Inherent Enhancement of Gain Flatness and Achievement of Broad Gain Bandwidth in Erbium-Doped Silica Fiber Amplifiers

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Abstract—We report new methods to inherently increase the flatness and bandwidth of erbium-doped silica fiber amplifiers from three perspectives: fiber design, pump-signal WDM coupler optimization, and amplifier structure. First, to achieve inherent control of the gain spectrum, a new type of composite fiber structure with an Er-doped core and a Sm-doped cladding ring is proposed and experimentally demonstrated. Interaction of the optical field with the Sm-doped cladding to produce evanescent wave filtering is modeled, which provides an in-line control of gain fluctuation in the erbium-doped fiber amplifier (EDFA) C band, 1530–1560 nm. Second, the effect of the spectral characteristics of WDM couplers over the L band of an EDFA is explored. A fused taper fiber coupler for a 1480-nm pump is optimized for signals in the wavelength range of 1570–1610 nm by measuring the small-signal gain, gain tilt, and noise figure in an L-band EDFA. Finally, a new all-fiber structure for a wide-band EDFA, where the L and C bands were coupled serially, is demonstrated with optimized pump-signal couplers. Further optimization of the new composite fiber structure and the transient effects in the serially coupled EDFAs are also discussed.

Index Terms—Erbium-doped fiber (EDF), erbium-doped fiber amplifier (EDFA), fused taper fiber coupler, gain flattening, WDM coupler, wide-band optical amplifier.

I. INTRODUCTION

In wavelength division multiplexing (WDM) systems, overall transmission capacity depends significantly on the spectral characteristics of the optical amplifiers, such as flatness, bandwidth, and the magnitude of the gain. Erbium-doped fiber amplifiers (EDFAs) have provided an efficient optical gain in the 1.5-μm communications window in conventional single-mode fibers (SMFs) [1]. When the population is highly inverted, the stimulated emission cross section of erbium ions in silica provides ample gain over the 1520–1560 nm range, called the conventional band or C band. The EDFA C-band gain, however, does show a peak around 1530 nm. This nonuniform spectral shape results in a serious reduction of gain bandwidth when EDFAs are cascaded in transmission links [2], [3]. To achieve flat gain in the C band, external filtering fiber devices, such as fiber gratings [4], [5], acousto-optic tunable filters (AOTFs) [6], [7], and tapered fiber filters [8], [9] have been developed. Even though these devices showed excellent performance in gain-flattening, elaborate control of operating conditions, such as temperature and strain with special packaging, are required. In order to achieve a broad and flat gain spectrum, attempts to vary the material parameters of the fiber have been also reported. Examples include changing the glass host material [10]–[12], and hybrid fiber configurations [13], [14]. In this materials research, detailed information on the interaction between erbium ions and the glass hosts is required for various values of the population inversion. Only a few glass hosts, such as germanosilicate and aluminosilicate glass, have been of practical interest due to the issues of connectivity to conventional SMFs and long term reliabilities. As an alternative to these methods, segments of samarium-doped optical fibers (SDFs) have been used in a serial configuration with conventional EDF [15], [16] in order to suppress the 1530-nm peak of erbium by absorption of the samarium ions. This method requires, however, complicated optimization of parameters such as dopant concentration and length for both the EDF and SDF. A new type of erbium-doped silica fiber with an inherent capability to control the gain spectrum would still be highly desirable today, as it would obviate external filters or at least relax their requirements and could simplify the tedious optimization of different types of fibers.

In a silica glass host, erbium ions show a flat and wide-band gain in a red-shifted wavelength range if the population inversion is maintained at a low level over a sufficiently long fiber length. Long-wavelength band or L-band EDFAs are based on this low population inversion and broadband gain in the 1570–1610 nm region has been achieved in erbium-doped silica fibers [17]–[20]. In order to couple the pump light along with signals to the EDFA, a pump/signal WDM coupler is required. The spectral characteristics of the WDM coupler directly affect the pump efficiency and the gain bandwidth of EDFAs. Presently, two different types of couplers are commercially available for L-band EDFAs, i.e., fused taper fiber couplers and micro-optic interference filter couplers. Interference filter couplers give broad transmission spectra at both the pump and the signal wavelengths, but they may suffer from degradation at high pump powers over a few hundred milliwatts [21]. Fused
taper WDM couplers, on the other hand, can sustain high optical power levels, but broad bandwidth has been reported only for the pump wavelength [22]. Previous studies on optimization of the spectral characteristics of WDM couplers were limited to C-band EDFAs [23]–[26]. Systematic studies on the optimization of WDM fused taper fiber couplers for the L-band EDFA in terms of amplifier performance are therefore required, in particular to take advantage of the high-power tolerance and low loss of all-fiber structures.

In order to exploit the available gain bandwidth of EDFA in silica fibers, extensive studies have been reported on amplifier structures coupling the C band with the L band in various configurations [27]–[31]. An EDFA with a gain bandwidth greater than 80 nm has been reported for a parallel structure in which signals in the L and C bands are separated to the amplification stage, then combined at the output [29]. The parallel structures, however, require various optical components for separation and combination of signals as well as gain flattening. A serial structure where the L and C band are cascaded in a serial manner using optimized WDM couplers would be of interest. This structure can use the inherent gain slopes of opposite signs of the two bands near the overlap region to provide control of flatness as well as broad bandwidth. Furthermore, optimized all-fiber WDM couplers with a low loss would improve the net noise figure in the EDFA by removing components with a high insertion loss such as circulators.

In EDFA, the important features are the erbium-doped fibers (EDFs) that provide the gain with a certain spectral shape, the pump/signal WDM coupler to combine pump light with signals in a certain wavelength range, and the topological structure, such as a certain arrangement of multiple stages combining C- and L-band EDFAs. The characteristics of other components such as gain-flattening filters, isolators, and pump laser diodes are also important factors, but they are beyond the scope of this paper. In this study, we report three new methods to inherently enhance the flatness and obtain broadband gain in a silica EDFA: 1) first, an EDF design that has a Sm-doped ring in the cladding to have a built-in filtering function; 2) second, a WDM coupler design that optimizes L-band EDFA performance; and 3) finally, an amplifier structure that takes full advantage of all-fiber components to configure C- and L-band amplifiers serially.

A new EDF design is discussed in Section II, starting with the principle of evanescent wave filtering, and then analyzing its effects by calculating the overlap of the signal field with a cladding ring doped with an absorber in a step-index co-axial structure. In Section III, issues related to pump/signal WDM couplers are discussed based on fused taper coupler technology. The optimization process is described for an L-band EDFA WDM coupler with experimental analysis of the impact of the WDM coupler spectral response on the amplifier performance. Experimental verifications of the proposed techniques are presented in Section IV. These include measurements of the gain and noise figure for the proposed EDF, systematic comparison of an optimized WDM coupler with a micro-optic interference filter in the L band, and the demonstration of a new serial EDFA structure using the developed WDM couplers.

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Fig. 1. Comparison of samarium absorption and erbium emission cross-section spectra. The Sm absorption data was taken from [15] and the Er emission cross section was calculated with the McCumber relationship from the absorption cross section of a commercial EDF.

II. DESIGN OF ERBIUM-DOPED FIBER WITH A SAMARIUM-DOPED INNER CLADDING RING

In Fig. 1, the erbium emission cross section and the samarium absorption [15], [32] spectra are shown. The Er emission cross section was obtained with the McCumber relationship from the absorption cross section [33] of a commercial EDF used in this study. The useful features of samarium ions are negligible absorption at 980 nm, a pump wavelength of the EDFA, and high absorption in the EDFA gain band, especially near 1530 nm. Furthermore, the Sm ions in silica glass generate negligible emission in the wavelength region of EDFAs. The high transparency of samarium at 980 nm will maintain the high pump efficiency of the EDFA in a composite fiber structure. The wavelength-dependent absorption of samarium, on the other hand, can efficiently attenuate the emission peak of erbium at 1530 nm and leave the longer wavelength band less attenuated. Therefore, Sm-doped fiber can be regarded as a wavelength selective filter. Utilizing these features, various configurations of EDFA have been reported that concatenate segments of samarium-doped fibers with EDFs [15], [16] to achieve a flat gain spectrum in the C-band EDFA. These serial concatenation techniques, however, require two separate fibers, EDF and SDF, and individual optimization of fiber parameters for each fiber would be necessary.

A unique dopant distribution for inherent control of the gain in a thulium-doped fluoride fiber has been initially reported by Sakamoto et al. [34] who radially incorporated terbium ions into the cladding. Utilizing the spectral overlap between the thulium emission in the core and the terbium absorption in the cladding, the thulium gain in the wavelength range of 1.7–2.0 μm was completely suppressed to result in a high gain at 1.65 μm, which was not achieved in conventional fibers without the doped cladding. The principle of evanescent wave filtering lies in the overlap of the emission from a dopant in the core with the absorption of another dopant in the cladding, which will effectively alter the net spectral distribution of the emission and the gain of the composite structure. Based on the overlap of the emission and absorption, as shown in Fig. 1, we propose a new evanescent filtering scheme by doping the core with Er and forming a Sm-doped ring in the cladding.
in a composite fiber structure. The principle of evanescent wave filtering is schematically described in Fig. 2, assuming simplified rectangular spectral shapes for both the Er emission and the Sm absorption. When pumped, ASE from Er in the core is guided in the fundamental HE_{11} mode defined by the refractive index structure of the fiber. The field intensity profile of the fundamental mode extends outward and a significant portion of the optical power exists in the cladding. Consider two photons at wavelengths \( \lambda_1 \) and \( \lambda_2 \) from erbium ASE in Fig. 2(a), such that there is a finite spectral overlap between the Er emission and the Sm absorption at \( \lambda_1 \), but not at \( \lambda_2 \). As the photons in the HE_{11} mode propagate along the fiber, the evanescent wave of the photon at \( \lambda_1 \) will be absorbed by the Sm ions in the cladding, while \( \lambda_2 \) experiences only the gain from Er in the core. The evanescent wave filtering mechanism, therefore, will selectively attenuate Er emission at \( \lambda_1 \), e.g. near 1.53 \( \mu \)m, by the spectral overlap with Sm absorption, leaving behind a net gain at longer wavelength, \( \lambda_2 \).

![Fig. 2. Basic principle of the evanescent-wave filtering in an Er-Sm fiber.](image)

Fig. 2. Basic principle of the evanescent-wave filtering in an Er-Sm fiber. (a) Simplified rectangular spectral shapes for the Sm absorption and the Er emission. (b) \( \lambda_1 \) is attenuated by the Sm absorption and \( \lambda_2 \) amplified by the Er emission. Evanescent wave filtering will selectively attenuate Er emission at \( \lambda_1 \) near 1.53 \( \mu \)m by the spectral overlap with Sm absorption, leaving behind a net gain at longer wavelength, \( \lambda_2 \).

Fig. 3 schematically shows the design parameters of the proposed fiber, where \( a, b, \) and \( w \) represent the core radius, the inner radius, and the width of the Sm-doped ring, respectively. Mode field distributions are schematically shown for 980 and 1530 nm. Note that 980 nm will have a small overlap with the samarium-doped ring, while 1530 nm will have a significant overlap. Evanescent wave filtering will be more effective around 1530 nm.

The evanescent wave filtering effect of the Sm-doped ring can be analyzed by calculating the overlap between the optical field and the ring with a certain geometry. In a single-mode fiber, the light intensity \( I(r, \phi) \), where \( r \) and \( \phi \) represent the cylindrical transverse coordinates, is expressed as [37]

\[
I(r, \phi) = P I_n(r, \phi)
\]

(1)

where \( I_n(r, \phi) \) is the transverse mode intensity profile, normalized according to

\[
\int_0^{2\pi} \int_0^{\infty} I_n(r, \phi) r dr d\phi = 1.
\]

(2)

where \( P \) is the total power in the mode, which is calculated by

\[
P = \int_0^{2\pi} \int_0^{\infty} S_z r dr d\phi
\]

(3)

and \( S_z \) is the time-averaged Poynting vector

\[
S_z = \frac{1}{2} \text{Re}[E_z H^*_r - E_r H^*_z].
\]

(4)

Here, the symbol \( * \) stands for the complex conjugate. The vector components of \( E \) and \( H \) are transverse electric and magnetic fields, which are the solutions of Maxwell’s equations.
in the cylindrical coordinate system [37]. They were solved numerically and the intensity distribution was calculated with the above equations. The normalized transverse mode intensity profiles for 980 and 1530 nm are schematically shown in Fig. 3. Note that the 980-nm pump can have a small overlap with the Sm-doped ring, while the 1530-nm signal does have a stronger overlap, which simultaneously ensures an adequate level of attenuation at the signal wavelength and a low loss at the pump. From an interaction between the evanescent field of the 1530-nm signal and the samarium ions in the ring, which is quantified by the overlap factor, a novel in-line control of the optical gain can be achieved.

Assuming that a uniform distribution of the Sm ions within the ring, from the radial position \( b \) to \( b + w \), the spatial overlap factor \( \Gamma \) between the signal mode and the Sm-doped ring is obtained from

\[
\Gamma = 2\pi \int_{b}^{b+w} I_n(r, \phi)rdr.
\]

In this analysis, a matched-cladding step-index single-mode fiber was assumed. The parameters of fiber listed in Section IV-A were used in the following simulations. The overlap factor was adjusted using the fundamental wavelength-dependent nature of the mode intensity profile and the range of integration. The direction of optimization for a Sm-doped cladding ring would be to spectrally localize the effective loss near 1530 nm, thereby minimizing the loss in the longer wavelength region.

In order to find the effects of the radial position \( b \) defined in Fig. 3, the overlap factors were calculated for three different values, 1.66, 2.16, and 2.66 \( \mu \)m, assuming \( w = 1 \) \( \mu \)m. The results are shown in Fig. 4(a). It is found that the spectral slope of the overlap factor does depend on the radial position of the ring. For a Sm-doped ring located next to the core (\( b = 1.66 \mu \)m), the overlap factor shows a negative slope, while those for the radial positions of 2.16 and 2.66 \( \mu \)m show positive slopes. The latter case needs to be avoided because a higher overlap at longer wavelengths would result in a higher additive background loss in the composite EDF. For the radial position \( b = 1.66 \mu \)m, the overlap factor was calculated for various ring widths \( w \) at 0.58, 1.0, and 1.5 \( \mu \)m, as shown in Fig. 4(b). The width of 0.58 \( \mu \)m showed the maximum contrast between the values at 1500 and 1600 nm. On the contrary, as the ring width was increased to 1.5 \( \mu \)m, no significant spectral dependence was observed in the overlap factor. It is found that the Sm-doped cladding ring needs to be confined near the core in order to reduce the additive background loss in the wavelength region beyond 1530 nm. This condition, however, may increase the loss at 980 nm due to the small but finite Sm absorption, resulting in degradation of the pump efficiency. More detailed optimization to resolve this tradeoff is being pursued by the authors.

The absorptive filter shapes of the Sm-doped ring fibers were then calculated by multiplying the absorption spectra shown in Fig. 1 by the corresponding overlap factors. The results are shown in Fig. 5. Two main issues are, first, the contrast of absorption between 1530 nm and the longer wavelengths and, second, the background loss in the entire C band. As expected from the overlap analysis, the ring tightly confined near the core shows the least background loss. From the interaction of the evanescent field of the 1530-nm signal and the samarium ions in the ring, in-line filtering of the optical gain can thus be achieved without external filters. In the proposed fiber, attenuation over 10 dB at 1.53 \( \mu \)m is achieved for fibers about 4-m long.

The effective attenuation due to the Sm-doped ring determines the fiber length required to meet the desired amount of band rejection. Thus, the concentration of Er in the core needs
to be optimized to reach the desired level of gain. In this study, a high concentration of Er was doped in the core to have a comparably high gain in a relatively short fiber. Detailed parameters are discussed in the following sections.

III. BROAD-BAND WDM COUPLER FOR L-BAND EDFA

Recent needs for all-fiber amplifiers have prompted development of WDM couplers to multiplex the signal wavelength with the pump wavelength. The most common all-fiber components used in single-mode fiber optic communication are $2 \times 2$ couplers made by the flame-brushing technique [38], where two identical optical fibers are fused laterally and elongated axially in a hot zone.

The coupling in a fused optical fiber coupler results from the beating between the lowest order symmetric and anti-symmetric modes of the composite waveguide formed in the taper region [38], [39]. The spectral distribution of the coupling ratio could be adjusted by providing an appropriate length for the taper waveguide. In the approximation of weakly guided waves, the coupling coefficient $C(z)$ along the composite taper waveguide can be expressed as below [39], where two adjacent cylindrical waveguides were assumed to touch each other:

\[ C(z) = \frac{\sqrt{8U^2(z)K_0(W_2)}}{bK_2^2(W)} \]  
\[ \delta = 1 + \left( \frac{n_{\text{air}}}{n_{\text{cladding}}} \right)^2 \]  
\[ V(z) = \frac{2\pi}{\lambda} U(z) \sqrt{\frac{n^2_{\text{cladding}} - n_{\text{air}}^2}{\lambda}} \]  
\[ U, V, W(z) \] normalized frequencies in a circular waveguide;  
\[ K_i \] modified Bessel function of the second kind of order $i$;  
\[ b \] radius of the cylindrical waveguide.

The normalized transported power of each branch is then described by a sinusoidal function as follows:

\[ P_1(z) = \cos^2 \int_{-\infty}^{z} C(z')dz', \]  
\[ P_2(z) = \sin^2 \int_{-\infty}^{z} C(z')dz'. \]  

To multiplex two given wavelengths for the signal and the pump, one has to adjust the sinusoidal wavelength response of a moderately elongated coupler by carefully controlling the degree of fusion and the elongation parameters [38], [39]. The main parameters are the cross section at the taper waist, the longitudinal biconical profile, and the elongation length.

For applications in C-band EDFAs, WDM-fused taper fiber couplers for a signal at 1550 nm and a pump wavelength at 800, 980, or 1480 nm are commercially available. Previous studies on the optimization of the spectral characteristics of WDM couplers, however, were limited to C-band EDFAs [22]–[26]. These C-band WDM couplers have a peak transmission wavelength near 1550 nm, as shown in Fig. 6(a), incurring a significant insertion loss of 1570–1610 nm at the L band. Micro-optic inter-
and $POCl_3$. The absorption are the coupler transmissions in each port. For a 980-nm laser diode and a 980/1550-nm WDM coupler, the measured spectra of these couplers were compared in the following sections.

Table I. The optical characteristics of a micro-optic interference filter couplers, on the other hand, show desirable spectral characteristics for L-band EDFAs, with a broad and flat transmission for both pump and signal bands. However, the cost of packaging is high and, more importantly, they may suffer from optical damage at high pump power [21].

Due to the low Er population inversion required in L-band EDFAs, a long length of fiber and a high pump power of over hundreds of milliwatts near 1480 nm are required [40]. An all-fiber fused taper WDM coupler with an optimal peak-coupling wavelength and a large bandwidth would be highly desirable for such high pump power requirements. Systematic studies on the optimization of WDM fiber couplers for the L-band EDFA in terms of amplifier performances are, therefore, required to take full advantage of the high-power tolerance and low loss of all-fiber fused taper couplers.

In this paper, we report detailed experimental studies on a new fused WDM coupler that was designed for an L-band EDFA pumped at 1480 nm, for the first time to the best knowledge of the authors. Three types of WDM couplers were fabricated using the hydrogen flame brushing method [38] with an automated translation system. The measured spectra of these couplers, labeled couplers 1, 2, and 3, are shown in Fig. 6(a)–(c). Note that the signal port transmission peaks were located at 1550, 1570, and 1590 nm, respectively. In the pump ports, the peak transmission was kept near 1470 nm, the center wavelength of the pump LD. Their optical characteristics, namely insertion loss, bandwidth, and channel isolation, are summarized in Table I. The optical characteristics of a micro-optic interference filter coupler, labeled as coupler 4, were also added for comparison. The polarization-dependent loss (PDL) of the four couplers was measured to be less than 0.1 dB. The bandwidth was measured at the signal port where the transmission was within 1-dB variation referenced to the peak. The isolation at a given wavelength was defined as follows:

$$I(\lambda) = 10|\log_{10} T_1(\lambda) - \log_{10} T_2(\lambda)|$$  \hspace{1cm} (10)

where $T_1$ and $T_2$ are the coupler transmissions in each port. For the signal band, the channel isolation was measured in the spectral range of the L band, 1570–1610 nm. Isolation at the pump was measured in the range 1460–1490 nm, which is within the specifications for commercial laser diodes.

The transmission spectra of the couplers are compared in Fig. 7. Coupler 3, with a peak-coupling wavelength at 1590 nm, showed a loss less than 1 dB across the whole L band, comparable to that of the micro-optic counterpart, coupler 4. It also showed a 0.41-dB loss at the pump port and an isolation over 8 dB in the whole L band. The L-band EDFA performances for these couplers were compared in the following sections.

IV. MEASUREMENTS AND CHARACTERIZATION OF AMPLIFIER PERFORMANCES

A. Self-Equalization of Gain in an EDF With a Samarium-Doped Inner-Cladding Ring

The proposed fiber was made using MCVD along with a solution-soaking technique [41]. After conventional cladding layers, we deposited porous SiO$_2$ cladding layers that were soaked in a samarium chloride solution. In the consolidation process, gaseous CF$_4$ and POCI$_3$ were used to match the index of the ring to that of the silica cladding. Subsequently, a porous core layer was deposited for erbium doping. The preform was then collapsed to a solid preform, which was drawn into fibers of 125-μm outer diameter. The relative refractive index difference and the cut-off wavelength of the fabricated fiber were 1% and 900 nm, respectively. The fiber had a core diameter of 3.32 μm. As described in the previous discussion on fiber design issues, a high concentration of Er was required in the core to have comparable gain in a relatively short fiber whose length range was determined by the Sm-doped cladding ring. In order to test the feasibility of the proposed fiber structure, a relatively high contrast in the concentration between Er and Sm was chosen. The measured concentrations were estimated to be 1000 ppm of Er$_2$O$_3$ and 100 ppm of Sm$_2$O$_3$, in molar fraction relative to SiO$_2$. The Sm-doped ring was located right outside of the core, and its width was estimated to about 0.5 μm. The absorption spectrum of the fiber was measured by a cutback method, and is shown in Fig. 8 (solid curve), along with that of a conventional EDF (dotted curve). The measured peak absorption value was about 63 dB/m at 1530 nm. A slight modification in the absorption spectrum was observed, which is attributed to the samarium-doped ring.

A single-stage C-band optical amplifier was assembled using the proposed fiber. We used a forward-pumping scheme with a 980-nm laser diode and a 980/1550-nm WDM coupler. The fiber length and the pump power were adjusted to produce the...
lowest gain variation across the entire C band. The fiber length was 110 cm and the pump power launched at the input end of the fiber was increased to 100 mW to reach the optimum inversion. To estimate the performance of the amplifier in a WDM multi-channel transmission, we measured the small-signal gain characteristics under a saturating condition that is denoted by the dynamic gain [42]. A saturating tone of 8 dBm at 1548 nm, is added in an amplifier as a small-signal probe being scanned to simulate the multi-channel gain. Firstly, the forward-propagating amplified spontaneous emission (ASE) spectrum was measured along with the saturating tone, as shown in Fig. 9. In the background ASE, the peak and the valley were located at 1533 and 1540 nm, respectively. The power difference between them was about 2.5 dB. Compared with a conventional EDFA, which shows more than a 6-dB difference in a high population inversion, the peak power near 1530 nm was significantly suppressed in the proposed fiber. The 3-dB bandwidth of the background ASE was about 41 nm, ranging from 1526–1567 nm. Secondly, under this saturating condition, we scanned a weak probe signal (35 dBm) from 1530 to 1560 nm in a 2-nm interval to measure the dynamic gain. The average dynamic gain was 11.5 dB and the maximum gain variation was less than 2.3 dB, as shown in Fig. 10.

In order to compare the gain flatness of EDFAs, a parameter \( \Delta G/G \) is generally used to characterize the gain variation within a gain band, where \( \Delta G \) and \( G \) are the gain excursion and the average gain value, respectively [43], [44]. In general, the flatness of an EDFA depends on the population inversion of the Er ions. In the proposed fiber, however, the Sm-doped ring affects the Er gain spectrum by evanescent wave filtering, adding one more degree of freedom to control the spectral gain variations. Due to the different nature of the gain variation, a fair comparison of the proposed fiber with conventional EDFAs would require different perspectives. The gain variation \( \Delta G/G \) was compared in the following way. Firstly, as described in the preceding paragraph, the proposed fiber was optimized for minimum gain variation across the C band. The gain difference between 1530 and 1555 nm was minimized to a value of 0.20 dB. Then for a conventional EDF (Lucent EDF HE980), the fiber length and the pump power were adjusted so that the gain difference between 1530 and 1555 nm was minimized to simulate the proposed fiber for a direct comparison under almost the same condition. This was accomplished for a conventional EDF length and a pump power of 13 m and 70 mW, respectively. The gain spectrum for the conventional EDF is shown in Fig. 10, where the gain variation \( \Delta G/G \) was 0.26 (or 3.1 dB/12.1 dB). Compared with a conventional EDF, the proposed fiber showed an advantage in \( \Delta G/G \) of 0.06 (or 23%) over the entire C band. Considering the fact that the proposed fiber has not been fully optimized, the advantage in the gain variation indicates the potential to internally control the gain variation using evanescent wave filtering. Using a long period grating (LPG) between two stages of EDFAs composed of
EDFs with a high aluminum content in the core, a low gain variation has been reported, namely $\Delta G/G$ of 0.045 for a deviation of 1 dB and an average gain of 22 dB [45]. Compared with external filters such as LPGs, the gain variation obtained in the proposed fiber still needs further improvement. Parameters in need of further optimization are discussed in Section V.

To explore the noise figure of the proposed fiber, the single-channel small-signal gain was also measured. In this case, the saturating tone was removed and only a small signal of $-32$ dBm was scanned over the C band. Results are shown in Fig. 11. The average gain was 22.7 dB and the average internal noise figure, measured by the ASE interpolation method [42], was 4.6 dB. Note that the gain difference between 1530 and 1550 nm was less than 1.5 dB. The gain valley observed near 1540 nm was attributed to a mismatch between the samarium absorption slope and the erbium gain slope. The gain variation $\Delta G/G$ was measured to be $0.20(\approx 4.5$ dB/$22.7$ dB), similar to the dynamic gain in Fig. 10. These values were comparable to those of previous studies concatenating segments of Sm-doped fibers with EDFs [15], [16], which again confirms the potential of the evanescent wave filtering.

B. Performance of WDM Fused Taper Fiber Coupler Optimized for L Band

The fundamental rule to optimizing the pump/signal WDM coupler would be to locate the peak transmission near the center of the L band, and then make the transmission band of the signal branch as broad and flat as possible to cover the whole gain band. If the peak transmission wavelength is set too far away from the gain band center, the WDM coupler can incur a significant loss due to the sinusoidal nature of the coupling, as described in Section III. Thus, the spectral shape of the signal port within a given gain band would be critical for the optimization of a WDM coupler.

To test the effect of pump/signal WDM couplers on amplifiers, an L-band EDFA was constructed as shown in Fig. 12. WDM couplers of four different types in Fig. 7 were tested in this configuration. At first, the lengths of EDF I and II were optimized to give a flat gain in L band with a micro-optic interference filter coupler, coupler 4 in Table I. Then the following parameters were kept constant for consistent measurements: the fiber lengths, the 980-nm pump power of 70 mW, and the 1480-nm pump power of 170 mW. The power of the saturating tone was about $-3.43$ dBm at 1567 nm and the probe signal of about $-25$ dBm was scanned for every 2.5-nm step. The output powers of the saturating tone were 13.99, 16.18, 16.01, and 16.59 dBm for couplers 1, 2, 3, and 4, respectively.
A minor length adjustment of EDF II was made for the case of coupler 1 to get the flattest gain band available in the configuration.

The performance of WDM couplers was evaluated by measuring the L-band EDFA characteristics. The dynamic gain was measured for the small signal and the noise figure was measured using the ASE interpolation technique as described in Section IV-A[42]. In Fig. 13, the small-signal gains and the noise figures are shown. The gains of the EDFA with couplers 3 and 4 were almost identical, within a difference less than 0.9 dB in the range of 1570–1600 nm. The noise figures were also similar with an average of 4 dB. Coupler 1, on the other hand, showed a large fluctuation of the gain and a significant reduction of the gain bandwidth as well as a degradation of noise figure. Coupler 2 showed intermediate performances in the small-signal gain and noise figure between those of couplers 1 and 3. Coupler 1 also showed a degradation in gain tilt, as shown in Fig. 14. Couplers 3 and 4 showed an almost identical gain tilt of ±0.5 dB/nm over the whole L band. The poor performance of coupler 1 is attributed to the large offset of the central transmission peak from the L-band center and the narrow transmission bandwidth in the signal port, which induces a significant insertion loss in the band.

The newly designed fused taper coupler (type 3) showed significant improvements over conventional WDM couplers (type 1) in terms of bandwidth, pump efficiency, noise figure and gain tilt in L-band EDFA. It is experimentally confirmed that the location of the transmission peak near 1590 nm in the signal port of WDM coupler, which is near the center of the L band, was optimal so as to result in optical properties almost identical to those for the interference-filter-type couplers. Among all the parameters of WDM couplers, the peak coupling signal wavelength was found to be the most dominant factor to affect the performance of the L-band EDFA. The measured minimum insertion loss of 0.34 dB in the optimized coupler could be improved to less than 0.1 dB with better packaging and better performance could be expected in gain and power conversion efficiency.

These results imply that fused taper fiber couplers could perform as well as micro-optic counterparts with higher power sustainability for L-band EDFA. It is also found that the WDM couplers could inherently tailor the spectral shape of EDFA as shown in Figs. 13 and 14. For a specific configuration and application of EDFA, WDM couplers need to be optimized with a desired spectral response. As an example, two of the couplers in Fig. 7, couplers 2 and 3 were used for a new type of wide-band EDFA, described in the next section.

C. Serial Coupling of C- and L-Band EDFA

In a C-band EDFA, the gain above 1560 nm rapidly decreases as the wavelength increases, but a finite gain still exists for a high population inversion, typically over 65% [33]. It is thus possible to amplify L-band signals using a C-band EDFA in a serial configuration to increase the efficiency of L-band amplification in the shorter wavelength region. Furthermore, the overall gain band could be inherently flattened in a serial configuration since the gain slope of the L band is almost opposite to that in the C band in the overlapping wavelength region. Serial coupling of the L and C bands has been initially reported by Sun et al. [28], where signals were split and recombined using two pairs of Bragg gratings and circulators. In this configuration, a boosting amplifier was required at the input end to reduce the noise figure to the level of 6 dB while increasing the output power. The serially coupled EDFA in this study was optimized in two aspects, a low noise figure and a flat gain by varying the parameters of WDM couplers, as well as EDF length, and pump powers.

The configuration of the proposed EDFA is shown in Fig. 15. The length of the EDFs was adjusted to give a uniform flat gain
in both the L and C bands pumped with a total power of 150 mW both at 980 and 1480 nm. Individual pump power is shown in Fig. 15. Note that no external filters are used, and the gain flatness is inherently achieved by the interaction of the L and C bands. Three tunable laser sources were used: two for the saturating tones at 1550 and 1590 nm, and the other for the probe signal. The C- and L-band signals were split and combined using a commercially available 1550/1580-nm coupler, which is made of interference thin film filters. It had an insertion loss of 0.25 dB for both the L and C bands with a band isolation of 25 dB. The flat spectral response of the coupler within the bands could isolate the effects of serial structure made with the special WDM couplers.

Longer wavelength input signals were amplified firstly in the front stage of an L-band EDFA. The amplified L band and the bypassed C-band signals were combined at one of the 1550/1580-nm couplers and then amplified together in the subsequent C-band EDFA. In order to implement this serial configuration, the specially designed fused taper fiber WDM couplers, couplers 2 and 3 as shown in Fig. 7, were used. The 1480/1590-nm WDM coupler was designed to have a minimum insertion loss at the center wavelength of the L band (1590 nm). The 1480/1570-nm WDM coupler was designed to give a moderately low loss over the entire C and L bands.

The output powers of the proposed EDFA with two saturating tones of 0 dBm at 1550 and 1590 nm were 12.29 and 12.58 dBm, respectively, and the output spectrum is shown as the solid line in Fig. 16. The background ASE fluctuated less than 1 dB over 50 nm, showing the amplification of the L-band signal in the C-band EDFA. The power at 1590 nm increased by 3.68 dB, from 8.9 to 12.58 dBm after the C-band EDFA. The signal gain and internal noise figure were measured using the same techniques as in the previous section [42] and the spectra are shown in Fig. 17. The probe signal power was maintained at 27 dBm with a variation less than 0.4 dB over the wavelength range from 1520 to 1605 nm. A flat and broadband gain was achieved using inherent gain slopes of EDFAs and transmission characteristics of all fiber WDM couplers without external filters. Within 1-dB variation, a gain of 11.5 dB was obtained over 50 nm. With a gain-flattening filter at 1.53 μm, the proposed structure could provide a broader gain bandwidth over 65 nm. The noise figure was less than 4 dB in the C band and 5 dB in the L band, except around 1570 nm. The high noise figure around 1570 nm is attributed to the low amplification at the preceding L-band amplifier. Compared with the previous results [28], the new EDFA structure showed a reduction of noise figure without an additional booster amplifier stage, which could be attributed to the low insertion loss and the optimized band location in the WDM couplers.

V. DISCUSSIONS

In this section, three issues will be addressed in conjunction with the preceding measurements. Firstly, design optimization of the new composite fiber structure will be discussed for better amplifier efficiencies. Then, the effects of the Sm-doped cladding ring in the proposed fiber structure over the L-band region will be addressed by measuring ASE spectra. Finally, transient effects in the serially coupled EDFA structure will be compared with conventional single-stage C-band EDFA to determine the potential for a benefit in the structure.

In the new fiber structure demonstrated here, the evanescent field of 1530-nm photons was found to interact with the samarium-doped inner-cladding ring to result in a reduction of ASE and gain, showing a strong potential to control the C-band gain of EDF inherently within a single fiber. However, the fiber demonstrated here suffers from lower pump efficiency and higher noise figure, compared with conventional EDFs. Amplifier performances of the proposed composite fiber structure (Fig. 3) could be further improved by optimizing the fiber parameters. The Sm-doped ring does induce an effective loss over the entire C band, as well as at the 1530-nm peak, as shown in Fig. 5. The loss in the C band accumulates along the fiber length, which will compete with the gain from the Er-doped core reducing pump efficiency. The Sm-doped ring also determines the range of the available fiber length and, subsequently, the Er concentration as described in the Section II. In this study, only a short length of the fiber—110 cm—was available as the Er gain medium, while tens of meters are generally used in conventional EDFAs. Furthermore, a relatively high erbium-ion concentration of 1000 ppm in this fiber would easily induce nonradiative concentration quenching processes such as cross relaxation among ions [46]. The finite-absorption
cross section of pump light at 980 nm in samarium ions could also reduce the pump efficiency.

Thus, the optimization steps would be required as below. Firstly, the Sm-doped cladding ring is to be optimized in order to provide a fiber length long enough for efficient Er amplification, as well as the evanescent filtering. The Er concentration in the core would be, then, optimized along with the Sm in the cladding ring to minimize quenching effects. Note that the optimization of the dopant concentration and the fiber length could not be separated. A set of transcendental equations for the optimization is being studied by the authors. In order to improve the pump efficiency in the fiber, optimization of dopants other than Sm would be an open issue. A doping element in the cladding ring whose absorption is highly localized near 1530 nm and its edge does not overlap significantly with the entire EDFA band would enhance the gain performances. Finally, the waveguide optimization could be further pursued. In this study, only the matched cladding structure has been assumed and an absorber-doped cladding ring with an appropriate index structure, raised or depressed, could change the overlap factors.

To compare the gain characteristics of the proposed fiber in the C band with those in the L band, we measured the forward ASE for fibers of various lengths. A pump at 980 nm of 100 mW was coupled to the fiber and the forward ASE spectra were measured as shown Fig. 18. The ASE power level was significantly lower than in a conventional EDF, and a valley from 1580 to 1600 nm was observed. The deterioration of ASE flatness and efficiency is attributed to the evanescent wave filtering of Sm-doped cladding ring in the L band. As shown in Fig. 5, a Sm-doped cladding ring induces an absorption peak around 1580 to 1600 nm, which corresponds to the valley in ASE spectra. As the length of the proposed fiber is increased to give a population inversion required for an L-band EDFA, the absorption induced by the Sm-doped ring becomes the main loss factor. Consequently, applications of the present structure might be restricted to C-band EDFAs where shorter fiber length is required.

As an application of the proposed serial EDFA structure, the transient response in the C band was investigated. Signal power level can cause, for example, the input signal to fluctuate during adding or dropping channels, thus inducing transient effects in EDFAs [47]. Methods to reduce such transient effects include feedback on the pump power [48] and the addition of a saturating tone to keep the saturation level of the amplifier constant [49]. Fig. 19 shows the output ASE power spectra when the saturating tone varies from 0 to −6 dBm, simulating a case in which seven WDM channels were dropped out of eight in C band. The results for a conventional single-staged C-band EDFA are shown in Fig. 19(a). The ASE peak power at 1532.4 nm varied by 9.80 dB from 29.82 to 20.02 dBm. In the serially coupled EDFA proposed in Fig. 15, the ASE spectra are shown in Fig. 19(b) for the same amount of change in the saturating tone in the C band. Note that, in the serial structure, all eight channels in the L band, simulated by a 0-dBm saturating tone at 1590 nm, are kept intact and fed into the C band where seven channels were dropped out of eight. Due to the interaction of the L-band signal with the C-band amplifier, the variation of C-band ASE reduced to 4.12 dB, from 26.67 to 22.55 dBm.

It is believed that the amplified signals from the L-band EDFA could serve as additional saturating tones to result in the reduction of the output power variation in the C band. In parallel structures, on the contrary, where L- and C-band amplifications are split, this cooperative effect between the two gain bands has not been reported, to the best knowledge of the authors. In addition to inherent gain control, the serial coupling of L and C bands could have a benefit in reducing transient effects by cooperative interaction with less burden to control and, subsequently, faster response than prior techniques [48], [49]. Further investigations on the pump or the signal feedback for the each stage in a serial configuration are being pursued.
VI. CONCLUSION

Evanescent wave filtering has been proposed and experimentally demonstrated in a composite fiber structure composed of an erbium-doped core and a samarium-doped cladding ring. In the C-band range, a gain variation less than 2.3 dB was achieved without external filtering for an average gain of 11 dB and a saturated output power of 9 dBm. The inherent filtering capabilities in the proposed structure could be further applied to a novel design technique for fiber devices such as the spectral shaping of a gain in rare-earth-doped fiber amplifiers and lasers. Further optimization of fiber structures adopting the evanescent wave filtering technique is being pursued by the authors. A new fused WDM coupler optimized for the L-band EDFA, pumped at 1480 nm, was designed and fabricated with a insertion loss of less than 1 dB over the whole L band. The location of the peak transmission wavelength in the signal port in the WDM coupler was found to be a most influential factor. When it is used in an L-band EDFA, a small-signal gain above 21 dB was obtained with 0.9-dB fluctuation, and the gain tilt was less than ±0.5 dB/nm. A wide-band EDFA, where the L and C bands were serially coupled using optimized WDM couplers, was experimentally demonstrated. Without using external filtering devices, a dynamic gain over 11.5 dB was obtained under a saturation condition, with the gain variations less than 1 dB over 50 nm and the noise figure less than 5 dB. The serial structure shows a potential to relax the burden to control the transient effects in EDFAs. Further investigations on the time transient response of the proposed wideband EDFA are being pursued.

REFERENCES


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