中国激光

国产高性能抗辐照掺铒光纤

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摘要 为了保证掺铒光纤在辐照环境下的工作性能与寿命，采用改进的化学气相沉积（MCVD）方法制备了 C 波段抗辐照掺铒光纤。在常温下使用^{60}Co 辐射源对自研掺铒光纤进行累积剂量为 1500 Gy、平均剂量率为 0.2 Gy/s 的辐照，结果发现，该光纤在 980 nm 和 1550 nm 处的辐致损耗（RIA）分别为 1.4 dB/m 和 0.8 dB/m。搭建了掺铒光纤放大器（EDFA）进行增益测试，测试过程中采用输入功率为－20 dBm 的 1550 nm 信号与波长为 980 nm 的泵浦源。测试结果表明，在 100 mW 和 500 mW 泵浦功率下，1550 nm 处的辐致增益变化（RIGV）分别为 0.8 dB 和 0.2 dB。

关键词 光纤光学；掺铒光纤；抗辐照；光纤通信；掺铒光纤放大器

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随着航天技术的飞速发展，掺铒光纤放大器（EDFA）凭借高增益、宽带宽和紧凑性好等优势逐步成为承担卫星通信任务的最佳选择[1-3]。然而，掺铒光纤作为 EDFA 的关键器件，对各类宇宙射线（如 γ 射线等）极其敏感。传统掺铒光纤为了增加铒离子的溶解度和降低团簇效应[4]而加入了铝、磷和锗等共掺剂，当其受到一定剂量的辐照后就会产生大量色心[5]，在掺铒光纤泵浦和信号波段产生额外的辐致损耗（RIA）[6-9]，从而降低了 EDFA 的放大性能。

为了保证掺铒光纤在辐照环境下的性能，各国研究人员提出了多种抗辐照手段，其中主要的抗辐照手段有铈离子掺杂技术、泵浦漂白技术以及载气技术[5]等。从国内外抗辐照掺铒光纤的发展来看，目前法国的 IXblue 公司已经实现了抗辐照掺铒光纤的产业化，该公司生产的抗辐照掺铒光纤的辐致增益衰减系数小于 0.005 dB/krad[10]；国内诸多单位在掺铒光纤抗辐照性能的提升上也取得了重大突破[11-13]。南开大学现代光学研究所的胡宗华等[11]设计了一种新型抗辐照掺铒光纤，搭建了光纤长度为 1.5 m、泵浦功率为 400 mW 的 EDFA 进行测试，结果发现，在 700 Gy 辐照剂量下该光纤的最大辐致增益变化为 0.35 dB。北京航空航天大学的武志忠等[12]研制了一种高性能抗辐照掺铒光子晶体光纤光源，通过“泵浦光功率闭环反馈控制”技术控制 980 nm 泵浦光功率，实现了光源整体的高抗辐照性能；在 2000 Gy 剂量的辐照下，抗辐照掺铒光子晶体光纤光源的整体功率衰减小于 0.2 dB。烽火通信科技股份有限公司研发了基于铒铈共掺技术的掺铒光纤和掺铒光子晶体光纤，在 1000 Gy 剂量的辐照下，两种掺铒光纤的辐射诱导衰减均小于 1 dB/m[13]。本研究团队基于改进的化学气相沉积（MCVD）工艺制备了铈铝锗镧共掺的 C 波段抗辐照掺铒光纤：采用铈离子掺杂技术消除了辐照产生的色心；通过调控铝和锗的掺杂浓度和比例进一步提升了光纤的抗辐照性能[14]；镧离子用来降低铒离子团簇效应，同时提升光纤效率[4]，最终 Er^{3+} 的掺杂浓度约为 1.9×10^{25}（ion/m^3）。所制备光纤纤芯和包层的直径分别为 9 μm 和 125 μm。考虑到真实太空环境下的辐照剂量处于 10^2～10^5 Gy 量级之间[6]，因此选择了 1500 Gy 辐照剂量来测试抗辐照掺铒光纤的辐致损耗与辐致增益变化。

图 1 为 C 波段抗辐照掺铒光纤在辐照前与经过 1500 Gy 剂量辐照后的吸收谱以及相应的辐致损

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耗谱，其中图1(a)为泵浦波段，图1(b)为信号波段。吸收谱均使用 Photon Kinetics 2500 吸收谱测试仪进行截断法测试，辐致损耗谱由辐照后与辐照前的吸收谱作差得到。可见，在常用的泵浦吸收波段(980 nm)的辐致损耗约为1.4 dB/m，在C波段信号(1550 nm)处的辐致损耗约为0.8 dB/m。

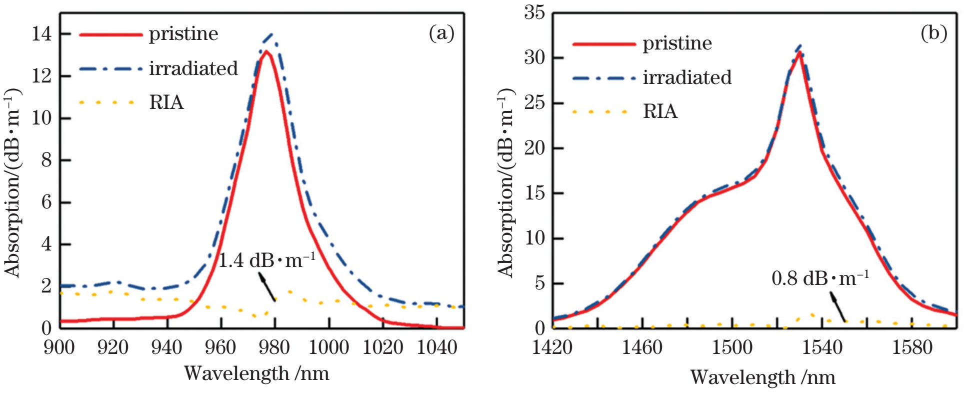

图1　抗辐照掺铒光纤辐照前后的吸收谱以及对应的辐致损耗谱。(a)泵浦波段；(b)信号波段

Fig. 1　Absorption spectra and corresponding radiation-induced attenuation of pristine and irradiated radiation-resistant erbium-doped fiber. (a) Pump band; (b) signal band

图2为C波段抗辐照掺铒光纤的增益测试结构图，测试系统采用典型的前向泵浦 EDFA 结构，其中 WDM 表示波分复用。信号光源采用可调谐C波段光源，泵浦源采用高稳定性980 nm泵浦源，原始掺铒光纤与辐照后的掺铒光纤的测试长度均为2.7 m。将原始光纤与辐照后的光纤分别接入增益测试系统进行测试，采用功率为−20 dBm的1550 nm信号，将980 nm泵浦源的功率由50 mW逐步提升至550 mW，同时记录掺铒光纤的增益水平。增益测试结果均由横河 AQ6370D 光谱仪测得。

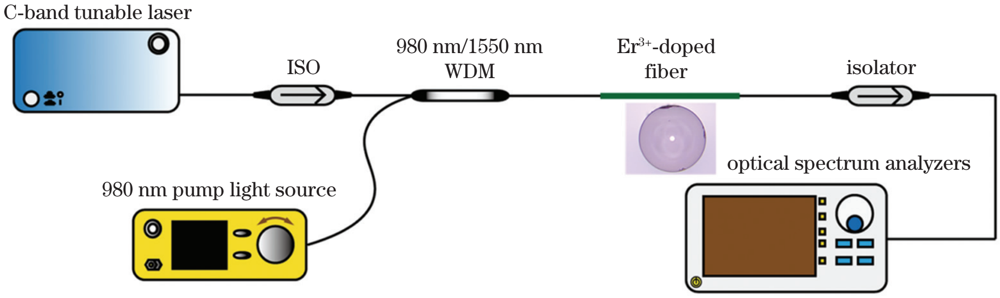

图2　C波段抗辐照掺铒光纤增益测试系统与光纤截面

Fig. 2　Gain test diagram and cross-section of C-band radiation-resistant erbium-doped fiber

图3为C波段抗辐照掺铒光纤在辐照前后的增益随泵浦功率的变化曲线。原始光纤在100 mW泵浦条件下的增益为27.0 dB，而在1500 Gy剂量下辐照后的光纤在同等条件下的增益为26.2 dB，两者作差得到辐致增益变化为0.8 dB。随着泵浦功率的提升，光纤逐步接近增益饱和。由于泵浦漂白作用，在泵浦功率为500 mW时，原始光纤的增益达到36.8 dB，而辐照光纤的增益为36.6 dB，辐致增益变化减小到0.2 dB。

采用 MCVD 技术制备的C波段抗辐照掺铒光纤经过1500 Gy剂量、0.2 Gy/s平均剂量率辐照后，在980 nm和1550 nm处的辐致损耗分别为1.4 dB/m和0.8 dB/m。搭建 EDFA 进行了辐致增益衰减测试，测试结果显示：在100 mW和

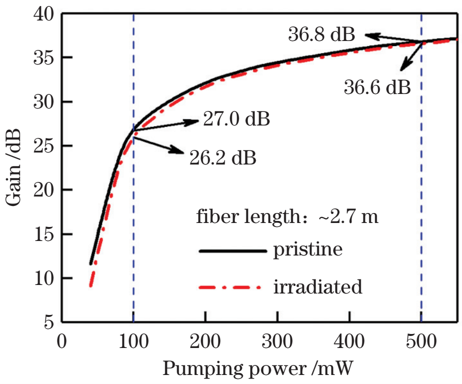

图3　抗辐照掺铒光纤辐照前与辐照后在1550 nm处的增益随泵浦功率的变化

Fig. 3　Variation of gain versus pumping power at 1550 nm before and after irradiation of radiation-resistant erbium-doped fiber

500 mW 泵浦功率下，1550 nm 处的辐致增益变化分别为 0.8 dB 和 0.2 dB。该掺铒光纤的抗辐照性能优越，在卫星通信、数据采集和太空探测等领域具有广阔的应用前景。

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Domestic High Quality Radiation-Resistant Erbium-Doped Fiber

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Abstract

Objective With the rapid development of aerospace technology, erbium (Er)-doped fiber amplifier (EDFA) has gradually become the best choice for satellite communication tasks because of its advantages such as high gain, wide bandwidth, and good compactness. However, the Er-doped fiber, a key component of the EDFA, is extremely sensitive to various cosmic rays (gamma rays, etc.). To maintain the performance and life of Er-doped fibers in the irradiated environment, the homemade radiation-resistant Er-doped fiber was developed.

Methods Radiation-resistant Er-doped fiber was fabricated using modified chemical vapor deposition (MCVD) technology. The homemade Er-doped fiber was designed with Al-Ge-Ce-La co-doping to strengthen the radiation resistance. Cerium ion-doping technology was used to eliminate color centers due to irradiation. The radiation resistance of the fiber was further improved by adjusting the doping concentration and the ratio of aluminum and germanium. Lanthanum ions were used to reduce the clustering effect of Er ions and improve efficiency. Our fiber's radiation-induced attenuation (RIA) and radiation-induced gain variation (RIGV) were tested based on Photon Kinetics 2500 and typical EDFA structure, respectively.

Results and Discussions The radiation-resistant Er-doped fiber has the core and cladding diameters of 9 and 125 μm, respectively. After irradiation by ^{60}Co, radiation source with a cumulative and average dose of 1500 Gy and 0.2 Gy/s, respectively, Fig.1 shows that RIA of radiation-resistant Er-doped fiber at 980 and 1550 nm is 1.4 and 0.8 dB/m, respectively. The gain-performance test was performed using a typical EDFA structure (Fig. 2) with −20 dBm signal at pump source of 1550 and 980 nm. As shown in Fig.3, RIGV at 1550 nm is 0.8 and 0.2 dB at 100 and 500 mW pumping power, respectively.

Conclusions In this study, we prepared a radiation-resistant Er-doped fiber through the MCVD process. RIA at 980 and 1550 nm is 1.4 and 0.8 dB/m, respectively. EDFA with −20 dBm signal at pump source of 1550 and 980 nm was built for the gain test. In addition, RIGV at 1550 nm is 0.8 and 0.2 dB at 100 and 500 mW puming power, respectively. The Er-doped fiber shows good antiradiation performance and broad application prospects in the fields of satellite communications, data acquisition, and space exploration.

Key words fiber optics; erbium-doped fiber; radiation-resistance; fiber optics communications; erbium-doped fiber amplifier

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