Fiber in Indiana

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***Abstract*— A detailed analysis of more than 70 million PMD data points (490 wavelengths x ~150000 continuous measurements) on 160 km of buried field fiber was executed. Both of DGD and SOPMD show wavelength dependency and temporal dependency over measurement periods. Discrepancy between measured JPDF and calculated JPDF suggested necessity of a re-visit to the calculation model based on a sequence of randomly birefringent sections.**

***Index Terms*—Field fiber measurements, Polarization mode dispersion, Temporal dependency, Wavelength dependency**

INTRODUCTION

Transmission of higher bit rate optical signals over installed fibers requires consideration of both first and second order polarization mode dispersion (PMD). [1] As the first and second order PMDs have statistical behavior, it is very important to validate theoretical models with experimental data. For most current systems, a single maximum tolerable differential group delay (DGD, originating from first order PMD) is specified for all wavelengths in order to simplify the system design. The probability for second-order PMD (SOPMD) effects is typically calculated from a model that assumes a sequence of randomly birefringent sections, taking the realistic worst-case scenario without enough verification over installed fibers. Upgrading of the theoretical model might be needed based on multiple measured data, for example, by comparing calculated joint probability density function (JPDF) with correlation between measured DGD and measured SOPMD.

Recently we reported that the DGD characteristics of installed fibers exhibit wavelength dependencies [2]. In order to increase the design efficiency of high bit-rate systems where PMD is a factor, it might be desirable to incorporate the wavelength dependency in a manner that reflects actual PMD behavior over installed fibers. The more advanced system design would then allow for extension of system reach.

It is supposed that environmental changes such as temperature changes, vibration, etc. cause statistical behavior of PMD. One of the most possible factors is temperature changes and we collected various locations' temperature data such as ambient temperature, temperature in hand hall, temperature in ground, etc., to compare those temperature changes with PMD changes temporally.

In this paper we report a detailed analysis of PMD behavior obtained from long-term measurements over 160 km of buried True-Wave RS fiber, lying between two campuses of Indiana University. The correlation between DGD and SOPMD, and temperature (ambient and ground) and PMD are studied, as well as the DGD distribution of specified wavelengths. The total number of measurements exceeded 73 million in order to grasp the entire picture of PMD behavior, including events with probability less than 10^{-5}.

MEASUREMENT SETUP

The fiber cable consisted of two 80 km lengths of True Wave RS fiber linking the Bloomington and Indianapolis campuses (Fig. 1).

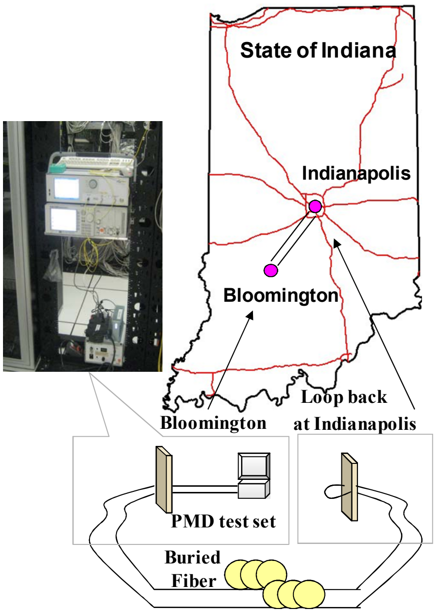

Figure 1: Fiber route and experimental setups

At least one 300 meter section along a bridge in Indianapolis was directly exposed to the atmosphere. Ambient temperature changes affect several meters of fiber at more than 160 hand halls (Photo). Other unexpected environmental effects could also occur at interfaces between buried fibers and patch panels.

Photo: Inside of a hand hall

An Agilent N7788A component analyzer (Adaptiv photonics A2000) was placed at the Bloomington campus. The measuring method was Jones-Matrix Eigenanalysis. The setup consisted of a tunable laser and a polarimeter. The wavelength of the tunable laser was swept from 1520 to 1620 nm at a rate of 20 nm/s, and data were recorded at 0.2 nm increments for a total of 490 measurement wavelengths. Each measurement took 30 seconds and recording was continuous. The measurement started in September, 2007 and ended in November. Ambient temperatures, ground temperature (at 30, 60, and 90 cm depths), atmospheric temperature at the bridge and hand hall temperatures were recorded.

RESULTS AND DISCUSSION

A. Wavelength-Dependence of PMD behavior

As DGD color maps of installed fibers have suggested, DGD behavior is wavelength-dependent [3]. Our results also confirm this dependency [2]. Figure 2 shows the maximum and minimum recorded DGD value for each of 490 wavelengths selected from 149030 measurements, as well as the average of all measurements. The clear wavelength-dependence suggests that the model, which predicts equal behavior for all wavelengths, is not always adequate. This was also recently reported [4]. The standard model also assumes fiber segments are comprised of randomly birefringent sections. Originally, optical fiber is drawn from a glass rod that has a diameter from tens to hundreds of millimeters. Assuming a diameter of 100 mm, 40 km of optical fiber can be drawn from a 6 cm portion of the rod. Considering this, correlations might exist between birefringence and non-circularity over long lengths of fiber even though cabling process randomizes them a little bit, in contrast to the model assumptions. Figure 3 shows an erratic pattern of DGD on a specific wavelength. The ratio between positive (standard deviation of DGD values more than mean value) and negative errors (standard deviation of DGD values less than mean value) from the average value is distributed closely around 1. This nearly symmetrical distribution of DGD on each wavelength is related to temporal changes, as explained later.

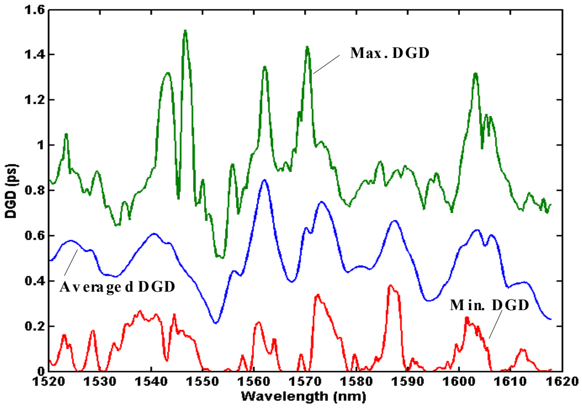

Figure 2: Max. & min. values of measured DGD over measurements

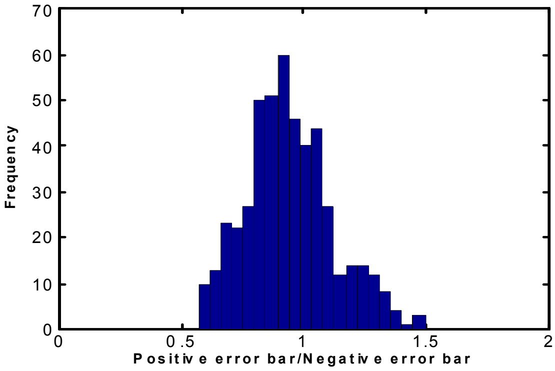

Figure 3: Distribution bias of DGD

SOPMD also exhibits a wavelength dependency, as shown in Figure 4 (color strips). At least, from 10/15 to 10/24, SOPMD value of each wavelength has similar values over the time frame. For example, around 1570nm SOPMD values is always around 0.5ps^2 (green color). We need more long term information to verify whether it would be randomized in long term, or not.

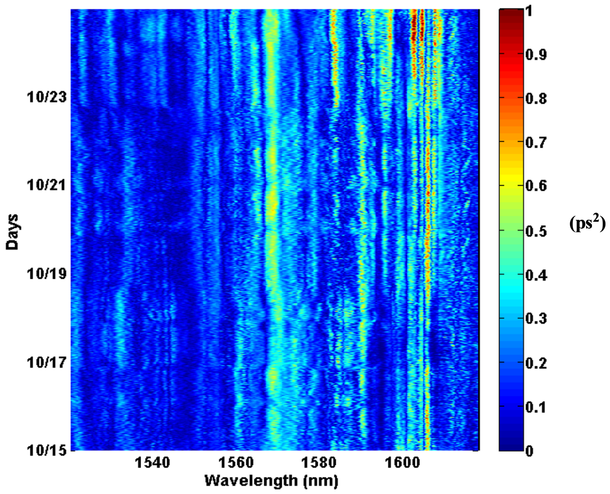

Figure 4: Color map of SOPMD from 10/15 to 10/24

Figure 5 shows a plot of the correlation between DGD and SOPMD, as well as JPDF curves of 10^{-5} and 10^{-6} calculated with the random model. The data of all wavelengths fit well in terms of DGD because the calculation implemented measured mean DGD, however depolarization elements of SOPMD do not fit well in the calculated curves. The measured data of 1553.1nm seems fit to the calculated curve. On the other hand, all wavelengths data differ from model predictions. For example, a large number of points lie outside the 10^{-6} boundary of the calculated JPDF in 1570.2nm case. This data does not claim that the theoretical model underestimate SOPMD of installed fiber. In other cases, the calculated curves have much wider area than experimental DGD/SOPMD plots. Those conclude that correlations between DGD and SOPMD of plant fibers have not been well investigated to this point, and more data is required for better modeling.

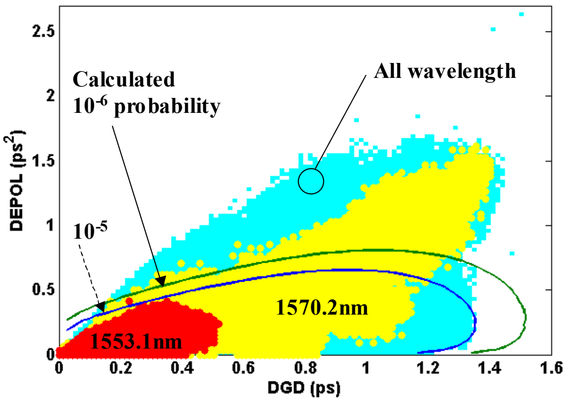

Figure 5: DGD and SOPMD correlation

B. *Temporal changes of PMD behavior*

To investigate the source of the symmetric DGD distributions, we compared DGD changes of certain wavelengths with ambient temperature changes in Bloomington. As Figure 6 shows, DGD changes at 1570.16 nm follow the change of ambient temperature (positive correlation).

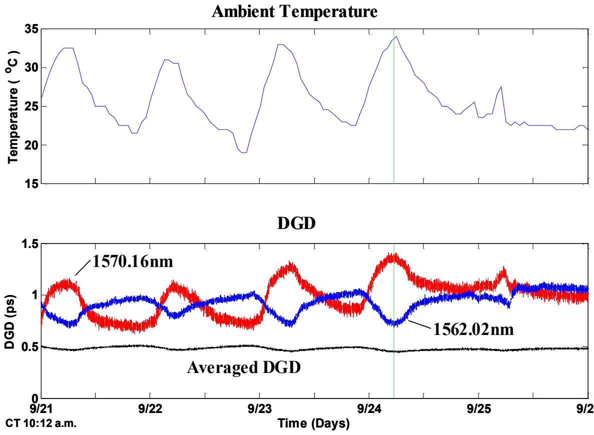

Figure 6: Temporal temperature and DGD changes

On the other hand, DGD at 1562.02 nm shows negative correlation. Careful observation of the measured data indicates that the peaks of DGD changes coincide with peaks of temperature changes, with either positive or negative correlation [5].

Figure 7 shows a comparison of changes of ground temperature (at depths of 30, 60 and 90 cm), bridge temperature in Indianapolis, and hand hall temperature in Bloomington with the ambient temperature at Bloomington. Most buried fibers feel temperature changes at a depth of 90 cm. Figure 7 indicates that, if the DGD was driven by buried fiber temperature, it would remain nearly constant from Fig. 7. However, the results indicate DGD values are highly sensitive to ambient, bridge or hand hall temperature (i.e. the temperature at exposure points). DGD averaged over a long measurement time seems to cancel out its temperature sensitivity with the positive and negative correlation.

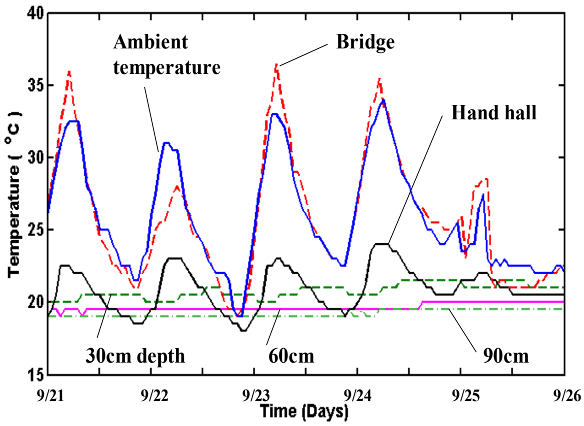

Figure 7: Temperature change of various locations

The clear correlation between DGD and temperature has only rarely been reported, and is likely related to the uniform installation environment of the fiber. The measured fiber runs along state highway 37 with only small height changes from one end to the other (Bloomington: 794ft, Indianapolis: 728ft). And also those two locations have similar longitudes (Bloomington: 86.49W, Indianapolis: 86.16W). It is likely all exposed segments feel the same temperature changes at hand halls and bridges. Insensitivity to temperature, which was supposed for buried fiber, might be due to the summation of different temperature changes along the fiber length. The close correlation between temperature and DGD could produce the symmetric distribution of DGD values for each wavelength. Superimposing those symmetric distributions may give a Maxwellian-type distribution for the data as a whole.

SUMMARY

The above measurements and analysis support the conclusion that PMD properties of installed fibers have tendency of wavelength dependent. The results indicate the DGD value at each wavelength is driven by temperature changes at exposure points (ambient temperature or at hand halls), leading to a symmetric distribution of DGD values around an average value. To grasp whole picture of DGD behavior, we might need to further long term measurement whether this wavelength dependency would be remained or not depending on measurement periods.

The correlation between DGD and SOPMD found in experiments is not in agreement with calculations that model fibers as a sequence of randomly birefringent sections. Because there are few comparisons between measured JPDF and calculated JPDF, more data would be needed for better modeling.

The correlation of the DGD value with temperature for a particular wavelength can be either positive or negative. These findings might be used for better system design in future.

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