Parallel Pump-Shared Linear Cavity Laser Array Using 980-nm Pump Reflectors or N Pieces of Gain Fibers as Self-Equalizers

Shien-Kuei Liaw, Horn-Yi Tseng, and Sien Chi

***Abstract*—By using fiber gratings as pump reflectors with various reflectivities or N pieces of gain fibers with various lengths externally to linear cavity as self-equalizers, a parallel-type, pump-shared linear cavity laser array (LCLA) is proposed and numerically studied. The average output power is increased and the maximum power variation among channels is reduced from 7.2 to less than 0.1 dB when the reflectivity of each pump reflector or the length of each gain fiber is adjusted appropriately.**

***Index Terms*—Fiber Bragg grating, linear cavity laser arrays, master oscillator power amplifier, power equalization, pump reflector, wavelength-division multiplexing.**

I. INTRODUCTION

IN ORDER to increase the information capacity using wavelength-division-multiplexing (WDM) transmission, the realization of stable, narrow linewidth and equal output power lasers with multiwavelength operation in the 1.55-μm band has attracted lots of attention and been extensively developed recently [1].Several previous techniques have been proposed for multiwavelength operations. These techniques are based on several short-period fiber Bragg gratings (FBG's) [2], a semiconductor optical amplifier array [3], splicing five distributed feedback lasers together and pumping with a 1480-nm semiconductor laser [4] and using two comb filters in the ring-cavity [5]. With the feature of wavelength insensitivity to temperature at least an order of magnitude better than that of semiconductor lasers, erbium-doped fiber laser (EDFL) is a promising candidate for multichannel lightwave communications [6].

In this letter, we propose a power-equalized linear cavity laser array (LCLA) based on parallel pump-shared configuration. The simulation is based on the spectral model of the optical amplifier [7]. A pump-diode is parallel pump-shared to an N-channel fiber laser array with the merit of avoiding mutual injection effects among channels. Several pump reflector gratings or gain fibers are added for individual channels to increase the pump absorption ratio and equalize the lasing signals. Theoretical analysis and calculated results of the power-equalized LCLA on varying the reflectivities of pump reflectors are addressed in Sections II and III, respectively.

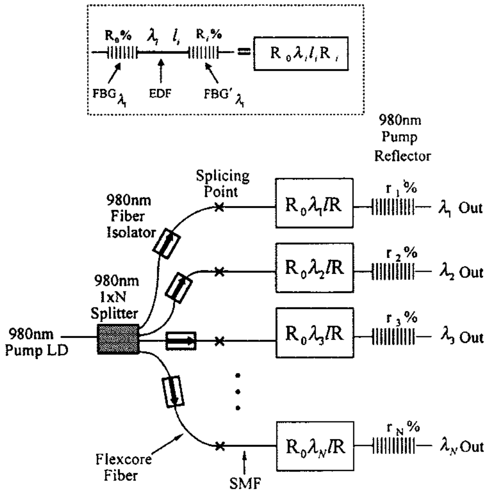

Fig. 1. Proposed configuration of the parallel-type, pump-shared scheme linear cavity laser arrays using grating-based pump reflectors as power-equalizers. Inset shows the ith linear cavity laser unit with $1 \leq i \leq N$.

II. THEORY

Fig. 1 shows proposed configuration of the N-wavelength, fiber grating-based LCLA with parallel-type, pump-shared (PTPS) scheme. N pieces of 980-nm grating-based pump reflectors are located at the output ends of the individual channels. They have various reflectivities and act as power-equalizers. The inset shows the ith linear cavity laser unit with $1 \leq i \leq N$, where R_o, λ_i, R_i are reflectivity of the ith left-hand side (LHS) $\mathrm{FBG_i}$, lasing wavelength of the ith cavity and reflectivity of the ith right-hand side (RHS) FBG_i, respectively. To avoid pump-diode end-faced damage by the residual-reflected pump light, in each channel, a polarization independent 980-nm fiber isolator can be inserted between the 980-nm splitter and the splicing point of the flexcore fiber and single-mode fiber (SMF). Without loss of generality, we consider 11-channel laser arrays having wavelengths λ_s ranging from 1530–1560 nm with equal-channel spacing of 3.0 nm. The range almost covers the whole spectrum of the amplified spontaneous emission (ASE) of the erbium-doped fiber amplifier (EDFA). The laser cavity of each channel is constructed by adding a piece of EDF (15 cm in length) between a pair of FBG's. We assume that the FBGs' with negligible (~0 cm) length are written directly at both ends of the EDF. The reflectivities of the LHS and the RHS gratings

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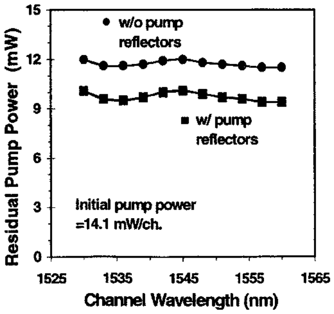


Fig. 2. Residual pump power at the output end of the linear cavity laser. For each cavity, the pump power is about 14.1 mW and the length of EDF is 15 cm. The reflectivities of FBG pair at both ends are 100% and 75%, respectively.

are denoted as R_o and R_i. Doping concentration (Nt) of the erbium ions is 2.8×10^{24} m^{-3} while the spontaneous emission rate is 100 s^{-1}. Signal absorption cross-section, signal emission cross section and pump absorption cross section are 0.55×10^{-24} m^2, 0.5×10^{-24} m^2 and 0.31×10^{-24} m^2, respectively. In our study, the value $R_o = 100\%$ is used to maximize the output power and the value $R_i = 75\%$ is above the lasing threshold condition. The 980-nm pump power with $P_P = 182$mW is launched into the common port of the 980-nm $1 \times N$ splitter and then pump-shared to these eleven channels (~14.1 mW per channel). Here, we assume that the insertion loss of each 980-nm fiber isolator is 0.7 dB. The erbium-doped fiber (EDF) is modeled as a homogeneously broadened two-level system. The input conditions are given as

$$P_P^+(\lambda_P) = P_P^o \text{ and } P_{\mathrm{ASE}}^+(\lambda_i) = P_S^+(\lambda_i) = 0 \text{ at } z = 0 \quad (1)$$

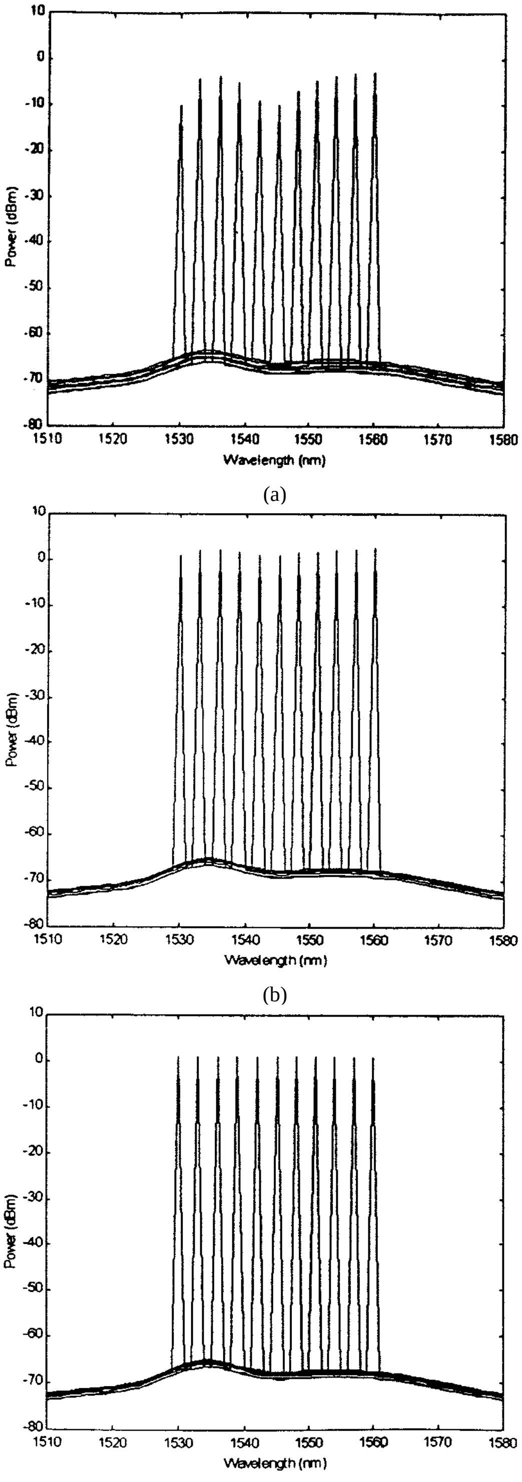
where P_P^o is the launched pump power at $z = 0$. Above the threshold conditions, the generation and amplification of the forward and backward ASE noises within the gain fiber are sufficient to give rise to the lasing condition. Using the Runge–Kutta algorithm, the ASE spectrum ranging from 1501–1600 nm is divided into N $(=100)$ slots of frequency bandwidth $\Delta\nu_i (= 1$ nm) centered at the wavelength $\lambda_i = c/\nu_i$. To describe the reflector effects, the following boundary conditions are given [8]:

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

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

where subscript n is the nth iteration number of the iterative loop, $R_o(\lambda_i)$ and $R_i(\lambda_i)$ are the reflectivities at the wavelength λ_i for $z = 0$ and $z = L$, respectively, and A_1 and A_2 are the losses due to the FBG-pair reflectors.

III. SIMULATED RESULTS AND DISCUSION



(a)

(b)

(c)

Fig. 3. Superposed output spectra of the eleven-channel linear cavity laser arrays. Power variations are: (a) 7.2 dB, (b) 1.6 dB before and after the 980-nm pump reflectors with 100% reflectivity are added, and (c) power variation is further reduced to 0.1 dB when the reflectivities of pump reflectors are properly adjusted.

To obtain single-frequency operation, the laser cavity length should be short. Fig. 2 reports the residual pump power as a function of different wavelengths for the LCLA before and after the pump reflectors are added. When these pump reflectors are added, the backward pumping is introduced (i.e., round-trip pumping). The average increment of pumping power absorption is 85% when compared to the condition without using pump reflectors. In the latter case, the average pumping absorption is 31%. The reason for low pump absorption may be due to the short cavity length or low Er^{3+} concentration. To further increase the pumping absorption ratio, high concentration Er^{3+} : Yb^{3+} codoped fibers could be applied as they are quite well-developed [9]. Fig. 3(a) and (b) shows the superposed output spectra of the eleven-channel LCLA. Before the 980-nm grating reflectors are used, the average output power is –5.8 dBm and the maximum

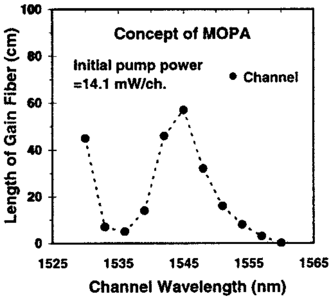


Fig. 4. EDF lengths against channel wavelength of the fiber laser array. The WDM sources are power equalized by varying the lengths of gain fiber.

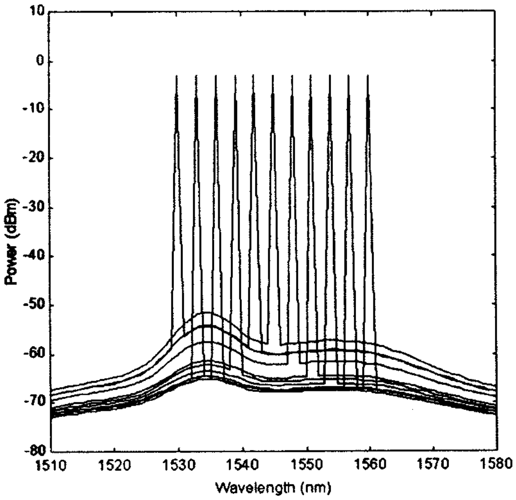


Fig. 5 Superposed output spectra of the eleven-channel linear cavity laser array. Power variation is less than 0.1 dB after the length of EDF in each channel is properly adjusted.

power variation among channels is 7.2 dB, as shown schematically in Fig. 3(a). After these 980-nm pump reflectors with 100% reflectivity are used, the average output power is increased to 1.8 dBm and the maximum power variation is decreased to 1.6 dB, as indicated in Fig. 3(b). Fig. 3(c) shows that power variation is further reduced to 0.1 dB when the 980-nm pump reflector gratings with appropriate reflectivities, ranging from ~100% for the weakest channel (ch. 6) and 55% for the strongest channel (ch. 11), are placed at the output ends of the fiber lasers. The result confirms the feasibility of using pump reflector gratings as power equalizers.

Another technology based on the concept of master oscillator power amplifier (MOPA) may also increase the power levels of these WDM sources. It is based on adding another section of gain fiber, rather than a pump reflector grating as shown in Fig. 1, at the output end of each fiber laser. The gain fiber is then pumped by the residual pump energy not absorbed in the laser cavity. The residual pump powers and output signals are different among channels. N pieces of gain fibers with various lengths are placed at the output ends of the fiber laser array for power equalization and further amplification. One important issue is that the residual pump power must be strong enough to provide adequate inversion of the ions within the small lengths of EDF segments. According to the calculated results, the required lengths of EDF's range from 0 cm for channel 11 to 57 cm for channel 6. Fig. 4 shows the required EDF length against channel wavelength of the fiber laser array. The WDM sources are power equalized by varying the lengths of gain fibers. Fig. 5 shows that the average power level is –2.9 dBm and the maximum power variation among channels is less than 0.1 dB. Compare to the pump-reflector-adding method, the SNR is 5~10 dB lower and the mean power level is 4 dB lower when the MOPA technology is used.

Considering the serial-type, pump-shared (STPS) scheme LCLA is similar to the configuration presented in [5], which is based on writing the gratings (e.g., fiber laser unit) in separate pieces of gain fiber. Such configuration has the benefit of higher pump absorption than that of the PTPS scheme LCLA. On the other hand, the pump power needs to provide enough population inversion in the N cascaded pieces of EDF, the STPS scheme LCLA may require low absorption gain fibers to ensure a reasonably identical pumping of the individual lasers. The issues to power-equalize these WDM channels sources is currently under study.

IV. CONCLUSION

We have proposed and numerically studied two technologies for power-equalizing the N-channel LCLA with PTPS scheme. Either one of these is based on adding pump reflectors or N pieces of gain fibers as self-equalizers. Beside the enhancement of pump power absorption, power variation among channels is reduced from 7.2 to 0.1 dB when the pump reflectors with appropriate reflectivities, or the EDF's with appropriate lengths are added into the LCLA. The power-equalized LCLA, with graceful features of easy power level adjustment and no mutual injection effect, may find high attraction for a wide variety of communications and fiber sensor applications.

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