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Ionizing radiation impact on communications performance of optical multi-hop inter-satellite relay link

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A R T I C L E I N F O

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A B S T R A C T

Ionizing radiation impact on communications performance of optical multi-hop inter-satellite relay links is studied in this paper. Essential optoelectronic devices involved in optical communication system were irradiated by Co^{60} gamma ray and BER models of OOK, DPSK and homodyne BPSK of multi-hop inter-satellite links were proposed. On this basis, performance degradations under ionizing radiation were simulated, and on-orbit performance degradations were further discussed. Research results show that EDFA of ionizing radiation is the dominant cause of optical relay link communication performance degradation and the choosing of relay satellite has significant influence on on-orbit performance of links. The anti-ionizing radiation capability of homodyne BPSK model obviously outperforms OOK and DPSK models.

1. Introduction

With high-speed optical inter-satellite links being a reality, the construction of large-volume data relay satellite network as part of a space-based information backbone network is now feasible. Optical inter-satellite crosslink becomes one of an extremely efficient ways for high-speed and real-time transmitting of mass information globally. In 2016, EDRS-A, the first optical communication payload of EDRS (European Data Relay System) was launched successfully. Earth observing images are relayed from satellite Sentinel-1A to EDRS-A by optical inter-satellite links [1,2]. NASA has a plan named Laser Communication Demonstration Project (LCDR). LCDR will fly two optical communications terminals on a commercial GEO satellite to communicate with two ground stations in 2019; its communication speed is 10–100 times of RF communication links [3,4]. However, optoelectronic devices in optical communication terminals for aerospace applications will be exposed to the complex space radiation environment for years, and radiation effects on these devices can cause serious degradations [5,6]. Subsequently, performance of communication system will be influenced and the reliability of communication is at risk [7]. Therefore, study on communication performance of inter-satellite optical relay links under space radiation is significant for ensuring the reliability of communication.

Total ionizing dose (TID) effect is one of the most serious space radiation effects for optoelectronic devices. Many experimental and theoretical studies have addressed TID effect on devices in inter-satellite optical communication system [8–23]. It induces degradation on key parameters of these devices. Several important parameters including output optical power [8–12], optical transmission [13–15], optical gain [16–19], dark current and optical responsivity [20–23] are tested and analyzed. Since the purpose of the above researches is to investigate device degradation, system performance degradation induced by radiation is not involved. However, as an important index of communication, there is only a few researches aiming at radiation impact on system performance [24–26], and the evolution of system performance along with on-orbit working time has not been taken into account. Hence, study on ionizing effects induced performance degradation in optical multi-hop inter-satellite relay links is required. Normally, space ionizing radiation impact on communications performance of optical inter-satellite links is focused on point to point link, that is to say one hop. However, there are always several hops from the source node to the destination node in optical relay satellite network. The received signals must be amplified and retransmitted in relay nodes. Each time when signals are processed in middle relay node, amplifying gain and ASE noise would be introduced simultaneously. Therefore it is necessary to

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study the accumulated noise of multi-hop inter-satellite links impact on communication performance.

In this paper, some essential optoelectronic devices were irradiated by Co^{60} and on-orbit performance of inter-satellite optical relay links was studies based on the experimental results. In Section 2, we demonstrated the Co^{60} irradiation experiment on optoelectronic devices and results of parameter degradation were listed. In Section 3, BER models of OOK, DPSK and homodyne BPSK based links were established. Next, link performance degradation under ionizing radiation was simulated and discussed in Section 4, and the on-orbit performances of some typical optical relay links were predicted in Section 5. The conclusions were drawn in Section 6.

2. Co^{60} radiation experiment of on-board essential optoelectronic devices

Gamma radiation causes ionizing effects in devices, so Co^{60} was used as radiation source. Taking into account the structure of terminals and the issue of optoelectric parameters in OOK, DPSK and homodyne BPSK based optical communication systems, the optoelectronic devices for irradiation were chosen and their key information is listed in Table 1. In experiment, the measurement accuracy of measurement devices is as following: Optical wavelength was measured using WA-1500-NIR-89 wavemeter with accuracy of ±0.0002 nm and displays resolution of 0.0001 nm. Optical power was measured using Newport 1930-C power meter with accuracy of ±1 pW. Dark current was measured using HP4156C analyzer with accuracy of ±1 fA. Photocurrent was measured using Victor VC9807A power meter with accuracy of ±5 μA (@200 mA–2 mA). Co^{60} gamma ray irradiation was conducted in air at room temperature at the Cryogenics Technology and Physics Laboratory Lanzhou Institute of Physics. The total gamma radiation dose was 30 krad and the dose rate during irradiation was 5 rad/s. The irradiation paused every 2.5 krad in the first 10 krad and then paused every 5 krad till the end of experiment for measuring performance variety of devices. Experimental results of gamma irradiation are listed in Table 2.

Experimental results show that there is no obvious change in the wavelength of DFB lasers, and there is only a slight decrease in the output optical power for both lasers. Output optical power of DFB Laser #1 and #2 degraded 0.004 mW and 0.007 mW, respectively, at 30 krad. These test results agree with Ref. [11] and Ref. [12]. Laser diodes in both researches show only a small or no degradation under gamma irradiation. Hence, DFB lasers are relatively insensitive to ionizing radiation.

The irradiation result of $LiNbO_3$ modulator is similar to DFB lasers. The performance of this device was steady during experiment with a small reduction of 0.6% in optical transmission. This result correspond with Ref. [14], in which the performance of $LiNbO_3$ devices shown no change at the total dose of 1-4×10^5 rad. Therefore we can deem that both DFB lasers and $LiNbO_3$ modulators have considerable ionizing radiation resistance.

EDFAs are more sensitive to gamma irradiation comparing with DFB lasers and $LiNbO_3$ modulators. The optical gain degraded seriously during irradiation. When total radiation dose reached 30 krad, the gain of EDFA #1 and #2 declined 7.15 dB (23.6%) and 3.55 dB (21.2%) respectively. Similar results have been achieved by Li and his team [17]. As we can see, radiation induced gain degradations vary from EDFAs. This is because radiation impact on EDFAs is significantly influenced by the EDF length and Er^{3+} ion density, and EDFAs with high density and short fiber length have less ionizing radiation induced degradation.

The optical responsivity and dark current of PIN photodiodes were both tested in this study. For optical responsivity, no observable degradation was measured during irradiation, and this agrees with the results of Ref. [23]. Whereas for dark current, serious increase was introduced by gamma irradiation. Dark current of PIN PD #1 and #2 increased 2.38 nA and 2.74 nA, respectively, at 30 krad. An approximate linear relationship was also found between the increments of dark current and gamma dose. The increase of dark current measured in this experiment is relatively higher than the results reported in Ref. [22,23]. This could be attributed to the influence of manufactural and structural differences among devices.

Note that, since no obvious degradation was found in the wavelength of DFB lasers and the response of PIN photodiodes during gamma irradiation, those two parameters are not listed in Table 2.

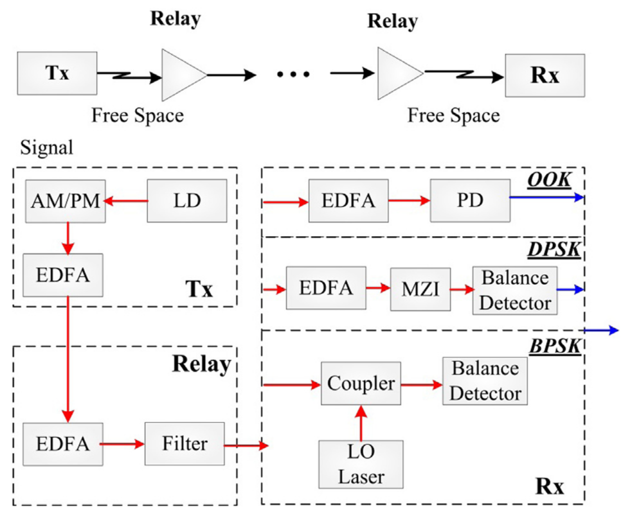

Fig. 1. Construction of amplifier and relay inter-satellite link model.

3. BER model of multi-hop optical relay links

Multi-hop inter-satellite links are called as amplifier and relay model links, in which original signals to be transmitted are modulated into the optics carrier wave and transmitted to relay node firstly. Then attenuated modulated signals are amplified in optics field and retransmitted to another relay node. Finally, in the last receiving node, signals across sever middle nodes are demodulated and recovered. Construction of amplifier and relay inter-satellite link model is depicted as Fig. 1.

The output optical power P_t of source node is made up of two parts, one is optical signal power S_t and the other is optical noise power N_t.

$$P_t = S_t + N_t \tag{1}$$

S_t is directly related with modulation model of transmitted node. Because of amplitude modulation of OOK, the average optical output power of OOK model is equal to half the product of optical output of laser P_{LD}, transmissivity of electrooptic modulator L_m and amplifier gain G_t. That is to say, $S_t = 0.5P_{LD}T_mG_t$. In DPSK and BPSK model, S_t is equal to the product of P_{LD}, L_m and G_t, that is to say, $S_t = P_{LD}T_mG_t$.

Received optical signal power and noise power of destination node are defined as S_r and N_r respectively. The input optical power of receiving end P_r can be expressed as formula (2):

$$P_r = S_r + N_r \tag{2}$$

During the transmitted progress from source node to destination node, modulated optical carrier wave will be impacted by inter-satellite link loss in any one hop and optical power will decrease. Then attenuated optical power would be amplified and recovered in relay node of this hop. However, it is necessary that amplifier noise will be introduced during the progress of the optical power amplifying of EDFA. The new noise combined with original noise will come into another relay and amplifying progress, till original signal arrives at the destination