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Field measurements of SOP transients in OPGW, with time and location correlation to lightning strikes

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Abstract: We monitored the state of polarization (SOP) of polarized light in an optical ground wire (OPGW) link located in North America using a test method and apparatus that measured Stokes space angular velocity and geographic location of SOP transients. We observed transients up to 5.1 Mrad/s and were able to correlate these events in both time and location to lightning strikes documented by the United States Precision Lightning Network (USPLN).

OCIS codes: (060.0060) Fiber optics and optical communications; (060.4510) Optical communications.

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1. Introduction

The rate of change of state of polarization (SOP) in optical fiber is an important consideration in the design of coherent polarization multiplexed transceivers. These must recover SOP to avoid polarization crosstalk. It is known that SOP transients can occur on propagation through fiber owing to electrical or mechanical transient changes to the fiber cable environment [1,2]. Thus the likelihood of SOP transients of various rates measured in installed links provides a

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basis for tradeoff of coherent transceiver performance versus design complexity. To assess the likelihood of SOP transients it is useful to determine the root cause.

The rate of change of SOP observed in optical ground wire (OPGW) cable is of particular interest. OPGW is a cable type which shrouds optical fiber with a ground wire to allow fiber deployment in power transmission networks. A typical OPGW cable contains optical fiber in either a central tube or a tube that is helically wrapped with layers of conductive strength members [3]. OPGW is an aerial cable and thus is subject to forces of nature with the potential to change SOP such as temperature, wind [4], and lightning [2]. In this study we focus on SOP transients correlated to lightning in a link of geographic distance 505 km in North America. The link comprised using 560 km of fiber cable of which approximately 500 km is OPGW and the remainder aerial All-Dielectric-Self-Supporting (ADSS) as well as underground cable [3]. Previous studies have reported rates of change of Stokes space SOP in OPGW as angular velocity on the order of tens of krad/s for field measurements [5,6], or hundreds of krad/s in fiber for lab measurements [2]. We report field measurements of Stokes space SOP transients having rates up to 5.1 Mrad/s on a long-haul fiber link. Differences from prior studies might be attributed to available instrument bandwidth, undersampling, local lightning incidence and intensity, cable design, or other environmental constraints.

We studied a link in a region of North America with a historic occurrence of lightning in excess of 8 strikes per km^2 per year [7] during a period of frequent lightning strikes, namely April 2016 to September 2016. Our test methods enabled detection of the point of origin along the cable path of an SOP transient. Compared with lightning data from the United States Precision Lightning Network (USPLN), we found a 95% correlation in time and location of SOP transients to lightning strikes.

2. Experimental setup

We monitored the SOP of a polarized light source propagating over a bidirectional link consisting of 7 amplified spans [Fig. 1]. The link was standard single mode fiber (G.652) housed primarily in an OPGW cable. Ingress and egress to and from the link was by way of add and drop ports of a reconfigurable optical add-drop multiplexer (ROADM). The polarized light was looped back after the seventh span at ROADM-A, propagated back through a parallel fiber in the same cable (14 spans of propagation), demultiplexed at ROADM-B, and measured with a polarimeter.

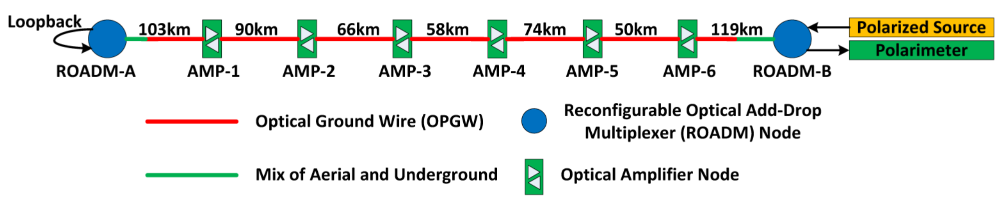

Fig. 1. Not-to-scale schematic of optical system under test.

The polarized light source was an unmodulated Ciena production 10G transponder. Stokes space SOP was measured using a Novoptel PM-500 polarimeter which sampled the Stokes vector at a rate of 100MHz with a per Stokes parameter analog bandwidth of 35MHz. The polarimeter was provisioned to perform a sixteen sample long running average and then decimate by a factor of sixteen prior to download giving an effective sample rate of 6.25MHz. Since the analog response of the polarimeter is approximately flat up to the Nyquist frequency of the effective sample rate it can be disregarded and the new bandwidth calculated using the response function of a running average:

$$H(f)=\frac{\sin(\pi fL)}{L\sin(\pi f)}, L=16, 0\le f\le 0.5 \quad (1)$$

We find the new bandwidth to be 3.8MHz. We report the rate of rotation of SOP as angular velocity in radians per second. The longest arc which may occur between any two samples of the Stokes vector without undersampling must have a length less than or equal to pi resulting in a maximum measurable angular velocity of 19.6 Mrad/s. The polarimeter SNR was >12.1 dB and the mean degree of polarization at 14 spans was above 0.9. Each recording was triggered by a fast polarization transient exceeding the trigger settings of 30 krad/s and 0.2 rad. The polarimeter was automated by a laptop which downloaded each trace once acquisition completed, appended a timestamp from its local system time, and then rearmed the triggering of the polarimeter. The test laptop clock was synchronized to local network time on a daily basis.

The two parallel fibers forming the bidirectional link were contained in the same cable. Because of this, it is assumed that an SOP transient induced by perturbation external to the cable will be observed on the light propagating toward ROADM-A and also on the light propagating towards ROADM-B. Owing to the loop back, each SOP transient that exceeded the trigger criteria was recorded as a pair of transients (one from each direction of propagation) separated by a round trip delay (RTD) which was twice the delay from the location of the transient to the loopback. The measurement of RTD and known propagation speed provide the location of the SOP transient as a fiber distance from the loopback point. Known geographical cable path and optical time domain reflectometer (OTDR) measurements of individual fiber spans allow determination of the geographic location of the SOP transient.

3. Incidence of observed transients

A total of 580 records of SOP events (polarimeter triggers) were captured over 82 observation days, from 2016 to 04-21 to 2016-09-21. Various network events (fiber cuts, network maintenance) prevented continuous monitoring. Table 1 provides per-month details of days monitored, days with triggers, and number of triggers.

Table 1. Per Month Details

	APR	MAY	JUN	JUL	AUG	SEP	ALL
Monitored Days	10	23	24	4	8	13	82
Monitored Days with Triggers	4	9	17	3	6	11	50
Triggers	17	73	205	35	157	93	580

All polarimeter measurements were triggered by an SOP transient superimposed on a 60 Hz background. The 60 Hz background was likely caused by electrical current induced in the OPGW by the aerial power carrying lines deployed along with it [4,8,9]. The maximum SOP deflection angle observed over all data exceeded 180° on the Poincaré sphere. Angular velocity of SOP was measured by applying the law of cosines to consecutive post-decimation samples of the unit magnitude Stokes vector as follows:

$$\theta_n = \cos^{-1}\left(1 - \frac{\left|\vec{s}_n - \vec{s}_{n-1}\right|^2}{2}\right) \tag{2}$$

The angle from Eq. (2) was then divided by the sample period to find angular velocity. We only consider the maximum angular velocity for each trace and per-month statistics of angular velocities are provided in Fig. 2. In many cases the angular velocity of the trace was below the noise floor of Eq. (2) and in those cases a low-pass FIR filter was applied to each Stokes parameter prior to calculation of angle. A FIR filter was chosen because linear phase response is desirable for RTD measurement. The bandwidth of the FIR filter was iterated so as to remove noise without producing a significant underestimate of the true angular velocity.

The boxplots in Fig. 2 describe the rates observed binned by month. A boxplot was chosen so that the distribution of rates for each month could be communicated without distortion by outliers. The red horizontal line is the monthly median angular velocity. The blue box shows the range of velocities which were between the lower quartile (the median of all velocities less than or equal to the monthly median) and the upper quartile (the median of all velocities greater than or equal to the monthly median). The black dots outside the box indicate outliers. Figure 2 shows that the upper fourth of angular velocities was typically about 100 krad/s, that the lower fourth was typically about 30krad/s, and that outliers beyond 1 Mrad/s existed. Angular velocities below our trigger threshold of 30krad/s were observed and this is attributed to the polarimeter trigger using a raw measurement while the velocities below were measured following digital filtering. The fastest measured angular velocity in this study was 5.1 Mrad/s and is shown in Fig. 3.

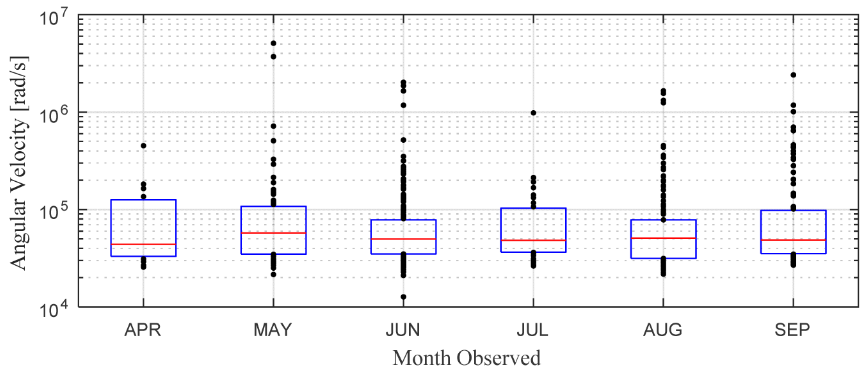

Fig. 2. Distribution of peak angular velocity versus month.

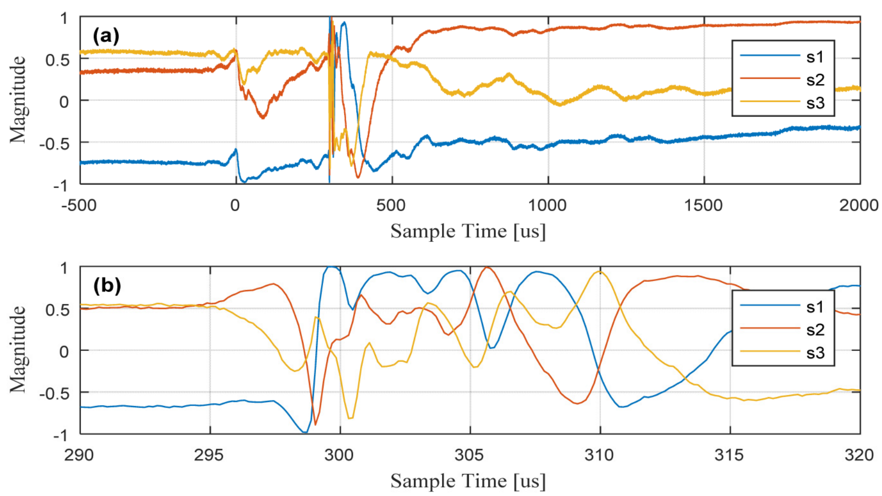

Fig. 3. Stokes parameters of fastest observed transient. (a) Full transient. (b) Close up.

4. Time and location correlation of SOP transients to lightning strikes

It has been reported that fast changes of SOP in optical fiber can be caused by lightning strikes [2,8]. To explore this possibility, we compared the time and location of lightning strikes reported by USPLN [10] with those of SOP transients as measured by our test set.

A model of the physical cable path was constructed using maps of the cable location and street addresses of key components such as ROADM or amplifier sites. By comparing modeled cable length to OTDR fiber length, we estimate the modeled cable position to be within 1 km of the exact location of the physical cable.

We measured 580 SOP transients, of which 561 were locatable using the RTD technique described. The reduced count is due to uncertainty in resolving the time between the dual pulses. Based on our knowledge of the length and location of the fiber, and because of the width of the pulses used in RTD calculations, we were able to bound the geographic location of the SOP transients to within ± 8.0 km along the modeled fiber path.

When searching for lightning strikes in the vicinity of an RTD location measurement, the strikes must be within a reasonable distance of the modeled path of the fiber plant. We chose a distance of 5.0 km based on the accuracy of our fiber plant path estimate, accuracy of lightning data [10], and uncertainty of the distance over which lightning may act upon the OPGW.

The preceding analysis defines an area wherein we search our lightning database for lightning strikes coincident in time and location with recorded SOP transients. Using a ± 1 second time window, which bounds the disagreement in time between the test laptop and USPLN, we found coincident strikes for 95% of locatable SOP transients. Based on a reported total of 33,471 strikes(U_t), assuming uniform strike density within 5 km of the length of the fiber path(L_p), from the mean time between strikes(T_s), the uncertainty in measurement of simultaneity(T_w) and path location(L_w) we estimate the number of the measured serendipitous coincidences between strikes and SOP transients(C_s) to be at most 6 [Eq. (3)].

$$C_s = U_t \frac{T_w}{T_s} \frac{L_w}{L_p} = 33471 \frac{2\text{s}}{388\text{s}} \frac{16\text{km}}{506\text{km}} \approx 6 \tag{3}$$

Of the cases where lightning strikes were coincident with an SOP transient, we observed more than one potentially correlated strike in 86% of the cases (suggesting that strikes are to some extent bunched) and in those cases we chose the strike nearest to the fiber path as the most probable cause of the transient. Strikes correlated to SOP transients were found typically (95% confidence) within ± 4.6 km along the fiber from the measured RTD location and within ± 2.0 km transverse from the modeled cable path.

Figure 4 shows the strong geographic correlation between strikes and SOP transient location. Each blue dot represents an instance of an SOP transient and its correlated lightning strike. The proximity of transients to the diagonal line indicates colocation of the SOP transient and lightning strike along the cable path. While the correlation of time and location of SOP transients and lightning strikes is strong, we were unable to show that lightning strikes which correlated with SOP transients made direct contact with the OPGW cable. Observations in other studies suggest that a direct strike on the cable is not required [2,8].

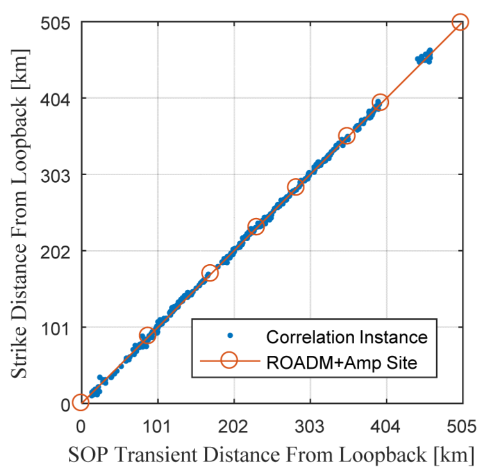

Fig. 4. Geographical correlation of lightning strikes to transient locations.

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5. SOP activity on a cable segment

To better understand the likelihood of SOP transients we investigated their relative probability of occurrence versus location along the fiber path. Figure 5 shows how lightning was distributed along the fiber path during our period of observation. The blue line in Fig. 5 shows all lightning within 5km of the fiber path and during our observation period (P_{all}), while the red line shows only the strikes nearest the fiber path of the sets correlated with SOP transients (P_{corr}). The magnitudes of both lines are normalize to their respective population size. We isolated all SOP transients to cable sections that are OPGW [Fig. 1].

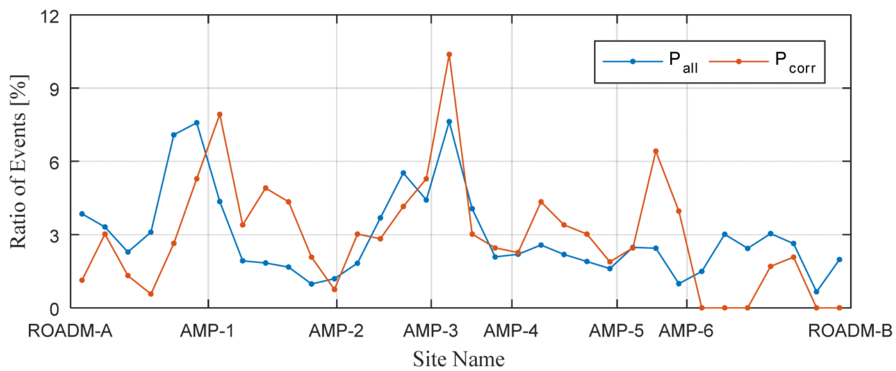

Fig. 5. Lightning strike and state of polarization (SOP) transient distribution.

The lightning observed consisted of negative polarity strikes (cloud-to-ground), positive polarity strikes (ground-to-cloud), and cloud-to-cloud strikes. The statistics of all strikes within 5 km of the fiber path and on monitor days are shown in Table 2. The statistics for the strikes coincident with SOP transients and nearest the fiber path are also shown in Table 2.

Table 2. Lightning Polarity Statistics

	Cloud-to-Ground	**Ground-to-Cloud**	**Cloud-to-Cloud**	**Total**
All Strikes	24,440	1,020	8,011	33,471
Strikes Coincident with Transients	497	9	27	533

There are two areas in Fig. 5 of further interest. First, the region between AMP-5 and AMP-6 experienced a high occurrence of SOP transients relative to that of lightning strikes. Second, the region between AMP-6 and ROADM-B experienced a low occurrence SOP transients relative to lightning strikes. The remainder of this section attempts to explain this disagreement.

In Fig. 6 we consider the statistics of the distance of lightning strikes from the fiber path as a function of distance along the path. We take the mean distance of all strikes within 5km of link during our observation period (D_{all}) and observe it to be ~2.5 km. This implies an even distribution of strikes about the fiber path. We next consider the distance from the fiber path of sets of strikes coincident with SOP transients and from each set record the nearest, furthest, and the mean distance. Figure 6 shows the mean of each of these metrics as a function of distance along the fiber path as D_{min}, D_{max}, and D_{avg} respectively. We observe that the statistics of the coincident strikes are reliably nearer to the fiber path than D_{all}, with D_{min} usually less than 1 km. This implies that distance of lightning from the fiber path is a factor in whether a strike can be correlated to an SOP transient.

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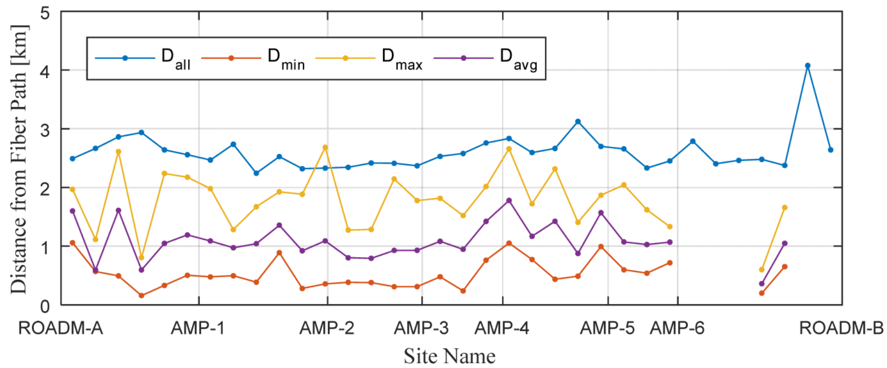

Fig. 6. Mean lightning strike distance from cable path.

In Fig. 7 we consider the statistics of cloud-to-ground lightning current intensity as a function of distance along the fiber path. We first consider the mean current intensity of all cloud-to-ground strikes within 5 km of the fiber path during our observation period (I_{all}) and observe near uniformity along the path. We next consider magnitude of current intensity from the sets of cloud-to-ground strikes coincident with SOP transients and for each set of magnitudes we record the minima, maxima, and mean. Figure 7 shows the means of each of these metrics as a function of distance along the fiber path as I_{min}, I_{max}, and I_{avg} respectively. We observe in Fig. 7 that only I_{min} tracks I_{all} which demonstrates that the sets of cloud-to-ground strikes coincident with SOP transients possess greater than average intensity.

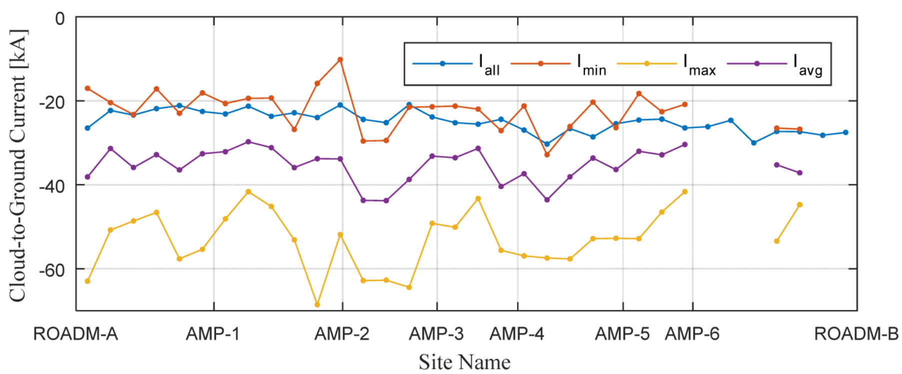

Fig. 7. Mean lightning strike intensity along the cable path.

While current intensity and strike distance appear to contribute to SOP transient correlation, from the projections of Figs. 6 and 7 we conclude that the character of strikes is not a strong function of geography across the length of the link. This suggest that differences in lightning susceptibility of the physical cable plant may be responsible for the site dependence observed in Fig. 5. Factors which influence lightning susceptibility in each OPGW segment may include cable construction (cross-section), cable grounding techniques, and local geography. We know that the cable between ROADM-A and AMP-6 differs from the cable between AMP-6 and ROADM-B simply by the documented fiber count. However, further details on cable construction and grounding are unknown.

6. Summary

We measured Stokes space SOP angular velocity on a cable installation that was predominantly OPGW and situated in North America. We found that SOP transients were distributed throughout the OPGW segments of the cable. We measured SOP angular velocity of up to 5.1 Mrad/s. We were able to show strong correlation in time and location of SOP

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transients with lightning strikes and that SOP transients were likely to correlate to strikes near the fiber path. We also showed that coincident strikes tended to have above average current. We speculate that the likelihood of an SOP transient is also influenced by other factors such as cable construction (cross-section) and cable grounding techniques.