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研究论文

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高增益二级双程L波段扩展掺铒光纤放大器

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摘要 近年来，L波段扩展掺铒光纤放大器（EDFA）由于能覆盖更宽的波长范围而备受关注，但其增益水平普遍较低。本文采用1480 nm激光泵浦Er/Yb/P共掺光纤，结合双程放大和预放大技术，研制了高增益的L波段扩展EDFA。实验装置在1556～1621 nm的65 nm范围内获得高于20 dB的增益，最大增益达48.8 dB（1566 nm），30 dB增益带宽达58 nm（1558～1616 nm），噪声系数在1580～1610 nm范围内低于5.8 dB。该研究工作有效提高了L波段扩展EDFA的增益水平，并将噪声系数控制在较低的范围，可有效提升常规光纤通信系统的传输带宽和容量。

关键词 激光器；L波段掺铒光纤放大器；光纤放大器；光纤通信

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1 引言

随着业务需求和数据总量的迅速增长[1]，现有的光纤通信系统正面临日益增长的扩容压力。传统掺铒光纤放大器（EDFA）有限的增益带宽，逐渐成为限制光纤通信系统传输容量扩大的主要障碍。目前，C+L波段掺铒光纤放大器的增益总带宽仅为75 nm（1530～1605 nm）[2-6]，其中L波段掺铒光纤放大器的增益带宽为40 nm（1565～1605 nm），与国际电信联盟设定的60 nm（1565～1625 nm）的带宽还有不小差距，因此L波段扩展EDFA近年来成为光通信技术领域的研究热点[7-11]。2020年，加拿大拉瓦尔大学的研究团队报道了基于C波段光源辅助泵浦的L波段扩展EDFA，其20 dB增益带宽达48 nm，最大波长为1618 nm，最大增益达26 dB（1605 nm）[12]。2021年，华中科技大学李进延团队通过调控掺铒光纤中磷（P）离子和铝（Al）离子的掺杂浓度来抑制铒离子的激发态吸收（ESA），将L波段扩展EDFA的20 dB增益带宽提升到52 nm，最大波长为1622 nm[13]。同年该团队将镱（Yb）离子掺入掺铒光纤内以降低铒离子在L波段长波长侧的ESA[14]，将增益带宽扩展至1623 nm处。2022年，该团队采用三级放大结构，在1625.3 nm处获得23.4 dB的增益[15]。同年，美国南安普敦大学的研究团队将富含Al的掺铒光纤与富含P的掺铒光纤组合用于光纤放大结构，20 dB增益带宽为48 nm，在1595 nm处获得24 dB的最大增益，最大波长为1613 nm[16]。综合上述研究进展，并与C波段EDFA的性能相比，可以发现，目前报道的L波段扩展EDFA尽管在增益带宽方面取得进展，但仍存在增益水平低、高增益带宽有限，以及噪声系数大等问题。

本文在采用1480 nm激光泵浦Er/Yb/P共掺光纤获得L波段扩展EDFA的基础上，结合预放大和双程放大技术提高L波段EDFA的增益，使L波段扩展EDFA的最高增益达到48.8 dB，20 dB和30 dB增益带宽分别达到58 nm和65 nm，1620 nm和1625 nm的增益分别达到22.7 dB和11.5 dB。同时，预放大器的使用使得二级双程结构EDFA的噪声系数保持在较低的范围，在1565～1610 nm范围内为5.61 dB±1.75 dB。

2 实验装置

图1是本文采用的二级双程L波段扩展EDFA的实验装置示意图。由主放大器和预放大器通过环形器1（OC1）级联构成二级放大结构，主放大器尾端连接由环行器2（OC2）构成的环镜，使单程放大后的信号光被反射回主放大器后再次被放大。其中主放大器由两个1480 nm的半导体泵浦激光器双向泵浦30 m的Er/Yb/P共掺光纤构成，Er/Yb/P共掺光纤由长飞光纤光缆股份有限公司制造，其纤芯直径为6.5 μm，数值孔

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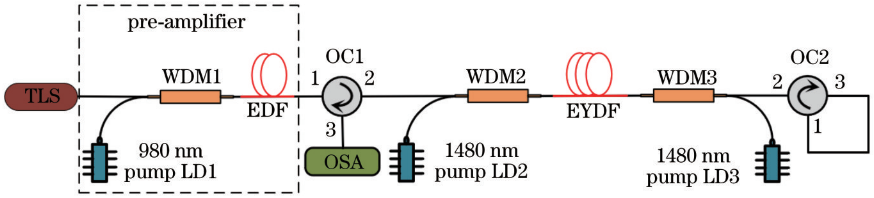
径为0.2，1530 nm处的吸收系数为30 dB/m。预放大器由980 nm的半导体泵浦激光器前向泵浦10 m掺铒光纤（美国OFS公司MP980，数值孔径为0.2，1530 nm处的吸收系数为6.5 dB/m）构成。信号光由可调谐激光器（TLS）产生，信号功率为-30 dBm，双程放大后的信号光经OC1输出，由光谱分析仪（OSA）进行测量。

实验中还测量了放大器的单程增益特性，实验时将OC2的1口和3口断开，信号光由3口输出至光谱分析仪。首先测试了主放大器的单程和双程放大性能。信号光通过OC1的1口输入，分别测得单程和双程放大结构下的增益和噪声系数。然后将预放大器与主放大器级联形成二级单程或双程放大结构，同样进行了对比测量。



TLS: tunable laser; WDM: wavelength division multiplexer; LD: laser diode; OC: optical circulator; OSA: optical spectrum analyzer; EYDF: Er/Yb co-doped fiber

图1　二级双程L波段扩展EDFA结构图

Fig. 1　Configuration of two-stage double-pass L-band extended erbium-doped fiber amplifier (EDFA)

3　实验结果及分析

L波段扩展EDFA主放大器的单程和双程放大性能的实验结果如图2所示。可以发现，主放大器在单程和双程放大结构中皆可实现L波段增益带宽的扩展，但在相同泵浦功率（前向300 mW＋后向50 mW）下，双程结构在1560～1620 nm范围内的增益显著高于单程结构，其最大增益在1566 nm处达47 dB，在1622 nm处的增益达20.25 dB，20 dB增益带宽达65 nm（1557～1622 nm）。双程放大结构在增益提升方面的效果非常显著。

由于此时的泵浦功率对于单程结构并不是最优设置，本文在前向泵浦功率保持300 mW的情况下，逐步增大单程结构的后向泵浦功率至250 mW，发现EDFA的增益水平虽然有明显提高，特别是在波长较短的1555～1570 nm范围内，增益提升了13 dB，但是在绝大部分的增益带宽（1562～1620 nm）范围内，其增益水平仍明显低于泵浦总功率比其低200 mW的双程放大结构。这进一步证实了双程放大结构在增益提升方面的优势。

在噪声系数比较方面，L波段扩展EDFA单程放大结构凸显出较低的噪声水平，最低为4.9 dB，即使增大后向泵浦功率至250 mW，噪声系数也基本保持不变。而双程放大结构却呈现出较高的噪声系数，在1555～1620 nm范围内普遍高于单程结构，均大于5.3 dB。这表明，单程放大结构具有良好的噪声性能，但增益低，即使增大泵浦功率以提高增益，也达不到双程结构的增益水平，而双程放大结构的增益水平高，但是噪声性能差。双程放大的高增益性能归因于信号的二次放大，相当于增加了掺铒光纤的有效长度，但信号光被二次放大的同时，作为噪声的放大自发辐射（ASE）光也同样被二次放大，导致噪声系数增加[17-21]。

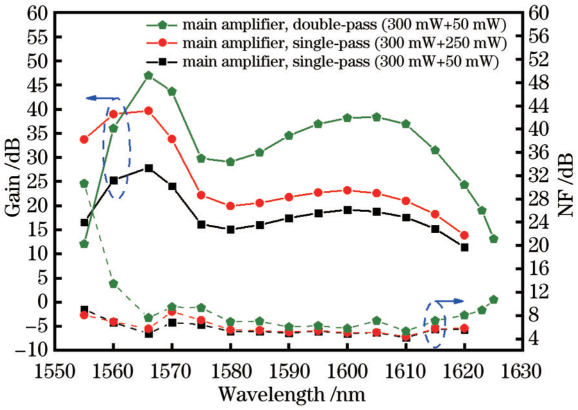


图2　主放大器单程与主放大器双程结构的增益和噪声谱

Fig. 2　Gain and noise figure (NF) of main amplifier in single-pass and double-pass configurations

二级双程结构和二级单程结构L波段扩展EDFA的实验结果如图3所示。预放大器中980 nm激光器的泵浦功率为50 mW。在相同主放大器泵浦功率（前向300 mW＋后向50 mW）下，二级双程结构在1558 nm之后的范围内的增益显著高于二级单程结构，其最大增益在1566 nm处，达48.8 dB，在1605 nm处的增益达39.7 dB，在1556～1621 nm的65 nm范围内增益高于20 dB，在1558～1616 nm的58 nm范围内增益高于30 dB。相较于主放大器双程放大结构，尽管增益在1614 nm以上的波长范围内略低，但是二级双程结构在1555～1614 nm的更大范围内增益有显著提高，最大提高了6.8 dB。

二级双程结构L波段扩展EDFA的噪声系数在1580～1610 nm范围内低于5.8 dB，最低为4.6 dB（1580 nm），相较于二级单程结构无显著增加，并且在绝大部分波长范围内低于主放大器双程结构，仅在

1615 nm之后略有增加。

以上实验结果表明，二级双程放大结构L波段扩展EDFA相较于二级单程结构和一级双程结构能有效提高增益水平，增益带宽具有明显优势，并且噪声系数尚保持在较低的范围内。这主要得益于预放大器的加入，其作用是既提高了增益水平，又抑制了噪声系数。因为二级放大结构EDFA的噪声系数[22]为

$$N_{\mathrm{F}}=N_{\mathrm{F1}}+\frac{N_{\mathrm{F2}}-1}{G_1},\qquad(1)$$

式中：N_{F1}和G_1分别为第一级EDFA的噪声系数和增益；N_{F2}为第二级EDFA的噪声系数。由式(1)可知，二级放大结构EDFA中的第一级放大即预放大器的噪声系数对整个系统的噪声系数起决定性作用，主放大器的噪声系数虽然较高，但对整个系统噪声系数的影响很小。因此，在预放大器中可采用低功率的980 nm激光器泵浦较短的掺铒光纤，使其ASE的积累处于较低的水平，进而使预放大器表现出较低的噪声系数。另外，位于两级放大之间的OC1能有效阻止主放大器产生的后向ASE进入预放大器中，使预放大器的粒子数反转状态不受影响。此外，二级双程放大结构在短波长侧边缘(1559 nm之前)的增益低于单程结构，噪声系数高于单程结构，这是因为二级双程放大结构相当于增加了掺铒光纤的有效长度，导致短波长侧的信号被部分吸收，增益性能劣化。这是提升L波段扩展EDFA长波长侧增益必须付出的代价。

图4为在二级双程结构的基础上不同波长信号的增益随输入信号功率的变化谱，测得1590、1605、1620 nm处的饱和输出功率(P_{sat})分别为16.77、20.58、15.57 dBm，其中1605 nm处的饱和输出功率最大。相较于常规的L波段EDFA在1605 nm处低且迅速下降的增益，本文提出的二级双程L波段扩展EDFA不仅扩展了L波段增益带宽，还在1605 nm处得到了最高的饱和输出功率，优势不言而喻。

表1所示为近年来国内外L波段扩展EDFA的主要参数对比。通过比较可以看出，本文提出的二级双程L波段扩展EDFA在最低的总泵浦功率下得到了最优的增益水平和增益带宽，虽然噪声系数整体上略有提高，但仍保持在较低的水平。相较而言综合性能最好，因此有望成为下一代L波段EDFA的主流技术方案，为光纤通信技术的发展和应用提供支持。

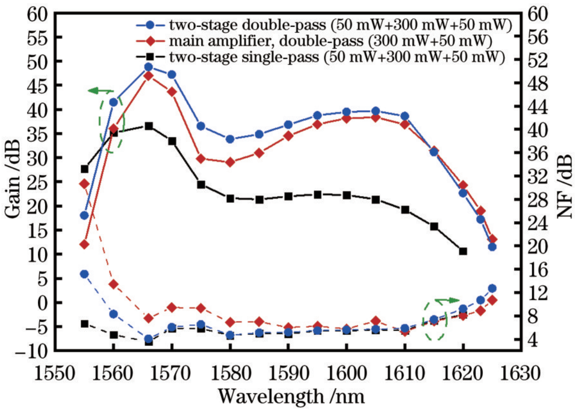


图3 二级单程结构与二级双程结构L波段扩展EDFA的增益和噪声谱

Fig. 3 Gain and NF of two-stage single-pass configuration and two-stage double-pass configuration in L-band extended EDFA

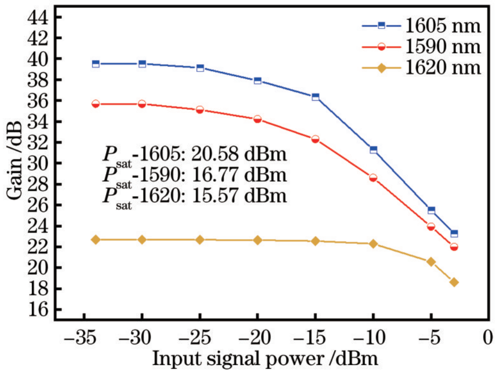


图4 二级双程结构L波段扩展EDFA的增益随输入信号功率的变化

Fig. 4 Gain of two-stage double-pass configuration L-band extended EDFA versus input signal power

表1 国内外L波段扩展EDFA的主要参数

Table 1 Key parameters of L-band extended EDFA at home and abroad

Configuration	Gain bandwidth $\Delta\lambda$ /nm	Maximum gain G /dB	Maximum wavelength for 20 dB gain /nm	Minimum noise figure /dB	Total pump power P /mW	Reference
Two-stage single-pass with C-band auxiliary pumping	48 (≥20 dB)	~26 @1605 nm	1618	4.0	650	[12]
Two-stage single-pass	52 (≥20 dB)	~29 @1570 nm ~26 @1605 nm	1622	4.4	1550	[13]
Single-stage single-pass	58 (≥20 dB)	~31 @1605 nm	1623	4.9	720	[14]
Three-stage single-pass	50 (≥23 dB)	~37 @1610 nm	1625	4.7	2180	[15]
Single-stage single-pass	48 (≥20 dB)	~24 @1595 nm	1613	3.1	765	[16]
Two-stage double-pass	65 (≥20 dB) 58 (≥30 dB)	~48 @1566 nm ~39 @1605 nm	1621	4.1	400	This work

4 结论

本文采用1480 nm激光泵浦Er/Yb/P共掺光纤，结合预放大和双程放大技术研制的二级双程L波段扩展EDFA，在1556～1621 nm的65 nm范围内获得高于20 dB的增益，在1557～1615 nm范围内获得高于30 dB的增益，在1566 nm和1605 nm处的增益分别达到48 dB和39 dB，在1605 nm处的饱和输出功率高达20.58 dBm，在1580～1610 nm范围内噪声系数低于5.8 dB，最低为4.6 dB。对比近年来国内外已报道的L波段扩展EDFA，本文在最低的总泵浦功率下得到了最优的增益水平和增益带宽，有望成为下一代L波段EDFA的主流技术方案，将广泛应用于未来高容量光纤传输系统中。

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Extended L-Band Erbium-Doped Fiber Amplifier with High Gain Using Two-Stage Double-Pass Configuration

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Abstract

Objective Due to the increasing demand for information transmission capacity, traditional wavelength-division multiplexing (WDM) optical fiber transmission technology cannot meet the requirements of communication technology advancement. In recent years, L-band extended erbium-doped fiber amplifiers (L-EDFAs) have become a research hotspot due to their ability to cover a wider wavelength range, enabling the transmission of more wavelength channels and thus a larger information amount. Consequently, this type of device has caught significant research attention. However, the initial research on L-EDFAs often results in relatively low gain levels, which could not satisfy the requirements for transmitting large information amounts. Thus, we propose a solution that may achieve high-gain and low-noise L-EDFAs. Experimental results demonstrate that the proposed L-EDFA outperforms similar devices in other references. This advancement could provide a foundation for further research, potentially leading to the industrialization of such devices. The proposed solution has promising prospects for meeting the growing demand for high-performance optical amplification in L-band applications.

Methods By utilizing 1480 nm lasers to pump Er/Yb/P co-doped fiber and incorporating double-pass amplification and pre-amplification technologies, an enhanced L-EDFA is developed. Ytterbium (Yb) ions and phosphorus (P) ions are initially introduced into the erbium-doped fiber to mitigate excited state absorption (ESA) of erbium ions in the longer wavelengths of the L-band, extending the L-band for the EDFA. Subsequently, a two-stage double-pass experimental setup for the L-EDFA is implemented to further enhance its gain. This experimental arrangement comprises a main amplifier and a pre-amplifier cascaded through a circulator to form a two-stage amplification structure. Once amplified through a single pass, the signal light is reflected to the main amplifier for secondary amplification. The initial testing involves evaluating the single-pass and double-pass amplification performance of the main amplifier. Pump power optimization for the single-pass structure of the main amplifier is conducted and compared with that of the double-pass structure. To minimize noise, we form a two-stage single-pass or double-pass amplification structure by cascading the pre-amplifier and the main amplifier. The pump power for the two-stage single-pass structure is also optimized and compared with that of the double-pass structure to reduce noise and improve performance.

Results and Discussions Based on the experimental results in the single-pass and double-pass amplification performance of the main amplifier in the L-EDFA (Fig. 2), it is evident that the main amplifier achieves an extended gain bandwidth for the L-band in both single-pass and double-pass amplification configurations. Notably, within the wavelength range of 1560‒1620 nm and equivalent pump power, the double-pass amplification structure demonstrates a significantly higher gain compared to the single-pass structure. The gain enhancement effect of the double-pass configuration is particularly remarkable. By progressively increasing the reverse pump power of the single-pass structure to 250 mW and maintaining the forward pump power at 300 mW, the EDFA gain is improved. However, it remains substantially lower than that of the double-pass structure, even with a 200 mW total pump power reduction across a substantial portion of the gain bandwidth. This further underscores the advantageous gain enhancement properties of the double-pass amplification structure. Regarding noise figure comparisons, the single-pass amplification structure of the L-EDFA maintains a lower noise level, even when the reverse pump power is elevated to 250 mW. Notably, the noise figure remains relatively stable. Conversely, the double-pass amplification structure exhibits a higher noise figure, suggesting a trade-off between gain level and noise performance. Possessing favorable noise characteristics, the single-pass structure presents a modest gain level. Conversely, the double-pass structure provides a higher gain level but compromised noise performance.

Based on the experimental results (Fig. 3), a comparison between the performance of the two-stage double-pass structure and the two-stage single-pass structure in the L-EDFA shows that the two-stage double-pass configuration yields significantly higher gain than its single-pass counterpart, particularly beyond the 1558 nm mark, with all maintaining the same pump power for the main amplifier. In contrast to the main amplifier's double-pass amplification structure, while the gain in the wavelength range above 1614 nm experiences a minor reduction, the two-stage double-pass structure exhibits substantial enhancement across the broader span of 1555–1614 nm. Meanwhile, the noise figure of the L-EDFA in the two-stage double-pass structure demonstrates minimal increase when compared to the two-stage single-pass structure, and it remains lower than that of the main amplifier's double-pass structure across the majority of the wavelength range. These findings underscore the effectiveness of the two-stage double-pass amplification structure in significantly boosting both gain level and gain bandwidth, exhibiting clear advantages over both the two-stage single-pass amplification and the main amplifier's double-pass structures. Additionally, the noise figure remains within a lower range. This achievement is primarily attributed to the pre-amplifier incorporation, which serves the dual purpose of elevating gain levels and mitigating the noise figure. During comparing the key parameters of L-EDFAs at home and abroad in recent years (Table 1), the two-stage double-pass L-EDFA achieves optimal gain levels and gain bandwidth with the lowest total pumping power. Furthermore, the noise figure remains consistently low, even though there is a slight overall improvement in the noise figure.

Conclusions We utilize a 1480 nm laser-pumped Er/Yb/P co-doped fiber and combine pre-amplification and double-pass amplification techniques to develop a two-stage double-pass L-EDFA. Within the wavelength range of 1556–1621 nm, a gain exceeding 20 dB is achieved, and within the range of 1557–1615 nm, a gain surpassing 30 dB is realized. Specifically, gains of 48 dB and 39 dB are respectively attained at 1566 nm and 1605 nm. Remarkably, the saturated output power reaches 20.58 dBm at 1605 nm. The noise figure remains below 5.8 dB within the 1580-1610 nm range, with a minimum of 4.6 dB. Comparing with L-EDFAs reported domestically and internationally in recent years, we achieve the optimal gain level and gain bandwidth while operating under the lowest total pumping power. This approach has the potential to become the mainstream technical solution for the next generation of L-EDFAs and can be extensively applied to future high-capacity fiber optic transmission systems.

Key words lasers; L-band erbium-doped fiber amplifier; fiber amplifier; optical fiber communication