Estimation of feasible exposure of lightning gamma rays upon optical fiber cable

Stanislav A. Sokolov

Professor, doctor of technical science

Moscow Technical University of Communications and Informatics

Moscow, Russia

stanislav.a.sokolov@gmail,com

Abstract. There is considering of feasible exposure of gamma rays arising during lightning stroke upon optical fiber cable. Radiation of X- and γ-rays discovery by lightning was happened not long ego. The radiation contains quanta with energy from 1 till 10 MeV and even more. Dribble of them reaches earth surface. Interacting with optical fiber material and generating Compton electrons (recoil electrons) they lead to atomic structure failure, color centers initiation and line attenuation increase. As quanta flux density near earth surface is smallish, it should not wait for great execution of optical cable at see level. When height rise quanta number in air increase strongly and at altitude about 2000 meters above sea level severe effects are enable for entirely dielectric optical fiber cable. In this paper there are considering mechanism and numerical analysis of lightning influence consequences.

Key words: lightning discharge, gamma radiation, half-value layer, radiation dose, exposure rate.

Introduction. J.R.Dwyer and his collaborators [1] have marked powerful gamma radiation from thunderstorm cloud briefly 0.3 millisecond. Following research has found out that during lightning formation process X-ray, γ- ray and electron-positron pairs radiation appears at the same time. Quanta energy can amount some tens MeV. Gamma-ray impact on fiber causes displacement process, lattice defects and color centers formation that lead to additional attenuation and other curses. Low hydroxyl group content reduces fiber radiation resistance.

Polymeric fiber is particularly sensitive to radiation in consequence of polymer chain destruction. When fiber lines are laid in mountains this phenomenon it is necessary to take into account.

1. Process of gamma radiation origin

The origin of gamma radiation take place during the first stage of leader process at descending (downward) lightning. Leader process can be as descending (negative) and ascending positive (bottom-up) which is beginning from earth. The ascending leader appears during reduced distance between cloud and earth, for example in mountains or near high structure (skyscraper, tower). Flash of radiation of gamma rays in this case occurs when ascending positive arrow-shaped leader arrived to cloud at some kilometers above earth surface. Interesting results have been found during trigger-lightning investigations. On the earth surface there are strong radiation observed of quanta with energy more then 10 MeV. Since gamma quanta absorption in atmosphere is very strong, originated on the altitude 6-8 kilometers quanta flux has very strong energy and density. Quanta density on the earth surface is equal to some units through square centimeter.

2. Damping of gamma radiation in atmosphere

Gamma radiation attenuates strong in atmosphere and quanta number on different altitude is not the same. Quanta density on the earth surface is equal to some units through square centimeter. Half-value thickness of gamma rays for some materials is shown in table 1. It is thickness of layer going through quanta density diminishes half.

Table 1. Half-value thickness of gamma rays for some materials

Material	thickness of layer, cm	specific weight, g/cm^3
Lead	1.8	11.3
Concrete	6.1	3.33
Steel	2.5	7.86
Packed soil	9.1	1.9
Water	1.8	1.00
Wood	29	0.56
Standard air	15000 (150 m)	0.0012

It can suppose that atmospheric density is constant up to altitude 4-5 kilometers and half-value thickness does not changes although atmospheric pressure drop a little. The normal pressure at sea level is 101.3 kilopascal. During lifting the pressure decreases by 12 kilopascal for 1 kilometer, so on the altitude 3 kilometers the pressure will be 65.3 kilopascal. It do not change strongly half-value thickness. With altitude increasing by 1000 meters the temperature fall for 6°C. If on the sea level the temperature is 25°C, on the altitude 2750 meters it is - 10°C. So temperature influence will not be essential. Humidity fall too but it appears in mountains weakly. Usually lightning stroke is brachiate and multiple and discharge reaches the earth in some points (on average 3), which are located distantly till some kilometers. It is unknown if γ-quanta appear only during leader stage or during iterated strokes too. We shall suppose for reliability that γ-quanta arise only once during leader stage. Spreading (flying off) is going to all directions. Total expansion area in cross-section can have near 1 square kilometer, so new strokes near to this place can cover already radiation-exposed area during preceding lightning stroke. It can suppose, that half-value thickness is invariable within 3-4 kilometer above sea level and it is equal 150 meters. Quanta number dependence on altitude show (1).

$$N_{whs} = N_{w0s} \cdot 2^{H/150} \qquad (1)$$

N_{whs} - number of quanta with energy w, that are passing by section S at altitude H;

N_{w0s} - number of quanta with energy w, that are passing by section S at sea level;

H – altitude at sea level, meter;

S – horizontal section (cm^2 or mm^2).

Number of quanta with high energy, that are passing by section S = 1 mm^2 at altitude H run up to some hundreds of thousands.

3. The energy of exposure, absorbed energy, exposure rate

Optical fiber can have structure 10/125, 50/125, 65/125 and other. It can produced of quartz, polimer or other material. Horizontal section of exposing fiber is S = d·l, where d and l – exposing fiber diameter and length. The energy of exposure W_{hw} by quanta with energy w and for 1g fiber mass at altitude H is:

$$W_{hw} = W_{ohw} / P = N_{whmm}\, d\cdot l\cdot w / [\,(\pi/4)\cdot d^2\cdot l\cdot p] \qquad (2)$$

$W_{ohw} = N_{whmm}\cdot d\cdot l\cdot w$;
N_{whmm} – number of quanta with energy w, that are passing by section S = 1 mm^2 at altitude H;
d – fiber diameter;
l — exposing fiber length (50 - 250 meters);
w – the one quantum energy;
P – mass of fiber with diameter d and length l;
p – specific weight, g/cm^3 , for quartz p = 2.2 g/cm^3.

If d is expressing micrometers, l – meters, w – MeV, section S = 1 mm^2 equation (2) takes the form

$$W_{hw} = 0.579\cdot 10^6\cdot N_{whmm}\cdot w/d \quad \text{MeV/g} \qquad (3)$$

Where w – the one quantum energy, MeV; d – fiber diameter, micrometer.

Absorbed dose is $W_{phw} = 0.88\, W_{hw}$ according to [3]. At the same time 1 MeV/g = $1.6\cdot 10^{-8}$ radian. Absorbed dose by fiber at the altitude H is W_{phw} = = $0.88\cdot 1.6\cdot 10^{-8}\cdot 0.579\cdot 10^6\cdot N_{whmm}\cdot w/d$ radian or

$$W_{phw} = 0.82\cdot 10^{-2}\cdot N_{whmm}\cdot w/d \qquad (4)$$

Exposure rate is absorbed dose which is divided down exposure time t. Exposure time is the first stage leader duration. According to [4] the first stage evolution duration is from $6\cdot 10^{-4}$ till $5.3\cdot 10^{-7}$ seconds. Appraised first stage length is 10 – 200 meters, leader speed is $1.5\cdot 10^5$ - $2\cdot 10^6$ м/sec. Average first stage duration is 100 – 150 microseconds. To Dwyer's traces according, gamma ray durations is 100 – 300 microseconds, that is agree with foregoing estimation. Let us take that exposure time t is 150 microseconds:

t = 150 microseconds

Then at the altitude H radiation power is m = $= W_{phw} / t = (0.82\cdot10^{-2}/150\cdot10^{-6})\cdot N_{whmm}\cdot w/d$ radian/second or

$$m = 55\cdot N_{whmm}\cdot w/d \quad \text{radian/second} \qquad (5)$$

where

N_{whmm} – number of quanta with energy w, that are passing by section S = 1 mm^2 at altitude H;

w – the one quantum energy, MeV;

d – core fiber diameter, micrometer.

Power value is different during impulse time and for different energy quanta. It is necessary to estimate the total power by summation of individual quanta power. To estimate maximal power is necessary taking up gamma ray principal part (without impulse decay). If cable is buried at depth in earth it is necessary to take into account. Half-value thickness of packed soil is 9.1 cm, so number of quanta is reducing at the depth 1 meter multiply. Usually cables are buried in mountains at the depth 0.4 meter. In this case reduction will be near 30. Cable can have some millimeter iron armor, but its influence is smallish because half-value thickness of iron is 2.5 centimeter. Thus gamma quanta flux can fall on optical fiber, that is buried or suspended in mountains at altitude 2 kilometers above see level.

4. Basic facts of radiation-dangerous influence and cable losses

Primary effect of radiation influence on optical fiber cable is attenuation rise. They depend on bond type and structure, impurities, microcrack and deformation availability, OH content, fabrication technique, drawing out conditions, chlorine presence, geometrical dimension (upsizing reduce internal stress). Compton electrons (recoil electron) give birth to atom displacement. Own glass and extrinsic microdefect do not interact with optical transmission before gamma exposure. They capture originated during exposure electrons and holes and they create absorption centers after gamma exposure. Relaxation that is restitution is feasible presently, but admixture presence has an influence on this process strongly. Phosphorus doping leads to sharp increase of absorption center number. Boron doping leads to losses growth in infrared range, hydroxyl group OH lead to liaison breakage of Si-O and to lattice strength attenuation and internal stress removal. The number of absorption centers is more considerably if there are little of water in optical fiber, but it is not always, because a great deal depend of fabrication technique. If chlorine is using in fabrication technique, it aggravates a situation sharply. Optical fibers have good characteristic if they do not involve chlorine. Pure quartz multimode fiber has the fewest sensitivity to radiation. Polymeric fiber is the most sensitive to radiation. Radiation influence upon optical fiber is investigated insufficiently, especially in 1.55 micrometer range. Information are missed of raying influence on signal dispersion in fiber. Not only energy exposure has an effect on absorption centers initiation, but its power too. The stationary irradiation causes absorption centers appreciably smaller than pulsed. If radiation dose is about some hundreds radian (100÷1000) attenuation increase till 4 – 9 dB/km in multimode fiber at λ = 1.3 micrometer. In single mode fiber attenuation increase till 1.5 – 4 dB/km. If dose grows till 10^4 radian the attenuation can increase till 100 dB/km at λ = 1.3 micrometer. If radiation power is more than 100 radian/second at the same radiation dose, absorption centers number rise double the amount or more. Dose rate changes uninterruptedly during pulsed irradiation passing through maximum. Absorption center number changes complex too. Usually attenuation increase till 4 -5 dB/km at dose some hundreds radian during pulsed irradiation in single mode fiber, then they can change and come greater or smaller, especially if there is serving. The maximal losses arise, when exposure rate is 10^7 radian/second. Relaxation and partial fiber property restoration can start after radiation and absorption center number can diminish. Stationary irradiation consequences can relax from some seconds till some years. Absorption centers lifetime is temperature-dependent. Relaxation time grows shorter during temperature lowering. Absorption centers lifetime is some minutes at temperature -55°C. Lifetime of absorption centers depends of dopant, power transmission. Boron dopant shortens relaxation time. The pure quartz multimode fiber are the most stable to radiation.

5. Energy and power of possible irradiation

Table 2 shows information about energy exposure, that single-mode fiber core with d = 10 micrometer receive at different height above sea level.

Table 2. Energy and power exposure, that single-mode fiber core with d = 10 micrometer receive at different height above sea level

H, meter	Total energy of gamma quanta, MeV	Radiation dose, radian	Power exposure, radian/second
1050	12	10^{-2}	65.5
1500	143	0.136	780
2100	2703	2,230	$14900 \sim 1{,}5 \cdot 10^4$
2550	18428	15	10^5
3000	292570	238	$1.6 \cdot 10^6$
3600	2307700	$1890 \sim 2 \cdot 10^3$	$1.25 \cdot 10^7$

It is seen from table 2 that radiation dose and power exposure begin rise sharply after altitude 2000 meters above sea level. Radiation dose is tens radian for single-mode fiber at altitude 2500 meter and hundreds radian at 3000 meter. Quanta with energy more than 5 MeV are carrying the most part of energy to fiber. The contribution of quanta with energy 1-2 MeV is little. Power exposure increase especially sharply, it can be 10^4 radian/second at altitude 2000 meter and 10^7 radian/second at altitude 3000-3500 meter.

Conclusion

If optical fiber cable is laid in mountains at the altitude over 2000 meter, attenuation can rise till tens dB/km during thunderstorm with continuous and unpredictable relaxation time. Susceptibility and relaxation time are closely related bond type and structure, impurities, microcrack and deformation availability, OH content, fabrication technique, drawing out conditions, chlorine presence, geometrical dimension (upsizing reduce internal stress). Destruction time of absorption centers can swing from some seconds till some years. Lifetime of absorption centers depends of temperature, dopant, power transmission. It reduce with temperature lowering. Absorption centers lifetime is some minutes at temperature -55°C. Boron dopant shortens relaxation time. The pure quartz multimode fiber are the most stable to radiation. Polymeric fiber has enhanced vulnerability to radiation.

We have considered single leader process consequences only and we have not take into account that lightning discharge density is more than $1/km^2$ during stormy season in area majority. If there are repeated lightning strokes in laid fiber cable area, new absorption centers can add to already in existence, and fiber state will become worse. This problem is serious and it is in need of complex study and experimental checkout. It should to have in view that the great electromagnetic field arises during lightning stroke that leads to the polarization plan rotating of spreading light in fiber and possible faults.

References

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