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Power-equalized parallel-type pump-shared fiber lasers based on parameter-adjustment

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Abstract

A parallel-type, pump-shared (PTPS) scheme linear-cavity laser array (LCLA) is proposed and numerically studied. Power-equalization of multiwavelength fiber lasers can be achieved by varying the pumping power ratio, length of the erbium-doped fiber or reflectivity of grating reflector for the individual channels. Before and after power-equalization, the maximum power variation among seven equal-spaced channels, ranging from 1530 to 1560 nm, is 5.8 and 0.2 dB, respectively. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Wavelength division multiplexed; Power equalization; Fiber lasers; Fiber Bragg grating

1. Introduction

The characteristics of fiber lasers have been extensively investigated for many important applications, both in digital and analog transmission systems [1], laser spectroscopy, fiber-optic sensors [2], optical signal processing and wavelength conversion, etc. In order to increase the information capacity using wavelength division multiplexed (WDM) transmission, the realization of stable, narrow linewidth and equal output power lasers with multiwavelength operation in the 1.55 μm band have attracted a great deal of attention and have been extensively developed recently [3,4]. With the advantage of wavelength insensitivity to temperature over semiconductor lasers at least in an order of magnitude, erbium-doped fiber (EDF) laser is a promising candidate for multichannel lightwave communication [5]. Some previous techniques [1,6–8] had been proposed for multiwavelength operations. These techniques are based on several short-period fiber Bragg gratings (FBGs) [1], and semiconductor optical amplifier arrays [6], by splicing five distributed feedback lasers together and pumping by a single 1480-nm semiconductor laser [7] or using two comb filters in the ring-cavity [8].

To reduce the cost and achieve a better relative intensity noise (RIN), in this paper, a linear-cavity laser arrays (LCLAs) is proposed. In contrast to the structure presented in Ref. [5], a pumping source is parallel-shared to N fiber lasers units with the merit of avoiding the gain competition effect among channels. Each fiber laser unit consists of a grating filter pair with identical wavelength and a piece of er-

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bium-doped fiber (EDF). The power level of each lasing signal is dependent of the pumping power value, length of EDF and grating filters reflectivity. Theoretic analyses and calculated results of the power-equalized LCLAs based on parameter-adjustment are addressed in Section 2. Before and after power-equalization, the maximum power variation among channels, ranging from 1530 to 1560 nm, are 5.8 and 0.2 dB, respectively.

2. Theory of the PTPS scheme LFLA

2.1. Configuration of fiber laser arrays

Fig. 1 shows the proposed diagram of the parallel-type pump-shared (PTPS) power-equalized LCLAs. The inset shows the ith $(1 \le i \le N)$ linear fiber laser unit. The 980 or 1480 nm pump power is directly launched into the cavity consists of a reflector grating which has $R_0 \sim 100\%$ reflectivity at the left-hand side (LHS) and the other reflector grating which has $R_i \sim 50\%$ reflectivity at the right-hand side (RHS). Two FBG reflectors have an identical central wavelength at λ_i $(1 \le i \le N)$, where R_i, λ_i, L_i, R_i are the reflectivity of the ith LHS FBG$_i$, the lasing wavelength of the ith fiber laser, the length of the ith EDF and the reflectivity of the ith RHS FBG$_i$, respectively. A $1 \times N$ 980 or 1480 nm variable-ratio coupler is used to adjust the power levels among the N fiber laser units. N units of 980/1550 or 1480/1550 nm WDM couplers are used to launch the pumping power to those N fiber laser units. r_i

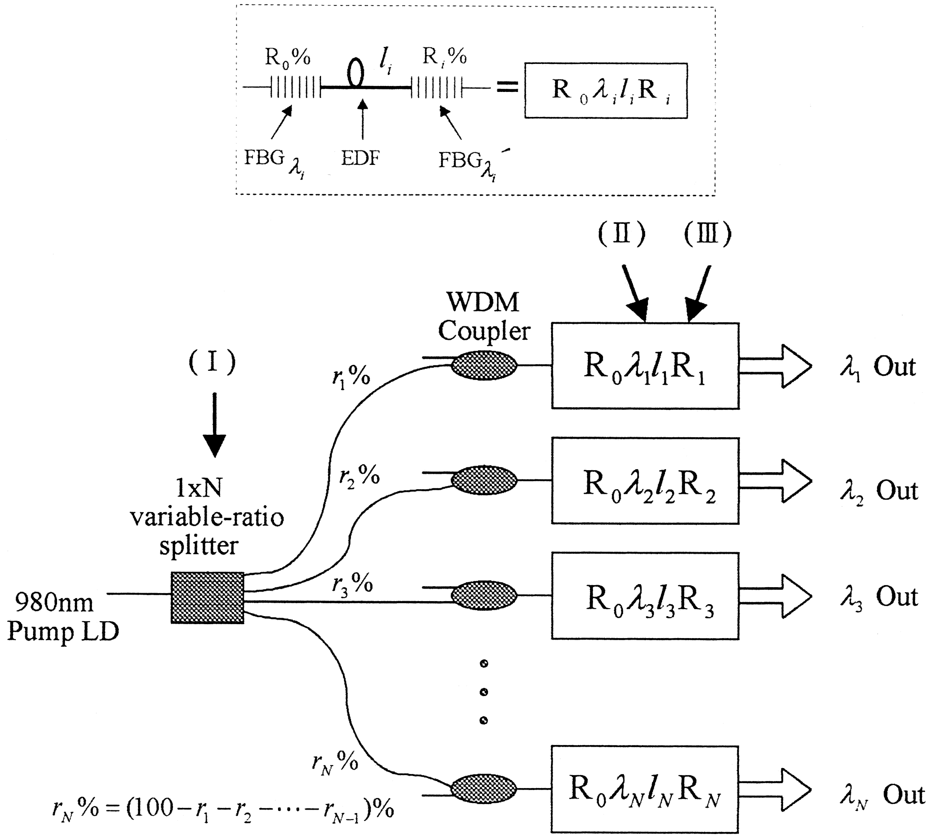

Fig. 1. Proposed configuration of the parallel-type, pump-shared scheme linear fiber laser arrays. Inset shows the ith linear fiber laser unit. r_i: pumping ratio of the common pump laser diode to the ith fiber laser unit, where $1 \le i \le N$. R_o: reflectivity of the LHS FBG$_i$ λ_i: lasing wavelength of the ith fiber laser unit, L_i: length of the ith erbium-doped fiber (EDF), R_i: reflectivity of the ith RHS FBG$_i$.

$(1 \leq i \leq N)$ is the pumping ratio of the common pump laser diode to the ith fiber laser unit with $0\% \leq r_i \leq 100\%$ and $r_1 + r_2 + \ldots r_N = 100\%$. Compared to the use of $1 \times N$ fixed ratio couplers combining N variable attenuators (VAs), a $1 \times N$ variable-ratio coupler is very cost-effective because of components saving. Also, it can achieve higher average output power because the conservation of total pumping power. On the other hand, using $1 \times N$ fixed ratio couplers combining $N-1$ variable attenuators (VAs), the other N VAs need to attenuate the power level of the $N-1$ higher channel signals to match the channel with the lowest power level. Thus, extra internal insertion losses (usually ~ 2 dB) induce from those N VAs is unavoidable.

2.2. General analysis

The EDFA can be modeled as a homogeneously broadened two-level system. Fiber grating reflectors can be used to build up the N resonant cavities. Both grating reflectors at the LHS and RHS are matched in central wavelength and transparent to the pump wavelength (980 or 1480 nm). At any point in the gain fiber there is pump light propagating from left to right. The lasing signals (standing wave) propagate in both directions and superpose with each other. No input signals have been considered to start the oscillation process. Above the threshold conditions, the generation and amplification of the forward and backward amplified spontaneous emission (ASE) noise within the gain fiber are sufficient to give rise to the lasing condition. Compared with the bulk mirrors, the grating reflectors can avoid the losses involved in coupling the fiber ends. Similarly to the analysis in Ref. [4], we assume that the length of EDF is L with the following input conditions:

$$P_p^+(\lambda_p) = P_p^{\mathrm{o}} \text{ and } P_{\mathrm{ASE}}^+(\lambda_i) = P_S^+(\lambda_i) = 0 \text{ at } z=0 \tag{1}$$

where P_p^{o} is the initial launched power at $z=0$, and the boundary conditions are given by

$$[P_S^+(\lambda_i)]_n = [P_{\mathrm{ASE}}^-(\lambda_i) + P_S^-(\lambda_i)]_{n-1} \times R_1(\lambda_i) A_1 \text{ at } z=0 \tag{2}$$

$$[P_S^-(\lambda_i)]_n = [P_{\mathrm{ASE}}^+(\lambda_i) + P_S^+(\lambda_i)]_{n-1} \times R_2(\lambda_i) A_2 \text{ at } z=L \tag{3}$$

where subscript n is the nth iteration during algorithm, $R_1(\lambda_i)$ and $R_2(\lambda_i)$ are the reflectivities at λ_i for $z=0$ and $z=L$, respectively, L is the cavity length, and A_1 and A_2 are loss due to the grating reflectors. For the linear fiber laser unit shown in the inset of Fig. 1, the LHS grating has reflectivity R_0 and the RHS grating has reflectivity R_i. If we define ε_1 and ε_2 as the intracavity loss for either side, the output laser power is given by

$$P_{\mathrm{Las}} = (1-R_2)\,\varepsilon_2\, P_{\mathrm{R}}^{\mathrm{out}} \tag{4}$$

where $P_{\mathrm{R}}^{\mathrm{out}}$ is the power at the fiber-laser wavelength out from the RHS end of the gain fiber. The lasing power after one round-trip of the cavity is given by

$$P_{\mathrm{R}}^{\mathrm{out}} = \varepsilon^2 R^2 P_{\mathrm{R}}^{\mathrm{out}} \exp\left[-2\alpha_S L + 2P_{\mathrm{P}}^{\mathrm{abs}}/P_S^{\mathrm{CS}} + 2P_S^{\mathrm{abs}}/P_S^{\mathrm{IS}}\right] \tag{5}$$

where $R^2 = R_1 R_2$, $\varepsilon^2 = \varepsilon_1 \varepsilon_2$, α_S is the absorption coefficient at lasing wavelength in the gain fiber, P_P^{abs} is the pump power absorbed in its single pass through the gain fiber, P_S^{abs} is the power absorbed at the lasing wavelength in the gain fiber, and P_S^{CS} and P_S^{IS} are fitted parameters defined as those in Ref. [9].

2.3. Theoretical results

Without loss of generality, we consider seven-channel laser arrays have wavelength λ_{S} ranging from 1530 to 1560 nm, covering the whole ASE bandwidth of EDFA, with channel spacing of 5.0 nm for theoretical analysis. Before power-equalized adjustment, we set $r_1\% = r_2\% \ldots r_7\% = 1/7 \cong 14.3\%$, $L_1 = L_2 \ldots L_7 = 30$ cm and $R_1\% = R_2\% \ldots R_7\% = 45\%$, where $r_i\%$ is the pumping ratio of the pump laser to the ith fiber laser unit with a total pump power is 140 mW. The maximum power variation is 5.8 dB among lasing signals (here, we superpose these seven output spectra of lasing signals for power levels comparison) as shown in Fig. 2(a). To equalize the power levels among these lasing signals, three methods are proposed by adjusting the pumping power ratio r_i $(i=1,2\ldots7)$, the length of the erbium-doped fiber L_i $(i=1,2\ldots7)$ and the reflectivity of the RHS FBG$_i$ is R_i $(i=1,2\ldots7)$ of the

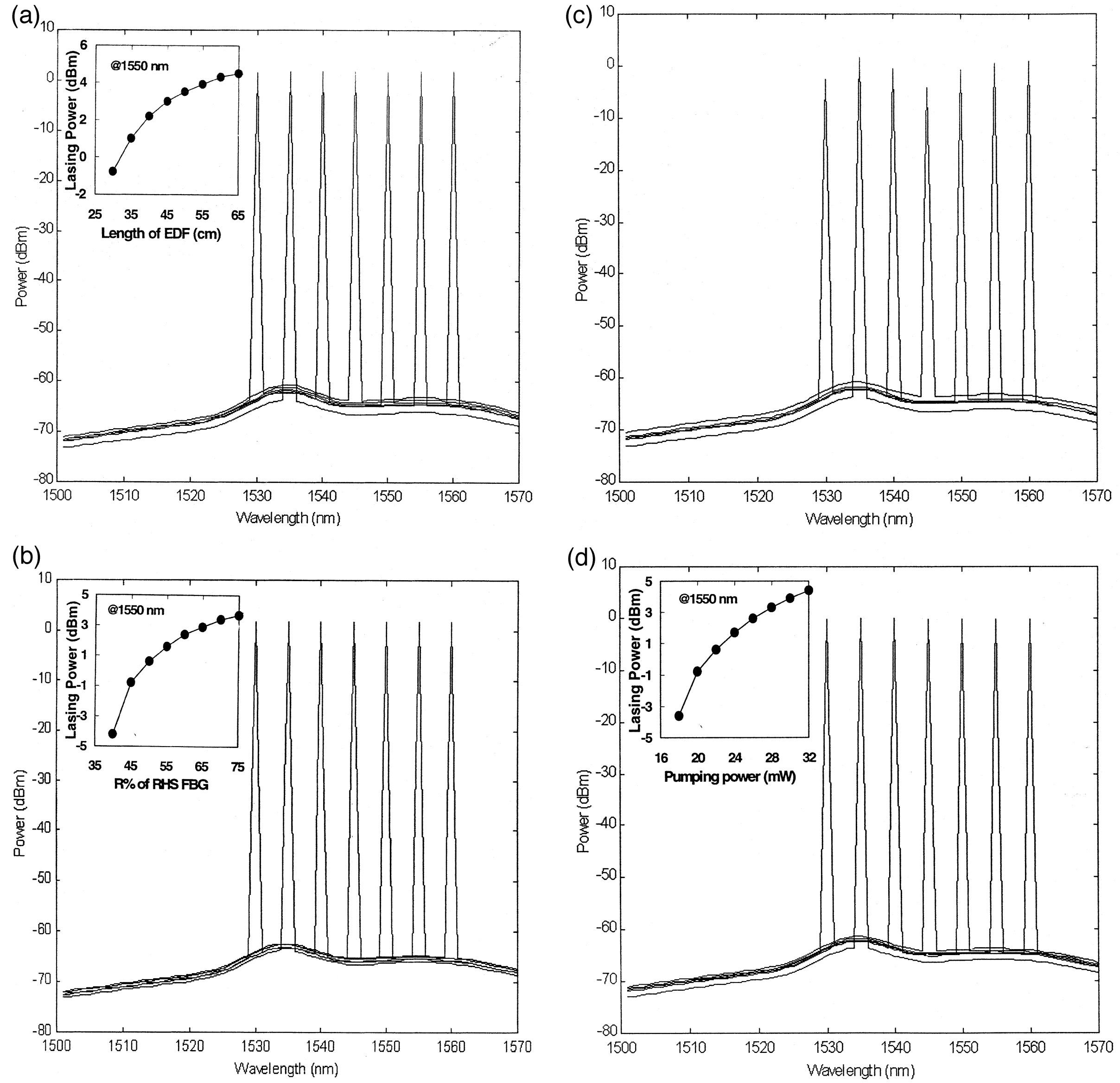

Fig. 2. Superposed output spectra of the seven-channel linear fiber laser arrays: (a) power variation is 5.8 dB before power-equalization ($r_i = 1/7$, EDF$_i$ = 30 cm and $R_i = 45\%$); and after power-equalization by adjusting: (b) the pumping ratio r_i, (with EDF$_i$ = 30 cm and $R_i = 45\%$); (c) the length of EDF L_i, (with $r_i = 1/7$ and $R_i = 45\%$); and (d) reflectivity of the RHS FGB$_i$ R_i (with $r_i = 1/7$ and EDF$_i$ = 30 cm), respectively, where $i = 1, 2 \ldots 7$. Insets of Fig. 2(b)–Fig. 2(d) show the output lasing power against the pumping power (dBm) (= 140 mW $\times\, r_i$), L_i and R_i, respectively, for the 5th channel at 1550 nm.

individual signals. For each case, only one parameter (r_i, L_i or R_i) is adjusted and the other two parameters are kept unchanged. Fig. 2(b), Fig. 2(c) and Fig. 2(d) show the numerical results when one of the three parameters (r_i, L_i and R_i) is adjusted to equalize the lasing power. Output power variation of less than 0.2 dB among channel signals could be achieved for all the three proposals. Insets of Fig. 2(b), Fig. 2(c) and Fig. 2(d) show the output lasing power against the pumping power (dBm), L_i and R_i,

Table 1
Summary of the parameters used and numerical results of the three power-equalized approaches

	Pumping ratio r_i (%)	EDF length L_i (cm)	Reflectivity R_i (%)
$i = 1,2\ldots7$	$\mathrm{EDF}_i = 30$ cm, $R_i = 45\%$	$r_i = 14.3\%$, $R_i = 45\%$	$r_i = 14.3\%$, $\mathrm{EDF}_i = 30$ cm
Channel 1 @ 1530 nm	15.64	45.0	66.0
Channel 2 @ 1535 nm	12.36	30.0	45.0
Channel 3 @ 1540 nm	14.60	38.5	57.5
Channel 4 @ 1545 nm	16.44	45.0	62.5
Channel 5 @ 1550 nm	14.60	37.0	55.0
Channel 6 @ 1555 nm	13.32	33.0	49.5
Channel 7 @ 1560 nm	13.04	32.0	48.0
Average power (dBm)	−0.23	1.7	1.7
Power variation (dB)	0.17	0.11	0.05

respectively, for the 5th channel at 1550 nm. The trends and curves are similar for the other wavelengths. In Table 1, we summarize the parameters used and the numerical results of three power-equalized approaches.

3. Discussion

Besides simple fabrication, LCLAs are wavelength insensitive to temperature at least an order of magnitude higher than semiconductor lasers, which are attractive in WDM systems where tighter wavelength tolerances are required. The PTPS scheme LCLAs may have narrow linewidth and better relative intensity noise (RIN) compared with those of fiber ring lasers. The unstable lasing and multiple-mode lasing effects are suppressed in LCLAs because of its short cavity. To further increase the pumping absorption, the erbium:ytterbium codoped fiber is a good candidate as the gain medium [3]. On the other hand, the cascaded-type, pump-shared (CTPS) scheme LCLAs usually have unequal output lasing power among channels (for example, power variation among five channels is 10 dB in Ref. [5]) due to the non-uniform ASE spectrum of EDF and the individual channels cannot be adjusted independently. It will degrade the performance of optical amplified transmission systems and optical networks. The effect of gain competition due to homogeneously broadened characteristic of EDF will restrict the CTPS scheme LCLAs for practical applications as laser sources. Also, the CTPS fiber lasers need an extra demux to separate different channel signals to carry different formats or information then combine together.

4. Conclusion

In summary, a PTPS scheme for N-wavelength LCLAs based on FBG reflectors is proposed. Power-equalization of the multi-wavelength sources by varying the pumping power ratio, length of EDF and reflectivity of the RHS FBG are numerical analysis. Output power variation among channels before and after either of the power-equalization technologies is 5.8 and 0.2 dB, respectively. Due to the ease parameter-adjustment method and graceful features, those power-equalized LCLAs can find extensive applications in high speed and/or long haul WDM lightwave systems.

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References

[1] S.-K. Liaw, C.-C. Lee, K.-P. Ho, S. Chi, Power equalized wavelength-selective fiber lasers using fiber Bragg gratings, Opt. Commun. 155 (1998) 255–259.

[2] Y. Shi, M. Sejka, O. Poulsen, A unidirectional Er^{3+}-doped fiber ring laser without isolator, IEEE Photon Technol. Lett. 7 (1995) 290–292.

[3] W.H. Loh, B.N. Samson, L. Dong, G.J. Cowle, K. Hsu, High performance single frequency fiber grating-based Erbium:Ytterbium-codoped fiber lasers, J. Lightwave Technol. 16 (1996) 114–118.

[4] A. Cucinotta, S. Selleri, L. Vincetti, M. Zoboli, Numerical and experimental analysis of erbium-doped fiber amplifier liner cavity lasers, Opt. Commun. 156 (1998) 264–270.

[5] O. Graydon, W.H. Loh, R.I. Laming, L. Dong, Triple-frequency operation of an Er-doped twincore loop laser, IEEE Photon. Technol. Lett. 8 (1996) 63–65.

[6] A. Hamakawa, T. Kato, G. Sasaki, M. Shigehara, A four-channel multichannel fiber-grating external-cavity array, in 1997 Conf. on Optical Fiber Communication, OFC'97, paper ThM3, Dallas, TX, USA, 1997, pp. 297–298.

[7] P. Varming, J. Hubner, M. Kristensen, Five wavelength DFB fiber laser source, in 1997 Conf. on Optical Fiber Communication Conference, OFC'97, paper TuH4, 1997, pp. 31–32.

[8] J. Chow, G. Town, B. Eggleton, M. Ibsen, K. Sugden, I. Bennion, Multiwavelength generation in an erbium-doped fiber laser using in-fiber comb filters, IEEE Photon. Technol. Lett. 8 (1996) 60–62.

[9] C. Barnard, P. Myslinski, J. Chrostowski, M. Kavehrad, Analytical model for rare-earth-doped fiber amplifiers and lasers, IEEE J. Quantum Electron. 30 (1994) 1817–1830.