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Radiation effects and protection technology for optical components of fiber optic gyroscope

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Abstract: The performance of optical components for fiber optic gyroscope (FOG) will degrade by ionizing damage effect and displacement damage effect in space radiation environment. Radiation effects on optical fiber, SLD optical source, and PIN-FET detector module were discussed respectively. In order to keep the performance of FOG in space, radiation protection technology was discussed from both radiation shielding and active hardening technology. Given that different optical components have different radiation sensitivity for different radiation damage mechanism, and there has a strict requirement on the weight of spacecraft payload, then the design of shielding was optimized on ionizing damage and displacement damage respectively. The active hardening technologies for every optical component were also discussed based on the analysis of radiation effects on each component.

Key words: optical components; radiation effects; radiation protection; FOG

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光纤陀螺光学器件的空间辐射效应及防护技术

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摘 要：针对光纤陀螺用光学器件在空间辐射环境下受电离损伤和位移损伤影响性能下降的问题，分别分析了光纤、SLD光源、PIN-FET探测器的空间辐射效应。为保证光纤陀螺在空间的工作性能，从被动屏蔽和主动加固两方面讨论了光学器件的辐射防护技术。考虑到不同光学器件对不同类型辐射损伤的敏感性以及航天器载荷对重量的严格要求，从电离损伤屏蔽和位移损伤屏蔽两方面对屏蔽厚度进行了优化设计。通过对各光学器件辐射效应机理的分析，讨论了提高光学器件本身抗辐射能力的主动加固技术。

关键词：光学器件； 辐射效应； 辐射防护； 光纤陀螺

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0 Introduction

Since the optical fiber has the advantages of small size, light weight, flexible structure and anti-electromagnetic interference, the optical fiber system in the space environment application attracts an increasing attention. For instance, the spaceborne fiber optic gyroscopes (FOG), optical fiber communication systems, and optical fiber sensing networks have been a hot topic. However, the performance of the optical components will degrade in the space radiation environment. As a result, the performance of the optical fiber system dropped to some extent. The investigations of radiation effects on the optical components and the radiation protection technology are essential to ensure the system to work properly.

The FOG is a typical optical fiber sensor with success application. It has the unique advantages in light weight, low consume, long life and high reliability which can work well in the space environment. Radiation effects on optical fiber, super luminescent diode(SLD) optical source, and PIN-FET detector module utilized in the FOG are analyzed in the paper. Furthermore, the anti-radiation hardening technology of the optical components is discussed.

1 Radiation damage of the optical components

The space radiation environment is a complicate and dynamic radiation environment, which includes many radiation components such as protons, electrons, heavy ions, and X-radiation and γ-radiation caused by the bremsstrahlung. Different particles interact with the substances in different physical mechanisms and lose energy. The radiation damage can be classified into two kinds by the energy losing effect: ionizing damage and displacement damage[1].

1.1 Ionizing damage

When the radiation particles pass through the optical substance, they interact with the electrons and the energy is imparted to the electrons of the material. If the gained energy of the electrons is larger than the binding energy, the electrons start the depart inside their track and become the free electrons. Then the atom becomes a charged ion, which is called the effect of ionizing radiation. The main product of the effect is the electron-hole pairs along the traveling path of the radiation particles.

1.2 Displacement damage

The displacement effect is caused by the collision of the incident particles with the nucleus of the atom of the radiation materials. The radiation particles make elastic collisions with the atom. When the energy of the radiation particles is high enough, the atom leaves the position of the crystal lattice and becomes an interstitial atom. The site of the crystal lattice becomes a vacancy and form a vacancy-interstitial pair, which is called displacement effect. These vacancy-interstitial pairs are called Frenkel defect, which damage the potential energy of the crystal lattice and form a new electron energy level in the forbidden band[2]. The displacement damage will influence the lifetime of the minority-carrier and the mobility of the carrier.

2 Radiation effect of the optical components

2.1 Ionizing damage

The radiation interacts with the optical fiber material and produces the ionizing damage and the displacement damage. The ionizing damage represents the ionization of the molecule of the material caused by the radiation and generates the electron-hole pairs. The electrons and the holes are captured by the eigendefect precursor or the displacement damage induced by the radiation of the material to form additional defects with specific structures. The defects result in the light absorption and called "color center" accordingly. The radiation interacts with the substance and yields the light absorption, namely radiation induced attenuation effect (RIA).

The relationship between the RIA of polarization-maintaining fiber and the radiation doses is shown in Fig.1. The more radiation doses of the fiber, the more color center and the light absorption producing.

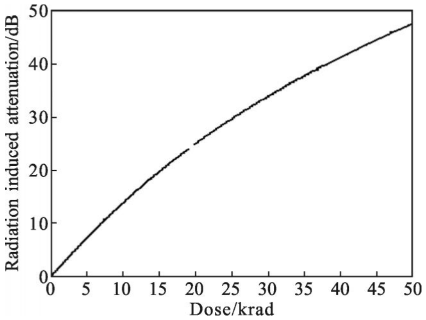

Fig.1 Relationship between RIA and radiation dose of one kind PM fiber

2.2 Optical source

The SLD has the advantages of broad band, high output intensity, short coherent length, and is widely employed in the FOG. The main factors affecting the performance of SLD is the displacement damage caused by the protons and the heavy ions. The defect energy level induced by the displacement damage in the semiconductor energy band structure of SLD can be regarded as the non-radioactive recombination center. It results in the non-radiative recombination of the carrier, decreases the luminous efficiency and reduces the optical power of the source. The performance degradation of the SLD can be evaluated by the Rose-Barnes equation:

$$\left[\left(\frac{p_0}{p_\Phi}\right)^n-1\right]=\tau_0K_p\Phi \qquad (1)$$

where p_0 is the optical power of the source before the radiation, p_Φ is the optical power of the source after the radiation, n is the number between 2/3 and 1, τ_0 is the lifetime of the minority-carrier before the radiation, K_p is the lifetime damage constant, Φ is the proton flux. The optical power of the source reduced dramatically on the condition of proton radiation[3]. Hence, we should utilize the anti-radiation hardening technology in the space application.

2.3 Photo detector

Since the performance of the FOG is restricted by the noise of the detector, the PIN-FET detector module is used, the main influence induced by the effect of ionizing radiation is the increase of the dark current. The comparison of the noise characteristics of the PIN-FET before and after the radiation of γ-ray with the dose of 200 Gy is illustrated in Fig.2. Although the dark current increases slightly, the noise characteristic is not significantly influenced as the dark current is much less than the photo current. The performance of the PIN is mainly affected by the displacement damage, which decreases the lifetime of the minority-carrier and reduces the diffusion length and the quantum efficiency of the PIN. Besides, the damage of depletion region increases the intermediate energy levels and the generated charge carriers lead to the increase of the dark current and the leakage current.

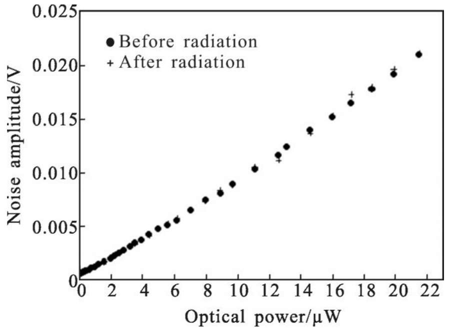

Fig.2 Comparison of detectors′ noise characteristic before and after irradiation

3 Radiation protection technology of the optical components

The radiation protection is indispensable for the optical components to guarantee the performance of the FOG in the space environment. The radiation protection can be considered in two aspects which are employing radiation shielding to decrease the radiation dose of the optical components and improving the workmanship of the optical components to raise the anti-radiation level of the components.

3.1 Radiation shielding

The radiation dose level can be reduced by shielding. The principle is demonstrated as follows: The charged particles passing through the shielding substance deposits as a result of loss of energy. When the thickness of the shielding material is larger than the range of the particles, the incident particle will settle in the material and the radiation dose of the fiber can be reduced.

3.1.1 Ionizing radiation dose shielding

The RIA is mainly influenced by the ionizing damage and the increase of the dark current of the detector is affected by the total dose of the ionizing radiation. So, the shielding of the ionizing radiation dose is an important problem that needs attention. The design of spacecraft makes great demands on the weight of the loads. Therefore, we must look for an optimal solution between the radiation shielding and the load weight. The shielding effect of total radiation dose for a five years mission at sun-synchronous orbit of 900 km calculated by the space radiation environment model is shown in Fig.3. The total radiation dose is determined by the electrons without the shielding, as illustrated in Fig.3. Since the shielding effect of the material is considerate for the electrons, the ionizing radiation dose decreases rapidly with the increase in the thickness of the material. When the thickness increases to 4 mm, the total ionizing radiation dose decreases three orders. However, as the thickness continually increases, total ionizing radiation dose is constrained by the protons. The decrease of the total dose becomes very slow because of the weak preventing ability of the material to the high-energy protons. In summary, the shielding substance with an equivalent thickness of 4 mm Al material can shield most radiation dose without raising much weight, which is suited for the shielding of the components sensitive to ionizing radiation dose.

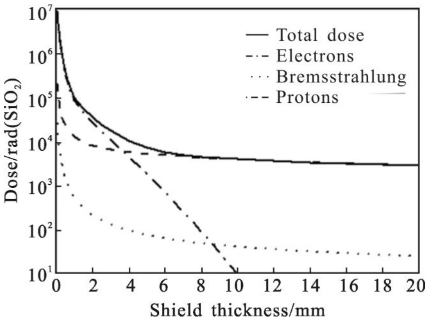

Fig.3 Shielding effect of total radiation dose for a five years mission at sun-synchronous orbit of 900 km

3.1.2 Displacement damage dose shielding

The reduction of the optical power of SLD and the responsibility of PIN-FET are mainly influenced by the displacement damage. Thus, the shielding of the displacement damage is an important problem that needs attention. The shielding effect of displacement damage dose for a five years mission at sun-synchronous orbit of 900 km is displayed in Fig.4. Like the total ionizing dose, the displacement damage dose decreases dramatically with the increase of the shielding thickness at relatively thin thickness. The displacement damage is reduced over one order by the Al shielding with 2 mm thickness and the shielding effect become gradually weaker with the increase of the thickness. The equivalent thickness of 2 mm Al material can be employed to shield the components sensitive to displacement damage due to the purpose of declining the influence of the displacement damage dose on optical components and minimizing the weight.

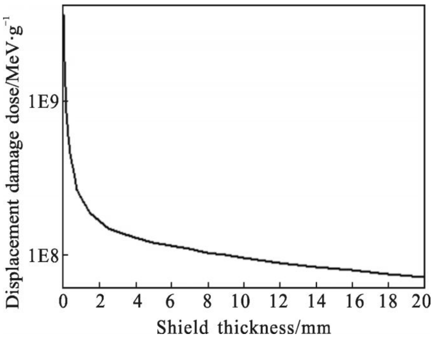

Fig.4 Shielding effect of displacement damage dose for a five years mission at sun-synchronous orbit of 900 km

3.2 Active hardening

3.2.1 Optical fiber

The active hardening technologies for the optical fiber are classified into seven kinds: (1) minimizing the doped core of the fiber to produce the fiber with pure silicon core and fluorine-doped cladding; (2) utilizing fluorine doped core and cladding to diminish the randomness and the stress of the Si-O bond[4]; (3)

producing nitrogen-doped core by substituting nitrogen for germanium to enhance the ability of anti-radiation[5-6]; (4) hydrogen loading because hydrogen is much active at room temperature and easy to react with silicon or oxygen dangling bond of the atom network terminal to prevent the formation of the nonbridging oxygen hole center (NBOHC)[7]; (5) pre-irradiation; (6) photofading; (7) thermal discoloration. Among them, fluorine-doped method will reduce the refractive index of the fiber core that is to the disadvantage to form the high refractive index difference between the core and the cladding. It is unfavorable for the fiber loop of the FOG. The nitrogen-doped fiber has higher chloride concentration that slightly increases the loss of long wavelength. In addition, the craftsmanship of the nitrogen-doped fiber is not mass-produced and the commercial products are rare. Although hydrogen loading prevents the formation of the NBOHC and enhances the ability of the anti-radiation at optical wavelengths, the hydroxyl ion levels of the fiber are increased and cause the absorption peaks within infrared waveband that is inapplicable for the fiber loop of the FOG within infrared waveband. The pre-irradiation can reduce the variation of the optical loss of the fiber, but the initial loss is very high. The thermal discoloration technology is not easily enforceable. The photofading technology can enhance the ability of the anti-radiation and the experimental system for FOG based on photofading technology is developed at present[8-9]. The optical fiber with pure silicon core is considered as the fiber with best anti-radiation capability[10]. Hence, the fiber with pure silicon core is utilized as a means of anti-radiation hardening.

In summary, the approaches including photofading technology and employing fiber with pure silicon core and fluorine-doped cladding to ensure the refractive index difference of the core and cladding is applicable to the anti-radiation hardening for the fiber loop of FOG.

3.2.2 Optical source

According to Eq. (1), the value of $\tau_0 K_p \Phi$ on the right of formula should be as small as possible so as to reduce the influence of the radiation on the optical power of the source. If the lifetime τ_0 of the minority-carrier before the radiation can be reduced, we can realize the radiation hardening of SLD source. In the researches about the radiation hardening of light emitting diode(LED), reference[11] shows that heavily doped in the emission region makes LED operate under the condition of high current density and reduce τ_0 which makes LED insensitive to the radiation. Considering the similarity between SLD and LED, the parameters of the SLD can be changed to decrease the lifetime of the minority-carriers to realize anti-radiation hardening of SLD.

The SLD includes SLD of double-heterostructure and SLD of quantum well structure. Since the active region of SLD with quantum well is composed of many quantum wells, the confinement effect of the quantum well to the carriers rises substantially compared with the active region and the radiation recombination rate increases drastically. It makes the radiation induced non-radiation recombination unable to compete against radiation recombination. Therefore, SLD of quantum well structure has more anti-radiation ability than SLD of double-heterostructure, which is demonstrated in reference [9]. In conclusion, the anti-radiation ability can be enhanced by using SLD of quantum well, which is an effective anti-radiation hardening technology.

3.2.3 Photo detector

The effect of ionizing radiation yields the electron-hole pairs within the semiconductor material of the detector. In contrast, the optical signal generates the electron-hole pairs only in the active region of PN junction of the detector. So, the radiation sensitivity can be reduced by decreasing the volume of active region and passive region. As Ⅲ-Ⅴ semiconductor has higher absorption coefficient, the active region can be thinner without degrading the responsibility of the detector and the PIN based on Ⅲ-Ⅴ semiconductor has better anti-radiation capability. The heterostructure can decrease the volume of the passive region and enhance the anti-radiation ability accordingly[12]. The noise characteristic of the PIN-FET module in the FOG is illustrated in Fig.3. The detector utilizes Ⅲ－Ⅴ semiconductor material and has the double-heterostructure. So it has better anti-ionizing radiation ability.

As the displacement effect induces the defects in the semiconductor crystal lattices, the minority-carriers caused by the optical signal increase the risk of recombination before they are collected by the electrode and reduce the responsibility consequently[13]. Thus, the thinner depletion region of the detector, the better anti-radiation performance[14].

4 Conclusion

The optical fiber, SLD source and PIN－FET detector module of the FOG are influenced by the space radiation effect in the space radiation environment. The RIA is increased due to the formation of the radiation induced color center in the optical fiber. The performance of SLD is influenced by the displacement damage. The optical power of the source is decreased because of the displacement damage induced by the protons and heavy ions. The space radiation effect causes the increase of the dark current and reduction of the responsibility of the PIN－FET. The above-mentioned space radiation effect of the optical components will affect the SNR of the signal received by the detector and degrade the measurement precision of the FOG accordingly.

The technology of combining active anti-radiation hardening and the passive radiation shielding is proposed to diminish the space radiation effect of the optical components. Considering the strict requirements on the weight of the spacecraft load, the shielding thickness of the components sensitive to ionizing damage and displacement damage are optimized. Based on the analysis about the space radiation effect of the optical components, the anti-radiation hardening technique is presented. The combination of the active hardening and passive shielding is favorable for proper operation of the FOG in the space radiation environment.

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