Lightning-Related ELF Transients as a Potential Source of Rapid State of Polarization Changes in Shielded OPGW

J. A. Santos, R. C. Moore, and W. C. Snider
Department of Electrical and Computer Engineering, University of Florida.
1064 Center Drive, Gainesville, Florida 32611, USA.
santos0002@ufl.edu, snider.wc@ufl.edu, and moore@ece.ufl.edu

D. Doucet and D. Charlton
Ciena Corporation.
383 Terry Fox Drive, Ottawa, Ontario, Canada, K2K 0L1
ddoucet@ciena.com and dcharlto@ciena.com

Abstract: This paper demonstrates that typical lightning currents cannot produce observed rapid state of polarization changes in shielded optical ground wires. Lightning flashes associated with large extremely-low-frequency components, however, are capable of doing so.

1. Introduction

Optical fiber data communications are supported in part by the optical ground wires (OPGW) positioned above overhead power lines. In addition to providing optical communications, OPGWs also serve to shield the associated power lines from lightning, and as a result, they occasionally suffer from direct lightning strikes. The state of polarization (SOP) of the optical signal regularly fluctuates with weather conditions and power line currents, for example, but these fluctuations are typically slow and manageable [1]. A direct lightning strike to the OPGW, however, can cause rapid changes (as large as 5–8 Mrad/sec [2, 3]) to the perceived SOP of the optical signal within, and these rapid changes can be difficult to manage by optical transceiver systems.

Snider et al. [4] modeled the variations in peak $d(\mathrm{SOP})/dt$ observed in coherent optical communications as a function of lightning current parameters expressed in the Heidler function [5]: peak current, current rise-time, and current fall-time. They also considered the effect of strike location along the line. The OPGW modeled by *Snider et al.* [4], however, lacked a conducting shield between the helical stranded wires and the inner fiber, which is typical in OPGW construction, and accounting for the shielding effects of this conductor are important to the analysis of peak $d(\mathrm{SOP})/dt$.

It is also important to understand that some lightning flashes produce extremely low frequency (ELF, 3–3000 Hz) transients. Lightning flashes that produce ELF transients tend to be extremely energetic [6], are related to high altitude optical flashes [7], and play an important role in the global electric circuit [8]. Large ELF components are not adequately replicated by the Heidler fuction.

This paper investigates the role played by a shielding conductor inserted between the helical stranded wires and the inner fiber. We evaluate the intensity of fields that reach the inner fiber portion for different shield materials and for different shield thicknesses. We demonstrate that for typical lightning currents that can be replicated by the Heidler function, the penetrating fields are not sufficient to produce observed $d(\mathrm{SOP})/dt$ values. On the other hand, realistic lightning flashes with enhanced ELF signal content are able to produce $d(\mathrm{SOP})/dt$'s of 1–2 Mrad/sec, which is on the order of magnitude of experimental observations.

2. Shield Thickness

In the absence of a shield, *Snider et al.* [4] expressed the magnetic field in the fiber and integrated it to calculate the change in SOP. Here, we use the same expresssions given by [4], except we apply the quasi-static approximation [9] to account for penetration into the metallic shield, thereby modifying the estimate of the magnetic field in the fiber. Magnetic fields diffuse, rather than propagate, into good metallic conductors and exhibit a frequency-dependent exponential attenuation factor that depends on the thickness of the metal normalized by the skin depth, as well as a frequency-dependent time delay (that also depends on the skin depth) [9]. The skin depth itself is

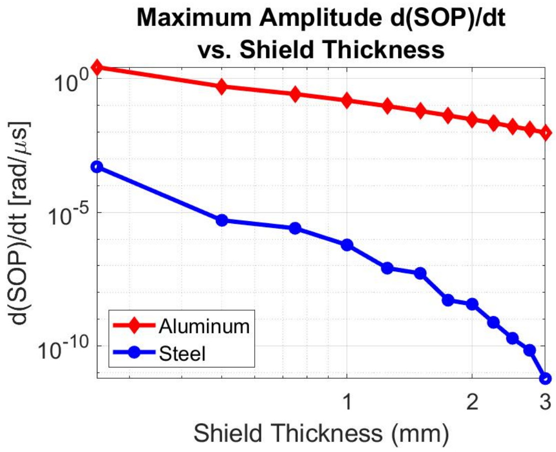

Fig. 1. Maximum $d(\mathrm{SOP})/dt$ for aluminum and steel shielding as a function of material thickness.

frequency dependent and is given:

$$\delta = \sqrt{\frac{1}{\mu\sigma\pi f}} \tag{1}$$

where f is the frequency, μ is the permeability of the medium, and σ is the conductivity of the medium [10]. As a simple quasi-static model, we reduce the field intensity of each frequency component of the magnetic field in the fiber by a factor of $e^{d/\delta}$, where d represents depth into the conductor, and apply the proscribed phasing factor, $e^{jd/\delta}$, to account for the frequency dependent delay [9].

Several designs of OPGWs are given in [11], which indicates aluminum ($\sigma = 36.9$ MS/m, $\mu = 1.00002\mu_0$) and conducting steel ($\sigma = 7.56$ MS/m, $\mu = 4000\mu_0$) are commonly used OPGW materials. It also indicates an aluminum shield thickness of 3 mm is common for OPGWs; a thinner steel shield could potentially serve the same purpose. Here we evaluate $d(\mathrm{SOP})/dt$ for both types of shielding materials as a function of thickness up to 3 mm.

Fig. 1 shows the results of the simulations for aluminum and steel conductors as a function of shield thickness. A peak current of 150 kA, a rise time of 1 μs, and an observation location 50 m from the lightning strike location, as described by [4], were employed. For both materials, $d(\mathrm{SOP})/dt$ decreases rapidly with shield thickness. For the aluminum shield, $d(\mathrm{SOP})/dt$ decreases with a nearly power-law form (linearly on log-log scale). The $d(\mathrm{SOP})/dt$ for the steel shield is much smaller than for the aluminum shield because the skin depth of steel is smaller. Despite the fact that the conductivity of aluminum is 4-5 times higher than the steel, the skin depth of the steel is smaller due to the much larger permeability of the steel. The permeability of the steel also results in a more pronounced frequency dependence on time delay, resulting in the more pronounced deviation from power-law as a function of shield thickness. In both cases, however, at the 3 mm industry standard thickness, the $d(\mathrm{SOP})/dt$ has diminished dramatically – by at least 99% – from the unshielded case.

3. Dependence on Peak Current and ELF Transients

Charlton et al. [2] presented field observations of $d(\mathrm{SOP})/dt$ reaching as high as 5.1 Mrad/s. *Pittala et al.* [3] conducted a laboratory experiment which yielded $d(\mathrm{SOP})/dt$ measurements of 8 Mrad/s. *Snider et al.* [4] simulated $d(\mathrm{SOP})/dt$'s as large as 6 Mrad/sec. The exceedingly high attenuation produced by the metallic shields discussed in the previous section indicate that the current lightning model may have significant difficulty predicting $d(\mathrm{SOP})/dt$'s as large as have been observed. In an effort to reproduce observed levels of $d(\mathrm{SOP})/dt$, we choose to push the lightning parameters to realistic limits: lightning current rise times as short as 0.1 μs and lightning peak currents up to 500 kA are considered [12].

Simulation results using the Heidler function model for lightning current and for a 3 mm thick aluminum shield are shown in the left panel of Fig. 2. Even for a peak current of 1000 kA and a current rise time of 0.1 μs, only $d(\mathrm{SOP})/dt$'s on the order of 0.1 Mrad/sec are predicted. It is clear that this lightning current and transmission line model cannot reproduce observations.

On the other hand, lightning may produce several large-amplitude ELF transients per minute [13], and the Heidler function does not represent these low-frequency lightning currents well. In order to evaluate the possibility that ELF transient-related lightning could produce significant SOP changes, we re-evaluate our simulations with the frequency content below 5 kHz increased by 40 dB. ELF transients with over 30 dB enhancements below

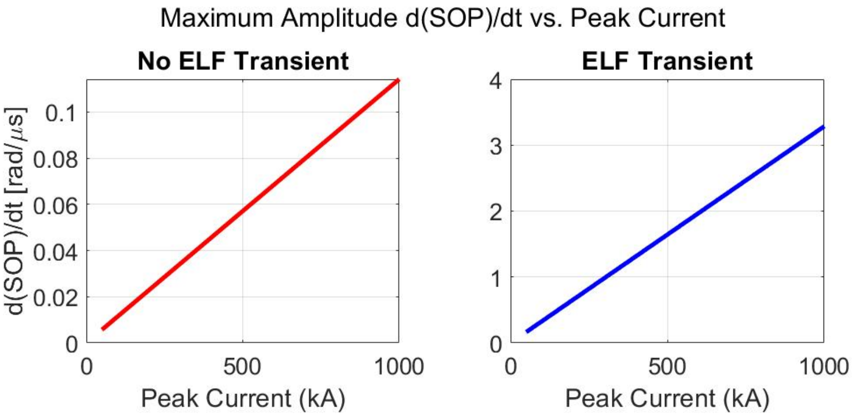

Fig. 2. (Left) Maximum $d(\mathrm{SOP})/dt$, for the parameters given in the text, for a typical lightning flash as a function of peak current. (Right) The same plot for a lightning flash with enhanced ELF content.

5 kHz are regularly observed; an enhancement of 40 dB would be considered large, but not unrealistic.

The right hand panel of Fig. 2 shows the simulation results including the ELF transient. According to the simplistic model, realistic large peak current values (up to 500 kA) can produce $d(\mathrm{SOP})/dt$'s of 1–2 Mrad/sec, if a large ELF transient is included. This value is approximately 3 times smaller than the largest $d(\mathrm{SOP})/dt$ observed in the field, but it is on the same order of magnitude.

4. Conclusion

A transmission line model is used to simulate $d(\mathrm{SOP})/dt$ of an optical signal propagating through an OPGW with a shield surrounding the fiber lines. Simulations of typical lightning currents using the Heidler function were unable to reproduce the field observations provided in [2]. By including a lightning model that includes ELF transients, we were able to produce $d(\mathrm{SOP})/dt$'s on the correct order of magnitude. A more complete model of quasi-static penetration into the conducting shield may improve these simulation results, but it appears to be the case that lightning currents with large ELF components play an important role producing large magnitude $d(\mathrm{SOP})/dt$ transients on OPGW lines.

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