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Intrinsically gain-flattened Erbium-doped fiber amplifier for metro networks

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Dedicated to Professor Bishnu P Pal for his enormous contributions to the advancement of research and education in science and technology through his unique vision and outstanding dedication

This study outlines the profile optimization of a dual-core fiber, having an erbium-doped inner core that gives a relatively flat gain spectrum in the C-band, compared to conventional erbium-doped fiber amplifiers. A typical metro network has multiple add-drop nodes, and signal traffic is fluctuating. It has been demonstrated that it is possible to achieve a low-cost fiber amplifier for metro networks that can operate in a stable fashion with the dynamic nature of these networks. The fiber parameters were optimized to achieve a median gain of ~ 23 dB, with *a* ± 2 dB gain excursion across the C-band.

Keywords: DWDM networks, EDFA gain-flattening, Metro networks.

1 Introduction

The technology of erbium-doped fiber amplifiers (EDFAs) has matured over the last three decades, enabling error-free dense wavelength division multiplexed (DWDM) transmission over hundreds of kilometers in long-haul terrestrial and undersea fiber-optic links. The growth of internet and data, as also the reach of optical fibers to the home, have altered the volume and nature of traffic in both long-haul and metro networks. The high-bandwidth DWDM technology has brought down the cost of every bit of transported data in long-haul, and should scale down costs for metro networks as well [1,2]. These networks offer low-cost, scalable, flexible support to increase the reach of fiber-to-the-home. A metro network should be designed to provide a high-degree of scalability and dynamism that is future proof to absorb hard to predict traffic growth, stable operation under fluctuating traffic with flexibility to add/drop signals at exchanges, and interoperability to carry a variety of signals and support protocols like SONET/SDH, ATM and IP, legacy equipment, provide connectivity to phones and laptops, etc [3]. This paper outlines the requirements for amplifiers that are needed in such networks, and how these can be achieved through an aymmetric dual-core EDFA design.

2 Gain-flattening with coaxial dual-core EDFA

Metro networks in larger cities may consist of two layers – metro access networks which connect the local exchange to individual subscribers, and the metro core networks having several nodes, that connect the local exchanges with each other and link them to the long-haul backbone network. In spite of the shorter distances involved (~ 200 km or less), the use of wideband amplifiers becomes necessary because of the large number of signal channels and the many add/drop nodes within the ring, which may increase the effective distance travelled by the signal [4,5]. Due to the different topology of metro networks viz-a-viz long-haul, the lower level of gain required [6], coupled with higher tolerances, it is possible to explore different options for

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signal amplification. The success of the EDFA in long-haul links make it a natural choice for metro networks as well. However, the 6-8 dB gain excursion of these amplifiers can significantly degrade optical signal-to-noise ratio (OSNR) even in metro links. To overcome the problem with the non-uniform gain of the EDFA, a dual-core fiber design is studied here. The refractive-index profile of the EDF is shown in Fig 1. It comprises two highly dissimilar cores – a low-index inner core and a high-index outer ring, which are evanescently coupled via a matched-clad layer. The principle of gain-flattening exploits the resonant coupling between the individual modes of these two (hereafter referred to as core-mode and ring-mode, respectively). The composite fiber would support the LP_{01} and LP_{02} modes, which are the supermodes corresponding to the coupled core and ring modes. The shaded portion shows the region where the erbium ions are doped. Such a fiber was fabricated, and the measured gain was found to be around 29 dB [7].

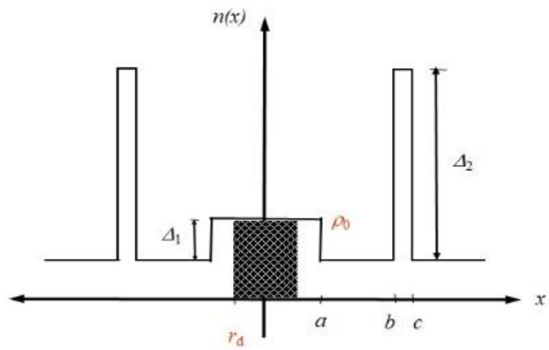

Fig 1. Refractive index profile and erbium doping in the dual-core EDF

Figure 2 shows schematically the variation of mode effective index n_{eff} of these modes with wavelength, around the phase-matched wavelength λ_p. Above λ_p, the n_{eff} of the LP_{01} mode matches the n_{eff} of the ring-mode, whereas below λ_p it matches the n_{eff} of the core-mode. This implies that all the modal characteristics of the LP_{01} mode would match the modal characteristics of the relevant mode in these wavelength regimes (for LP_{02} mode, this wavelength dependence is reversed). Around λ_p, the n_{eff} of the LP_{01} (and LP_{02}) mode varies rapidly with wavelength, which results in a corresponding change in the power distribution of the mode between the inner core and outer ring. To illustrate this, the schematic variation of

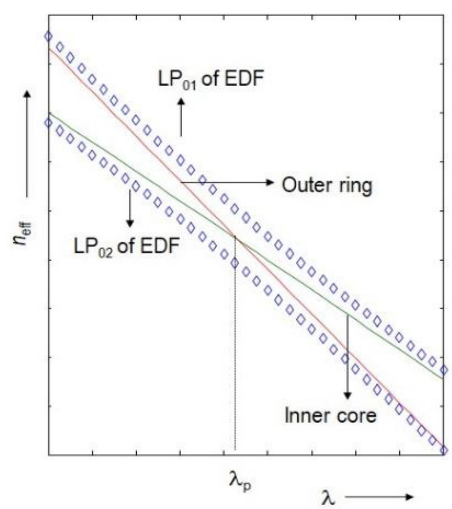

Fig 2. Variation of n_{eff} with λ for core, ring, LP_{01} and LP_{02} modes.

the normalized modal power of the LP_{01} mode with the radial coordinate, for $\lambda < \lambda_p$, $\lambda \sim \lambda_p$ and $\lambda > \lambda_p$ has been shown in Fig 3. As can be seen from the figure, for $\lambda > \lambda_p$ a much larger fraction of the modal power would be in the inner core as compared to $\lambda < \lambda_p$. So, if erbium is doped in the inner core alone, it leads to a reduced overlap of the modal power with the erbium for $\lambda < \lambda_p$ in comparison to $\lambda > \lambda_p$ and consequently, a lower gain coefficient in the $\lambda < \lambda_p$ region. Since a typical EDFA has a gain peak of ~ 6-8 dB at 1530 nm, the refractive index parameters of the dual-core fiber were adjusted to attain a λ_p ~ 1535 nm. This off-sets the higher gain around 1530 nm, resulting in a more uniform gain profile across the C-band. This also requires careful splicing of the EDF to the transmission fiber to ensure selective excitation of the LP_{01} mode alone.

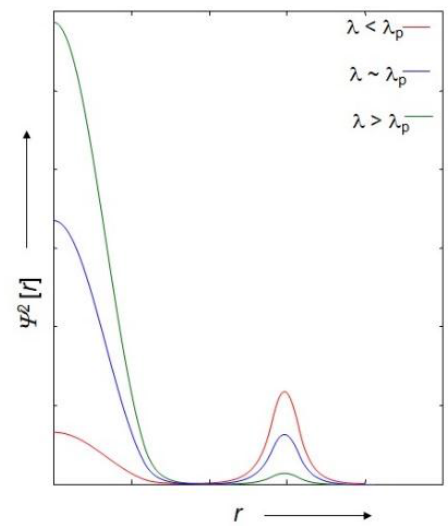

Fig 3. Schematic variation of modal power with r for LP_{01} mode

3 Results and discussion

The profile optimization was carried out by adjusting the fiber parameters Δ_1, Δ_2, a, b and c to achieve phase-matching around 1535 nm. The targeted gain (~ 20 dB) was achieved by optimizing the doping profile parameters ρ_0 and r_d, the input pump power and the length of the EDF, respectively. The pump wavelength is 980 nm. The pump power needs to be sufficient to ensure complete population inversion along the length of the EDF to stabilize against transients in the signal power due to channel add/drop. To further improve the uniformity of the gain spectrum across the C-band, the coupling strength of the core and ring modes was fine-tuned by adjusting the inter-core separation c-b. The optimized parameters are listed in Table 1.

Table 1. Optimized parameters of the EDF**

a	:	5.78 μm
b	:	14.0 μm
c	:	15.8 μm
Δ_1	:	0.006
Δ_2	:	0.012
ρ_0	:	1.25×10^{25} m^{-3}
r_d	:	1.5 μm
Pump power	:	200 μW
Length	:	14.0 m

** Signal power chosen as 0.1 mW, targeted median gain 23 dB

The gain of the EDFA has been evaluated by solving the general rate equations for a 3-level laser system, following the procedure outlined by Desurvire [8]. Figure 4 shows the gain spectrum of the dual-core EDFA, which has a relatively uniform gain of 23 ± 2 dB across the C-band. The result has been compared with that for a fiber with the same doping and inner core parameters, but no outer ring. The difference between these two spectra clearly demonstrate the gain-flattening feature of the chosen profile. The pump power has been assumed to be in the LP_{02} mode at 980 nm, whereas the signal is assumed to be in the LP_{01} mode. This has been assumed on the basis of splice loss calculations, for a 15% taper of EDF and SM-980™ before fusion-splicing. This process couples almost 90% of the pump power in the LP_{02} mode.

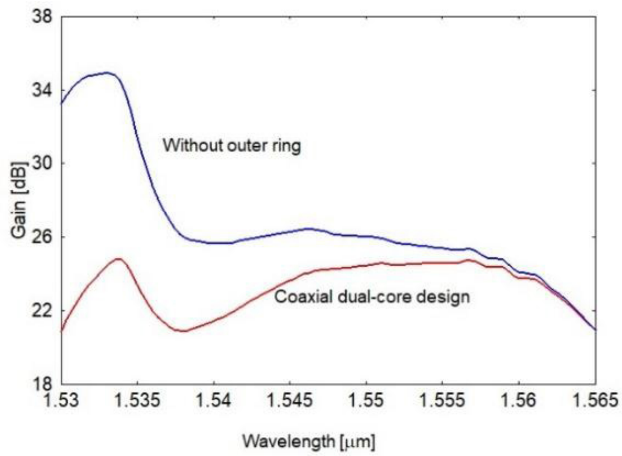

Fig 4. Calculated gain of the EDF with the parameters of Table 1, with and without the outer.

To study the effect of channel add/drop, the EDFA gain has been evaluated for three different channel counts (8, 16 and 32 channels) of the DWDM system, under the same pump power. The wavelength channels are spaced 1nm apart in the C-band. The gain has been plotted in Fig 5. It can be seen that the gain is nearly identical at every wavelength, irrespective of channel count, confirming the stability of the EDFA gain against variation in channel count. The noise figure of the amplifier is also constant at around 6 dB across the C-band. This should be within the tolerance limits of metro networks. The overall chromatic dispersion of the EDFA module is negligible across the C-band for the proposed length of the fiber.

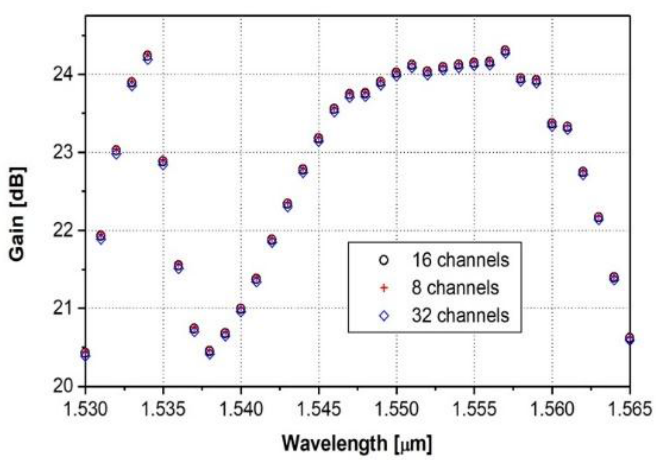

Fig 5. Calculated gain of the EDF with different WDM channel count.

4 Conclusion

The present study has demonstrated that it is possible to achieve a low-cost fiber amplifier for metro networks that can operate in a stable fashion with the dynamic nature of these networks. The fiber parameters were optimized to achieve a median gain of ~ 23 dB, with $a \pm 2$ dB gain excursion across the C-band. The proposed design exploits the resonant coupling between the modes of a coaxial dual-core fiber, to achieve a gain-flattened output. Such an amplifier would not require additional gain-clamping or gain-flattening devices, thus making it a potentially cost-effective and reliable component of the metro core networks.

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