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Gain flattening of erbium-doped fibre amplifier using fibre Bragg gratings

Jeng-Cherng Dung, Sien Chi and Senfar Wen

A new technique, using fibre-Bragg gratings with different centre frequencies to reflect the different channel signals at different positions, is proposed for flattening the gain spectrum of an erbium-doped fibre amplifier. A designed gain excursion of <0.1dB can be achieved for 16 channel multiplexed signals with 0.1mW input power in the 1532–1562nm wavelength region.

Introduction: Wavelength division multiplexing (WDM) technology has become very attractive for high-speed and high-capacity optical transmission systems. The inherent wavelength dependence of the gain, causing unequal optical signal powers among the WDM channels in cascaded erbium-doped fibre amplifier (EDFA) chains, degrades the performance of optically amplified transmission systems and networks. Several approaches have been proposed to broaden and flatten the gain bandwidth. One approach is to add Al_2O_3 and P_2O_5 to erbium-doped silica glass fibre [1, 2]. Fluoride-based EDFAs have been shown to have better characteristics than silica-based EDFAs in WDM applications [3]. Another approach is to use a gain equalising optical filter such as the Mach-Zehnder optical filter [4], the acousto-optic filter [5] or the long-period fibre-grating filter [6]. Because these filters function primarily as a wavelength-dependent attenuator, the use of the optical filter tends to lower the efficiency and the output power.

In this Letter, we propose a new technique employing the fibre-Bragg grating (FBG) to flatten the signal gain of a WDM system. FBGs with different centre frequencies can be written at different positions of the EDFA to reflect the signals from different channels. By designing the written position of each FBG in the EDFA, signals from different channels can attain equal gain in the backward direction without sacrificing the signal-to-noise ratio and the power conversion efficiency.

Theory: The EDFA can be modelled as a homogeneously broadened two-level system. We consider 16 channel signal wavelengths λ_s ranging from 1532 to 1562nm with an equal channel spacing of 2nm. The amplified spontaneous emission noises (ASEN) are assumed to be optical beams of effective frequency bandwidth $\Delta\nu_k$ centred at the wavelength $\lambda_k = c/\nu_k$ to resolve the ASEN spectrum. Under the steady-state condition, the equations to describe the spatial development of the pump power (P_P), signal power (P_s, s = 1, 16) and ASEN power (P_k, k = 1, N) in the EDFA can be written as

$$u^{\pm}\frac{dP_P^{\pm}}{dz} = (\sigma_{ep}N_2 - \sigma_{ap}N_1)\Gamma_P P_P^{\pm} \qquad (1)$$

$$u^{\pm}\frac{dP_s^{\pm}}{dz} = (\sigma_{es}N_2 - \sigma_{as}N_1)\Gamma_s P_s^{\pm} \qquad (2)$$

$$u^{\pm}\frac{dP_k^{\pm}}{dz} = (\sigma_{ek}N_2 - \sigma_{ak}N_1)\Gamma_k P_k^{\pm} + 2\sigma_{ek}N_2\Gamma_k h\nu_k\Delta\nu_k - \alpha_P P_k^{\pm} \qquad (3)$$

where N_1 and N_2 are the population densities of the ground level and metastable level. σ_{ej}, σ_{aj}, Γ_j, α_P and $h\nu_j$ are the emission cross-section, absorption cross-section, confinement factor, intrinsic fibre loss, and photon energy, respectively. The superscript (±) designates the optical beam propagating along the $\pm z$ direction and $u^{\pm} = \pm 1$. The pump wavelength λ_P is 980nm and the EDFA length L is 40m. The pump powers P_P = 150mW are launched into the amplifier at z = 0 and L bidirectionally, and the total pump powers equal 300mW. The reflectivity of the FBG can be calculated from the coupled-mode equations

$$\frac{dA^+}{dZ} = \kappa(z)\exp\left[-j\int_0^z B(z')dz'\right]A^- \qquad (4)$$

$$\frac{dA^-}{dZ} = \kappa(z)\exp\left[j\int_0^z B(z')dz'\right]A^+ \qquad (5)$$

where A^+ and A^- are the amplitudes of the forward and backward propagating modes along the z direction, $\kappa(z)$ is the coupling coefficient and $B(z)$ represents the phase mismatch of the grating.

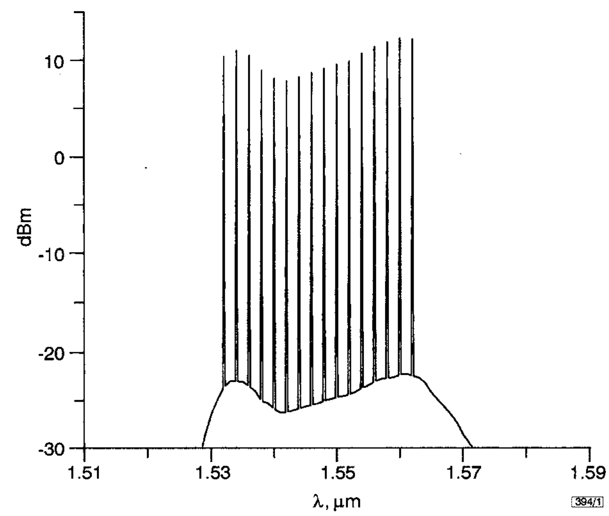

Fig. 1 *Optical spectrum of 16 channel WDM amplified signals without FBG for –10 dBm input power of each channel*

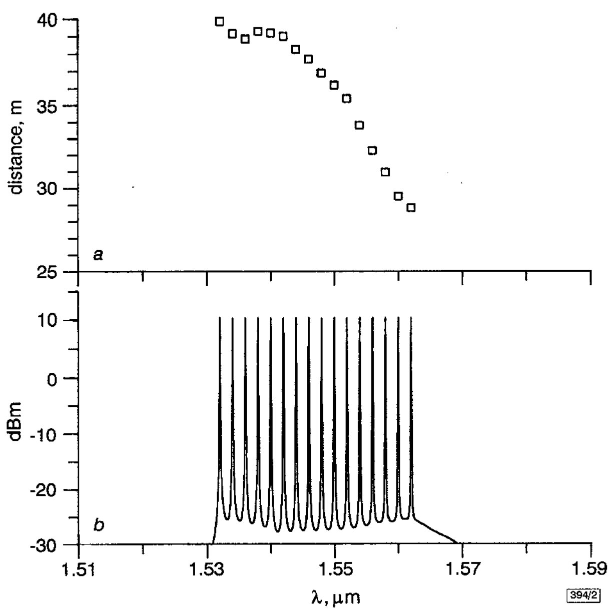

Fig. 2 *Optimum written positions of FBGs for different channels, and optical spectrum of 16 channel WDM amplified signals for FBGs shown*

For –10dBm input signal power of each channel
a Optimum written positions of FBGs for different channels
b Optical spectrum of 16channel WDM amplified signals with the FBGs shown in *a*

Numerical results and discussion: Fig. 1 shows the optical spectra of 16 channel output WDM signals and ASEN after the 40m Al co-doped EDFA without the FBG for −10dBm input power of each channel. The 16 channel WDM signals are allocated from 1532 to 1562nm, and the channel spacing is 2nm. The average signal gain is 20.4dB. The maximum interchannel power difference is 4.5dB at the output of the EDFA (the minimum power is 6.08mW at 1542nm, the maximum power is 16.98mW at 1560nm). The gain can be flattened by the FBGs written at the different positions of the EDFA. Each FBG is designed to be centred at assigned frequencies with the bandwidth 0.6nm. Each individual FBG position should be designed so that it has a maximum average gain over the 16 channel signals and an optimum gain flatness for the given input signal power level.

The optimum written position of each FBG along the EDFA for gain equalisation is shown in Fig. 2*a*. For the FBG with a centre frequency of 1532nm, the optimum written position is 39.9m and, thus, the longest amplifying distance for the 1532nm signal is 79.8m. For the FBG with a centre frequency of 1562nm, the optimum written position is 28.8m and, thus, the shortest amplifying distance for the 1562 signal is 57.6m. By using the set of FBGs shown in Fig. 2*a*, Fig. 2*b* shows the flat signal amplification with the same condition shown in Fig. 1. The average signal gain is 20.4dB and the gain excursion is < 0.1dB for 16 channel multiplexed signals. The power conversion efficiency of the EDFA with the FBG is equal to those of the EDFA without the FBG. The signal-to-noise ratio of each channel is > 35dB.

Conclusion: A gain flattening method in EDFAs has been proposed for the WDM systems by using FBGs. We have optimised the written positions of the FBG to achieve the maximum flat gain. The signal-to-noise ratio and energy conversion efficiency are not decreased by using FBGs.

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High efficiency 0.5W/A at 85°C strained multiquantum well lasers entirely grown by MOVPE on *p*-InP substrate

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An efficiency of 0.5W/A, the highest ever reported for conventional quaternary InGaAsP materials, and a high maximum output power of 40mW at 85°C were realised for 1.3μm strained multiquantum well (MQW) lasers entirely grown by MOVPE on a *p*-InP substrate.

Introduction: Passive optical networks (PONs) are very attractive access networks due to their low cost. In the optical network unit (ONU) of this system, 1.3μm laser diodes (LDs) with high output power (>15 mW) and a low driving current are required in the temperature range −40–85°C, because these LDs are needed to compensate for excessive optical link loss (~15dB) caused by a star-coupler. Moreover, from the viewpoint of increased output and reduced costs, the high uniformity of the entire MOVPE process is suitable in the production of these LDs. Considerable effort has been devoted to realising 1.3μm uncooled LDs [1 – 3], and extremely low threshold currents have been realised for optical interconnection use by employing strained MQWs [3]. However, the operation of those LDs is impaired when output power exceeds 15mW at high temperature.

To improve the high temperature characteristics of long wavelength LDs, carrier injection efficiency needs to be high enough to suppress both carrier overflow into separated confinement heterostructure (SCH) layers and carrier leakage into a current blocking region. Moreover, internal loss principally caused by intervalence band absorption (IVBA) [4] should be reduced.

This Letter reports high efficiency and low changes in both efficiency and threshold current successfully attained over a wide temperature range up to 85°C, by designing an SCH structure for high-carrier injection efficiency, and employing a buried heterostructure with low current leakage.

Device structure: The active region consists of seven compressive 0.7%-strained InGaAsP wells separated by λ_g = 1.13μm InGaAsP barriers and SCH layers for optical confinement. These were grown by MOVPE on a *p*-InP substrate. To reduce carrier leakage flowing outside the active region, an effective current blocking RIBPBH (recombination-layer inserted blocking planar buried heterostructure) was introduced as has been previously reported in [3].

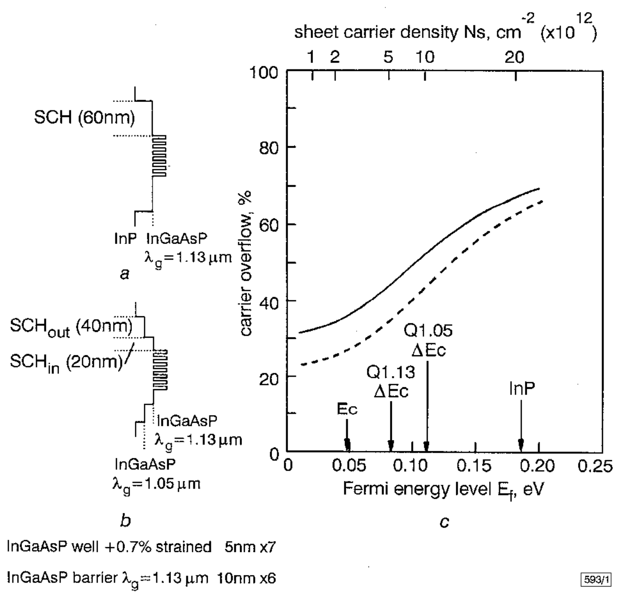

Fig. 1 *Schematic band diagrams of InGaAsP strained MQW active layer and calculation result of carrier overflow against Fermi-energy level*

a One-step compositional SCH structure
b Two-step compositional SCH structure
c Carrier overflow against Fermi-energy level
——— Q1.13:60nm; corresponds to *a*
– – – – Q1.13/Q1.05:20/40nm; corresponds to *b*