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ELECTRONICS

EXPERIMENTAL MEASUREMENT OF ERBIUM-DOPED OPTICAL FIBRE CHARECTERISTICS FOR EDFA PERFORMANCE OPTIMIZATION

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The paper presents experimental study of the major erbium-doped fibre amplifier **(**EDFA) features such as gain at low signal and gain saturation by an application of different erbium-doped optical fibres (EDFs). The main objective of the research is to estimate how the performance of EDFA varies depending on the length of doped fibre, pumping configuration scheme, as well as excitation source power. It is shown that a high gain coefficient of 16–20 dB can be practically achieved.

Keywords: *erbium-doped fibre amplifier, gain coefficient, gain saturation, rare earth doped fibres, pump power*

1. INTRODUCTION

Significant growth of traffic intensity and increase of data transmission rates in fibre optic transmission systems (FOTS) require higher optical signal-to-noise ratio (SNR) and bit error ratio (BER), which inevitably increase as signal propagates along the optical fibre [1], [2]. Typical fibre loss around the 1550 nm wavelength is about 0.2 dB/km and as the distance increases to 100 km, signal is attenuated by 20 dB. Respectively, optical power depletion affects the performance of transmission systems and in this case, development of optimised optical amplifiers is required.

In today's FOTS, erbium-doped fibre amplifier has been widely used for amplification of signals in wavelength division multiplexed systems. The primary EDFA component is a glass optical fibre doped with Er^{3+} ions (typically in the region of 100 to 500 ppm) and pumping light source. When a beam of light carrying signals passes the erbium-doped optical fibre, a pump laser provides the amplifier energy at erbium absorption peaks of 980 and/or 1480 nm. It has several advantages: immunity to crosstalk among wavelength-multiplexed channels, insensitivity to light polarization state and high pump power utilissation (conversion into signal amplification up to 50 %). However, the presence of major drawback such as an influence of amplified spontaneous emission (ASE), limited gain bandwidth and non-uniformity of a gain curve requires a solution aimed at the improvement of EDFA performance.

Preliminary analytical studies have shown that the performance improvement of the EDFA should be guided by the optimal benchmark against the effectiveness of the gain. This optimal criterion includes the combination of an erbium-doped fibre (EDF) and pump source power, which would ensure a maximal gain coefficient with a minimal noise factor. Moreover, the solution must also be beneficial in terms of energy efficiency, i.e., maximising the gain for a given available pump power and minimising the needed pump power for a desired gain [4]. In present study, we have investigated the performance of EDFA experimentally by using different erbium-doped fibre samples of two manufacturers. Since operating of doped-fibre amplifier depends on fibre geometrical parameters, such as core and cladding properties, absorption and emission coefficients as well as fibre numeric aperture (NA), it is crucial to investigate how they affect EDFA characteristics.

2. METHOD ANALYSIS

EDFA gain is implemented when the amplifier is optically pumped to achieve population inversion of erbium ions at the excited state versus ground state. Gain coefficient depends not only on the wavelength of the incident signal, but also on the local beam intensity at any point inside the amplifier. Considering the case with the gain medium model as a homogeneously broadened two-level system, the gain coefficient can be written as follows:

$$g(\omega) = \frac{g_0}{1 + (\omega - \omega_0)^2 T_2^2 + \frac{P}{P_s}}, \qquad (1)$$

where g_0 is the peak value of the gain, ω is the optical frequency of the incident signal, is the atomic transition frequency, and P is the optical power of the signal being amplified. The saturation power P_s depends on the parameters of the rare-earth element used, such as population relaxation time T_1 (it varies in the range of 100 ps–10 ms depending on the media) and the transition crosssection; T_2 is known as the dipole relaxation time and is typically quite small (< 1 ps).

In the unsaturated regime when $P/P_s \ll 1$ throughout the amplifier by neglecting the term P/P_s in (1), gain coefficient becomes

$$g(\omega) = \frac{g_0}{1 + (\omega - \omega_0)^2 T_2^2} \, . \qquad (2)$$

Respectively, the gain is maximal when the incident frequency ω coincides with the atomic transition frequency ω_0. The amplifier gain G known as the amplification factor shows the relationship between the continuous-wave (CW) signal input power P_{in} and output power P_{out}:

$$G = \frac{P_{in}}{P_{out}}; \tag{3}$$

$$gP = \frac{dP}{dz}, \tag{4}$$

where $P(z)$ is the optical power at a distance z from the input end. A straightforward integration with the initial condition $P(O) = P_{in}$ shows that the signal power grows exponentially as follows:

$$P(z) = \exp(gz). \tag{5}$$

Both $g(\omega)$ and $G(\omega)$ are at maximum when the frequency is at resonance $\omega = \omega_0$ and decrease when the frequency is detuned from resonance. However, the amplifier factor G decreases much faster than the gain coefficient g. Practically, gain coefficient is denoted as G and calculated as the ratio between P_{in} and P_{out}.

In the gain saturation region, the signal growth is linear. This occurs when the signal intensity I_s field grows to a large value comparable to saturation intensity field I_{sat}. The signal growth is then damped by the saturation factor:

$$\frac{1}{1+\frac{I_s}{I_{sat}}}. \tag{6}$$

The ratio of I_s and I_{sat} becomes large compared to unity $I_s/I_{sat} \gg 1$. The growth of signal in the saturation region is determined by:

$$\frac{dI_s}{dz} = I_{sat}\left(\frac{I_p-1}{I_p+1}\right)\sigma_s N, \tag{7}$$

where I_p is a pump intensity field, N is a population inversion, σ_s is a signal absorption and emission crosssection. I_{sat} is linearly dependent on pump power, when signal saturation varies with pump power. The saturation output power is inversely proportional to emission crosssection of fibre; it causes the saturation power being higher at 1550 nm than at 1530 nm [3].

3. EXPERIMENTAL SETUP

Taking into account the simulation results from our previous studies on EDFA mentioned in [5] and [6], practical experiments were carried out using co-pumping and bidirectional pumping scheme to determine an optimal combination of the doped-fibre length and excitation source power that could be used to improve EDFA characteristics. Experiments focused on evaluating EDFA low signal gain and gain saturation. Low signal gain criteria were chosen since the EDFA had a nonlinear nature and measurement of the large-signal saturating gain might not completely characterise the amplifier.

The first part of the experiment represents co-pumping EDFA configuration and the relevant experimental scheme is shown in Fig. 1. Continuous-wave laser operates at the wavelength of 980 nm (maximum power 80 mW) and ensures pumping at 1550 nm. Optical isolators reduce reflections at the input to the amplifier and lowpass filter limits the transmission of amplified spontaneous emission (ASE) frequency components.

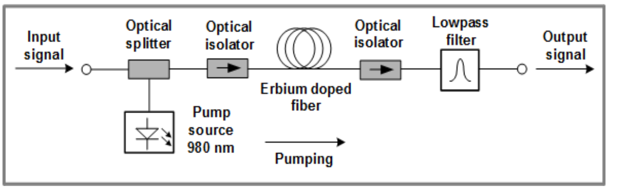

Fig. 1. EDFA experimental scheme with co-pumping configuration.

Measurements were performed with two types of erbium doped-fibres intended for the C optical band: FIB-1 (samples of 5m and 15m) and FIB-2 (sample length 12m). The gain coefficient is introduced as the maximum ratio between the small signal gain (in decibels) and the launched pump power (in milliwatts). The usage of different sample lengths is mandatory as it shows more precise dynamic of stimulated emission process. Input signal power was set to 13.2 dBm and it was constant for all the measurements. General parameters for mentioned fibres are listed in Table 1.

Table 1

Parameter List of the Used Erbium-doped Fibres

Parameter	**FIB-1**	**FIB-2**
Absorption coefficient at 1530 nm	5.45 dB/m	7.5 dB/m
Absorption coefficient at 1480 nm	2.4 dB/m	2.8 dB/m
Cut-off wavelength	942 nm	1014 nm
Attenuation at 1200 nm	2.8 dB/km	< 10 dB/km
Primary cladding diameter	125 +/- 1 μm	125 +/- 1 μm
Secondary cladding diameter	245 +/- 10 μm	245 +/- 10 μm
Core radius	4.1 μm	3.2 μm
Numerical aperture (NA)	0.22	0.26

Excitation source power was obtained through middleware measurements by changing the current level of 980 nm pump module since EDF samples used in experiments were with different erbium ion concentration. Pump power values used in low signal gain evaluation are from 21.1 mW to 54.1 mW.

The second experiment was done with bidirectional pumping scheme (Fig. 2) where two light sources were used. Those sources ensure simultaneous pumping in opposite directions: the one at 1480 nm with high quantum efficiency operates in counter-propagating regime, while 980 nm source in co-propagating regime. Input signal power for 980 nm pumping source remains the same and is 13.2 dBm respectively but for 1480 nm it is fixed at 11.2 dBm. Moreover, in the present experiment we also used 2m and 5m long erbium-doped fibre samples from another manufacturer (FIB-3). The relevant parameters of FIB-3 are shown in Table 2.

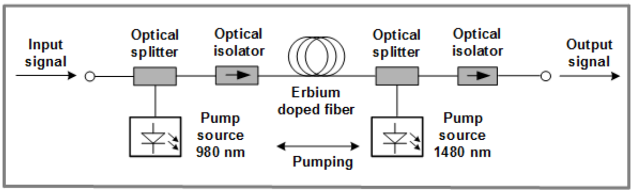

Fig. 2. EDFA experimental scheme with bidirectional pumping configuration.

Table 2

Parameter List of the Used FIB-3 Sample

Type of the fibre	I-12 (980/125)
Absorption coefficient at 979 nm	11.2 dB/m
Attenuation at 1200 nm	4.3 dB/km
Secondary cladding diameter	239.2 µm
Core radius	0.1 µm
Cut-off wavelength	950 nm
Primary cladding diameter	124.8 µm
Mode field diameter	6.1 µm
Numerical aperture (NA)	0.22

4. RESULTS AND DISCUSSION

Figure 3 represents the dynamics of low signal gain using FIB-1 and FIB-2 samples with co-pumping EDFA configuration. It can be seen that gain coefficient variations are negligible since with an increase in pump power it changes only for 1–2 dB. As may be seen below, from the energy efficiency perspective it is optimal to use 12m long FIB-2 when the gain of 17.1 dB is achieved at 37.4 mW. It was also observed that the usage of 15m long FIB-1 led to a faster reach of EDFA saturation regime: after an increase in pump power by about 8 mW (from 46.2 to 54.1 mW), the gain coefficient changed by 0.8 dB. The overall measurement results using co-pumping EDFA scheme showed that the maximal gain coefficient of 19.1 dB corresponded to pump power of 54.1 mW.

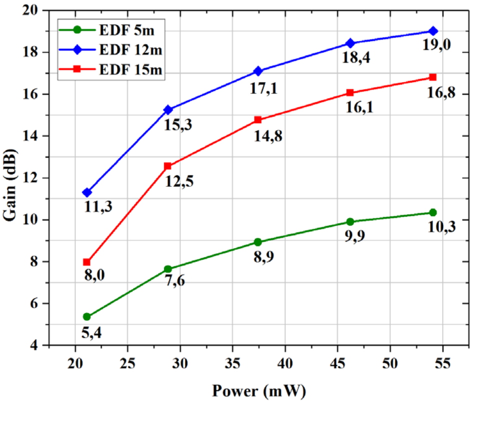

Fig. 3. EDFA gain at a low signal for 5m (FIB-1), 12m (FIB-2) and 15m long (FIB-1) using co-pumping configuration.

In theory, bidirectional EDFA pumping should increase both output power and gain coefficient. After an analysis of the obtained results using a bidirectional pumping scheme, this statement was practically proven. The results for 15m long FIB-1 (Fig. 4) show that the minimal pump power of 21.3 mW corresponds to the gain coefficient of 14.4 dB. In comparison with the single-direction pumping scheme, it is a notable benefit since the previously mentioned gain coefficient required pump power of 37.4 mW. From this observation, it can be clearly seen that the application of bidirectional pumping leads to energy preservation by up to 16 mW. Maximal gain coefficient for 15m and 20m long samples is in the range of 19–20 dB.

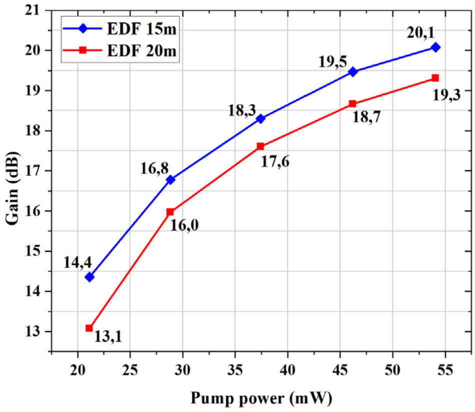

Fig. 4. EDFA gain at a low signal for 15m and 20m long FIB-2 using bidirectional pumping configuration.

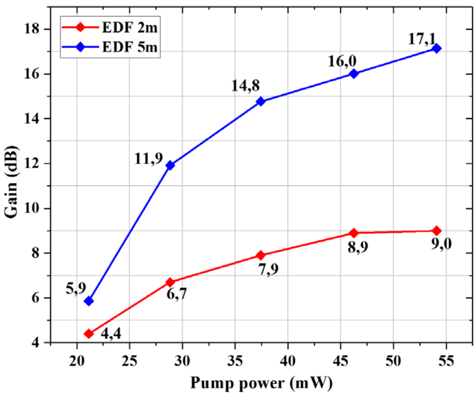

Fig. 5. EDFA gain at a low signal for 2m and 5m long FIB-3 samples using bidirectional pumping configuration.

The usage of FIB-3 erbium-doped fibre with bidirectional EDFA configuration (Fig. 5) gives a maximal gain coefficient of 9 dB with 2m long EDF at pump power of 46.2 mW. With an increase in fibre length to 5 m, maximal gain increment is 7.2 dB. Summing up the results for both FIB-3 samples, it can be concluded that present fibres are suitable for an optimised EDFA design since short lengths are preferable from the construction perspective.

Gain saturation is experienced when the metastable energy level population is severely depleted by a high rate of stimulated emission. Consequently, as the input signal power is increased past the low-signal region, more photons will enter the erbium-doped fibre stimulating emission of photons and depleting the metastable energy level faster than it can be filled. Therefore, the amplification will reach a saturation limit and with the growth of input signal power the gain will decrease. The relevant gain saturation measurement results are depicted in Figs. 6 and 7.

When comparing the results for FIB-1 of 5m and 15m (Fig. 6) by maximal achievable coefficient, it is seen that the usage of a longer fibre does not affect gain indicators since the maximum value differs only by 1 dB: 19.8 dB for 15m and 18.3 dB for 5m, respectively. However, from the energy efficiency perspective the usage of 5m fibre is more effective as the maximum gan is achieved with the power of 3.3 mW. For a 15 m long sample pump power states to 4.6 mW. In the case of Fibrecore EDF-s (Fig. 7), the greatest gain values of 18.5 and 21.2 dB correspond to 2 m and 5 m long fibres. The relevant pump source powers, where the most active stimulated emision process is observed, are at 3.4 and 6.3 mW.

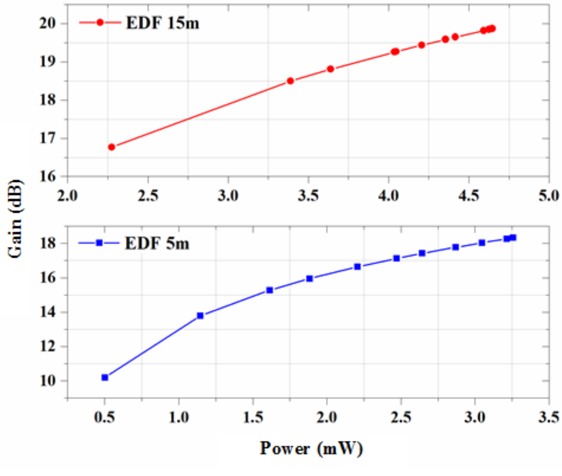

Fig. 6. Gain saturation for 15m and 5m long FIB-1 samples.

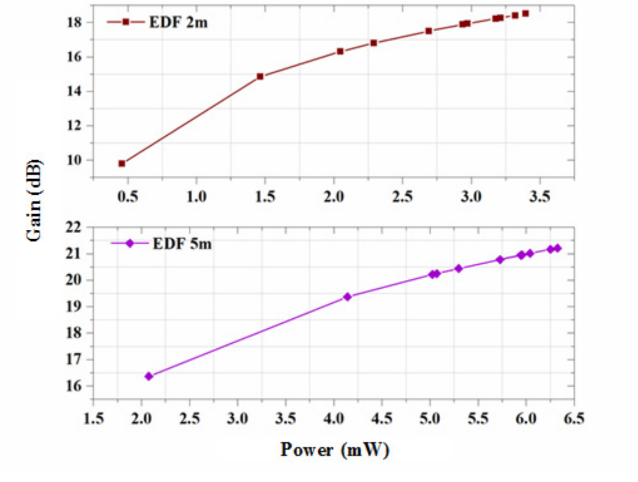

Fig. 7. Gain saturation for 2m and 5m long FIB-3 samples.

5. CONCLUSIONS

In the present study, the major erbium-doped fibre amplifier features, such as gain at a low signal and gain saturation by the application of different erbium-doped optical fibres, have been experimentally evaluated.

The obtained results have shown that the usage of 15m long FIB-1 leads to a faster reach of EDFA saturation regime: after an increase in the pump power by about 8 mW (from 46.2 to 54.1 mW), the gain coefficient has changed by 0.8 dB. The present findings are of direct practical relevance.

It has been demonstrated that the application of bidirectional pumping setup where 1480 nm light source operates at counter-propagating direction and 980 nm source at co-pumping direction, respectively, allows achieving a higher low-signal gain with less power consumption. Overall, the maximal gain achieved with 15m and 20m long FIB-1 samples is in the range of 19–20 dB.

In conclusion, during this study we have obtained the optimal range of doped fibre length (5–20m), which makes it possible to provide the gain within 16–20 dB at the pump power of 54 mW. Further research will be focused on simulations and experimental analysis of other rare-earth dopants and their application in optical signal amplification solutions.

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REFERENCES

1. Supe, A., Porins, J. & Ivanovs, G. (2013). Optical fibre nonlinear coefficient measurements using FWM. In *Progress in Electromagnetics Research Symposium (PIERS) Proceedings*, 25–28 March 2013 (pp. 339–341). Taiwan, Taipei.
2. Miyamoto, Y., & Takenouchi, H. (2014). Metro dense space-division-multiplexing optical communications technology for petabit-per-second class transmission. *NTT Technical Review Regular Articles*. 1–7.
3. Agrawal, G.P. (1997). *Fibre-optic communication systems.* New York: John Wiley & Sons.
4. Essiambre, R.J., Kramer, G., Winzer, P.J., Foschini, G.J., & Goebel, B. (2010). Capacity Limits of Optical Fibre Networks. *J. Lightwave Technol., 28*, 662–701.
5. Lavrinovica, I., Porins, J., & Ivanovs, G. (2015). Estimation of EDFA performance in 40 Gbit/s 8 channel DWDM transmission system. In *Progress in Electromagnetics Research Symposium (PIERS) Proceedings*, 6–9 July 2015 (pp. 502–505). Prague, Czech Republic.

6. Lavrinovica, I., & Porins, J. (2015). Noise figure analysis of EDFA with different pumping configurations in 40 Gbit/s 8 channel DWDM transmission system. In *Advances in Wireless and Optical Communications (RTUWO) Proceedings*, 5–6 November 2015 (pp. 1–4). Riga, Latvia.

AR ERBIJU LEĢĒTO OPTISKO ŠĶIEDRU RAKSTURLIELUMU EKSPERIMENTĀLIE MĒRĪJUMI EDFA PASTIPRINĀTĀJA DARBĪBAS OPTIMIZĀCIJAI

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K o p s a v i l k u m s

Mūsu darbā tika eksperimentāli pētītas ar erbiju leģēto optisko šķiedru pastiprinātāja (EDFA) pamatīpašības, tādas kā spēja pastiprināt vājos signālus un pastiprinājuma efektivitāti, izmantojot dažāda garuma ar erbiju leģēto optisko šķiedru (EDF) paraugus. Pētījuma mērķis bija novērtēt EDFA darbību atkarībā no leģētās šķiedras garuma, pumpēšanas konfigurācijas un ierosinošā avota jaudas. Mērījumos tika izmantotas trīs dažādas EDF šķiedras no diviem ražotājiem: FIB-1 (garumi 5m, 15m un 20m) , FIB-2 (garums 12m) un FIB-3 (garumi 2m un 5m). Ierosinošā avota jaudas diapazons ir no 21.1 mW līdz 54.1 mW.

Noteikts, ka vāja signāla pastiprināšanas režīmā ar divvirzienu pumpēšanu 15m garai FIB-1 šķiedrai pie minimālas ierosinošā avota jaudas 21.3 mW atbilst 14.4 dB pastiprinājums. Tas nodrošina 16 mW jaudas ietaupījumu salīdzinājumā ar vienvirziena pumpēšanu, kur šādu pastiprinājuma koeficientu iegūst ar jaudu 37.4 mW. Mērījumu rezultātā iegūti optimālie EDF šķiedru garumi (5-20m) ar kuriem iespējams nodrošināt pastiprinājumu 16-20 dB robežas pie ierosinošā avota jaudas līdz 54 mW.

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